Mechatronic Design in Textile Engineering

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Mechatronic Design in Textile Engineering

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PREFACE

In recent years, mechatronics products and manufacturing systems have begun to dominate the consumer goods and office equipment markets and the manufacturing industry. Application of mechatronics design concepts have also been apparent in textile machines.

Most engineering products or processes have moving parts and require manipulation and control of their dynamic construction to a required accuracy. This may require the use of enabling technologies such as sensors, actuators, software, communications, optics, electronics, machine dynamics and control engineering. A key factor in the mechatronics philosophy is the integration of microelectronics and computer science/information technology into the design of mechanical systems, so as to obtain the best possible solution. Design of such products and processes, therefore, has to be the outcome of a multi-disciplinary activity rather than an interdisciplinary one. Mechatronics is therefore not a new branch of engineering, but a newly developed concept that underlines the necessity for intensive interaction between different branches of engineering. Hence mechatronics challenges the traditional engineering thinking because the optimum solution required for the best functional design must involve crossing the boundaries between the traditional engineering disciplines.

Increased flexibility, versatility, intelligence level of products and systems, safety and reliability as well as lower energy consumption and cost are the gains achieved through applying the mechatronics concepts to the design process. These advantages translate into a product or a system with more customer appeal, produced quickly at reduced cost and serving larger markets.

The days of electronic add-on in textile machines have now gone and the mechatronics design concepts find a suitable breeding ground and a major application field within the textile machinery industry. There will be a significant increase in the number of textile machines and systems which are designed using mechatronics philosophy. This, of course, will translate into increased efficiency, productivity and quality.

These proceedings contain a selection of lectures presented at the NATO Advanced Study Institute entitled "Advancements and Applications of Mechatronics Design in Textile Engineering" held in Side, Antalya, Turkey, 5-16 April 1992. Lectures were presented by leaders mainly from Europe and North America in disciplines contributing to the emerging international focus on mechatronics design and its applications in textile machines and systems. Participants in the ASI were specialists in mechatronics and/or in various disciplines in textile engineering and technology, a number of whom presented contributed papers during the Institute and all of whom participated actively in discussions on technical aspects of the subject.

The extent and variety of the lectures and contributed papers presented in these proceedings illustrate the contribution of numerous individuals in preparation and conduct of the ASI. The Institute Director wishes to thank the Organising Committee members for the advice and the guidance that he received, and all the contributors to these proceedings and participants in the ASI. Special thanks go to Mrs Brenda Cole who provided much useful administrative and secretarial assistance before, during and after the Institute. I am also grateful to the staff of the Pinto Travel Agency and the Saray Regency Hotel for looking after us so admirably and feeding us so well. Finally, without the financial support* of the NATO Scientific and Environmental Affairs Division, The ASI and these proceedings would not have been possible. Their support is gratefully acknowledged by all concerned with the Institute.

Memiş Acar

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MECHATRONICS

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1. Introduction - What Is Mechatronics ?

Mechatronics, as a discipline, has been around for a long time. The combination of mechanical rastering with electronic image production used by John Logie Baird in his early TV research was a good example of integrated design. Indeed, most early workers in that branch of physics which was to become electrical engineering were equally at home with electronic and mechanical artifacts and combined them in various experiments and products.

However, as a name, Mechatronics is only about 15 years old. It was coined in the later 1970s by an employee of the Japanese Yasukawa company - a major manufacturer of industrial robots. In Japan today Mechatronics is often taken to be synonymous with Robotics and many Mechatronics laboratories are devoted entirely to robotics research. However, the rest of the world has tended to use the word to encompass a far wider spectrum of products and systems which includes as a very important subclass that of the modern industrial robot.

If we consider the definition of Mechatronics it is easy to see why the robot is an outstanding example of the class. There are many definitions - as might be expected of a discipline in a state of evolution and self-determination. We give three:

The first is the ‘EEC’ version. "The synergistic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacture of products and processes." Here the emphasis is on ‘synergy’ - a word which conveys the idea that the final product is greater than the mere sum of its parts. The design integration has led, in some sense, to a product which exceeds previous performance levels by something more than just being better - a new dimension of performance has been attained.

The second definition was coined by myself and colleagues at Loughborough University of Technology. "The design and manufacture of products and systems possessing both

M. Acar (ed.), Mechatronic Design in Textile Engineering, 1–26.

a mechanical functionality and an integrated algorithmic control." Here we attempt to differentiate between Mechatronics and other intersecting fields such as Information Technology and Electromechanical Design. The Mechatronics product has "mechanical functionality", i.e. parts of it move in a purposeful manner to achieve some function. By contrast, Information Technology has concentrated upon the mere processing of data. Often even the transducers and sensors which provide the data to be processed are ignored by the Information Technologists, who are concerned only with algorithms for converting the data into new forms and architectures for optimising the conversion process (usually by speeding it up).

The Mechatronics product has 'algorithmic control'. By this is meant control implemented by means of a more or less complex computing programme. By contrast, Electromechanical engineering has been more usually concerned with systems in which the control actions have been by means of simple switches, solenoids and similar on-off actuators, and in which the controls have been implemented by fixed parameter analogue controllers typical of which is the '3-TERM' PID type.

The third definition should be considered if only for its succinctness "The Design of Intelligent Machines".

2. Robotics - The Breeding Ground

The crucial difference between simple electromechanical thinking and mechatronic thinking can be seen clearly in the impact made on robotics by the genius of Bruce Shimano [1] who was responsible for the conception and development of the VAL programming language.

Prior to this, industrial robots were viewed as a collection of individual joints. Each joint had its own transducers and actuator. Each was controlled individually. The overall system was considered to be a collection of N single degree of freedom subsystems. The result was that it was difficult to programme these early robots, their motions were jerky and awkward. VAL, on the other hand, embodies a multivariable conception. The joints were each to be controlled taking explicit account of all the others. The system was considered to be a single N-degree of freedom system. This change in viewpoint has been the reason, more than any other, that industrial robots have found wide application in tasks ranging from arc welding to industrial assembly.

3. An Example - Materials Handling Machine

We can take a deeper look at this aspect of Mechatronics - that it leads to quantum changes in performance capabilities - by considering a materials handling machine.

The JCB 520 is a popular vehicle for use on building sites and similar rough terrain applications. The basic purpose of the machine shown diagrammatically in Figure 1 is to control the position of the forks to lift pallets and to stack them as required. The forks are deployed at the end of a telescopic boom which is also able to rotate about a

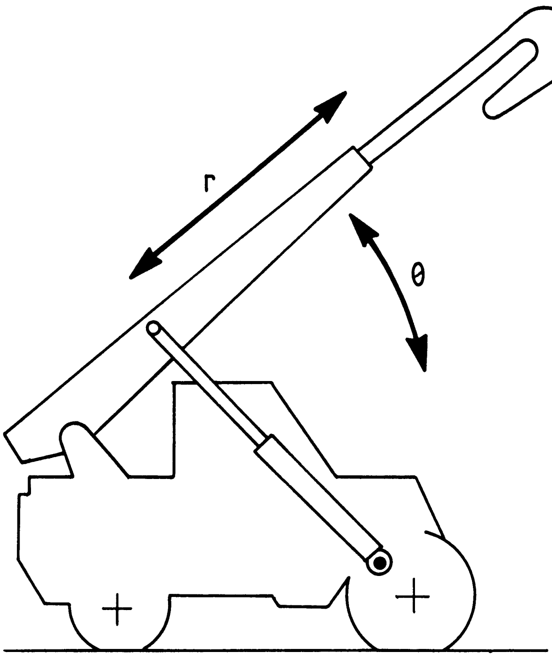

Figure 1 Diagrammatic illustration of the basic purpose of the JCB 520 materials handling machine

horizontal axis. This mechanical structure which is of the (r,θ) type as shown, is chosen for reasons of load capacity and reachability.

This structure is not, however, well suited to the palletising tests which are the staple of the machine. In palletising, the operator usually wishes to move the forks horizontally (to engage and disengage pallets) or vertically (to lift or stack pallets). The 'task space' is therefore (x,y), in contrast to the 'joint space' which is (r,θ).

The consequence is that if the operator wishes to move the forks in the x or y direction, natural to the task, he must operate two control levers simultaneously <u>and</u>, moreover, the amount by which these levers must be moved varies all over the task space. The difficulties imposed by this should not be underestimated - for example, if the operator wishes to move the forks vertically from the ground upwards, his control of the telescopic degree of freedom changes part way through from retraction to extension - in control theory terms the sign of the loop gain changes!

The result of this complication in control actions is that the operator is rarely able to move the forks in true horizontal or vertical directions. Often a stack of pallets will be pulled or pushed out of the vertical and may fall over to the hazard of the driver and other workers.

Of course, it would have been possible to design a truly (x,y) machine (Figure 2). However, it would have been unacceptable for other reasons, including reachability.

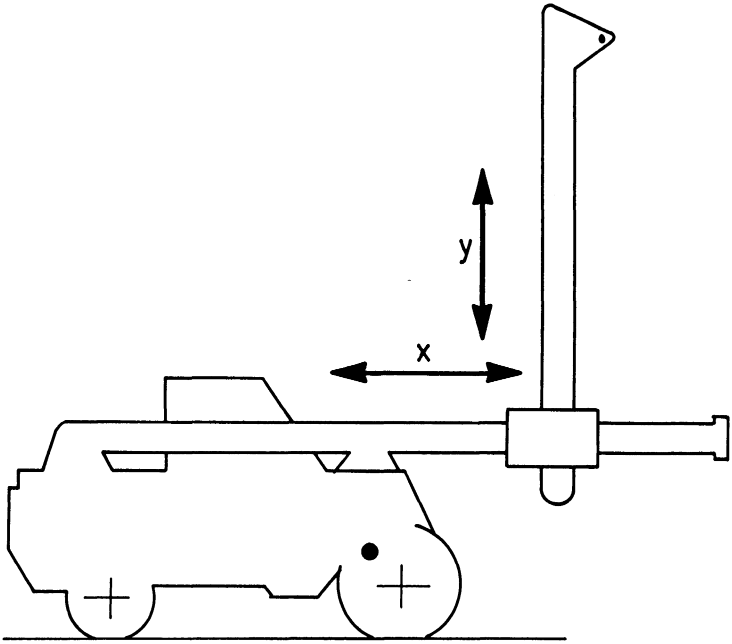

Figure 2 An (x,y) machine to perform the same task

Mechatronic thinking allows the vehicle (like the robot) to be viewed as an integrated 2 degree of freedom system. The relationship between the joint space and the task space can be invoked as:

$$\begin{Bmatrix} x \\ y \end{Bmatrix} \equiv \begin{Bmatrix} x(r,\theta) \\ y(r,\theta) \end{Bmatrix} \qquad \text{(a)}$$

and differentiated to give

$$\begin{Bmatrix} x \\ y \end{Bmatrix} = \begin{bmatrix} \delta x/\delta r & \delta x/\delta\theta \\ \delta y/\delta r & \delta y/\delta\theta \end{bmatrix} \begin{Bmatrix} r \\ \theta \end{Bmatrix} \qquad \text{(b)}$$

or $$\underline{z} = \underline{J}(\underline{\Phi}).\underline{\Phi} \qquad \text{(c)}$$

where J(Φ) is the so-called Jacobian matrix. Inverting (c) leaves

$$\underline{\Phi} = \underline{J}^{-1}\ (\underline{\Phi})\ \underline{z} \qquad \text{(d)}$$

which allows the computation of the joint speeds required at any time to cause the forks to move at any required speed in the task space. The equation is, at least for this case, very simple and straightforward to implement on a microprocessor.

The overall implementation of the controller is shown in Figure 3.

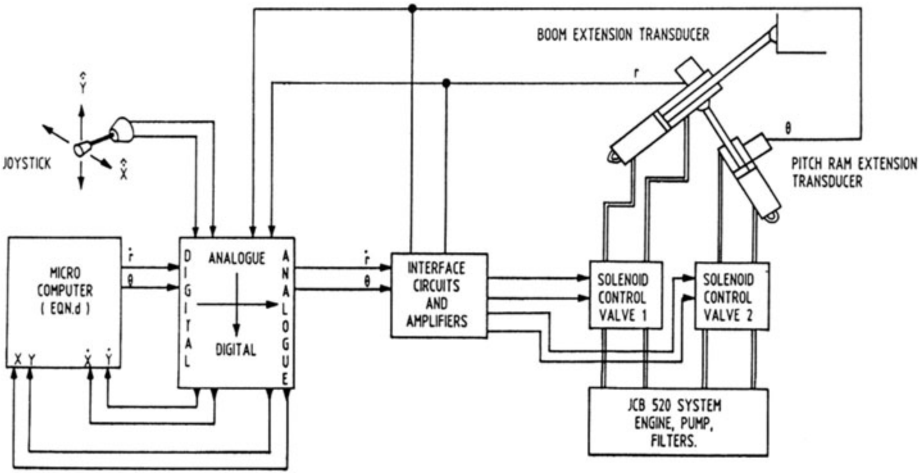

Figure 3 Overall implementation of the controller

The effect of this Mechatronics design is dramatically illustrated in Figure 4, which shows the improvement in the operator's efficiency in moving the forks around a rectangular path. Since the machine appears to the operator to have an (x,y) construction, it is safer and easier to learn. The operator can be given a one-handed control stick, leaving his other hand free to operate other controls [2].

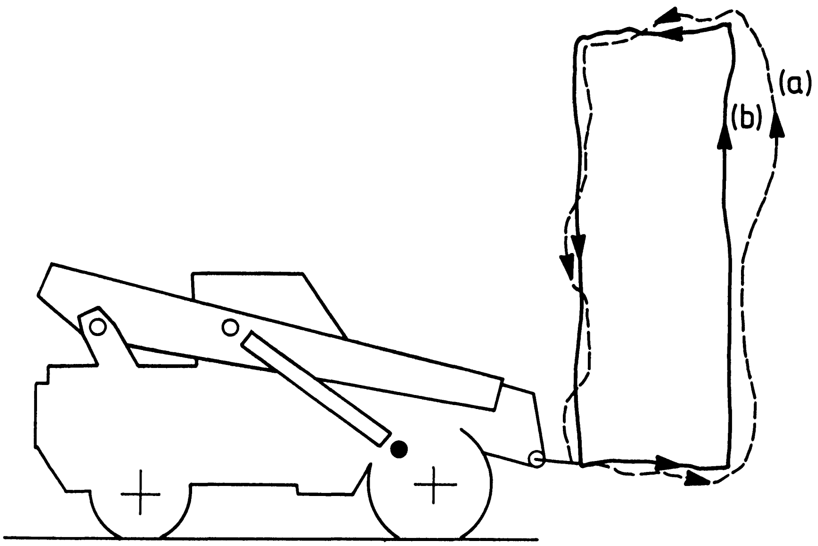

Figure 4 Effects of the mechatronics design

4. True Mechatronics - Intelligent Rams From Finland

It is emphasised that while this example shows the benefit of Mechatronic thinking, it does not illustrate true integrated design since the transducers necessary to measure r and θ were added later as were the servo valves. In particular, one shortcoming of the above example is that the transducers measuring the extensions of the two rams render the system less robust and prone to accidental breakage.

A true Mechatronic design would have included, from the start, the type of intelligent ram now being researched by, among others, the Finnish Mechatronic programme [3]. In this type of smart actuator, the transducers (for ram position and velocity), the servovalves and the interface circuitry are contained within the outer ram housing. Figure 5 shows a typical ram. This design philosophy allows each ram to be considered, as electronic devices routinely are, as something simply to be connected to a standard bus,the only difference being that it requires power connections to hydraulics as well as electrics (Figure 6).

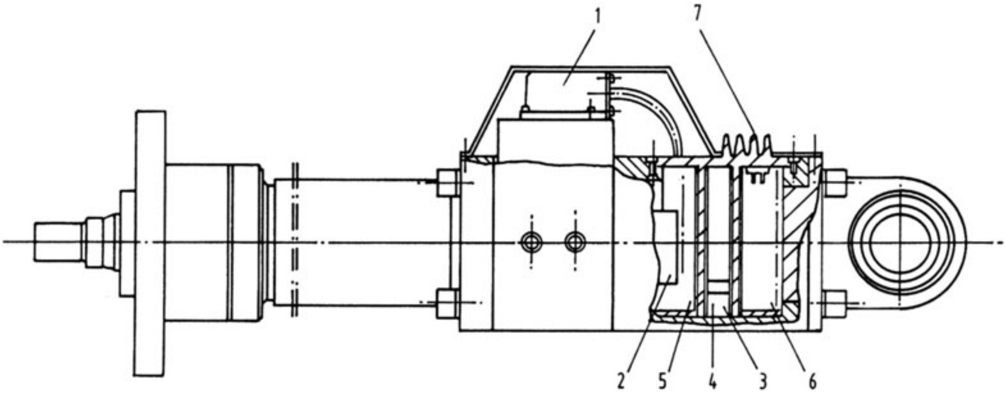

Figure 5 Structure of the actuator: 1 Control valve, 2 Position/velocity sensor, 3 Communication unit, 4 Servo-controller, 5 I/D unit, 6 Power source, 7 Connector

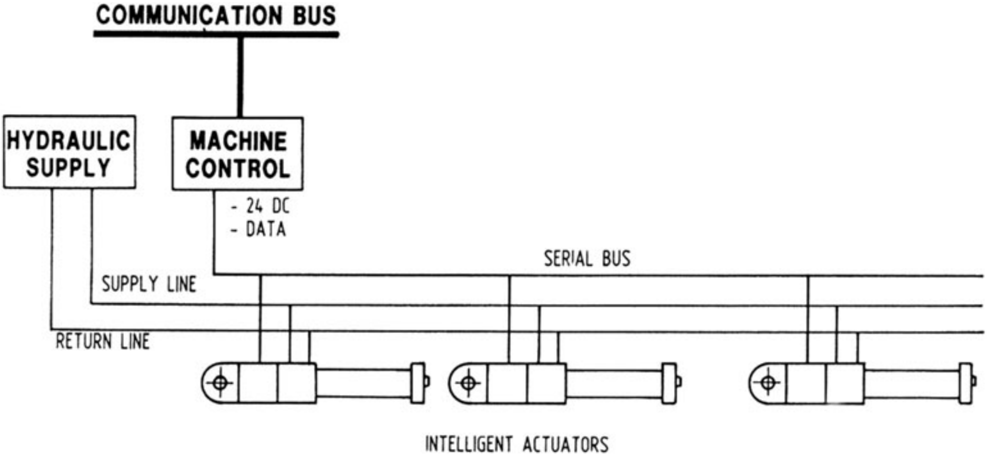

Figure 6 The centralised control principle

5. Pseudo Mechatronics

Although it is undeniable that the Japanese have led the world in their exploitation of the Mechatronics design philosophy based upon attention to quality and the use of design teamwork, care must be taken to discriminate between Japanese products which embody true Mechatronics and those in which pseudo-Mechatronics is employed in a cosmetic or even meretricious sense.

It is often suggested that the best example of Mechatronics design is to be found in the range of Japanese SLR cameras which in recent years have flooded the market. Such a camera has the ability to:

1. Identify film type.
2. Sense ambient light level, often selectively.
3. Set the exposure via aperture setting and shutter speed.
4. Adjust the focus.
5. Control flash level and duration.
6. Provide features such as multiple exposure, low battery warning and so on.

All of these features are implemented within the camera body itself and so require miniature design.

However, it is not at all certain that these features are really improvements.

Someone who cannot focus a camera manually would be better advised to use a focus-free version. Many of the focusing systems use a small area at the centre of the image to provide the necessary information. If this is used inadvertently to take a picture of two people standing with a space between them, then the focus will latch on to the background and the subject pair will be out of focus. It takes considerable concentration to avoid this type of problem in a modern feature-packed camera.

True Mechatronics design certainly led to the integration of light meter, range finder and so on into the main body of the camera. There is also a high Mechatronics content in the ultrasonic motor used in some AF lens systems. The rest, however, is pseudo mechatronics.

The very slight advantages of this type of camera are heavily outweighed by cost and a built-in obsolescence inevitably associated with a large number of miniature components each of which can go wrong.

The real reason for the success of this type of product is a very deliberate and effective exploitation of a general desire on the part of the public to possess ‘high-tech’ products with a prestigious cachet.

6. Generalism Versus Specialism

It is also often opined that, because Mechatronics is a broad discipline requiring the integration of a wider spectrum of technologies, there is a need for engineering generalists rather than specialists. If by generalist is meant someone whose sum total of engineering knowledge is the same as that of the specialist, but whose knowledge is spread more widely, then it is unlikely that these generalists will be able to cope with the high technology demands of Mechatronics. What is needed is a body of specialists who have deliberately educated themselves in fields other than their own specialisms. A team comprising a number of such specialists who are able and encouraged to communicate is a much more effective grouping than either a group of generalists or a group of narrow specialists.

This leads naturally to consideration of the implications of an education or training programme best suited to Mechatronics engineering.

Figure 7 shows, in a diagrammatic way, the knowledge levels of different types of designer. The 'generalist' has relatively shallow knowledge across a broad spectrum. The 'specialist' has a very deep knowledge but of a limited breadth. The Mechatronics designer, while possessing a deep knowledge of one or more areas, has a generalist's understanding across the board.

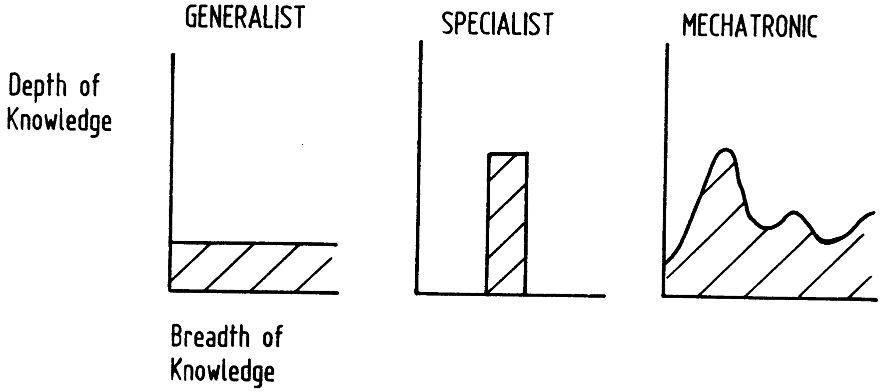

Figure 7 Knowledge levels of different types of designers

This diagrammatic view can be extended to illustrate why neither a generalist nor a specialist education is suited to the cross-disciplinary nature of Mechatronics design.

Figure 8(a) illustrates the fact that it is not possible by combining the resources of several generalists to increase the depth of knowledge contained within the team.

Figure 8(b) illustrates that a team composed of disparate specialists will not possess the necessary cross-couplings to permit adequate communications.

Figure 8(c) shows several Mechatronics designers, with different major specialisms, combining to produce a team with optimal coverage of technology.

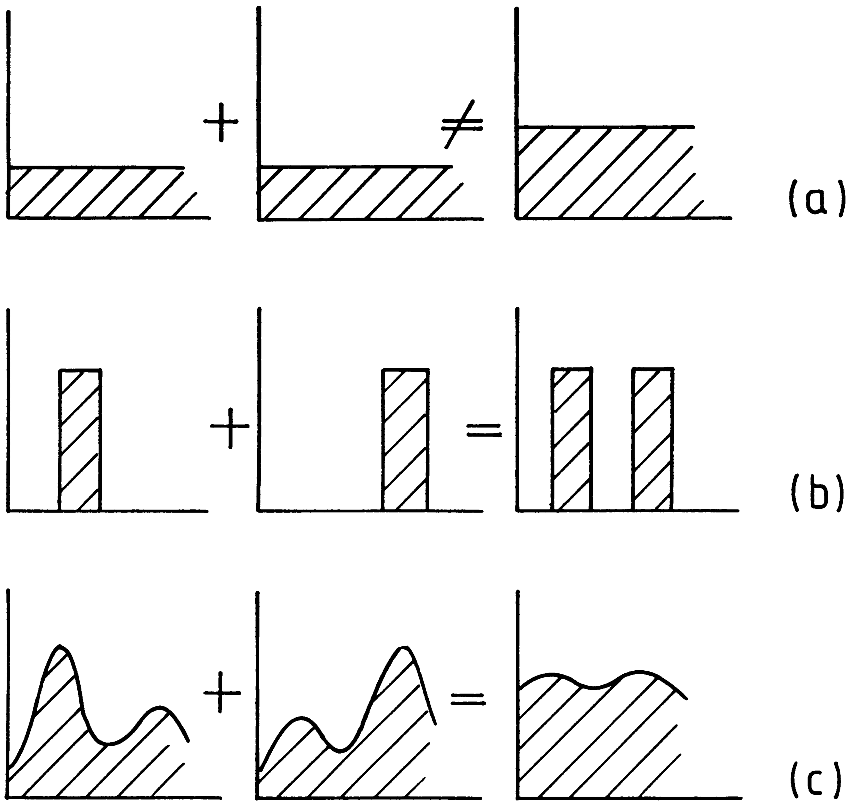

Figure 8 Various combinations of (a) "generalist" (b) "specialist" and (c) "mechatronics" designers

In view of this analysis of the team-capabilities of generalist and specialist designers, it is not considered (at least by this author) that there is a need for undergraduate education in Mechatronics per se. There is an overriding need for well educated specialists - in Mechanical, Electrical and Electronic Engineering and in Computer Science. Where effective education and training can take place is at postgraduate level (Masters or Doctors), or within a company. This company training can be in the form of attachment to teams of designers with a consequent gaining of wide experience and an ultimate role as the Mechatronics team leader.

In University or other higher education it is necessary to choose very carefully the type of project which the student is given to do. All too frequently in the past the PhD student has been directed towards some specialist and rarefied problem which no doubt tests his or her intellectual powers, but which has very little relevance to any future career. At the end of their research period the PhD student is unwanted by industry which feels that his skills are not directed to real world problems.

Instead, a good Mechatronics based PhD project would include all of the following:

- Design of a real physical artefact for the solution of a real technological problem.
- Simulation used as part of the design process but not regarded as sufficient in itself.
- Industrial participation from the outset at least in an advisory capacity.

This emphasis on 'real-world' problems does not mean that projects should necessarily be industry-oriented or industry-based. Rather that the problems require solution methods which are generic and applicable to advanced industrial problems. Thus, in Japanese university laboratories, one sees a proliferation of locomotory robots, flexible arms, robots which can play musical instruments and, in the case of Tokyo University's Mechanical Engineering Department, a robot which can use chopsticks. It is not that the Japanese industry needs now, or is likely to need in the future, robots with these capabilities. Rather, it is an undeniable fact that a student who has mastered the control theory and practice demanded by the solution of these tasks is a very strong candidate to join an industrial Mechatronics design team.

The most urgent message of Mechatronics is that there is a tendency, which must be resisted at all costs, to view one end of the overall design spectrum as 'high-technology' and hence more worthy of research effort than the other. This 'high-technology' end is, at present anyway, the 'information technology' end. The other, disregarded, end is that involving Mechanical design.

Figure 9 shows the various elements in a piece of Mechatronics design. At the left is a machine system; a textile machine, a computer memory, a motorcycle. This will be equipped with sensors of various types to monitor performance; these will include say yarn tension meters, read-head positional transducers; engine temperature meters. The data from these sensors will be fed raw to a computer system, with a particular architecture and supplied with appropriate software. The raw data is processed to provide a useable set of signals which should be fed back to mediate the machine's operation.

However, as noted above, it is common to regard the left hand of this spectrum as being of low research level and to concentrate the majority of research level at the right hand information technology end. The result is a lack of communication at two interfaces; firstly at the interface between the information technologists and the electronics technologists responsible for sensor design and secondly at the interface between these groups and the mechanical designers. Synergy is lost.

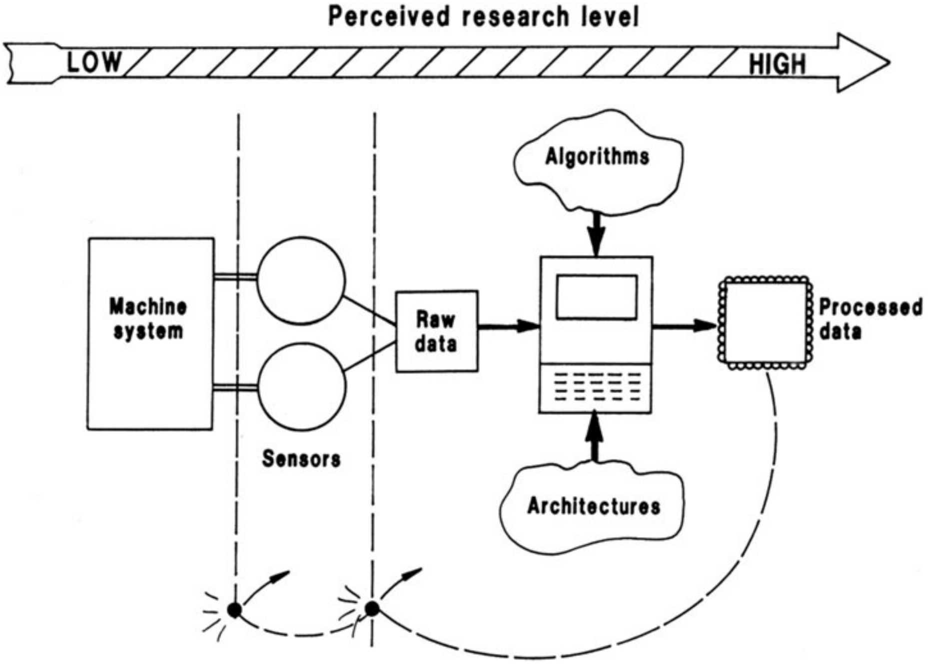

Figure 9 Elements in a piece of mechatronics design

7. Mechatronics Design Methodologies

It is perceived among Mechatronics practitioners that while there is a lot of high level software available to support Mechanical design, Electrical and Electronic design and Software design, there is little available to support the interdisciplinary design philosophy of Mechatronics.

Mechatronics opens up to the design engineer an enormous spectrum of choices and frees him to use his creativity in ways hitherto unfeasible. It is perhaps this very creativity which stands in the way of software support. In exactly the same way that attempts to emulate human intelligence have so far failed almost entirely so that the so-called AI remains locked in a 'blocks-world', so it appears likely that attempts to mechanise human creativity are also doomed to failure and that AD ('Artificial Design') is likely to remain capable only of routine selections of options from previously prepared lists.

There is, nevertheless, good reason to seek to put together software which will perhaps take the tedium out of the Mechatronics design process - if, by nothing else, by allowing easy transfer of data from one analysis package to another.

This, at least, is the rationale behind Fujitsu's "Integrated System to Support Computer Analysis in Preliminary Aerospace Design" [4].

This type of design demands programmes for modelling, simulation, dynamic analysis and optimisation which use huge databases. Figure 10 shows the software structure.

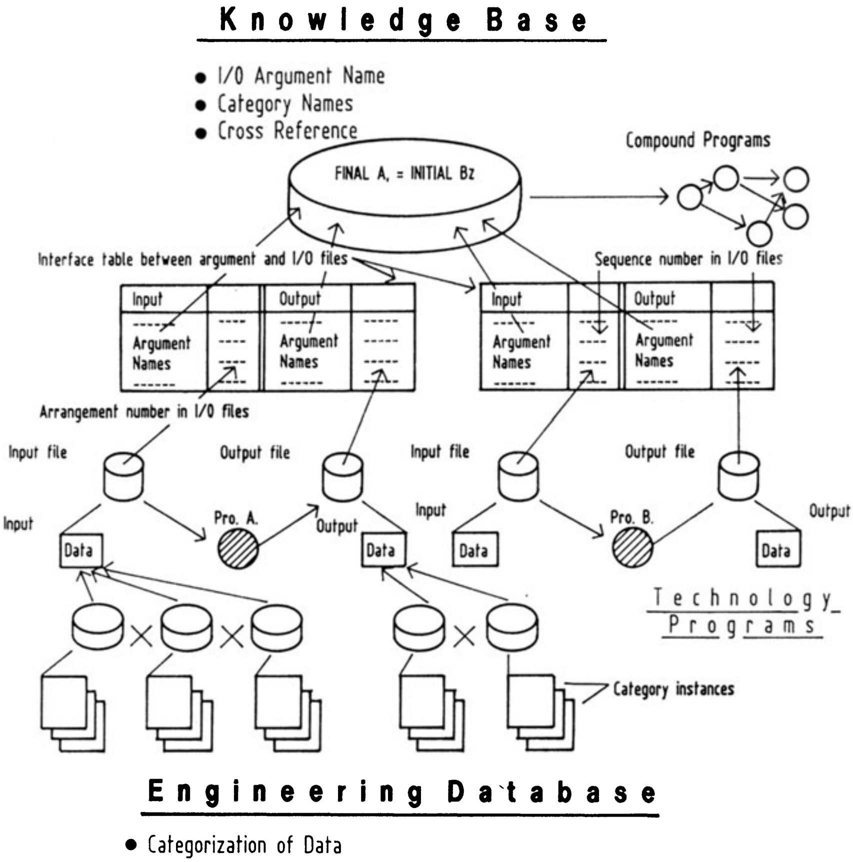

Figure 10 Software structure for "Integrated System to Support Computer Analysis"

Inefficiency in the design process is caused by:

1. Awkward data transfer from programme to programme due by the fact that each programme has hitherto been the province of a different 'department'.
2. Design data being generated and used by each group separately.

The Fujitsu software uses knowledge bases to allow convenient cross-reference between different programmes. The technology library contains a large number of technology programmes each of which can be plugged in or unplugged to suit an application.

It is claimed that "any unfamiliar engineer can execute programmes, manage data and interface with other registered programmes easily".

The system is implemented in the LISP language.

The Hitachi company is also working towards integrated software for design support. The industrial interests of Hitachi cover such a wide spread that it is very easy for a company engineer to gain the sort of multidisciplinary experience needed for Mechatronics design work. However, it is also necessary to try to gather data from this wide effort together in a useable form. Hitachi have evolved a system known as HIDESS II [5]. Although it is not clear how the interfacing between packages is accomplished, the basic outline of the coverage of the programme is in Figure 11. Notice that Mechatronics is seen as a subset of Analysis and Simulation, no doubt because Hitachi, in common with many Japanese companies, sees Mechatronics as synonymous with Advanced Robotics.

In the UK a special Engineering Design Centre (EDC) with the theme of Mechatronics Design has been set up at the University of Lancaster. This has a major aim to develop software to support Mechatronics, but little has yet emerged.

In Denmark, the Engineering Design Institute at Lyngby has done a great deal of work on Design methodologies. Buur, in particular, has made an in-depth study of Japanese design and manufacturing methods [6], and has evolved a classification of design which explains much of the Japanese success. For instance, he shows how the Japanese introduce new products much faster than we do in the West. This is necessary to keep up with the competition from other companies.

It is ironic that while JIT manufacture was originated in Japan with Toyota, it cannot now be applied in many companies because the very high rate of introduction of new products means that there is not enough time to get the manufacturing lines working in an error free manner before they have to be modified for the new models. The Canon company of Japan accept that true JIT is impossible for this reason.

8. Mechatronics In Japan

As stated in the Introduction, Mechatronics was pioneered in Japan. Since then Japan has developed the Mechatronics approach to product design to a very high degree. Many would argue that it is precisely because of this that Japan now enjoys its predominant position in the global marketplace for high technology consumer products like cameras, videos, music synthesizers and motorcycles.

Buur has conducted an in-depth study of Japanese design and manufacture and has analysed the situation in order to provide some guidelines for other manufacturers. The present author recently conducted a short series of visits to Japanese industrial establishments working in the Mechatronics field, and the following are some impressions aimed at providing insight into the Japanese way of progressing the design and manufacture process.

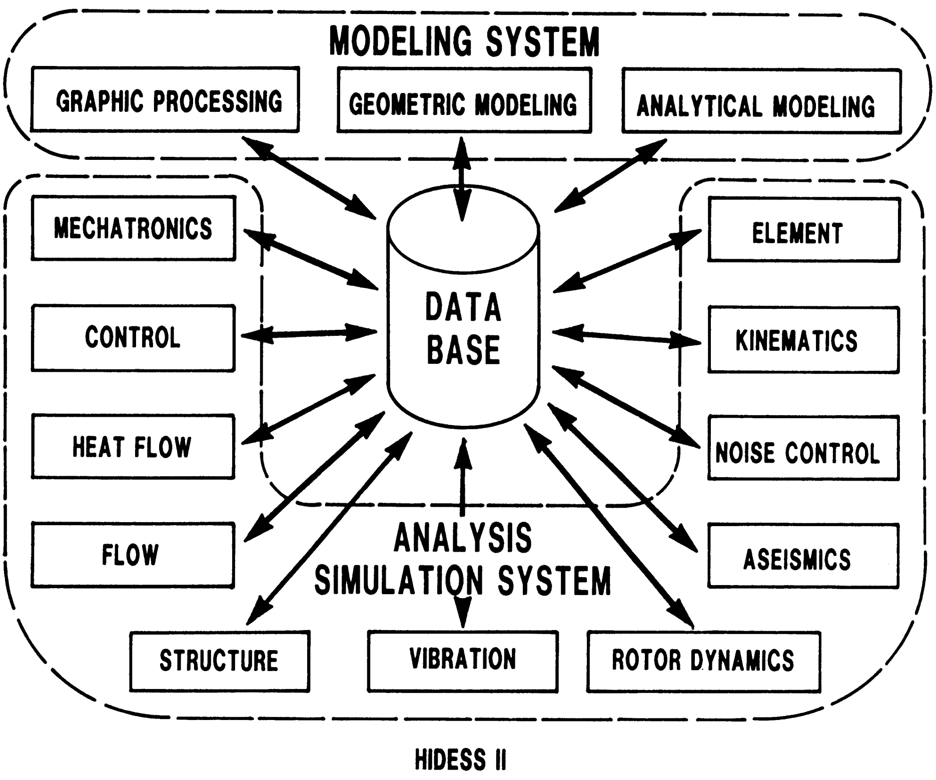

Figure 11 Hitachi's HIDES II Basic outline of the

8.1. THE YOKAGAWA COMPANY

The Yokogawa Company of Tokyo, Japan is heavily involved in the Mechatronics approach to motion control - in its case by developing an electric motor/controller combination capable of out-performing existing products by a long way.

The Research and Development Department of Yokogawa employs 200 engineers in four sections:

Mechatronics
Electronics
Physics and Materials
Computer Science

The Mechatronics Section has developed the DYNASERV Direct Drive Servo Actuator and the route of this product from conception to marketable form reveals much of

Yokogawa's Mechatronics approach to product development. The seeds for the DYNASERV range came from the research interests of some staff in robotics. A number of direct drive robots have been designed worldwide to take advantage in terms of speed and precession to be obtained by the elimination of transmission elements such as gears and cables. This required a new type of motor - one which could rotate slowly but produce a high torque and with the capability of being precisely controlled in both position and speed. It was clear that such an actuator, together with an integrated controller, would find a large market not only in robotics but also in machine tools and automation generally. Having had the idea, the staff members then put the proposal to the Yokogawa management, whose procedure then is to consult with a large number of academic researchers and also industrial R&D workers (carefully chosen not to represent competitor companies). This high profile research evaluation team meets in several brainstorming sessions under the auspices of the Yokogawa Technology Board. This team decides whether the idea should be supported and taken forward, or dropped. If the evaluation team manage to convince the Technology Board that the potential profit is high and that the product fits the Yokogawa profile, then the next part of the sequence is initiated.

Within the Research and Development Department a small interdisciplinary team of researchers is set up. This consists of a project manager, a mechanical designer, an electronics engineer, a software specialist, a manufacturing specialist, any other specialists whose knowledge is deemed useful (in this case an electromagnetic design specialist) and, crucially, a young engineer recently recruited to the Yokogawa staff. A typical team will have between 10 and 20 members. This team meets regularly in brainstorming and evaluation sessions and eventually there emerges a product in prototype form yet possessing features of manufacturability which puts it close to the final form.

Yokogawa see this team formation and operation as the key to their Mechatronics design success.

In the case of the DYNASERV actuator/controller sets the result is a motor which has enormously reduced torque ripple (achieved partly by careful electromagnetic design and partly by feedforward of the expected ripple profile) and, via the application of real-time adaptive control techniques, the ability to self-tune to handle inertia variations of 10:1. The eventual aim, very near to achievement, is to be able to handle up to 1000:1 inertia variations found in automatic indexing tables.

The next Yokogawa product will be the MOTIONACE Universal Motion Control System. This will be modular with integral libraries for inverse kinematics, joint transformations, transmission mechanism characteristics and, eventually, full dynamics capability. There will also be modules for incremental and absolute encoders, vision sensing, torque sensing, analogue i/o and so on. Around forty different modules written in C language are envisaged.

The key to Yokogawa's success lies in the team design philosophy which is central to all Mechatronics. Figure 12 attempts to show diagrammatically the operation of Mechatronics team design as practised at Yokogawa and other successful Mechatronics companies. Here, new staff members are included in design teams. When the team has done its work and the product has been brought to the prototype stage, the team is broken up and its members included in new teams for new products, maybe of quite different types. This demands two features:

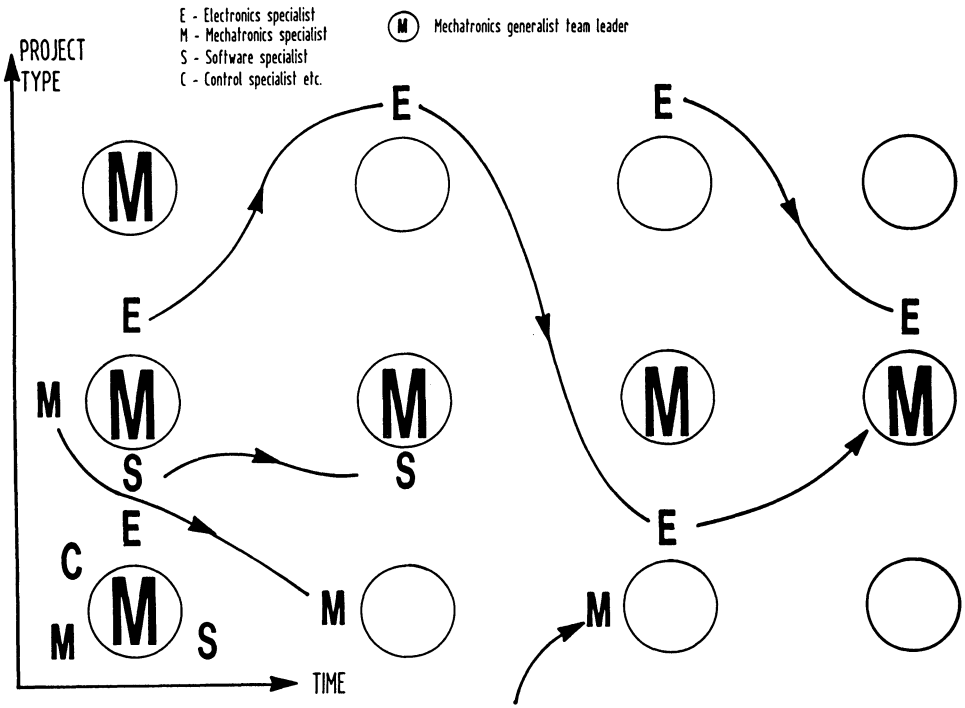

Figure 12 The operation of mechatronics team design as practised at Yokogawa

1. The company must be large enough to be able to support the development of a large number of diverse products and systems.

2. The company must be confident of holding on to its key engineering staff as they develop their Mechatronics design skills through a large number of teams.

For companies such as Hitachi, Fujitsu, Toshiba and so on in Japan, and Bosch, Siemens, IBM and the like in Europe and USA, requirement (1) poses no problem although in the less "Mechatronically inclined" of these there may still be a tendency to compartmentalise - leading to units for mechanical design, electronics and so on with less than optimum inter-relationships.

Requirement (2), however, is better able to be satisfied by Japanese companies with their jobs-for-life ethos. It is perhaps ironic that the very success which Japan has enjoyed via its Mechatronics design exploitation is leading to an increasingly Westernised (or Americanised) way of life, including a tendency for key staff to 'job-hop' to better salaries and conditions. The job hopping, it is feared by many Japanese, will inevitably erode its companies' ability to develop design teams with sufficient experience to maintain their Mechatronics ascendancy.

8.2. TOSHIBA CORPORATION

The Engineering Science and Technology Laboratory of Toshiba Corporation is situated at Kawasaki and comprises four main sections:

1. The Manufacturing Engineering Laboratory
2. The Research and Development Centre
3. The ULSI Research Centre
4. The Systems and Software Centre

As with Yokogawa, Mechatronics at Toshiba is seen as an extension of robotics. Mechatronics is defined as the interaction of Mechanics, Electronics and Control, and much of the Mechatronics effort in Toshiba is concerned with the design of various manipulators for remote handling and similar applications.

Of particular interest is a multi-degree of freedom manipulator arm designed for inspection [7]. Each of the 8 joints has two degrees of freedom with yet another at the wrist point. The whole effect is rather 'snake' like.

Actuators are a subject of much research. One project is into actuators which are similar in some respects to human muscles. They consist of rubber elements like long narrow balloons. However, by the particular method of fabrication these elements are made to contract when high pressure air is blown into them. This leads to a very light compact (high power to weight ratio) actuation system.

Another project involves small versions of this pneumatic 'muscle'. Each microactuator resembles a short fat cigarette into which air is blown. By careful design of the airways inside the element it is possible to arrange that it bends, twists or extends. By combining a number of elements in series, a manipulator arm can be made which has a prehensile quality like an elephant's trunk; having no joints and being completely enclosed, such a design of arm would be ideal for hazardous and dirty environments.

8.3. FUJITSU LABORATORIES

Fujitsu Laboratories is a company employing 1500 people situated in two main centres near Tokyo. The Kawasaki site is concerned with telecommunications, space operations, information systems and personal systems, while the Atsugi site concentrates on electronics devices, systems and materials.

At the Kawasaki centre there is a laboratory devoted to Space Mechatronics and this is presently devoted to a project which, for the wide range of technology it encompasses, surely must be classed as super-Mechatronic.

The purpose of this project is to observe the effect of prolonged weightlessness on the division of animal cells. The animal being used is the newt and apparatus is being designed to enable a pair of newts to be lifted into orbit, to be mated and for the resulting eggs to be examined. The life-support capsule consists of two chambers, one for each newt, containing water and connected to a gas exchange system to enable oxygen to be replenished from a chemical source. Underneath the chambers a CCD camera is sited so as to observe the eggs.

During this experiment, which is due to last for 40 days, it will be necessary to slice eggs in half so as to observe the material inside. This slicing is to be done by means of a scalpel-welding micromanipulator inside the capsule. The micromanipulator is to be controlled remotely from earth via a master arm using visual feedback. To handle each egg a thin glass tube is used whose inside diameter is less than that of an egg. Water is sucked up the tube and an egg is thereby held against the tube end. The slicing is then done using full bilateral force control. Fine control is obtained by a 10 to 1 reducing factor between master and slave movements. The difficulty of the whole operation is compounded by the 2 second time delay caused by the distance of the capsule from the earth.

In order that a project of this complexity be successful it is necessary to integrate, from the outset, the design of each of the component subsystems. This can only be achieved by team design under a project manager capable of understanding and evaluating all of the technology involved. As discussed earlier, this teamwork approach to design (and manufacture) lies at the heart of the Japanese success in exploiting Mechatronics.

8.4. NEC (TOHOKU) LTD.

NEC (Tohoku) is part of the NEC network of companies which comprises 30 Japanese and 200 overseas plants and offices. NEC (Tohoku) itself employs 1750 people and operates with a capital of 400M Yen. It is situated some 50 miles north of Sendai.

Mechatronics pervades all of the design and manufacturing operations of the company whose product range is grouped into four main categories:

1. Electronic Devices - subminiature relays, hybrid IC's
2. Telephone Switching Systems
3. Computer Printers - serial impact and dot matrix, English and Japanese
4. Robots - sequence control, automatic manufacturing

A typical manufacturing process involves the production of computer keyboard switches.

The process starts with reels of metallic contact strips being delivered up to plating machines in which is essentially a KANBAN system. Each cart is 'pulled' to the upstream process and is flagged by ticketing. The reels pass on to punch machines, then to plastic moulding machines where the plastic parts of the switches are welded. Then a plate soldering operation is followed by spring assembly and a cleaning operation before the final assembly takes place of the complete keypad systems.

A similar manufacturing line is set up in a clean area for the production of subminiature relays.

An interesting feature of these manufacturing operations has been a steady drop in the amount of gold needed for plating the keyswitch and connector contacts.

Originally all of the metal comprising the connector and mounting was plated; this occupied 15% of the total metallic area. Then by careful design of the plating machines this was reduced to 3%. Now only 0.7% of the metal is plated - just around the very points of contact themselves. The savings have been very great.

Of particular 'Mechatronics' interest is the way in which mechanisms for printer heads are assembled. There are basically two types of printer head - the 'clapper' type which requires current to operate, and the 'leafspring' type which is spring-actuated and operates a break of current. In the 'clapper' type there are 178 components of 33 different types, in the 'leafspring' type there are 147 components of 32 different types.

In the whole assembly process the most difficult operation is that of guiding into the head the 24 wires which actually perform the print function. Each wire is like a very small golf club, the printing wire being the shaft and the solenoid actuator stub the head. All 24 wires must be slotted through a central shaft and then each must individually be guided through one of 24 holes. The time to perform this one operation manually used to be 10 minutes. The automatic machinery designed by NEC Tohoku now takes 45 seconds. The entire head assembly system uses 42 robotic devices working in a series of stations. Eight of these robots are dedicated to the wire guiding operation. It took the company design team only five months to design and install the entire automatic assembly system but with manual wire guidance. Automating the wire guidance system took a further three years!

8.5. CANON INC.

Canon is a large multinational company employing 40,000 people around the world. The main administrative building is at Shin-Kawasaki near Tokyo. The Shin-Maruko factory (3 miles away) is the main centre for Mechatronics design.

Much of the Mechatronics work at Canon is aimed at the design and assembly of Canon's range of products such as cameras, recorders, and so on. The aim is to make more and more use of the so-called Flexible Assembly Centre or FAC. This consists of an x-y gantry system from which hangs downwards a wrist element able to pick up and deploy any one of a large number of different grippers. Beneath the gripper is a table on which the actual assembly takes place. To the side are magazines containing pallets which contain the individual parts. The magazines are loaded and unloaded by AGV's. For any particular assembly there may be 20 different parts in 20 different pallets. Each pallet is accurately machined in polystyrene and holds its part to within 0.1 mm. The x and y drives are friction driven to within 0.01mm. 30% to 40% of all assembly work at Canon is done on the FAC.

Since the FAC can only perform insertion operations in the z-direction (the wrist cannot 'tilt') the products must be suitably designed a-priori. Although the FAC is presently 'blind' it is proposed in the near future to include vision. In particular a 3-D ranging system using two cameras is proposed to obtain distance information. The two cameras look at the same scene. One camera is panned until its image coincides with that of the other. The angle of pan allows triangulation to calculate distance.

As mentioned above, the design methodology at Canon reflects the need not only to prioritise manufacturability, but to emphasise 'manufacturability-by-the-FAC'.

Canon have a regular management policy for design. As a new product is mooted a series of phases A, B and C is initiated.

<u>Phase A</u> is the <u>concept</u> phase. A team is set up including:

Senior management
Sales and marketing specialists
Designers with different backgrounds
Outside consultants (including University professors)

Brainstorming sessions attempt to formulate ideas of what new features will make the 'next' product attractive. There is a wide use of matrix evaluation methods.

<u>Phase B</u> is the <u>prototype design</u> phase. Various non-functioning and partly functioning models are constructed to get a 'feel' for the product.

<u>Phase C</u> is the <u>key-technology</u> phase. Here a fully functioning prototype is constructed. The different technological demands made by the product are analysed and assessed. For example, the types of actuators and sensors are examined. If the product needs a new ASIC chip then its specifications are determined. (It was during this phase of the design of the FAC itself that it was decided to use friction drives for the x-y movements). During this phase also the design team is joined by members of Production Engineering. Drawings of the product are examined for manufacturability and for assembly by the FAC. Location marks are specified for vision systems. Constraints on manufacturing processes are specified - for example, if a lens is to be picked up it must not be touched on its coated surfaces.

After these three phases have been successfully completed the project is given the go-ahead.

The Japanese experience of the global marketplace has led to a reappraisal of production methodologies. Until around 10 years' ago, Canon adopted a Just-in-Time (JIT) policy. Batches of products were made to order and a minimum parts inventory was maintained. A batch might be 1000 - this would be typical for their laser printer.

This JIT policy was successful when product cycle time was 5 years. In the beginning of the 5 year period there was time to 'massage' the production system to free it from problems and get it working in a defect-free mode.

However, now, cycle times are as low as 1 year and there is no time for 'massaging'. All products are now manufactured on what is essentially a 'new' system.

8.6. HITACHI LTD.

Hitachi is a huge multinational company employing around 250,000 people worldwide. Its product range covers almost the whole of human activity from bubble memories for computer data storage to large scale industrial plant.

The Mechanical Engineering Laboratory of Hitachi is at Kandatsu a few miles from Tokyo. It began as a research organisation, investigating the fundamentals of heat transfer, fluid mechanics, vibrations and strength of materials. However, it has latterly seen an enormous expansion in research into the interdisciplinary areas of mechanical engineering, electronics and physics. This is referred to as Mechatronics. The staff of the Mechanical Engineering Laboratories used to be 100% mechanical engineers. Now the proportion is only 50%.

The Mechatronics group undertakes 'venture research' of a long-term, commercially risky nature.

There are three main areas of effort:

1. Manipulation
2. Legged and tracked locomotion
3. Vision and brain research

The group has not yet shown any profit for Hitachi but various spin-offs have been profitable. For instance, the work on manipulation has led to an understanding of how to handle flexible materials and this has been useful in the design of an automatic cash dispenser for high speed processing of banknotes.

The Mechatronics design work at Hitachi centres around the CAE package called HIDESS described previously (see Figure 11). Using this package Geometric Modelling or 3-D can be accomplished automatically using 2-D numerical data. Finite element analysis is available with automatic optimisation of mesh points. The mesh is automatically made finer at regions of high stress. HIDESS has a database which supports a wide range of activities and it would appear to be one of the most truly integrated Mechatronics design packages available today.

The use of this package has been instrumental in the design of the Hitachi magnetic disc file storage devices. These range from large 9.5" discs storing 2 Gbytes at 12.5 ms access for mainframes, to small 3.5" discs storing 500 Mbytes at 16 ms access for microcomputers.

The Mechatronics team believes this design problem to have been truly 'Mechatronic'. First, there is the need to control the read-write head unit in both 'speed' mode for moving between tracks and 'following' mode for the actual read/write operations. Position signals are embedded in the data lines to accomplish this, while the disc is divided into sections each of which has positional information. Next is the problem of vibration isolation and the related one of keeping the head floating just above the disc surface. Heat transfer analysis properties of the head supports is crucial in ensuring that thermal distortion does not affect the performance. During the design process for this product most of the HIDESS libraries were used in an integrated fashion with results from one being input to another.

Hitachi are also developing an interesting dual processor control system which, it is claimed, is similar in some respects to the human brain. The 'cerebrum' is based upon a floating point unit with a 286 processor. This performs the low level control functions. Another 286 processor implements the 'cerebellum' which performs high level information processing. The whole is termed a 'base processor element'. So far Hitachi have managed to get 14 of these base units working together. In a typical robotics application, of the 14, one might be devoted to control, one to force/torque calculations and 12 to vision processing. This focus on parallel processing is a common feature of Japanese Mechatronics research where serial processing has reached its limits in many cases due to real-time constraints.

8.7. AIST-MITI LABORATORIES

The AIST-MITI Laboratories are situated in Tsukuba Science City not far from Tokyo. The two laboratories mainly concerned with Mechatronics projects are the Electro-Technical Laboratory (ETL) and the Mechanical Engineering Laboratory (MEL).

8.7.1 *The Electro-Technical Laboratory.* The major work of the ETL is based upon developments of new generations of autonomous robots for hazardous unstructured environments. This type of robot cannot be 'taught' like industrial robots since the human cannot enter the workplace. The simplest type of robot system suitable for this work is the master-slave. However, this type is very inefficient and cannot really accomplish complex tasks. ETL is adopting a half-way house approach. Since pure master-slave systems are inefficient and true autonomous robots are beyond present technology, ETL is designing semi-autonomous versions in which the machine operates autonomously until something occurs for which it is unprepared. At that point it calls for human intervention.

This requires an environment model. The more the robot knows about the environment the more autonomous it can be. The ETL way of getting environmental knowledge into the robot's database is to use a laser spot which can be moved around and used to point to objects and features of objects. It is integrated with a CAD system. When the spot lands on a face of an object it is input to the CAD system along with a name such as VALVEI:TOP. When all features have been logged the robot is able to match what it sees with what it expects to see. It can thus become familiar with its environment.

One of the key features of the recognition system is the use of centres of rotation of bodies being manipulated. If the vision system is observing a parts mating operation, for example, the two parts may be rotating relative to each other about some point of contact between them. If this point changes suddenly to a new position it is likely that the line joining the two points is in a shared face. The system continuously monitors this phenomenon to infer information regarding the mating operation.

These facilities are incorporated into the ETA.3 Direct Drive robot arm. The overall control strategy is a version of the Hybrid Control method of Raibert and Craig. Disambiguation of force feedback data is accomplished by mode matching using convex hull generation, identification of the centre of gravity and a knowledge of stable states for resting.

In the view of ETL, this Mechatronics work will continue with a particular emphasis on job analysis to determine the features which allow categorisation of jobs into those which autonomous robots of the future can be expected to do and those which will always be too difficult and will hence need human intervention.

The work will require developments in hardware of computers to support hierarchies of computers with local shared memory. Certain distinct architectures are anticipated. For example, it is expected that architectures suited to high level control of machines will emerge. Special designs will be developed for the trigonometrical transformations, for trajectory placing calculations for vision processing.

Software too will be specially structured. The usual load-sharing software for number crunching will be replaced by function-sharing software. General purpose computers are not needed. Multi-tasking, for example, is not a necessary feature, and in future instead of a single computer multitasking to serve 6 degrees of freedom robot, 6 microprocessors cooperating will operate simultaneously.

8.7.2. *The Mechanical Engineering Laboratory (MEL).* 'Mechatronics' is under way in the Robotics Department of the Cybernetics Division of the MEL. Around 25 researchers are working on:

- Advanced Robotics
- Autonomous Machines
- Locomotory Mechanisms
- Sensory systems
- Teleoperation
- Telepresence and teleexistence

Various machines have been built and tested including:

MELWALK	a hexapod walking machine
MELSPIDER	an autonomous wall-climber
MELCRAB	a hexapod stair-climbing machine
MELDOG	a robot guide dog for the blind

The work on telepresence is aimed at providing operators of remote machines with a feeling of actually being at the work site. Visual feedback is by far the most important for this.

The simplest method used is to fit two cameras to the 'slave' at head height. The operator wears a helmet whose rotation and pitch are measured by potentiometers. As the helmet moves so do the cameras. The cameras send back their two slightly different pictures to two LCD displays within the helmet so that the operator 'sees' what the slave 'sees'.

A more sophisticated approach uses small coils set into the helmet. These detect a magnetic field set up by a generator in the operator's vicinity. Any head movements cause small changes in magnetic field strength which are picked up by the coils. Thus, the helmet is unrestrained and much more comfortable to wear. To give full 6 degrees of freedom telepresence, the operator sits in a specially constructed chair. The helmet is suspended from a complex mechanism so that any movement of the operator is converted to full camera movements. The command joystick also has 6 degrees of freedom with full bilateral force feedback. Using these systems the operator obtains a very strong impression that the slave arm is actually his own.

Of particular interest is a vehicle with four legs each of which is equipped with an active suspension. The controls for each suspension system operate in conjunction with all three others so that the system is multivariable. The object is to keep the 'deck' of the vehicle horizontal no matter what degree of surface undulation it meets as it moves. This could be used as the basis of a patient handling scheme to transport an injured person across bumpy ground at high speed. The basic feedback principles involved use gyroscopes for inertial monitoring of horizontality.

There is also work going on on high-resolution tactile sensing. Here a silicone rubber mat with surface indentations is pressed against a transparent acrylic plate by the object being tactilely examined. The resulting frustration of internal reflections allows a CCD camera to 'see' where tactile pressure has been applied. The system, of course, only monitors normal pressure and cannot deal with shear force. Since shear force is generally more important for robotic (and other mechatronic) manipulation, this is a serious defect and limits the system to uses in simple pick and place or object recognition applications.

9. Conclusion

There is a growing world-wide appreciation of the benefits to be gained from the adoption of Mechatronics as a philosophy for design and manufacture. By employing, from the project initiation, a team comprising specialists from different technological divisions together with systems analysts and management practitioners, it is possible to obtain a synergy in the design function which passes over into the product itself.

The Japanese have successfully capitalised on this philosophy while much of the rest of the industrialised world has remained locked into its traditional compartmentalised view of engineering as being composed of separate departments - mechanical, electrical, electronic and so on [8].

We have attempted to show how Mechatronics can be used to move forward to a more communicative and integrated mode of industrial operation - a mode which can lead to better, more reliable and cheaper products with a far greater attractiveness to the customer.

Acknowledgements

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THE MECHATRONICS DESIGN PROCESS

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Design is a complex process, which cannot be described as a simple sequence of activities or as a computer algorithm. It may be regarded from many different points of view: planning, organization, creativity, design tools, task assignment etc. When proposing methods and procedures to aid the designer, we must be very distinct about the viewpoint we take, and about the scope within which the methods are valid.

A suitable framework for describing design has been suggested by Andreasen and Hein [1]. It distinguishes three levels of resolution:

1. *Problem solving*, based on the human way of thinking.

2. *Product synthesis*, based on the characteristics of technical systems.

3. *Product development*, based on the company organization.

Any design task will require activities related to all three levels. For each level we can divide the design activities into phases and recommend a suitable sequence of working a design procedure and we can attach various design methods and models to each phase. The following sections will describe each of the three levels in turn. We shall see that the design of mechatronic systems or products mainly differs from machine design or electronics design on the level of product synthesis.

1. Problem Solving: Designer's Mental Activity

We will use the term *problem solving* for the activity carried out by humans, when finding and deciding on a solution to a complex problem. By complex we mean 'open-type' problems which have many possible solutions, as opposed to 'closed-type' problems with only one or two solutions that can be found by some calculation

M. Acar (ed.), Mechatronic Design in Textile Engineering, 27–32.

method. The solution achieved through the problem solving process may be material (e.g. products) or non-material (e.g. services, schedules).

To suggest a method for solving problems, one must study how a designer as a human thinks: creativity, decision making etc. The phase plan of 'General Problem Solving' presented in Figure 1 recommends a sequence of five activities to be completed for any problem during a design work, Jones [2]. It implies that evaluating a number of ideas will always yield a better result than considering only one, intuitively found solution. In order to limit the field of possible solutions, the problem should be defined in advance, and criteria should be determined for the evaluation of alternatives.

Figure 1. The five phases of general problem solving.

Problem solving may be regarded as an elementary activity to be applied to every sub-problem and in every iteration cycle of the design work. Naturally the number of necessary alternatives and the care taken in evaluation must be determined by the priority of the problem and the degree of innovation (i.e. how new and how difficult the problem is).

In each phase of general problem solving, a number of design methods and tools may be applied. For instance methods for creative and systematic idea generation (brainstorming, morphological methods, hierarchical methods), methods for evaluation (point scale methods, pair-wise comparison), and CAD tools for specification of geometry and structure. The main purpose of these methods is to encourage the designer's imagination, and to prevent 'human blocks' due to preoccupations and limited knowledge.

There isn't anything particularly 'mechatronic' about the general problem solving process. This activity is based on the human way of thinking, and therefore almost independent of technologies. We will however find that creativity and qualified decision making are important preconditions for mechatronic design, and that both these activities will be severely limited, if the designers involved do not have a wide, interdisciplinary knowledge of mechanics, electronics and information technology.

2. Product Synthesis: the Evolution of the Mechatronic System

On the level of product synthesis, we concentrate on the characteristics of the technical artefact to be designed: it's purpose, functions, organs, interfaces, parts structure, total form, etc. *Synthesis* is the activity of combining separate elements (or problem solutions) into a complex whole. To synthesize a product means to combine a multitude of decisions on every single one of those characteristics of the system.

Methods for product synthesis must be based on a general theory of technical systems and in particular of mechatronic systems. The theory proposed by Hubka [3] and Andreasen [4] constitutes such a foundation. It states that the designers' activities at any one point can be located in one of the four domains: process, function, organ and parts domain. Each domain covers a subset of the characteristics of the technical system. Once the design is completed, the characteristics of all four domains have been established. Figure 2 shows the rough strategy of product synthesis.

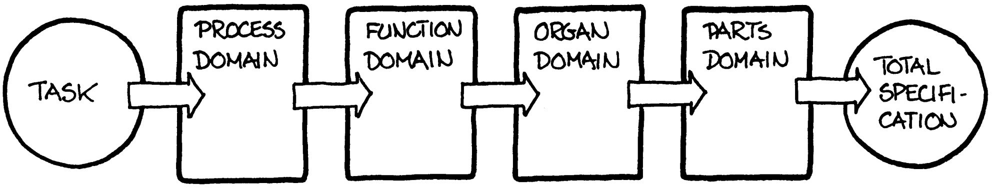

Figure 2. Product synthesis means establishing characteristics of the technical system within four domains.

The human designer has the capability of freely jumping back and forth between domains in his mind in an iterative sequence. He may for instance think of the abstract function of 'supporting a rotating shaft' and simultaneously consider the very concrete properties of a ball bearing. Similarly in electronics design, he may think of the function of 'converting analog to digital signals' and simultaneously consider price and specifications of a particular SMD-type component. This makes the suggestion of a detailed design phase plan on the level of product synthesis unrealistic.

The knowledge of domains in product synthesis, however, permits us to develop design methods specifically for one domain or for the transition from one domain to another. Using a catalogue of electronic components for example, is a method for proceeding from an abstract description of function to a physical realization.

Since product synthesis is based on characteristics of the technical system, methods at this level are specific to mechatronics, even though some of them will resemble methods from machine design, electronics design or software design.

3. Product Development: Design in a Company Context

The level of product development reflects the total activity of a company. In fact, the goal of product development is not the product itself, but rather the successful business it creates for the company. Therefore it is insufficient to concentrate only on product design, we must also consider market research and the establishment of production and sales.

On this level, we can explain the restrictions laid upon the product design by the customers and competitors (the product must be saleable) and by production (the product must be produceable).

For many years, companies have considered product development as a fixed sequence of activities, each performed by a different department: market research by marketing, product design by engineering, production preparation by manufacturing, and sales by the sales department. With increasing international competition and pressure to reduce product leadtimes, this routine is no longer viable. Activities must be performed in parallel to ensure that sufficient attention is paid to market needs and manufacturing technologies during design. In the sequential strategy, too much information is lost at every transition from one department to another, resulting in numerous changes in product specifications along the way.

The catch-phrases for the new strategy are 'Integrated Product Development', 'Simultaneous Engineering' or 'Concurrent Engineering'. As shown in Figure 3 it is possible to describe those activities in marketing, product design, and manufacturing that should be performed simultaneously to ensure a successful product development project, Andreason and Hein [1].

The starting point of the process of 'Integrated Product Development' is a rather undefined situation of 'need' to be examined. The process is then divided into 5 phases to be completed in sequence by the joint forces of marketing, product design and production (symbolized by the three arrows).

The amount of work to be completed in each phase depends on the nature of the product: is it a totally new product type, a revised model, or production rationalisation ? Special attention should be paid to the transition points between phases, as these are indicators of the progress and direction of the total project.

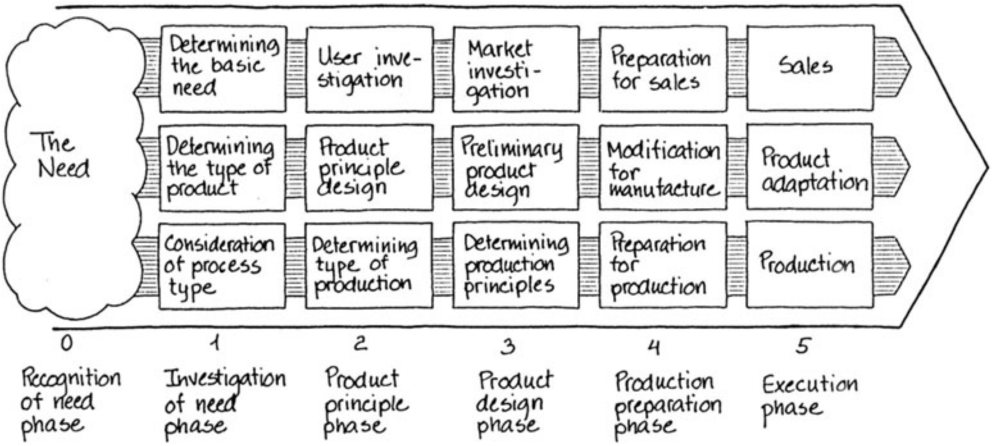

Figure 3. Integrated product development - simultaneous activities in design, marketing and manufacturing.

Working methods may be attached to each phase of the product development process, e.g. specification methods to the 'investigation of need' phase and design review methods to the transition points.

What is typically 'mechatronic' about the product development process ? No matter which kind of product technology is used, the marketing and manufacturing aspects must be considered to create sound business for the company. The interdisciplinary nature of the mechatronics technology may just add to the complexity of the engineering design activities, if mechanics, electronics and information technology are handled in separate departments. Mechatronics possibly requires even closer links between design and manufacturing than the pure mechanics or electronics do separately.

4. Designing Mechatronics - But How ?

How should one actually go about developing mechatronic systems ? Is this three-level perception of the design process of any help ?

All three levels recommend a series of activities to be completed, but the underlying theories are different, and in particular the result of each process is different: a solved problem on the first level, a mechatronics system on the second, and successful business on the third. Also the course of the design process on each level is very different: problem solving is performed again and again during the project, product synthesis is completed once (or a few times), but with numerous iteration cycles, and the phases of product development are performed once in straight sequence.

To work systematically with design, the designer must choose methods suitable for each task, since not all methods are applicable in all situations. It is very difficult to give general guidelines as to which methods apply in which situation. The three-level approach is a framework, which helps subdividing the designers' toolbox. Let us take brainstorming as an example to clarify the point. Brainstorming is a method for creating ideas, which relates it directly to one of the phases of general problem solving. It can be used for many types of problems. When using the method at a particular point during a design project, the problem in question must be described clearly, to allow participants to voice their ideas. Since the designer is dealing with some particular characteristics of the mechatronic system, the level of product synthesis will provide methods for describing the problem. When deciding on, for instance, who should participate in the brainstorming sessions, the level of product development will offer the arguments for bringing in marketing and manufacturing expertise.

So to conclude: there is no single, recommended procedure for designing mechatronic systems, but depending on the viewpoint we take, there are systematic ways of solving problems, synthesizing mechatronic systems, and developing products.

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DESIGN MODELS AND METHODS FOR MECHATRONICS

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In order to discuss and compare design ideas at an early stage in the design process, we need ways of describing (or *modelling*) such ideas long before the system exists in hardware. With mechatronic systems, this is particularly difficult, because one idea will usually involve considerations of both mechanical, electronic and software subsystems. We will use the term *design concept* for such a principle solution. This section deals with methods for generating and describing mechatronic design concepts. We will limit the discussion to the *functional interaction* of mechanics, electronics and software since methods needed for the spatial arrangement of subsystems (e.g. electronics packaging) are usually of a different kind.

When speaking about the 'function' of a product or system, we are normally not very precise about whether we think of what the system does (its purpose) or how it does it (how it works). In order to design systematically we need to be more explicit about the terms we use. Otherwise we cannot describe abstractly what we want before we start looking for detailed technical solutions. In particular three terms need to be defined more closely:

Transformation functions,	i.e. the transformations of inputs into outputs performed by the mechatronic system.
Purpose functions,	i.e. the effects required in the mechatronic system for performing the transformations.
States of the system,	i.e. the logical situations, which determine what transformations will be performed by the mechatronic system.

In the following sections we will study these terms and the relations between them. This material is mostly based on Buur [1].

M. Acar (ed.), Mechatronic Design in Textile Engineering, 33–46.

1. The Mechatronic System Transforms Material, Energy and Information

A mechatronic system can be described by its ability to transform material, energy or information. A robot for instance moves material, a motor transforms energy, and a telephone transmits information. We may regard the mechatronic system as a structure of *transformation functions,* which processes one of the following type of transformation operands: material, energy or information (Figure 1).

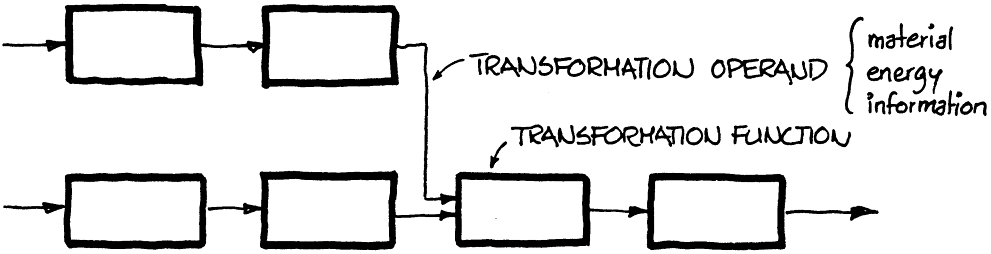

Figure 1. A mechatronic system described as a structure of transformation functions.

The transformation function concept is well suited for describing the purpose of both mechanical, electronic, and software systems. It is worth noticing, however, that electronics can transform information only.

We can visualise the transformation functional structure in a diagram of black-boxes. the diagram shows *what* happens to a transformation operand, not *how* the mechatronic system makes it happen. Therefore the diagram is independent of technical realisations, so it can be used for creating alternative designs on a high level of abstraction. Typical ways of creating alternatives are to

- relocate the systems border
- subdivide one transformation into subfunctions
- integrate subfunctions
- change the sequence of subfunctions
- establish parallel branches of transformations
- insert transformers or conductors
- relocate information inputs or change information carriers.

Mechatronic systems primarily transform information, either as their main purpose (e.g. a telefax) or when controlling material or energy processes (e.g. an electronic sewing machine, an intelligent motor). Note that information can only exist in mechatronic systems, if attached to either material (e.g. a photocopy, a blood sample) or to energy.

(e.g. an electric signal, a sound signal). When information is coded on an energy form, we will use the term *signal.*

Generally, mechatronic systems handle two kinds of information:

1. *Process information,* which is transformed by the mechatronic system regardless of its semantic value (its meaning), and

2. *Control information,* which the mechatronic system applies to control internal functions (the information is 'understood' by the system).

On any one level it is comparatively easy to distinguish between process and control information, but if one regards the flow of information on several hierarchical levels, the distinction is not so clear any longer. An electronic feed-back loop in a robot, for instance, carries control information, since its purpose is to control the movements of the robot. If we focus on the sensor and the signal processing circuit of the feed-back loop however, the same information is of process type. From the point of view of sensor and circuit the semantic value of the processed information has no influence on their function.

In mechatronic systems, process and control information appears alternately in a hierarchical structure: Control signals need signal processing and signal processing systems often need control on a lower level.

2. The Mechatronic System Realises a Set of Purpose Functions

The mechatronic system has the ability of creating necessary effects. We will call such an ability *a purpose function.* It is very common for machine designers to think in terms of such functions. For instance, "I need something which creates rotation", the designer might say. Here *rotation* is a required effect, and *create rotation* is the purpose function of a subsystem (a motor).

We can regard the mechatronic system as a structure of purpose functions. Typical examples of purpose functions are: 'measure level', 'allow for manual adjustment', 'store value', 'compare to reference' and 'support shaft'. The structure of purpose functions contains all those effects necessary for the mechatronic system to fulfil its purpose.

An important point in methodical design is that functions can be sub-divided into secondary functions on a lower level. For mechatronic systems a basic principle states that to realise any function in the system, one or more of the following secondary functions will be required:

- *Power function* to provide energy supply
- *Control function* to govern the state of the system
- *Interface function* to convert inputs and outputs
- *Protection function* to prevent undesired interaction with the environment
- *Communication function* to interact with other systems
- *Structural function* to provide mechanical support.

let us take the lamp of an overhead projector as an example. The lamp itself provides light, but in order to do so, there must be an AC-inlet and a transformer (power function), an on/off switch (control function), a lamp socket (both interface and structural function) and a fan (protection function). We will refer to this principle as 'the complex of secondary functions'

How can we distinguish between purpose and transformation functions? The transformation function of an electric motor is to transform electric power (input) into mechanical rotation (output). It is a transformation of energy. The purpose function of the motor is to 'create rotation'. Here the transformation is a means to realise the desired purpose function: "How do we create rotation? By transforming..." - and one could think of many other transformations, which could realise the same purpose function (e.g. hydraulic motor, mechanical clockwork).

On the other hand, a particular transformation can only be accomplished if on a lower level there is a set of effects (purpose functions) available. For the electric motor 'accept electric power', 'create rotating magnetic field', etc. We can say there is a kind of causal relationship between transformation and purpose functions.

3. The Systems Model

When expressing the complex of secondary functions in transformation terms, we can derive a general black-box model of mechatronic system, Figure 2. This shows the main transformation function and all the secondary functions of the complex.

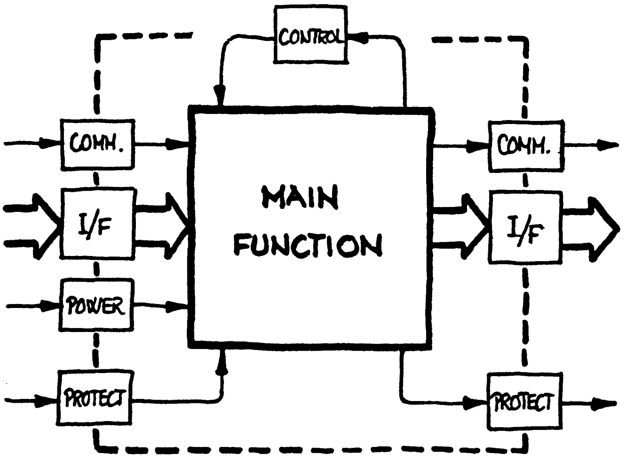

Figure 2. A general model of the functions of mechatronic systems.

Secondary functions are placed on the systems border to indicate that they may be shared with connecting systems. Between two systems of a signal processing line, for instance, there will only be one interface function. The structural function has not been included in this model, since it cannot readily be expressed in transformation terminology.

This systems model is *recursive*: it can be applied to describe mechatronics on all levels - components, modules, products and systems. The main advantage of the model is that it explains the relations between primary and secondary functions. It can hardly be used as a design tool, because the relations between several blocks will quickly become too complex to allow easy sketching on paper.

4. The Logic Behaviour of Mechatronic Systems

All mechatronic systems function in a number of *states*, two being the smallest number (on and off). For a photocopier, there will typically be five states on the coursest level: *off, warming up, ready, copying* and *error.* The system functions in a different way in each state.

The point at which the system changes from one state to another is decided by logical conditions internally in the system or interactions between the operator and system. The photocopier changes for instance from the *warming up* to the *ready* state, when a heating element reaches a required temperature, and the transition from *ready* to *copying* occurs when the user pushes a button. Logical relationships can usually be expressed in the form '*When... (condition), then...(transition)*'.

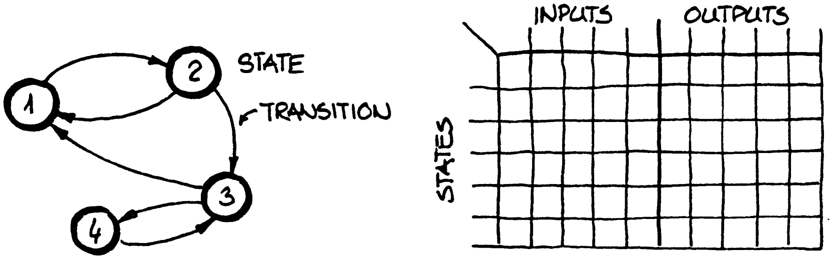

Figure 3. The logic behaviour of mechatronic systems can be described in a state-transition diagram or matrix.

The designer will often describe the structure of states and transitions in a state-transition diagram or a state-transition matrix, Figure 3. Both the diagram and the matrix list the total number of possible states and all the permissible transitions between the states. The diagram is suited for illustrating the state-transition structure, whereas the matrix is good for checking completeness and disclosing ambiguities.

Both mechanical, electronic and software systems behave in a way, which can be described in state-transition form. The state-transition structure is a must for developing control software for mechatronic systems.

Naturally the state-transition description of a mechatronic system must somehow relate to the transformation and purpose functional structures. Since the system operates in a different way for each state, the functional structures must change according to states. In fact we need to describe a different transformation functional structure for every single state of the system.

Think of a video recorder for instance: The transformations occurring in the *record* and in the *play* states are completely different. In the former, an electronic video signal is transformed to a magnetic pattern on the videotape. In the latter state, the reverse process happens.

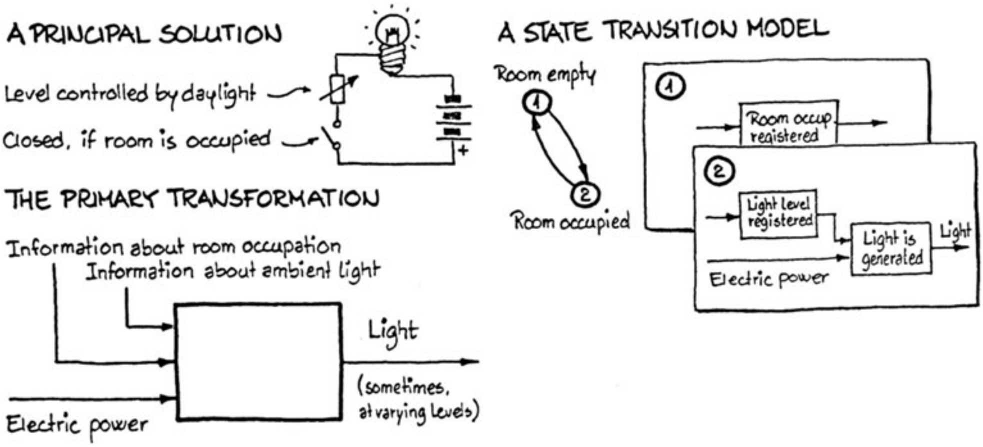

Figure 4. An intelligent lighting system: an example of the relations between the transformation functional and state transition structure.

To make a precise description of the transformation functions and the logic behaviour of the mechatronic system, we must ensure that the transformation functional structure for each state is stable or *continuous*, i.e. that it cannot suddenly change to a different output. A simple example may illustrate the point.

Let us assume that we want to design an intelligent system for room lighting: the system should automatically switch on the light when people are present in the room, and the lighting level should be adjusted according to the level of ambient daylight. If we try to describe the transformation function of the system without thinking about logic states, then the output will be 'light now and then at varying level', see Figure 4. The transformation is not continuous. The output will change abruptly depending on the information input about the state of the occupation of the room.

Instead we can decompose the transformation functional structure into two separate structures, one for each of the two states *room empty* and *room occupied.* We must add a state-transition diagram, which shows how the system will change from one state to the other.

Now let's have a look at the relations between the purpose functional structure and the logic behaviour of the mechatronic system. We can regard the purpose functional structure as a table contents of all the effects necessary to make the system work. Then only some of the functions will be active in each state of the system. Figure 5 gives a full example of the purpose functional structure of a telephone and shows which functions are active in each of four states.

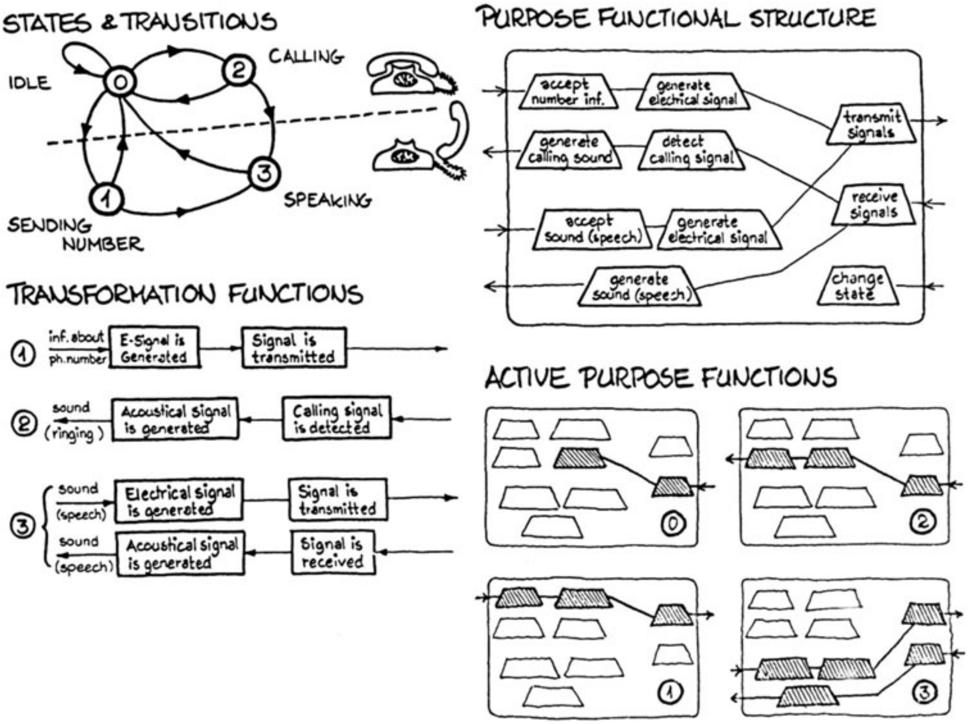

Figure 5. The logic behaviour of a telephone and its two functional structures: a transformation and a purpose functional.

5. The Mechatronic System as a Structure of Organs

We are now leaving the solution independent domain of functional description and turning attention to actual physical solutions. For this, we need to describe the term *organ*: an organ is a set of parts, which exploit physical, chemical or biological phenomena to create a required function. An electric motor for instance is an organ, which exploits the electromagnetic effect to create rotation.

The word ‘organ’ was chosen to underline the analogy with organs of the human body, which are typically entities that realise one particular function. We can understand a mechatronic system as a structure of organs, each of which realises one or more functions. This comes very close to the way most designers think, when suggesting solutions. For instance, "We could use a motor with suitable gearing and an angular encoder..." suggests a structure of three organs: *motor, gear reducer* and *angular encoder* to provide the required function.

Figure 6 shows a collection of organs, which can realise the three different functions of a testing apparatus. Note how informative simple symbolic sketches of organs can be.

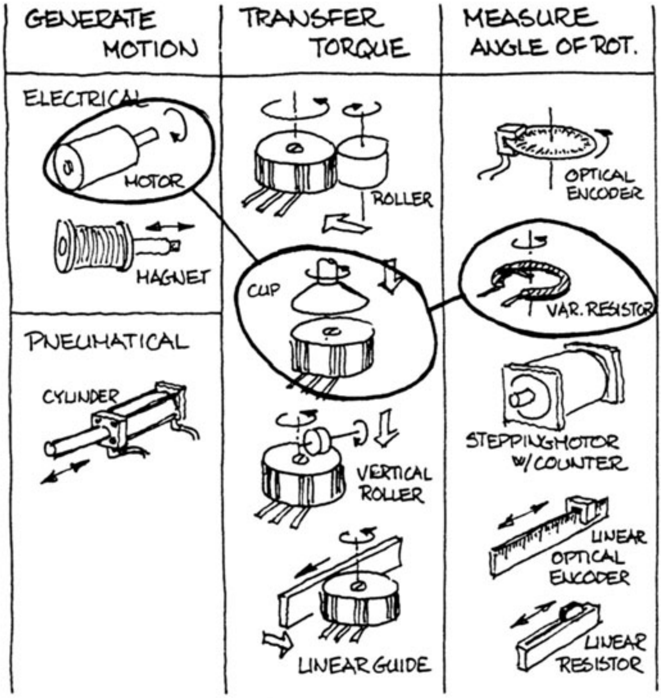

Figure 6. Alternative organs which realise each of the three functions required for testing a small hearing aid potentiometer; one possible combination is suggested.

Electronic components, e.g. a transistor or a potentiometer, can also be regarded as organs for as long as the designer is thinking about its functionality and not about its precise type or dimensions. A microprocessor cannot be considered as an organ without the intended software - only with software does it fulfil a particular function, and software in itself cannot be an organ.

Let us look at the relations between (purpose) functions and organs. Organs are the physical artefacts, which realise functions, but a direct mapping between functions and organs is seldom possible. This is because an organ can sometimes cover more than one function. For each required function we can usually choose between several alternative organs which provide the same effects. This is what makes design so difficult and interesting: one must choose the most appropriate solution for each function.

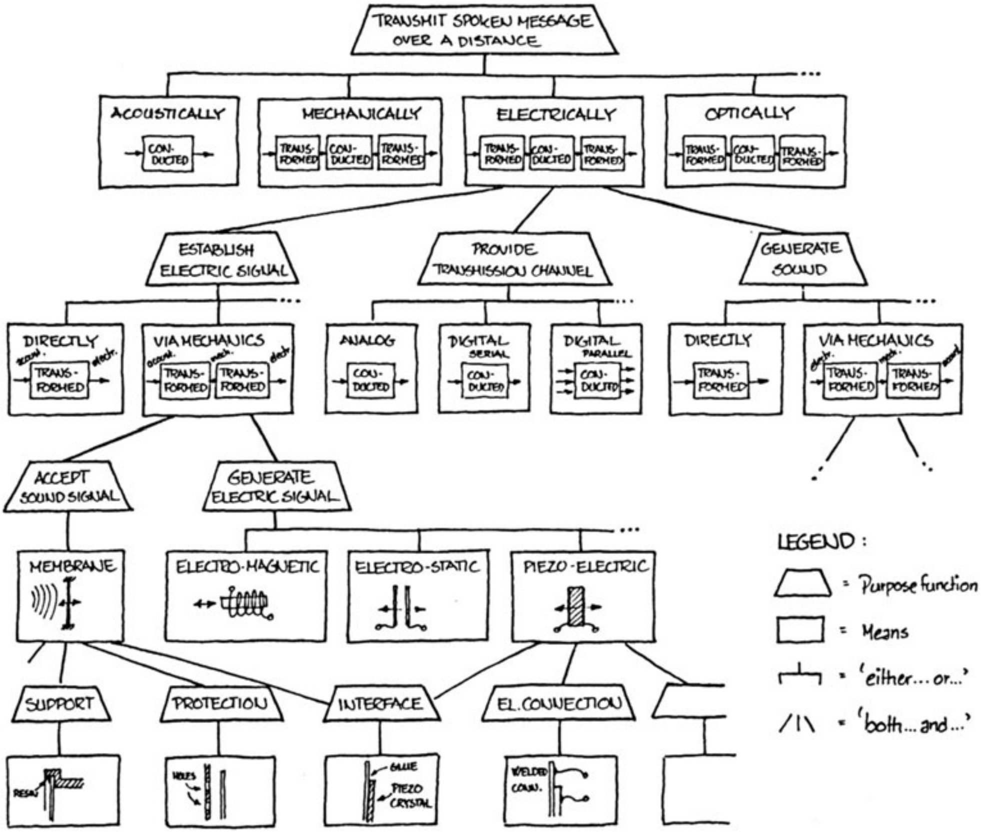

Figure 7. A function/means tree for a telephone system.

There is a cause/effect relationship (*causality*) between functions and organs. Those organs which cause a particular function on one level, will require the realisation of a set of subfunctions on the next lower level. Each subfunction can again be realised by (sub)organs. This relationship is illustrated in the *function/means tree* as shown in Figure 7.

A function/means tree is a design tool which maps the hierarchical pattern of functions and alternative solutions of the mechatronic system. At the top of the tree the means that realise the (purpose) functions are transformation structures; further down they become organs.

The complex of secondary functions will be of help, when trying to formulate which subfunctions a particular choice of organ will require on the next level. Often it will not be possible to make the choice between alternative organs, until one has examined the consequences of each choice a couple of levels down the tree.

6. Interface Organs

One type of organ, which requires particular attention in mechatronics design, is the *interface organ,* that defines the borders between the system and its environment and between subsystems internally. We shall study some characteristic interfaces and their organs.

The man/machine interface is primarily made up of organs which send and receive information (displays and controls), but occasionally there will also be a condition of energy input , e.g. levers, crank handles. Since information must be tied to either energy or material, it is comparatively easy to systematise those organs, from which the designer can choose. Figure 8 gives examples of control elements.

The systems interface defines the relationships between the neighbouring systems. Mechatronic systems can exchange material, energy and information. The interface between a photocopier and a sorter, for instance. handles paper. Mechanical interface organs are typically couplings, while electric interface organs are types of connectors. For electronic communication interfaces, the organs must often be supplemented with a communication protocol and a common set of characters.

The environmental interface typically covers casings, cooling structures, ventilators etc. They exchange material, energy and information with the environment of the system.

The electro-mechanical interface defines the border between mechanical and electronic subsystems. The interface organs can only be of the type sensors and actuators, see Figure 9. The organs cannot exchange material, but only energy and information.

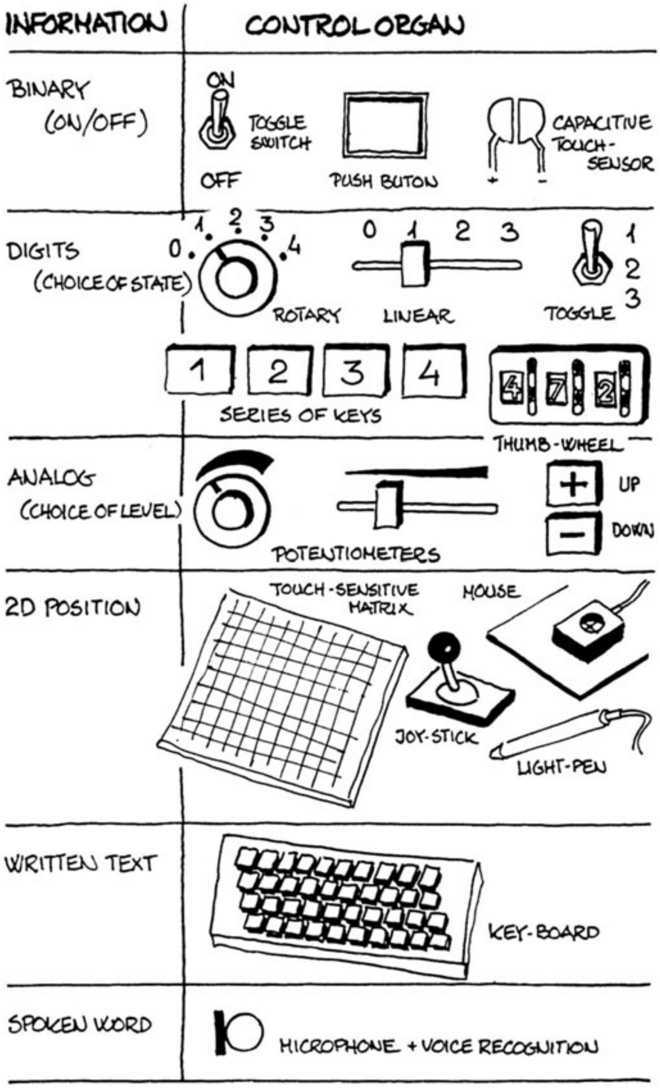

Figure 8. Examples of control elements for the man/machine interface of mechatronic systems.

7. Activity Structure

The description of an organic structure is only complete, when information about the logic behaviour of all organs and their relations is added. From software engineering we can adopt some tools for modelling the *activity structure* of the mechatronic system. Figure 10 shows different tools, which define four different aspects of logic behaviour.

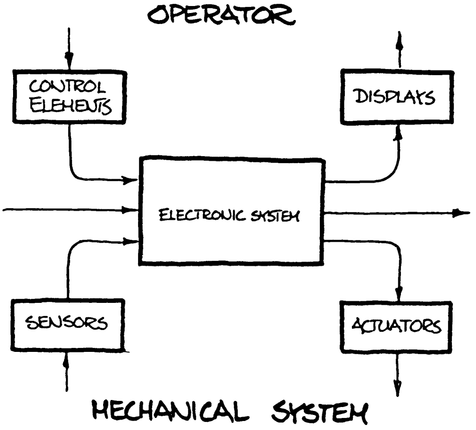

Figure 9. Electronic circuits can only realise their purpose through one or more of four organ types: control elements, displays, sensors and actuators.

1. *States and transitions*, i.e. the states of the organ, permissible state transitions and conditions for changing from one state to another.

2. *Sequential procedure*, i.e. the activities (operations) and how they follow one by one in sequence.

3. *Hierarchical pattern*, i.e. the activities (operations) and how they relate to each other on superior and subordinate levels.

4. *Timing*, i.e. constraints in time on the performance of activities.

The tools vary as to their abilities to express detail or an overview. The flow chart for instance can be refined until the smallest detail, where as state-transition diagrams can only be used to give an overview.

The activity structure must typically contain information about the software instructions which control how organs work, and the expected behaviour of the operator of the system.

8. The Mechatronic Design Concept

Based on the previous sections we are able to describe more closely, what we mean by a *design concept*. It is a principal solution to a problem described in a way that enables us to evaluate the major decisions regarding both mechanical, electronic and software subsystems. The design concept of a mechatronic system is characterized by:

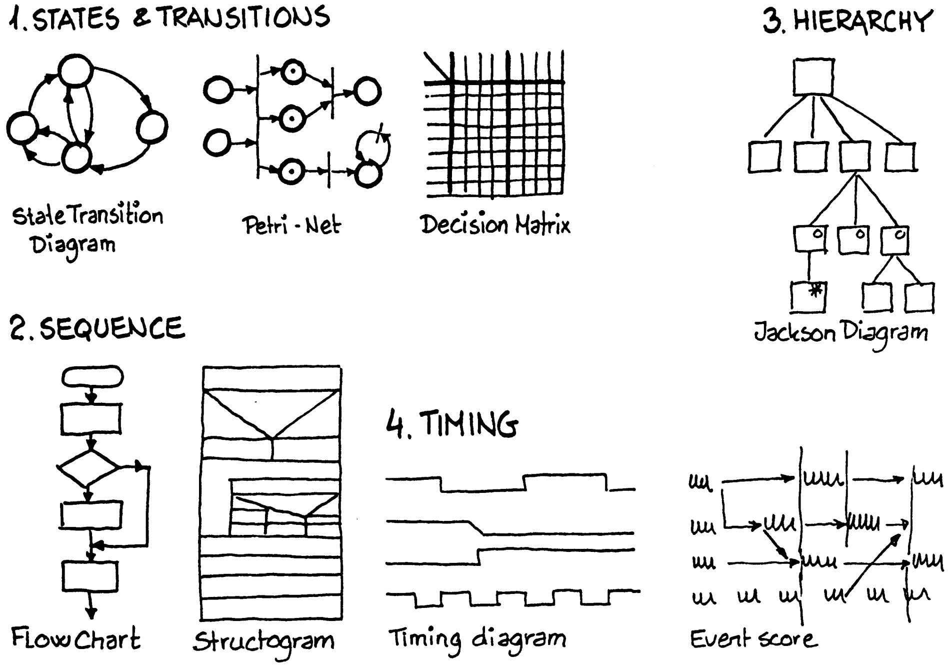

Figure 10. Tools for describing logic behaviour in the organic structure of mechatronic systems.

1. The structure of those organs, which realise the most important functions of the system.

2. The structure of those interface organs, which define the border of the system (man/machine, systems and environmental interfaces) and the borders between electronic and mechanical subsystems.

3. The activity structure of the organs, including the software instructions for programmable organs and the expected behaviour of the operator.

4. The basic mechanical structure and lay-out of organs, industrial design, production methods etc.

In other words: when comparing design ideas at an early stage in a development project, we must make certain that they are comparatively complete, i.e. that all of the four aspects mentioned above have been considered to some level. An example is shown in Figure 11.

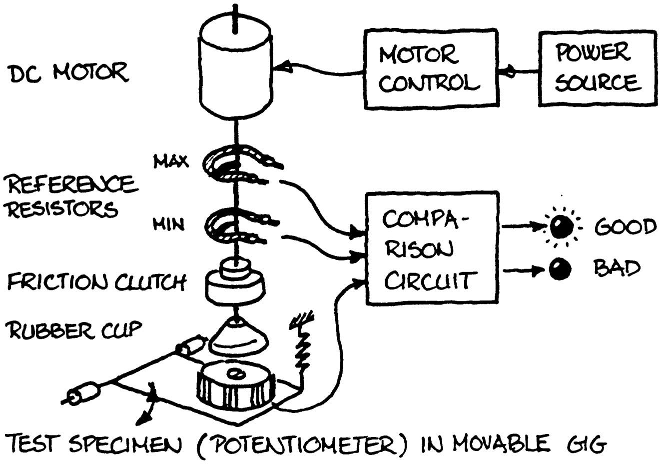

Figure 11. Design concept for a test apparatus for hearing aid potentiometers.

How does one go about generating design concepts for mechatronic systems, then? A single method, which will always yield success does not exist. Rather we must experiment with the different forms of functional description to get an idea of the purpose of the system. And then look for physical realisations (organs) for each function and suitable structures of organs. Because of the complexity of mechatronics, we need to be careful in describing (modelling) the design concepts on the same level of completeness, before comparison is made to find the best concept.

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ADVANCEMENTS IN TECHNOLOGY AND ITS IMPACT ON THE FUTURE DEVELOPMENTS OF MECHATRONICS CONCEPT

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The interconnections between mechanical and electrical engineering and computer science are characterized by the term mechatronics. Such interconnections are the basis for an "intelligent " behaviour of a machine, depending on its ability to pick up information about its environment, and to process it in such a way that it reacts according to the situation /SCH 91/. This potential for “intelligent interaction” will be one of the most dominant trends in future machinery. In our working environment most often an interaction with a human operator will be necessary or desirable. A machine where this growth of “intelligence” is most obvious is the robot. Subsequently some robotic projects of the ETH will be presented where this man/machine interaction has been realized under various intentions and constraints, demonstrating methods, feasibility and trends: a pingpong playing robot, a cooperating robot with visual and tactile abilities, and a “polite“ mobile robot.

1 Introduction

Poets and utopian writers, the true creators of the term "robot", saw robots as intelligent beings /CAP 20, ASF 85/. This vision of an intelligence has been lost in the real world of technics, and it does not or rather not yet exist in actual industrial robots. The requirements on the performance of industrial robots increases, however, as they tend to be used for more demanding tasks than simple handling jobs. This trend can be visualized by a diagram (Fig. 1), where the "autonomy" of a machine is plotted against its "flexibility" /HAM 83/. A machine without flexibility but with a high degree of autonomy is represented, for example, by a fully automated transfer street for the mass production of just one part. And a simple transportation means, for example a bicycle, enlarges the velocity and the range of the rider in a very flexible way, but, without the human operator it will be without any autonomy. In each case it would be desirable to extend the range of operation and to add the missing capabilities. For a machine, this leads to robots that can be used more flexibly for a broader spectrum of tasks. Manipulators, however, will obtain more and more autonomy by suitable support of sensors in order to relieve human beings from heavy or tedious work. The "intelligence" of a machine for such work depends on its ability to pick up information about its environment, and to process it in such a way that it reacts according to the situation. This desired extension of flexibility and autonomy sooner or later will always require

M. Acar (ed.), Mechatronic Design in Textile Engineering, 47–59.

an interaction with a human being and an "intelligent" behaviour of the machine. Other modern machinery, too, has the definite need of communicating with the operator in a convincing and accepted way.

2 The "Intelligence" of a Machine

We are used to think of machinery as part of the technical world: production lines, consumer goods, robots. And one might think that robotics, or in a wider sense, Mechatronics, is just another way of making machines work faster and production cheaper. This, however, is only one side of the medal, and presumably not even the most important one. The other side is: we all know that machinery is part of our daily life, that technical systems do coexist with biological systems. This coexistence will come to a cooperation, and it is the cooperation with biological or to some extent "unstructured" systems where the use of Mechatronics will be of eminent necessity. In such cases there is little chance of circumventing the use of "intelligent" machinery as it is still done nowadays in the industrial world, for example by redesigning a product in such a way that it can be handled, packaged or assembled more easily. Therefore we will have to come up with machinery with some kind of intelligence. But inevitably this intelligence will hardly ever be enough. There will always be the need to deal with exceptions, i.e. situations which have not been foreseen. And the best exception handler we can think of is the human being. This brings us to the point: We want to have a machine that can work autonomously up to a certain level of complexity, and in critical situations or for high level intervention there should be means of interaction with the operator. And this interaction requires adequate means, not just a warning light, a sound, or a simple emergency shut down.

Subsequently three robotic projects of the ETH will be presented where this man/machine interaction has been realized under various intentions and constraints: a pingpong playing robot, a cooperating robot, and a polite, mobile robot.

3 A Pingpong Playing Robot

The pingpong playing robot was initiated by research on fast gripping and touching with a robot. For that project we needed a robot capable of fast and controlled motions. And additionally the control of the robot should react very quickly to signals of external sensors, in order to actually perform this controlled touching at all. Such a robot was not yet available on the market. Therefore we built the robot ourselves, mainly by partitioning the task into student projects and integrating them into our educational activities. In order to make the tasks attractive to the students, they were asked to design the robot in such a way that is could play pingpong against a partner. It took nearly three years, 25 student projects and some dedicated work of our tutoring assistants until the machine worked (Fig. 2). The students came from mechanical and electrical engineering, and from computer science. There are several questions arising in that project. How does it work? What are the areas where the essential difficulties lie? What ideas can be derived from that project for future research in robotics and intelligent machines?

The difficulties arise at various levels. At first the information processing is more complex than in usual robot tasks - it must be faster and in "real time". The sensors have to pick up the spatial motion of the ball fast enough and, above all, we have to generate a goal oriented spatial motion of the robot. For this purpose we need a sophisticated control of mechanical energies with corresponding requirements for the mechanical construction and for the drives /FBN 88/. Therefore the playing of PingPong with a robot is of interest as a study project in other places, too, as in the US at the AT&T Bell Labs, or in Japan at the Toshiba Company, where it is considered as a benchmark test for advanced motion control.

In the meantime a contest between pingpong playing robots has been set up, initiated by Prof. Billingsley from the Portsmouth Polytechnic in England. Contests have taken place several times already. In August 1988, during the Congress EUROMICRO in Zurich, we were lucky enough to win against three other teams from England, Sweden and Finland. The rules of the game, of course, are a subset of the conventional ones. The table is smaller (2m x 0.5m), at the beginning the white ball is released from a caging mechanism in the middle of the table, the ball has to pass through a frame at the end of the table, and it may hit the table only once after crossing the net. This restriction of rules is intended to decrease the size and with it the costs for the mechanical construction of the robot.

The mechanical set up is shown in Fig. 2. The basic design is that of a universally usable industrial robot. The three main degrees of freedom allow a motion in cylindrical coordinates, i.e. a rotation about the vertical, an up and down motion of the arm, and a horizontal motion of the carriage which is carrying the hand with the paddle. The rotation about the vertical is not even necessary for playing according to the simplified rules. The driving system consists of brushless dc-servomotors with a nominal power of 1 kW, which can be overloaded for a short period of time for generating four times the nominal torque. In future such controllable drives probably will be more and more used instead of mechanical gears in various textile machinery for generating controlled motions in a versatile and easily programmable way. For the robot under consideration, in order to keep the movable masses low, the drives of arm and carriage do not participate in the translational motions. The forces are transmitted by cables and pulleys. The arm and the carriage are a special lightweight construction consisting of aluminum and carbon fibers, they move on rollers on especially developed guideways. This mechanical construction allows extremely high accelerations of the hand of up to 25g. The hand is the only mechanical element which has been designed for pingpong playing only. Its three additional degrees of freedom allow an orientation in space and a controlled hitting with the paddle. It is driven by bowden cables, an element used in bicycle brakes as well, and activated by drives fixed in the workspace.

The motion of the ball is picked up by two CCD-cameras at a rate of 50 half-frames/s. The single gray images are transformed into binary images, and from that the spatial position of the ball is determined with an accuracy of one millimeter or less. The complicated task of calibration is done with photogrammetric means /BFW 89, FBW 90/, and it runs nearly automatically. The velocity vector is derived from sequences of such images. The difficulties associated with vision, mainly concerning the correct exposure time and the illumination of the scene, were considerable but not of a basic nature.

Even the fast information processing could be handled. Three microprocessors of the Motorola 68000 family were connected to a multiprocessor system on a VME-bus. They were responsible for the three tasks of image proces-sing, playing strategy, and drive control. Programming was done in the high level language MODULA 2. Thus with this configuration it became possible to position the paddle in its working range of 0.3 x 0.3m within a time interval of 0.1s, and to return the ball about 3 to 4 times against an other robot or against a willing human partner. This may look like a nice result for the beginning, but of course the question comes up as to potential improvements, especially taking into account any human performance.

The mechanical and electronic hardware components of the robot are, with respect to velocity and response time, more than sufficient for that task. Deficiencies, however, appear to be primarily in the available software, *the intelligence of recognizing and acting*. One of the next, more easily realizable steps will therefore be to improve the model for the trajectory of the pingpong ball on which the playing strategy is based. In addition to the air drag which is already taken into account, we will also have to consider the spin of the ball in the algorithms for the on-line precalculations. But this will not be enough. The basic question seems to be: will it be sufficient to proceed only "technically", refining the algorithms for the precalculations and the control, or don't we rather have to look at the behavior of the human player, ie. to proceed in a more "biological" way? In our long term research activities we therefore will study questions like: how does a human being see a motion, and how does he or she learn to interpret it? Or, how does the human being control his or her usually quite fast and goal oriented motion with such little effort in mechanical power? For the future use of advanced robots in industry, it will not be sufficient to just provide more sensors, as is often assumed nowadays. It will be essential to have much more sophisticated software which right now we can see only in somewhat vague terms /ISH 89/. Thus this project of the pingpong playing robot goes beyond the actual technical requirements. It gives some incentive for interdisciplinary problem definitions, and that is one of the reasons why we look for and support contacts in these directions. For example, recently a group on *Neuro-Informatics* has been founded jointly at the University of Zurich and the ETH (Swiss Federal Institute of Technology), a collaboration of natural and medical scientists with engineers, connecting biological and technical aspects of information processing.

4 Cooperating Robot with Tactile and Vision Sensors

This robot will have to work in an only partially structured environment, performing industrial tasks like assembling, complex sorting, inspecting or repairing in a rather autonomous way. Unavoidably there will be exceptions where the supervising operator, without endangering himself or herself, should be able to take actions within the working range of the working robot. Therefore the robot has to be able to really cooperate with its operator. As a benchmark and as an application in the area of service tasks, we would like to use the robot for removing dishes from a tray in a cafeteria and to put them into a dishwasher. The problems to be solved for that task require a close multidisciplinary cooperation across departmental borders (Fig. 3). This is a challenge for the organisation of the project, quite typical for most problems in mechatronics. At the ETH we already have an interdisciplinary group since 1985, which is responsible for research and teaching in mechatronics, and we have split up the project into specific tasks according to the expertise of the members of this group:

- 3D visual object identification and high speed data processing (Prof. Kübler, Computer Vision Lab, and Prof. Guggenbühl, Electronics Lab)
- intelligent robot gripper (Schweitzer, Robotics), /XSS 90/, /SCV 91/
- selfcalibration of the robot (Hugel, Electrotechnical Design and Construction Lab)
- interactive cooperation between human operator and robot (Schweitzer, Robotics Lab), /BAE 92/, /VIS 92/

The *intelligent robot gripper* (Figs. 4 to 6) demonstrates that even a mechanically simple gripper can be made intelligent and versatile using task specific sensors and appropriate software /SHV 91/. The kinematics of the gripper are simple and therefore less expensive: three stiff and straight fingers can move independently for grippping objects of various shapes and sizes, the objects can even be soft and flexible. The most important sensors for grasping are the strain gauges and the fibre optics in the fingers. For each finger four strain gauge bridges are measuring the finger forces and their contact points. From these signals further information about the object, e.g. stiffness and slippage, can be derived. A special small-sized fibre-optic range-finder is mounted in the axis of the finger and measures the distance from the finger tip to an object in front of the finger. A six-component force-torque sensor mounted between the gripper and the robot measures the object weight and can also stop the robot in the event of unexpected contact with the environment. Two ultrasonic range-finders prevent collisions between the robot and the environment during robot motion. The grasping data for known objects are derived from the vision information and the object specification stored in a data base. In the case where the object is unknown or not recognizable, the vision system still provides a set of points describing the contour of the object. Based on these points a neural network computes three suitable finger locations for a force stable grasping /XSS 90/. The combination of the two methods guarantees a high success rate of grasping.

The question of robot *safety* becomes increasingly important as future robots will be required to share their working area with humans. A failure of the robot's hardware or software can result in an unexpected robot motion which may be dangerous for the operator or user. For the cooperating robot two additional safety systems using accelerometers and a camera to supervise the robot were implemented /BAE 92/. The first safety system is based on three perpendicular accelerometers mounted on the robot wrist. An emergency stop is initiated if the difference between measured and expected accelerations exceeds a certain limit. The resulting "runaway protection" can be easiliy applied to any existing (industrial) robot or any other motion controlled machine. A second safety system uses a camera to supervise the robot's workspace. The system checks, whether the desired position of the robot corresponds to its real position. Furthermore, it provides the location of the human operator. This information allows to temporarily stop the robot or to change its path thus avoiding to interfere with the human. The vision algorithms were implemented on a dataflow machine (Datacube) and permit a realtime detection of moving objects.

One of the major results of this study and directly applicable to industrial problems was the ability to perform handling tasks in a certain unstructured 3D environment. It was demonstrated in a test setup for the *perception and control for sorting simple 3D objects*. The sorting of objects is a substantial task in industry and has a large potential market. The benchmark chosen was the sorting of postal parcels with rectangular but otherwise arbitrary size and position, which have to be removed from a pile as shown in Fig. 7 /BAE 91/. The system uses a range-image sensor for object recognition and fibre-optical short-range sensors, mounted in the fingertips of the parallel-jaw gripper, to guide the robot right before contact. The rang-image sensor is based on illuminating the scene with structured light and using triangulation (Fig. 8). Lines of light are projected onto the scene and observed by a camera. The deformations of the lines reflect the shape of the scene and can be used to compute the depth of the object at the illuminated points by triangulation. From several hundred lines projected over the entire scene a complete range image can be computed. This is achieved by projecting a set of light patterns representing different bits of a binary code. By producing n patterns we are able to identify 2^n different lines. The patterns are generated with a very fast LCD shutter (Liquid Crystal) combined with a strong stroboscope thus reducing the influence of the ambient light. The data are used by a simple "realtime" vision algorithm to segment the 3D image into a set of planes (Fig.9). The robot is guided by the vision system towards the approaching face of the target parcel (Fig. 10). The vision system itself, however, is not able to guarantee collision-free grasping of a parcel. To correct these shortcomings the optical sensors in the fingertips are used. If one of the fingertips is obstructed by an adjacent parcel before the grasp position is reached, the robot stops and closes its gripper to grasp the parcel. This "grasp- and -stop reflex" provides a high robustness of the grasping process and effectively corrects errors or inaccuracies of the vision information. Additionally, when a situation occurs where several parcels with equal height are lying so close together that no free space is available for the gripper finger or when the vision system cannot make a suggestion for a gripping approach for any other reason, the robot changes the configuration of the pile by pushing some parcels aside and offers the vision system a new chance. The suggested *sensor fusion and exception handling* leads to an autonomous and very robust sorting system, which is able to perform its task in realtime. The image-processing takes about 0.3 sec, the gripping cycle about 2 to 3 sec.

5 A Polite, Mobile Robot

The interaction of the human user with an intelligent machine can be shown in another example, too. The objective is to design a collision avoidance strategy for an *automated guided vehicle* in a textile factory /AGU 90/. The vehicle is supposed to deliver heavy cans from a supply area to a number of processing machines. The necessity for the avoidance of obstacles, be it edges, other vehicles or unexpected objects is obvious, and there are means to do it. Special consideration, however, is necessary for humans, operators, maintenance people or visitors. It is not sufficient to concentrate on the safety aspect and to avoid injuries. People working in these areas want to feel secure and they do not want to be regarded as intruders by a vehicle flashing a light at them or just sounding a horn when it approaches. They expect the vehicle to be "polite". In a project like this and in others we try to solve such questions with the active participation of the Institutes of Ergonomy and of Work Psychology of the ETH (Profs. Krüger and Ulich), which in these areas, too, leads to new scientific questions. In our case the vehicle was equipped with additional optical near- and far-range sensors, and with a hierarchical control. This allowed a gradual approach to human "obstacles", with adequate warnings. This *socio-technical approach* was very supportive for the acceptance of the AGV by the employees, which can be quite essential for the success of the automation and the expected increase in productivity.

6 Conclusions

Three projects have demonstrated a continuing effort to develop robots into "intelligent" machines and into cooperating helpers for the human being in his or her working environment. It is felt that it is one of the main objectives of mechatronics to make machines more intelligent, thus giving them a potential for communicating and interacting with humans, users or operators /ISH 89/. The advancements of mechatronics will lead to a higher degree of automation, *soft automation*, where above the mainly technical aspects, it appears to be essential to put human beings, their demands, expectations and limitations, into the centre of the effort of designing intelligent machines.

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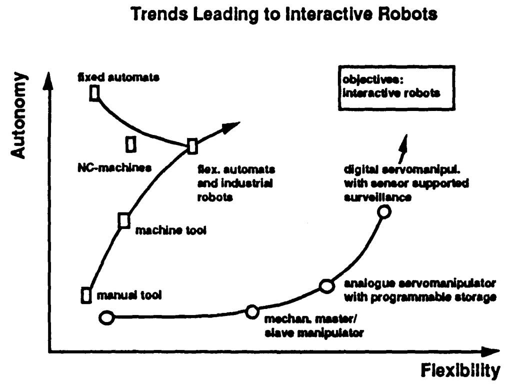


Fig. 1 Tendencies for the development of flexibility and autonomy for machines and technical devices

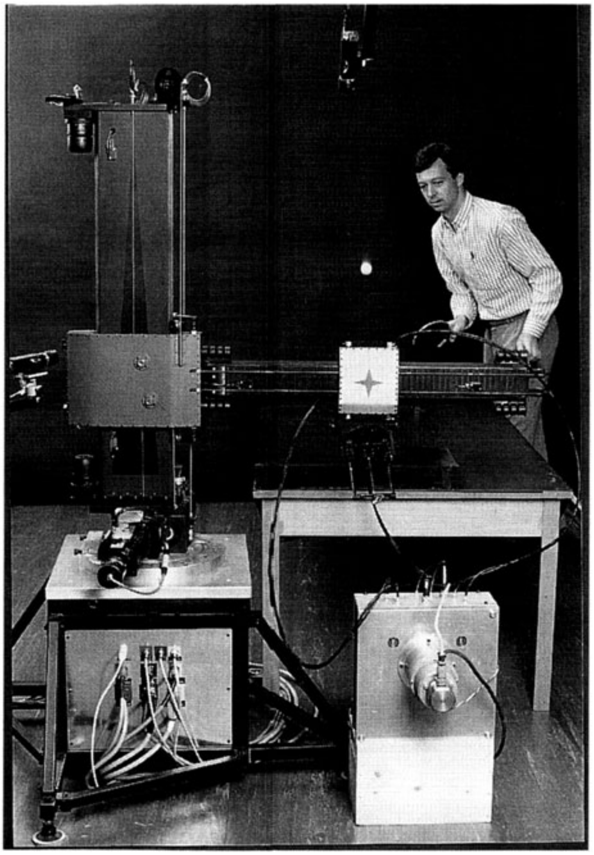


Fig. 2 The PingPong Playing High-Speed Robot with two CCD-cameras for stereo vision. The wrist of the robot can accelerate with 25g

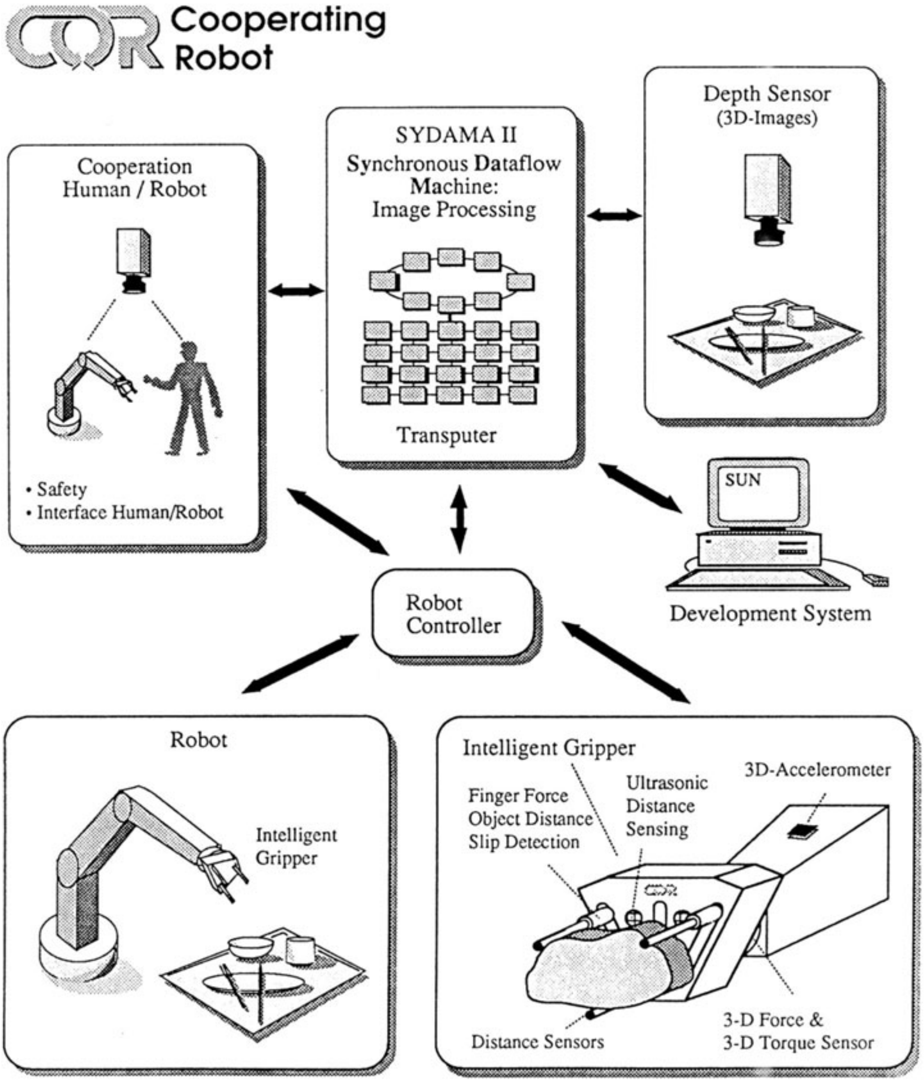


Fig. 3 Project tasks for the Cooperating Robot clearing dishes from a tray /VIS 92/

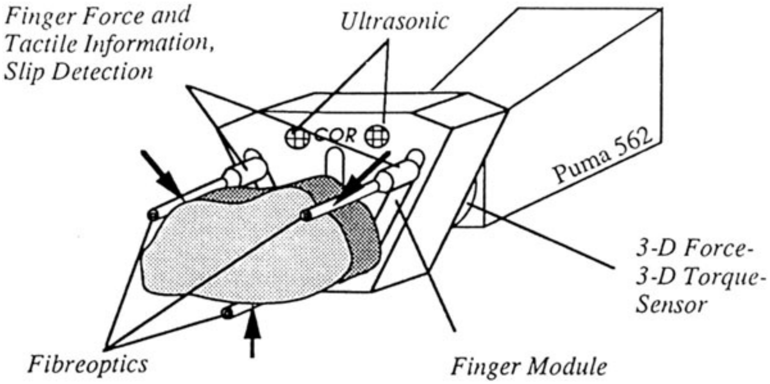


Fig. 4 Sensors of the intelligent robot gripper

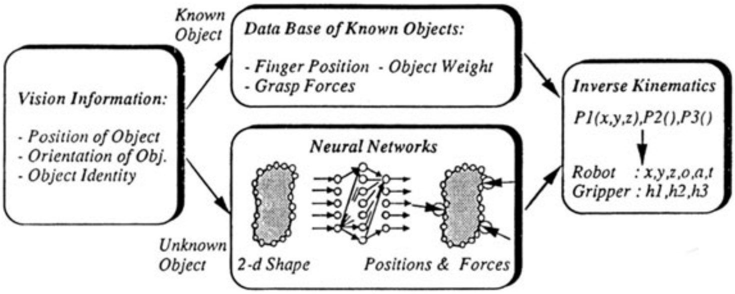


Fig. 5 Generation of grasping data

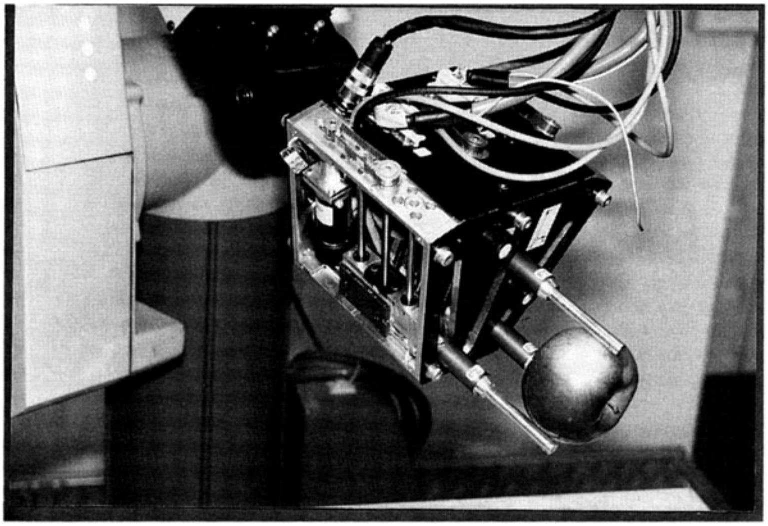


Fig. 6 Gripper in action

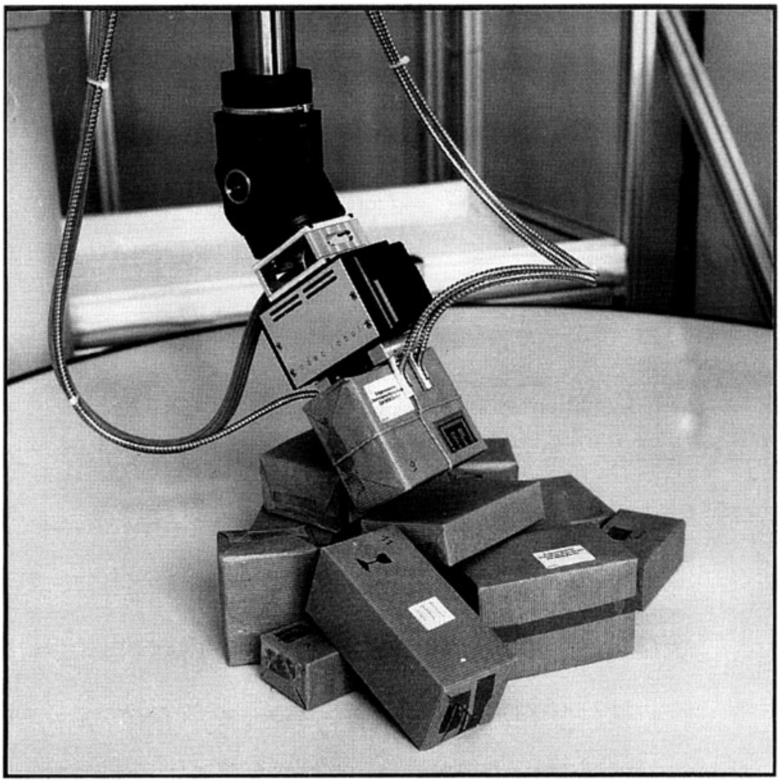


Fig. 7 Typical pile of postal parcels

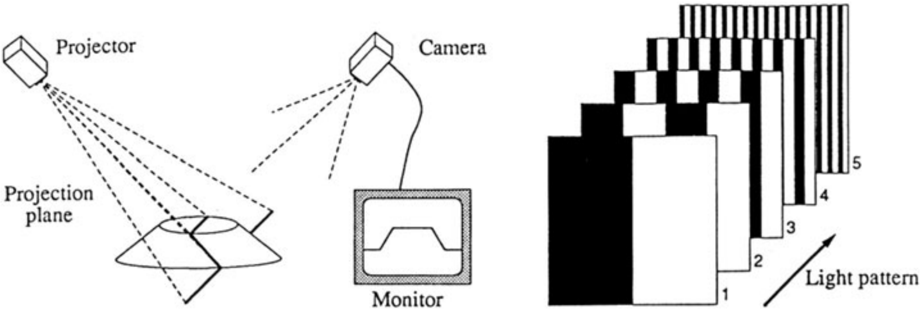


Fig. 8 Principle of the structured light range-image sensor with a set of binary light patterns

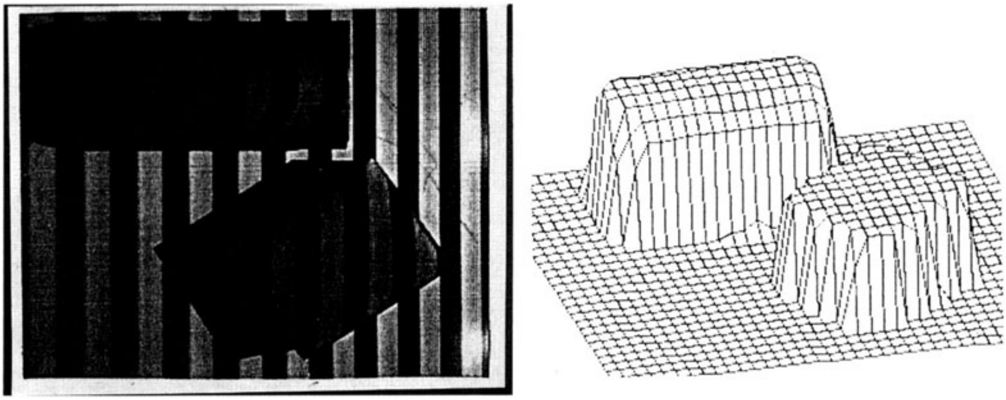
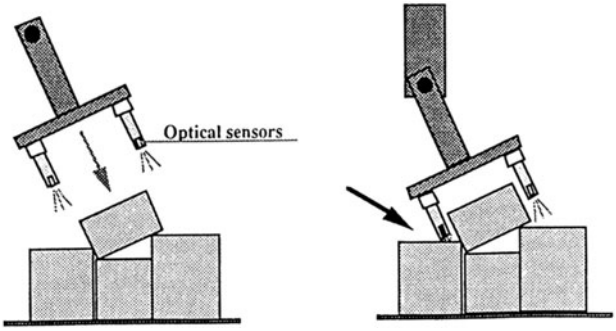


Fig. 9 Pattern projected on sample scene and reconstruction of sample scene



Approaching Phase
Guided by 3-D Vision

"Stop-and-Grasp" Reflex
Triggered by Optical Sensors

Fig. 10 Grasping a parcel using vision information and multiple sensors in the gripper

INTELLIGENT TEXTILE MACHINES AND SYSTEMS

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1. TEXTILE MACHINERY INDUSTRY

The desire to increase the productivity of a machine inevitably leads to higher production speeds. This can be achieved at the design stage by reducing the moving parts on the machine and/or their inertia and consequently causing less wear and tear. This desire, of course, provides vast opportunities for the integration of microcontrollers, sensors, and information technology with precision designed machine components in order to reduce fast moving mechanical parts.

Modern textile machinery, one of the largest industrial sectors in the world, contrary to common perception, reflects the state of the art in integrated machine design and incorporates the most advanced technology. This is because of the diversity and high volume of products which demand versatile machines to respond to the changes in a highly competitive market. The days of electronic add-on in textile machinery have now gone and the mechatronics design concepts find a suitable breeding ground and a major application field within the textile machine industry.

The ITMA'1991 in Hannover was the scene of engineering excellence, design perfection, and integration of microelectronics, sensing and control, and information technology in high speed machinery, with the Japanese companies leading the field, followed closely by the major European companies.

2. FIBRE AND YARN PRODUCTION MACHINES

Completely automated man-made fibre plants were displayed at the ITMA'91 where robots carried out all the operations from feeding the machine with raw material to grading and packing the final product. Interlinked sensor networks and computers provided the required information to the plant managers.

M. Acar (ed.), Mechatronic Design in Textile Engineering, 61–65.

Winders or take-up units are typical examples of high speed operations, where speeds of 6000 m/min are typical in industry. Traversing mechanisms for such winders were the focus of attention and a digital traversing system which superimposes a modulation on the traverse speed to avoid patterning was demonstrated. A novel non-contact yarn speed measuring device which gives a measure of the yarn bulk was also displayed.

The most common trend in the yarn production machinery is the expansion of microelectronic control and automation. To give an example we can mention the unit for automatically changing the travellers on a ring frame. Given the higher spindle speeds and shorter traveller life, automated traveller changing may become the future of the high-speed ring spinning frames.

3. WEAVING MACHINES

In the weaving machinery sector, there was a dramatic growth in the integration of advanced microprocessors with engineering excellence in the design of machine components in order to automate wide ranging aspects of fabric production. Such integration improves weft insertion rates and versatility, reduces stoppage times at fabric changes, enables detection and repair of weft breaks, and removal of faulty wefts. Machine production data, such as machine speed, weft insertion rate, weft entry angle, weft density, and cause of stoppages are monitored using appropriate sensors, hence important weaving functions can be regulated and optimised.

For example, increases in weft insertion rates and reductions in compressed air consumption of air-jet looms have been achieved as a result of improvements in the nozzle designs and integration of microcontrollers. With such integrated systems it is now possible to achieve automatic adjustments of (i) pressure for the main and relay nozzles according to the yarn structure, and (ii) the start and duration of nozzle blowing when a new style is woven. Intelligent weft accumulators can now measure the yarn strength during winding and coaxial exit brake systems help maintain a specific basic tension in order to reduce the peak tension.

A typical example of mechatronization of the weaving machine is the let-off motion. This brought about the following results: (i) controllability was improved and the fluctuation of the warp tension was reduced, (ii) the machine structure was simplified because the mechanical transmission gears used for driving the peripheral devices were removed, and (iii) remote operations became possible.

Filling motion control is another area of application of the mechatronic design. In the case of full mechanical systems it was very difficult to adjust the timing precisely. Mechatronization of the filling motion system enables the operator to set the timing easily, quickly and precisely by means of key-input at the operation panel or downloading the timing data using a LAN (Local Area Network) system. This improves the productivity of the machine.

Intelligent weaving machines designed and built with a view to be networked with a central processing unit and integrated information control system are paving the way towards complete process monitoring via LAN systems.

The production methods in weaving factories has been changing from mass production to small scale production of different kinds of textile fabrics. To maintain high productivity, new flexible production management systems suitable for textile plants are required. LAN systems provide the required total management system for weaving plants.

4. KNITTING MACHINES

In knitting machinery too, the integration of microcontrollers and associated software with precision manufactured high quality machine systems has been one of the most significant advances. This has already brought about a simplification in mechanisms and an increase in reliability and speed.

Complex mechanical needle selection systems have been replaced by direct acting electronic and electromagnetic needle-by-needle methods, developed to exceptionally high degrees of reliability, while feeder selection by direct acting, electronically controlled devices, assisted by pneumatic or simplified mechanical power, can be timed with great accuracy.

Patterning in the widest sense is often on-line from a sophisticated, customised pattern preparation system directly to the machine. With microelectronic control of all major machine functions now implemented and coupled to interactive computerised patterning systems, the fabric possibilities are no longer limited. On the straight bar machines, all operations can be electronically controlled from a built-in programme console and an automatic rib-transfer carriage is now also available.

5. RESEARCH AND TECHNOLOGICAL DEVELOPMENT AT UNIVERSITIES

Universities have also been active in developing mechatronic systems for the textile industry. Their research and technological development findings have been disseminated through meetings and publications. These include the current proceedings of the NATO Advanced Study Institute, one-day seminar at Loughborough entitled "Mechatronics Design in Textile Industries" [1], and Special Issue of the Mechatronics Journal (Pergamon) on 'Mechatronics in Textile Engineering', to be published in the near future [2].

The following are several examples, but by no means a comprehensive list, of the research and technological development activities taking place at a number of universities.

Tension Control:

Controlling the tension fluctuations during high speed winding has always been a difficult problem for textile machinery producers. For structurally sound packages the average tension should decrease in a controlled manner from the centre to the outside. Short-term variations, introduced mainly by the necessity to take the point of wind to and fro across the take-up bobbin, lead to poor quality of wind with unevenness, even to breakage of the yarn or to residual points of weakness. The problem becomes more complicated when winding conical packages from a fixed rate supply.

For low winding speeds, simple passive mechanical compensators have successfully been used but these are not adequate for high winding speeds. The problem of tension fluctuations in cylindrical package winding has been tackled by researchers at Coventry University (a full paper will appear in the Special Issue of the Mechatronics Journal) whilst the tension variations in conical package winding was the subject of a research programme at Loughborough University of Technology (see the full report in the current proceedings). Researchers at both institutions developed mechatronic tension compensators, which integrate electronics, microprocessing, mechanics and modern control theory. Both programmes proved to be successful in achieving reduced tension variations at increased yarn winding speeds.

Vision systems:

Further work at Loughborough integrates artificial vision with a laser cutting system for fabric processing. By using vision systems to identify fabric defects, pattern orientation and distortion, adaptive cutting path generation can take place so that this information can be fed to the cutting machine controller [3]. A prototype system has demonstrated an application of such a system to lace scalloping. A further research programme at the De Montfort University investigates the automation of the inspection of lace by using vision systems which will also be fully reported in the Special Issue of the Mechatronics Journal.

Garment Manufacture:

University of Hull, over the years, specialised in providing mechatronic solutions to the handling and joining operations of automated garment assembly, with special interest in sensory perception and error recovery techniques. Work at the Cimtex Research Centre at Leicester, as will be discussed by Wray in these proceedings, also addressed various issues of automation in garment manufacture. The importance of automation in the garment manufacturing industry has also been recognised by the various research initiatives of the European Commission, such as ESPRIT and BRITE/EURAM, which funded a number of research programmes across Europe.

Machine Design:

Researchers at Clemson University have been working on the application of mechatronics to braiding processes, particularly those processes that afford a measure of flexibility in controlling braid patterns. In the meantime at the Mars Mission Research Centre of the North Carolina State University, a research team has developed a new mechatronized method of 3-D weaving of net shapes. Both of these researches are fully reported in these proceedings.

Researchers at the University of Ghent, University of Technology Aachen and University of Manchester Institute of Science and Technology have also been working on various aspects of design for weaving machines with a view to improving the machine efficiency and product quality, to reduce the setting up times and to optimise the processes.

Intelligent machines for textile processes:
We do not need to look at a crystal ball to predict that there will be a significant increase in the number of intelligent machines exhibited at the next ITMA Exhibition in 1995 which have been designed using mechatronics philosophy. This, of course, will translate into increased efficiency, productivity and quality.

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RECENT DEVELOPMENTS IN YARN AND FABRIC FORMING MACHINES

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1. Introduction

In many respects the textile art of making yarn and fabric structures is older than humankind itself, spiders, caterpillars and silkworms drew out fine threads, and birds wove intricate nests long before humans arrived and learned how to imitate them. Indeed, the Textile Institute recognises this by featuring weaver birds on its coat of arms.

Textile manufacture was the first mechanised industry. Consequently, it was not surprising that by the middle of the nineteenth century the machines for processing cotton and wool staples had achieved a high degree of efficiency. It is true to say that they have shown very little change in principle over the subsequent years. For example, the machinery for performing the basic operation of opening carding, combing and drafting have altered only in detail during the last century. The spinning operation itself has been subject to much change and a steady trend towards increased overall automation can be discerned.

There are many factors which control the design of textile machines, an area of fierce international competition. For example in spinning (which was the first mass production industry and is probably still the largest) thousands of identical components are used in a typical plant so that each must be as inexpensive as possible. More expensive items would have to show either savings in yarn production costs or improved yarn quality which, in turn, could reduce the cost of fabric manufacture by reducing the number of machine stoppages. The integration of separate processes is limited not only by costs but also by the need for product variety in an industry which has to be very fashion conscious. for the same reason, machine speed at any one operation is not the sole criterion affecting output.

The machine designer also needs a considerable knowledge of fibre, yarn and fabric technology, since in nearly every type of textile machine, the product actually forms part

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of the mechanical operation; consequently, a change from (say) wool to synthetic fibres will change the conditions prevailing in the machine because of the different physical properties of the two textile types. For example, in ring spinning the yarn being spun serves to rotate the traveller which inserts twist in the yarn; in knitting the yarn closes the latched needles to form the knitted stitches; in the false-twist bulking of synthetic filament yarns, the yarn can be rotated at more than 7M rev/min by friction-driving their small cylindrical peripheries and one wonders where else in manufacturing does one see mass production of quality products being produced 'round the clock' at speeds of 120,000 revolutions per second! Again, in mechanical and/or electrical control various devices, textile faults are used to operate detectors which either stope the machine or automatically rectify the fault and, in many types of machinery, the strains undergone by the product are part of a servo-control system which limits the applied tension.

Consequently, the textile machinery makers have traditionally and of necessity developed machines in close cooperation with the customers and this has led to a 'love-hate' relationship because of their conflicting technological and commercial requirements. For instance, the machinery maker aims at series product of standardised machines whereas the customer is often looking for maximum versatility. Again, the supplier would wish to retain proven designs as long as possible whereas the customers are often looking for machines designed to fit in with new versions of other machines in the production line.

In general, textile machinery is now being built to higher standards and to more exacting performance requirements with the trend increasingly being towards more automation, often by micro-electronic means. This have inevitably resulted in higher machine prices and rapid obsolescence. Technological progress is so fast that the textile manufacturer cannot afford to neglect new types of machines. Nor can the machine manufacturer rely merely on his traditional and valuable links with customers for the feedback of information for design purposes. Developments on the broader horizons of technology are such that the company which skimps on its R & D is courting extinction.

2. Ring Spinning - the Product becomes an Element of the Machine

The ring-spinning machine (the ring frame) was pioneered in the United States around 1828 by Charles Danforth and John Thorp who each took out separate patents for this deceptively simple but highly ingenious continuous spinning device. It perhaps also owed some of its origins to Arkwright's Water Frame because, imagine the bobbin in Arkwright's machine to be fixed to the rotating spindle, and the flyer above to revolve freely; the bobbin would pull the flyer round - a reversal of the usual condition. Next, dispense with the flyer and instead, surround the bobbin with a steel ring, and clip a C-shaped piece of wire to the flange of the ring so that it might travel freely round it. This wire clip, called the traveller, took the place of the imagined freely revolving flyer, and the yarn, on leaving the drafting rollers, passed through it on to a bobbin. In doing so, it pulled the traveller round the circular track provided by the stationary ring. This was another excellent example of the textile product actually forming part of the machine which often occurs in textile machinery. If not yarn was present, then no twist would be inserted since each revolution of the traveller inserted one turn of twist. The ring was given a vertical traverse to distribute the yarn along the bobbin. Since the yarn had to pull and extremely light piece of wire instead of a heavy bobbin, as in the Water Frame, the yarn tension was lower, and it became possible to spin finer and more softly twisted yarns, although many people in Lancashire vehemently argued that they were still not as fine, nor as soft, as those produced by the mule.

The ring frame had one other important advantage over the mule - relatively unskilled labour could be used to tend it; skilled mule spinners were not very plentiful in countries other than Britain and this factor undoubtedly contributed to the energy with which it was developed in the United Stated. In subsequent years, higher engineering standards, so improved the ring frame that it eventually replaced the mule even in Lancashire where it was used to spin much finer yarns that was possible when it was first introduced. One of the reasons for this was the use of small conveyor belts, known as aprons for controlling the fibres during the action of the drafting rollers.

3. Recent Developments in Spinning Machinery

The most serious challenge to the ring-spinning machine has been the invention of the rotor open-end spinning system in Czechoslovakia some 30 years ago. rotor spinning machines are now available from virtually every textile machinery manufacturer. The most serious defect in ring spinning has always been the necessity to rotate the high inertia bobbin-spindle combination to insert twist into the yarn; this leads to high power costs. The output of the ring frame depends on the rotational speed of the bobbin, but it is limited by three factors: wear on the traveller (the small wire clip which inserts twist to make a satisfactory piecing at high speeds; and increased yarn breakages due to higher bobbin winding tensions. Despite notable attempts to devise automatic piecing systems, only a limited improvement of these factors has occurred. Much effort has therefore gone into eliminating ring spinning completely by the new techniques known generically as open-end spinning since these avoid the basic limitations of the bobbin rotating at the twisting speed.

In a commercial method of rotor open-end spinning the fibres are fed as a sliver from a can into an opening and cleaning unit, which comprises a revolving beater with saw-tooth blades. The separates the individual fibres prior to their entering the spinning rotor via a feed tube. Then, loose fibres enter from a feed tube and are assembled centrifugally as a fine web round the inside surface of a rapidly revolving drum known as a rotor. The fibre assembly is continuously peeled off as it is withdrawn along the axis to form a yarn; the rotating ‘open-end’, at which fibres are being attached, serves to insert the twist necessary to bind the fibres together. Thus, twisted yarn is withdrawn from the rotor at a maximum delivery speed of 150 m/min and can be wound on a separate large bobbin which does not have to rotate rapidly for twist insertion, as in the case the ring spinning. The number of preliminary processes is therefore greatly reduced as is the necessity for re-winding the ring-spun bobbins on to packages suitable for the resultant fabric manufacturing stages.

The fact that the fibres are themselves twisted as they are extracted from the mass somewhat resembles the situation in hand-spinning, this poses the question "are we going full-circle?" It is only fair to indicate that the physical properties and structural characteristics of open-end years are somewhat different from those of ring-spun yarns but there seems little doubt that the new method has progressed rapidly and now account for most of the new machines sold today for spinning coarse to medium yarns. It cannot as yet produce the wide range of yarns possible by ring-spinning.

An automatic piecing carriage which can be precisely programmed by a microprocessor so that the pieced section can hardly be distinguished from the regular yarn. A sensitive piecing tested monitors the quality of the piecings by checking the yarn so that the correct count is maintained both before and after piecing. If a piecing is outside the pre-determined tolerances, a repeat operation is performed. At each piecing operation, the rotor is cleaned by mechanical and pneumatic means and additional cleaning is automatically carried out at pre-determined frequencies without yarn breaks occurring.

Although many other new types of spinning methods are evolving, open-end spinning using rotors has so far proved to be the only really effective challenger to ring spinning, but such yarns are generally confined to the 200 to 20 tex range of linear density. Because there is no spinning package to rotate the insert twist, the twist insertion rate is more than 5 times that of ring spinning, but its limitation is still the twist insertion rate, just as in ring spinning. Later systems such as air-jet spinning and friction spinning have greater twist insertion potential because these are not limited by their twist insertion methods but by the drafting and fibre transport systems which present the fibres to the twist insertion zone. Air-jet spinning is the only newer technique to produce yarns approaching the finer end of ring spinning, although friction spinning extends into the medium yarn count range and its production potential is claimed to be higher than that of any existing system. In fairness, it should be said that neither of these two new techniques has yet attained significant industrial acceptance.

A major drawback with all open-end spun yarn systems is that, to form the open-end, the fibres must be deposited from an airstream. It is difficult to achieve the same degree of fibre alignment that can be obtained with a drafted strand of fibres, and therefore the physical characteristics and properties of all the new yarn forming methods are very different from ring spun yarn by virtue of their unconventional methods of manufacture.

Despite the fact that rotor spinning, air-jet spinning and many other interested new spinning systems have evolved over the past 30 years, there is good reason to consider that ring spinning will maintain its dominant position at least until the turn of the present century. This is because ring spinning is still the most versatile system for making a spun yarn from short or long staples over a wide range of linear densities, i.e. from 300 to 6 tex, and this product range cannot be approached by any other system. the most recent trend in spinning automation has therefore been the linkage of ring spinning with the roving operation which proceeds it and with the winding operation that succeeds it.

4. Link Spinning Systems

At the ITMA 91 exhibition in Hannover, nearly all the world's leading spinning machinery manufacturers were exhibiting link spinning systems and these have no doubt been brought about because many of the newer types of spinning systems, such as rotor spinning and friction spinning, take as their input a drawn sliver and output the yarn on to wound packages. Indeed, at that exhibition, a leading Japanese manufacturer was offering a fully automated spinning plant from raw cotton through to fully wound yarn, the few operatives being mainly seated at computers. However, such a CIM plant can only be feasible for the high production of a narrow range of yarn counts. Therefore, the advantages of these newer developments are causing the older technique (ring spinning) to attempt to provide the same facilities by linking several machines together. The most common linked ring spinning system has an automatic doffing and bobbin transfer system for automatically feeding the winding frame from the spinning machine. The incorporation of winding has been made easier by the introduction of splicing of yarns as a substitute for knotting them. The introduction of the splicer has enabled link spinning to become practicable and automatic doffing has removed the limitations of ring and traveller dimensions, and spindle speeds. Therefore, the package size from the ring frame has reduced considerably from the large packages used in the early 1960s (300mm lift and 75mm ring diameter). The use of the direct link system for yarns within the medium to coarse count range is undoubtedly intended to make ring spinning an effective productivity competitor with rotor spun yarns.

5. CAD/CAM in Fabric Manufacture

The use of computers and associated equipment for automatic control and data acquisition has become an accepted feature of modern fabric manufacturing throughout the world. It has also helped to make the machines more productive as well as more flexible and versatile. The visitor to the ITMA 91 exhibition in Hannover could immediately see that the trend was towards ever more computerisation, automation and electronic programme control, in other words an advancement of "mechatronics". There is every indication that all textile manufacture is moving towards the CIM m(Computer Integrated Manufacturing) phase and this trend is likely to continue, particularly in western countries with their high labour costs.

CAD/CAM has greatly affected areas such as weaving, knitting, printing, apparel and carpet manufacture. CAD alone started to have its first major impact in the sophisticated world of graphic design. This is because both knitted and woven textiles are particularly influenced by the demands of fashion and therefore the design and produce development times must be short if companies are to remain competitive in high-fashion products. A decade ago, most CAD systems were in reality on computer-aided pattern preparation systems which allowed designs to be more easily made suitable for translation into knitted and woven fabrics. Many computer software houses improved on this theme by devising CAD programmes for desk-top computers. Such developments enabled fabrics to be simulated on VDUs with the various components being built up stitch-by-stitch or pick-by-pick on the screen. More advanced CAD development allowed the designer to work through from a fashion idea to a completed garment because it was possible to see the 'resultant' garment being modelled on the graphics screen with many possible variations of colour and fabric structure. It has even been possible to simulate such properties as texture and drape into 'modelled' garments. Such properties are normally only associated with the tactile and visual appreciation of a real garment. CAD has therefore become established as an almost indispensable working tool for the modern textile fashion designer.

The most recent advances have started to couple such CAD facilities to CAM (Computer Aided Manufacture). CAD/CAM can thus be seen in its early stages in examples such as jacquard or dobby punching machines for use with conventional pattern weaving looms. In more advanced form, CAD/CAM can be seen in electronic dobbies or jacquards, drawing-in machines and in the control of the weft insertion components of sample looms, and knitting machines. It is now possible for a complex jacquard-type textile sample to be completed in less than an hour where forely it could have taken up to a week. Some systems also allow a garment design to be created as a 3-dimensional model and then converted into 2-dimensional pattern pieces which can feed the computer-controlled grading, laying and cutting systems. Apart from fabrics intended for apparel uses, the applications of CAD/CAM techniques can be as wide as upholstery, terry towelling, table and bed linen, furnishing and automotive fabrics. Tufted carpet manufacture can similarly be controlled by CAD/CAM by the technique of over-tufting. Printed carpets have been produced for nearly 20 years by computer controlled jet printing systems such as the Militron process.

The proper management and handling of such CAD/CAM systems can enable companies to enhance their profitability and shorten lead times when bringing new designs on to highly competitive fashion markets which demand quick response and individual styling. Therefore, this is seen as an important trend towards the ultimate goal of computer integrated manufacture (CIM). Moreover, the separation of CAD and CAM enables a design studio in one country to be linked to a production unit even on the other side of the world and yet the garments and fabrics can be produced just as quickly as if the whole operations were conducted under one roof!

6. Automation in Garment Manufacture

The most urgent areas currently needing Computer Aided Manufacture are the apparel making-up stages, i.e. the assembling and sewing of clothing. Garment production is still highly labour intensive and economic manufacture is critically affected by labour costs. This means that the clothing section has been increasingly located in countries with low labour costs and this has led to a rapid decline of the clothing industries in most western countries. Therefore, there is a critical need to convert the clothing sector into the same state of machine dependence as exists in the manufacture of textile yarns and fabrics. CAD has already been well developed as an aid to fabric cutting, laying and marking stages of production, and there is currently much research going on in Britain and elsewhere into automation in the assembly and sewing stages.

With British government aid, the CIMTEX Research Centre for Automatic Garment Production has been founded in the UK with the intention of cooperation and participation by forward-looking industrial and academic partners, of which Loughborough University of Technology is one. The intention is to incorporate the latest research and development work in computer-controlled machinery to form the basis for a national demonstration of computer integrated manufacturing system by linking together the results of the research work undertaken by all the collaborating partners. The project will comprise five research work cells and three linking packages. The work cells are described as "discrete islands of automation which together cover all the manufacturing operation necessary to produce knitted leisurewear garments". The linking packages are those research areas which are of major influence in determining the successful operation of inter-cell operatability.

The five work cells are:

i) The generation of computer-based specifications from the creative design process;
ii) Fabric spreading, cutting and pattern matching;
iii) Semi-automated and automated sewing;
iv) Automatic finishing and packing; and
v) Automated methods for the making-up of knitting blanks.

The three-linking packages are:

i) Overall integration of manufacturing cells;
ii) Automatic vision inspection; and
iii) Objective assessment of textile materials.

The CIMTEX initiative is therefore to be seen as the start of a much needed coordinated programme bringing together textile, production, electronic, mechanical, computing and management experts from research groups throughout the UK with similar experts from British industry who have the practical production expertise to lead the way in a more profitable clothing industry.

Due to the rapid proliferation of computer hardware and software, many large weaving plants unfortunately have installed difference computer systems for production monitoring, production planning, inventory control and CAD. Consequently, their overall effective use can only be guaranteed if a network can be installed to link all the systems into one plant databank. Therefore, CIM in such weaving plants can be defined as a system solution having the following characteristics:

i) all computer systems in the production plant are linked into one network;
ii) all data structures are integrated in one plant databank; and
iii) information must flow from the central system to the machine microprocessors and reverse.

The author has seen many weaving plants throughout the world where impressive separate computer facilities have been used for production monitoring and planning, yet such plants are not true computer integrated manufacturing because they fail to measure up to the above characteristics.

7. Conclusions

Because textiles is the world's most fashion controlled industry, often necessitating small runs of relatively new types of product, the effects of digital processing techniques on automatic control and data acquisition in many sections of the textile industry might not be as large as in some other major manufacturing industries, such as chemicals, steelmaking and foodstuffs. The development of simple and servo-controlled actuators which have been successfully applied in spinning, weaving and warp knitting machines to replace the more traditional mechanical linkages will inevitably continue. Control systems with process sensing, as seen in open loop and closed loop systems of auto-levelling during the various stages of yarn manufacture and in the let-off systems for weaving and warp knitting machines, will also progress with the need for quality improvements.

The complex nature of textile processes where there is a possibility of different process routes, different machine settings and product requirements, and an inherent variation in the raw material, means that many process decisions will still require a high level of human expertise which most probably will be needed for some time yet. Nevertheless, decision making systems based on artificial intelligence such as expert systems will undoubtedly evolve in the few large plants which concentrate on the mass production of reasonably standard products.

SOME ASPECTS OF CONTROL OF TEXTILE PROCESSES

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ABSTRACT. This chapter describes the application of feedback technology to a number of textile processes. Although the actual implementations vary enormously some common features can be observed.

INTRODUCTION

Process control of textile production is not trivial, as the raw materials vary enormously. Fibres, which constitute the fundamental building block of any textile, vary in length, diameter and physical properties. Further variability is introduced in conversion to fabric in dyeing and finishing. Dealing with such irregularities provides a continuous challenge to the textile engineer to maintain product regularity and uniformity.

The production speed of textile machinery in all fields of textiles has increased enormously over the past 30 years. High operating speeds in textiles usually result in deterioration of product quality unless more sophisticated control systems are employed.

Process control in textile machinery has been applied for many years before the introduction of electronics. Examples can be found in the regulation of slivers on cards and draw frames, tension control in looms etc. The first impact of electronics and microprocessor control has been in the field of programmable actuators; mainly rotary speed drives for the control of, for example, loom or card cylinder speed. These were followed by rotary or linear position type drives for the control of, say, guidebars on a warp knitting machine or the X-Y table of an embroidery sewing machine. These developments were a direct replacement of existing actuators with the benefit of fast change over and flexibility. They did not, however, form a close loop with the process itself and in many cases for a very good reason.

The examples where the product is measured continuously and the process is corrected, are increasing, but for many applications the field is still open for further development.

One major area of difficulty is process monitoring sensors which are either too expensive or unavailable for many applications. For example, carding quality can only be assessed

M. Acar (ed.), Mechatronic Design in Textile Engineering, 75–95.

manually by a carding engineer using a complex combination of sound and vision. Programmable actuators are in many cases significantly slower than their mechanical counterparts and therefore their relative operational flexibility cannot justify their cost.

The following are some examples from work carried out or still being pursued in the Department of Textiles at UMIST in the field of web monitoring and sewing machine control. All the projects had their share of difficulty and some are still pursued with no obvious solution in sight.

1. Case Study 1 - The Monitoring of Web Uniformity Using Laser Scanning

1.1. INTRODUCTION

The requirement of the system is to detect variation in fibre distribution (uniformity) both along and across the webs.

Systems have been developed before for this purpose based either on radiation or optical technology. Radiation technology, although technically successful, was perceived (probably not justifiably) by the trade as a health risk.

Optical technology is based on variation in light transmission which relates to variation in weight for a given blend of fibres. Although the technology was proven right in principle, back in the sixties, it was prone to drift. This meant that for a constant web the output signal varied over time because of one or more of the following reasons:-

(i) Change in light intensity of the source itself,
(ii) Instability of the electronic systems,

Optical systems with one measuring head were based on one source and two detectors (one for calibration). Another non-commercial system was based on one fluorescent light across the web width with multiple detectors. Another non-commercial system was based on one source divided equally across the web using fibre optics with multiple detectors including one for calibration. All those systems were prone to drift.

To facilitate across-the-web detection with those devices based on single head detection, the head itself had to be moved. This required a complex and expensive mechanical system. In addition, the cycle of scanning across the web was limited by the system inertia.

1.2 LASER SCANNER DEVELOPMENT

1.2.1. *Preliminary Consideration.* The drift mentioned above can be minimised to some extent by proper design of the electronic circuitry and careful selection of sources and detectors. However, from the beginning it was clear to us that to reduce long term drift to an acceptable level we would have to use ONE SOURCE and ONE DETECTOR which could be periodically automatically calibrated in a zone outside the main detection area.

If we use one source and one detector it is possible either to move the measuring head mechanically across the web or alternatively to direct the light beam and the detection path across the width. The second option is clearly more attractive as potentially higher scanning rates can be achieved.

If light beam control is the route chosen, then laser technology is preferred as the beam divergence is very small and can be directed from considerable distances. In addition, as the laser beam is monochromatic, by using suitable filters the effect of ambient light can be virtually eliminated.

As the mechanism of the beam obscuration relates mainly to a shade type effect, the wave length is not critical provided that reflection and diffusion effects are kept to a minimum, and since laser tends to be cheapest at the 623nm wave length this was adopted. Provided that artificial or natural light are not pointed directly at the device ambient light interference could be ignored.

1.2.2. *System Configuration.* With the combination of one source and one detector, a number of design configurations are possible but we decided to use the scanner type approach for both economic and practical points of view.

Our system was configured of the following:

a) Laser: (Class II, 623.8 nm, beam dia. 0.6 mm., workable range 50 ft.)
b) Detector: Photo detector, using single band filter to separate the laser light from the ambient light.
c) Revolving reflector at a speed of 20 revolutions/s,
    (i) cycle completion (360 degree) : 50 ms
    (ii) usable scan 90 degree : 12.5 ms
d) Interface box
e) Computer and VDU
f) Reflective Tape (SIGNAL RETURNING UNIT OR BALLATINE)

1.2.3. *Operation.* The laser beam scans the web 20 times/sec. A small portion of the reflective tape which lies outside the web is used for on-line calibration, Figure 1. The signal detected in this zone is reflected directly to the scanning device and therefore gives an indication of the long term drift expected. This drift as compared with the signal received from this portion of the reflector after switching on, is used to compensate the values obtained from the actual web.

At present 28 readings are captured across the width. This was regarded by the trade as sufficient. The actual readings are captured by specially designed hardware at precise locations across the width, so that processor timing which is subject to memory refresh signal and interrupt is not crucial. The beam size is approximately 3mm in diameter, but with extra filtration the scan profile is about 30 * 3 mm. The distance between the scans depends on the speed; if you run the web for example at 100m/min., we can detect the web speed approximately once per 8cm.

1.2.4. *Development and Performance.* On starting our work with this system we have found that the calibration technique used i.e. calibrating from a specific zone, did not actually work. This was quite puzzling until careful investigation showed that the laser tube exhibits a randomised short burst of intensity changes with a duration shorter than one scan.

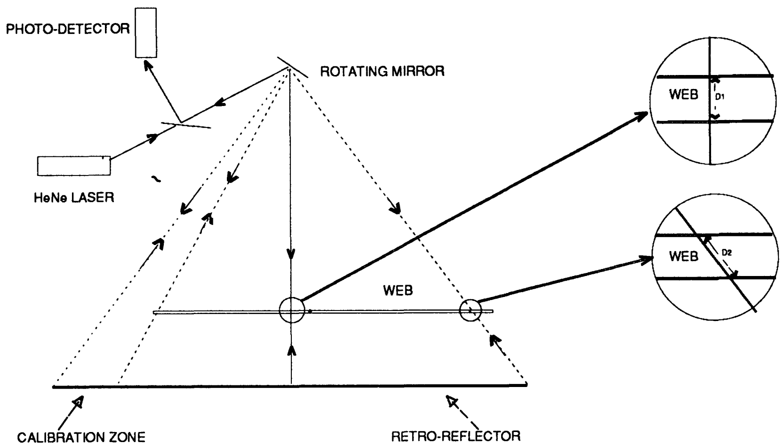


Figure 1. Direct scanning system.

Further investigation suggested that some polarised lasers are more stable for short term variation and consequently the tube was replaced. The calibration technique was then working and proved itself extremely well with long term drift of less than ± 0.3%. of full scale. This was regarded as more than adequate for the purpose.

The next problem was to translate the electric output from the laser and to relate it to transmission rates. This was achieved by using grey type calibrated filters placed instead of the web on top of the reflective surface. See Figures 2 and 3.

Initial investigation shows that the reflective tape properties change slightly across the web width and did not exhibit the same reflective properties for all light intensities, Figure 4.

Fortunately for the practical working range i.e. up to 20% transmission the variations proved very small and the system was calibrated for individual points accordingly.

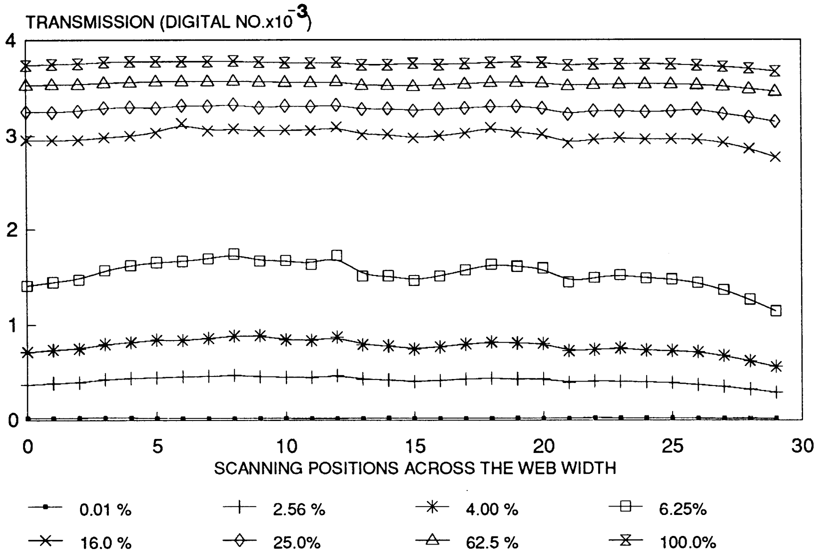


Figure 2. System calibration for transmission with standard neutral density glass filters (scan angle = 60 degrees).

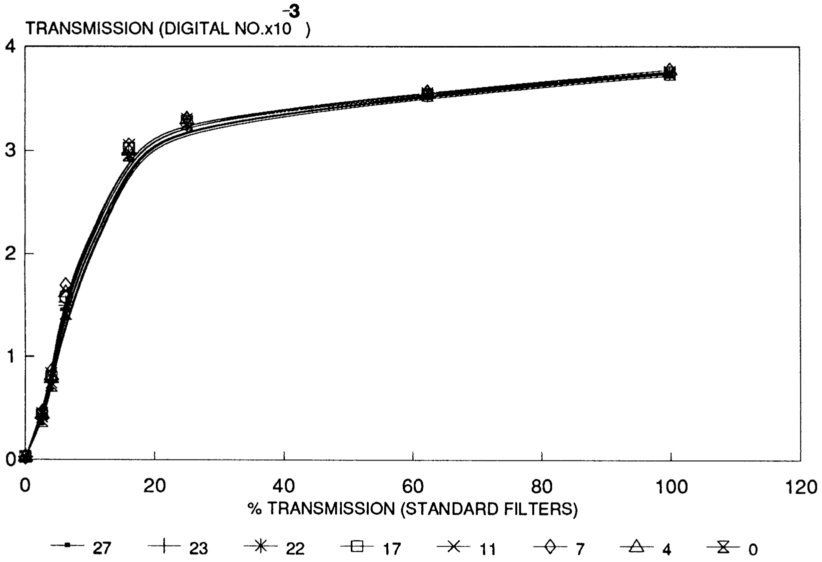


Figure 3. Transmission at different scanning positions (0-27) across web width.

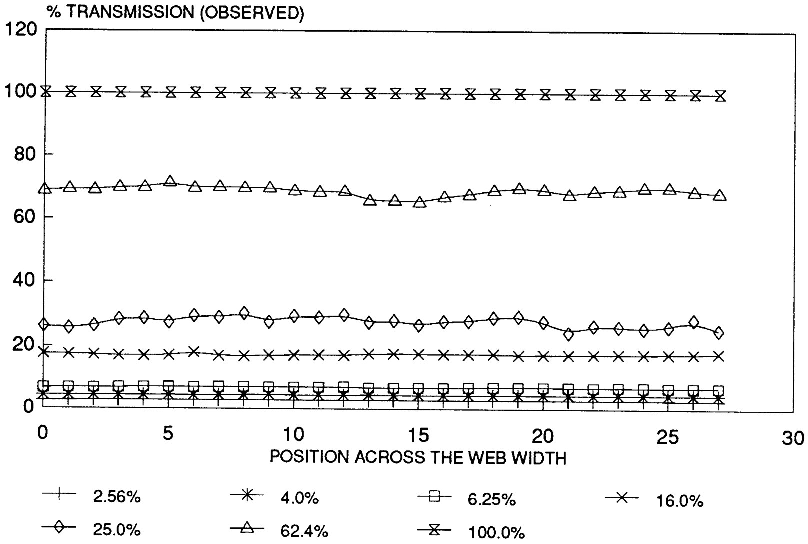


Figure 4. Percentage transmission across the web width with standard neutral density glass filters (2.56%-100%).

When, instead of grey filter, pieces of nonwoven fabric were placed across the web, there was a more pronounced difference in transmission values near the edge, as the path of the beam is increased, Figure 5. It seems that a general purpose calibration could be worked out based on the Figure 6, but to provide precise calibration either a piece of the fabric to scan should be placed across the web width and a calibration method computed, or the other solution is to provide a teach mode so that an acceptable web will be monitored for say 10 or 20m and an averaged transmission rate followed by a correcting factor, will be computed. In most applications this probably will not be required.

The next level of calibration relates to the relationship between weight and transmission level and this of course varies somewhat with the fibre type, fibre diameter, and the process applied to the nonwoven. A typical relationship is shown in Figure 7.

From the data obtained it was possible to compute the uncertainty of the system as a weigh measuring device, taking into account the measured drift as shown in Figure 8.

The other problem which potentially affects the system performance is reflectance. Generally speaking the thicker the web the more light is reflected back to the detector. Since this phenomena interferes with the transmission as measured, it should be kept at a minimum.

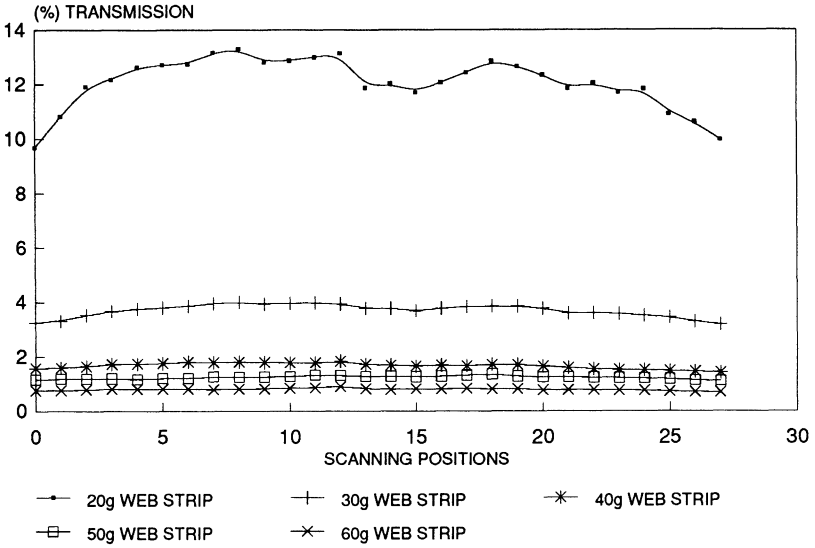


Figure 5. Percentage transmission of different web weights at different scanning positions.

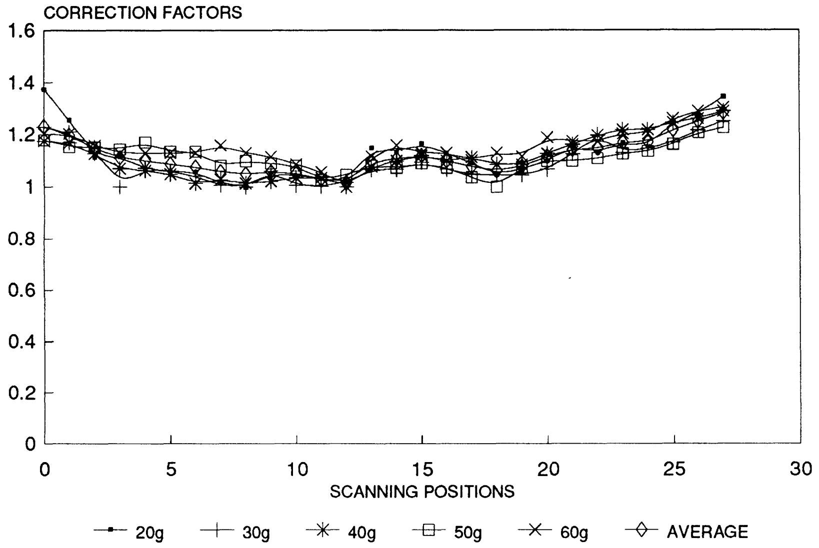


Figure 6. Correction factors for different webs at different scanning positions.

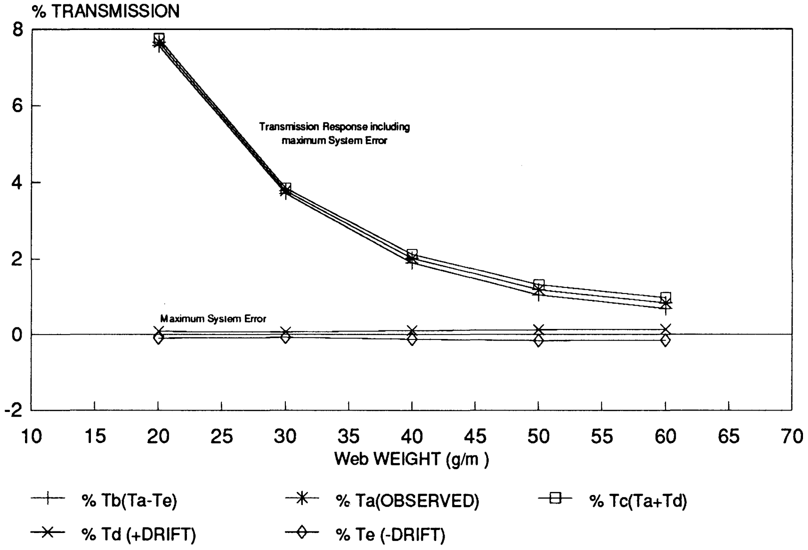


Figure 7. Relationship between web weights and percentage transmission (calibrated).

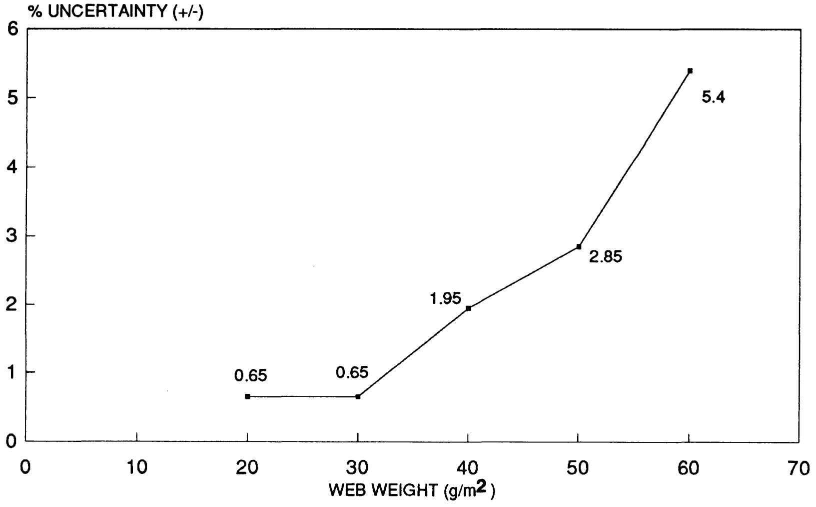


Figure 8. Web weight uncertainty due to system drift.

The reflectance to the system was investigated, positioning the nonwoven fabric (or web) on top of a black paper preventing the beam from reaching the reflective strip. The values obtained will depend on the reflectance curve of a particular web and those which exhibit no measurable reflectance in the red wavelength used will obviously exhibit no problem. Our measurements on typical white web which can be regarded as close to the worst case are shown in Figure 9. It can be seen that this becomes a more serious problem with heavier webs, although the contribution to the actual transmission value for say 40 gr/m^2 is about 10% of the total transmission reducing to less than 2% for 20gr/m^2 web. This phenomena does not reduce the accuracy of the system since it is calibrated taking reflection into account. It has however the effect of reducing the sensitivity of the system with heavier webs.

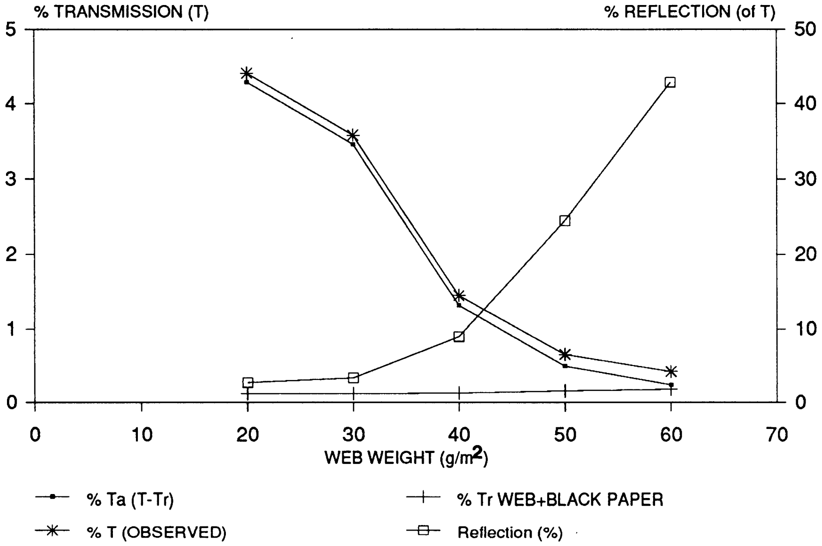


Figure 9. Study ofreflection from web surface (spun bonded)

Taking reflection and the limitation of drift on system accuracy the system's limitation for commercial exploitation was set at fabric with no less than double transmission values of 1%. This corresponds, pending on processing conditions, to web weighing about 40gr/m^2.

Industrial trials of the system were encouraging with stability figures confirming those achieved in the laboratory tests. This device can provide relative uniformity information across and along the web. This information is no doubt useful, but what can it be used for ? The nonwoven industry is in many ways in a similar situation to the yarn industry in the fifties before the emergence of the yarn evenness tester and the USTER standards. Clearly these standards should be next on the agenda.

The system could also connect to volumetric feeders to provide along-the-length feedback control, for example. It should also be possible to provide feedback control for across-the-width calibration, but this is not now possible as there are no actuators (but for one potential example i.e. sectionalised feeders) to achieve this.

2. Case Study 2 - Monitoring and Control of Chainstitch Machine

2.1. INTRODUCTION

When we were asked to look at some of the problems associated with chain stitch sewing machine control, there were among other things, two areas which were perceived by industry as being problematic. These were the control of mis-stitch and that of garment dimensional stability illustrated in the next case study.

Mis-stitch or skip stitch as it is sometimes called, is one of the most important problems arising during sewing operation. Occasionally the sewing machine 'misses out' one or more stitches and then 'picks up' the stitch and carries on normally. The result in lockstitch and single needle double chainstitch seams, is that when mis-stitches occur stitches in the upper surface of the seam are twice the normal size or even larger. In double chain stitch seams mis-stitch can unravel the properly formed stitches and render the seam useless. In lock stitch seams, however, the interlocking of needle and bobbin threads secures the faulty seam.

Mis-stitching is more common in knitwear manufacturing where the knitted fabric tends to vibrate slightly with the vertical movement of the needle, affecting the shape and size of the thread loop. In practise, mis-stitch may happen frequently in which case the sewing machine is checked for settings, damaged parts, timing of the machine operation, etc. In some cases thread and thread/fabric combination for the particular application have to be reviewed. Mis-stitch, however, can happen quite randomly without any apparent reason in a way which is difficult to predict and hence detect. The faulty seam in most cases is recognised in the quality control stage after which the seam is unpicked and then resewn, this is expensive.

One approach to this problem is to dynamically monitor the thread tension. This was used by the Japanese, later in a study at Durham University and recently by some machine manufacturers. This approach required extensive signal processing and data analysis that may prove expensive to implement on high speed machines. Furthermore this technique is not entirely reliable as it may be prone to a certain degree of error since it monitors the dynamic thread tension which is affected by a large number of factors, one of which is mis-stitch.

2.2. SYSTEM REQUIREMENTS

A reliable and relatively cheap method to detect mis-stitch on-line can substantially reduce the cost of subsequent quality control and the following necessary action in order to correct the faulty seam. This can simply be carried out by stopping the sewing machine automatically as mis-stitch occurs and hence preventing the continuation of sewing operation which would produce a faulty seam. Furthermore, a robust mis-stitch detector can also be considered as a must for further automated sewing work stations.

The work that we carried out was specifically aimed at developing an optical system to detect mis-stitch as it occurs. The emphasis was on keeping the system as simple and cost effective as possible.

As indicated earlier the problem associated with mis-stitch is more critical in the case of double chain stitch seams i.e. seam number 401 as shown in Figure 10. Therefore a single needle chain stitch sewing machine was selected for this study. Considering the formation of 401 stitch, the mis-stitch can occur if the triangle consisting of needle thread loop, looper and looper thread is not in place or complete, Figure 11. In practice the great majority of mis-stitches are caused by the looper failing to enter the loop of the needle thread trailing from the needle eye as the needle rises. Hence when the looper traverses without a needle thread loop in that particular cycle, a mis-stitch occurs. The mis-stitch can thus be detected on-line if the presence of the needle thread loop on the looper can be monitored during each individual cycle and its absence actuates an alarm and stops the sewing machine. Loopers are normally made from a polished stainless steel which forms a shiny surface in comparison with that of the thread. If an appropriate light beam is focused on a particular part of the looper where the thread is expected in the cycle, the level of reflection is reduced if an object such as thread obstructs the light path. While the light reflection can be monitored continuously, the meaningful data should only be obtained in the critical part of the cycle where the light beam is focused on the looper.

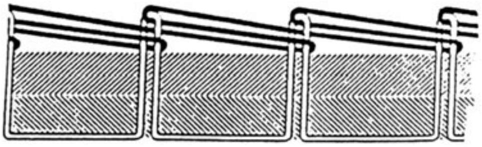


Figure 10. Single needle double chain stitch seam (seam number 401).

The main difficulty in applying such a technique is the small size and inaccessibility of the observation area, which makes the use of ordinary sensors difficult. In the system described, a fibre optic probe was used as a flexible light guide to transmit light to the looper and collect the reflected light from the looper surface. Basically a Y shaped fibre optic (Figure 12) connects the control box to the sewing machine. An LED emits infrared light into the common end of the fibre optic facing the looper, the reflection from the looper or the thread/looper is transmitted back to a receiver via the same probe. The amount of reflected light can thus indicate the presence or absence of needle thread loop on the looper.

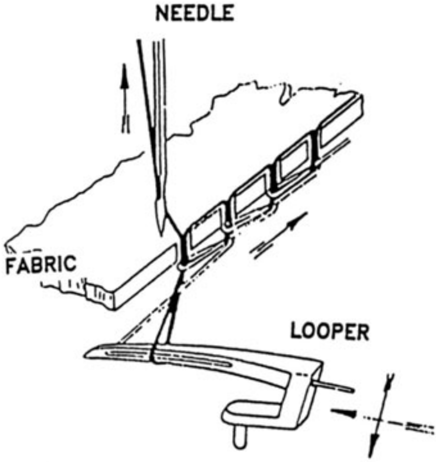


Figure 11. The formation of single needle double chain stitch seam.

Figure 12. Reflective fibre optic scanning.

2.3. ELECTRO-OPTIC INTERFACE

An infrared light was selected as a light source due to its relative insensitivity to thread colour. The sewing thread always reflects a reduced amount of light as compared with the looper shiny surface. In our case the infrared emitter uses a glass focusing bead to focus a narrow beam of radiation into the fibre optic probe which is coupled to the infrared LED housing via a special connector. A photodetector and amplification circuitry produces an analogue signal the amplitude of which is proportional to the level of light reflection. The signal is digitised and read by a computer through a purpose built interface board containing an 8 bits A/D converter. Data on the machine position is derived from pulses generated by an optical switch connected to a slotted disc located on the sewing machine drive shaft. These pulses are generated once every stitch cycle and provide an accurate window in which the thread presence is checked. The window angle or duration can be varied by changing the slot size and position.

2.4. SYSTEM DEVELOPMENT AND MODIFICATION

A small model was designed to simulate the relevant part of the stitching process. The looper in this model could be moved along the place of detection manually with or without a sewing thread loop around it. Initial trials indicated that a crude termination of the fibre optic was not satisfactory. Therefore a specially designed electro optical system using the fibre optic probe specified earlier (with the numerical aperture and acceptance cone angle of 0.66 to 82 degree respectively) was adapted and checked on the model. Monitoring the reflected light indicated the sensitivity to the distance between fibre optic end and the target i.e. looper or looper/thread. Small changes of the above distance caused saturation which was considered to be due to a wide angle of propagation of the light. A more precise optical arrangement was thus employed to provide a zone of strongly focused light of 1.5 mm. in diameter centred on the target (thread/looper or looper); a distance of 15-20 mm. to the target thought to be adequate. An optical device was arranged to fit over the fibre optic's common end, Figure 13. It consists of lenses coated to reduce back reflected infrared light, so as to obtain a high signal to noise ratio at an effective aperture of f/1.5 at the light input face, and depending on the projection range f/2.5 to f/5 at the projection face.

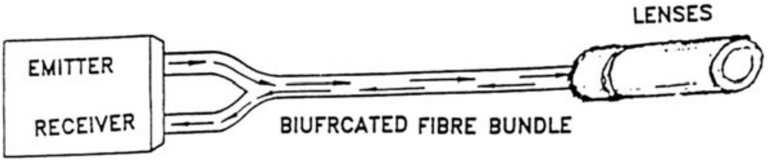
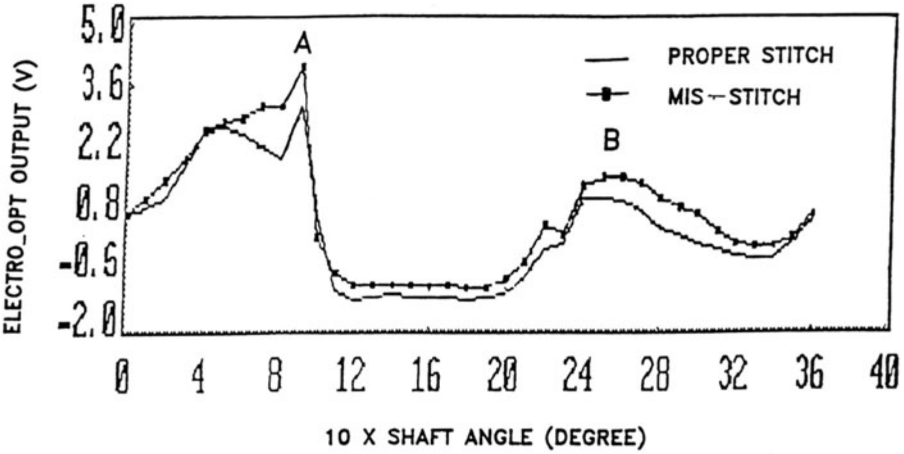


Figure 13. Fibre optic end coupled with lenses.

The modified system was tested on the model and proved satisfactory. It was subsequently installed on the sewing machine. The lens housing was inserted through a hole drilled under the throat plate so that the light beam could be projected perpendicular to the target resulting in maximum reflection. The feed dog was slightly modified to allow clear light path.

2.5. SYSTEM VERIFICATION

To test the system statistically, the sewing machine was rotated slowly and fibre optic output was recorded for a properly formed stitch and a mis-stitch. The pattern for a complete sewing cycle is shown in Figure 14 from which two distinct peaks can be noticed (A, B). These peaks occurred when the looper was in front of the fibre optic


5.0
3.6
2.2
0.8
-0.5
-2.0
ELECTRO_OPT OUTPUT (V)
A
B
PROPER STITCH
MIS-STITCH
0
4
8
12
16
20
24
28
32
36
40
10 X SHAFT ANGLE (DEGREE)

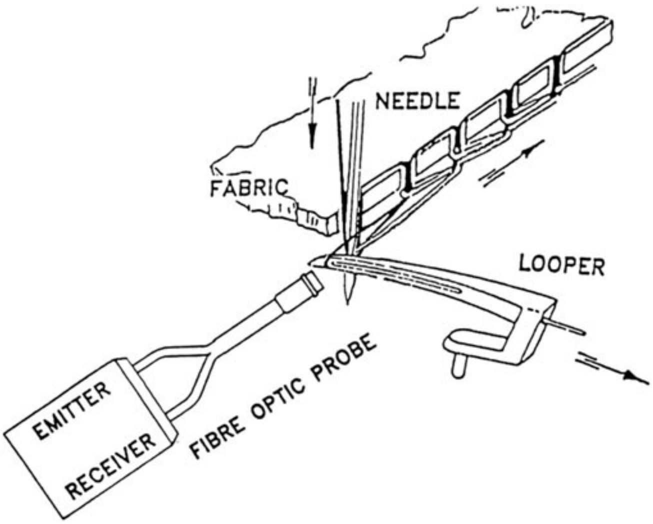


Figure 15. Position A : Needle descends in the back of the looper as needle thread loop is released.

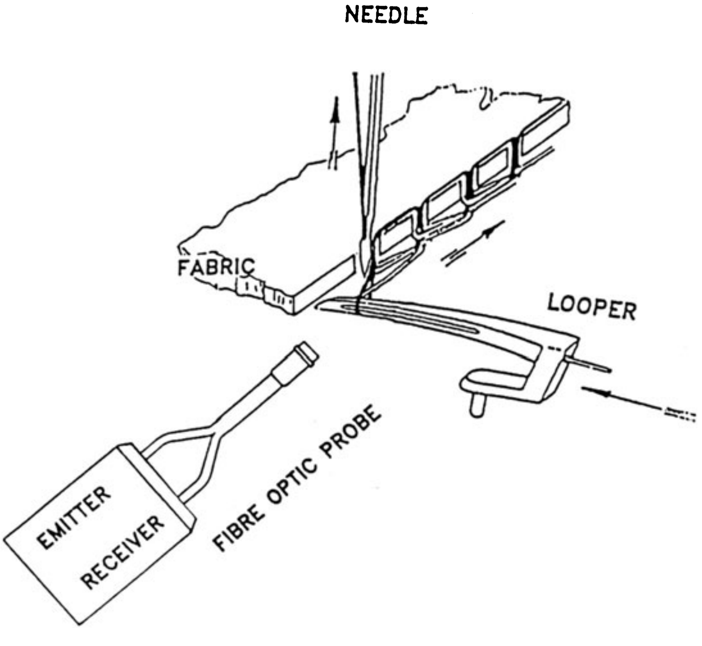


Figure 16. Position B : Needle ascends in front of the looper as needle thread loop is picked up.

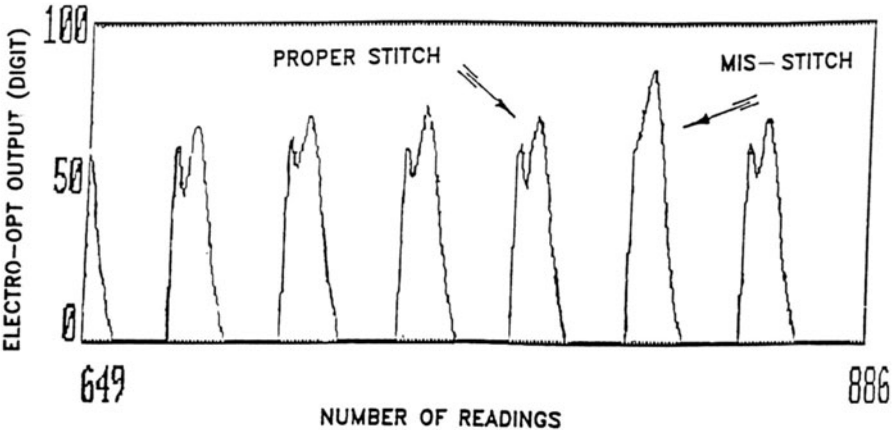


Figure 17. Light reflection pattern within a window recorded at 2100 spm.

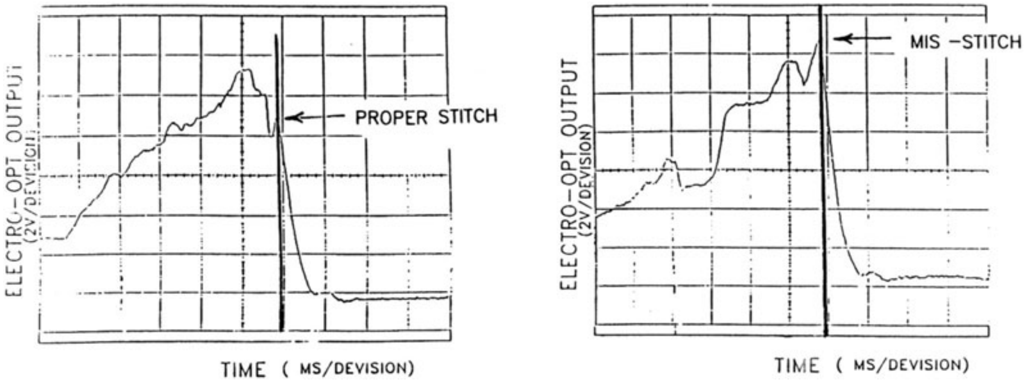


Figure 18. Light reflection pattern within a window recorded at 6500 spm.

Actual detection is obtained by recording the reflection within the narrow band indicated in the critical point of the cycle. Extensive trials on a range of fabrics proved the system to be entirely reliable. The same principle can be used to detect mis-stitch on lock stitch sewing machines. In this case the needle thread is monitored for its movement around the bobbin case. Further work is being carried out in the Department of Textiles at

UMIST to optimise the system towards commercial exploitation. Patent applications are pending.

3. Case Study 3 - The Control of Knitted Fabric Dimensional Stability

3.1. INTRODUCTION

Knitted fabric properties are dramatically different from those of woven fabrics. Extensibility, recovery, surface irregularity, drape and above all dimensional stability are some examples of these differences, resulting in different behaviour of knitted fabric during various stages of garment manufacturing. This necessitates a special procedure and care with handling and making up of these fabrics.

One of the major problems affecting the clothing industry is to control the knitted garment's final dimensions. It is known that different machines and sometimes different operators can produce sewn pieces of different dimensions from the same original panels.

Whilst a considerable amount of literature is available on lock stitch seams and their link to woven garment parameters, very little information has been published on the interaction of sewing variables of chain stitchers (normally used in sewing of knitted fabric) and properties of the knitted garments. In particular, there is a lack of available information on dimensional stability of a knitted piece during various stages of the making up process. It has been suggested that in virtually all knitted structures the seam is the most inextensible part of the garment, in a way that the garment dimensions in the worn state are determined by the length of the seam, rather than the dimension of the garment pieces.

If this observation is correct, thread consumption could potentially be used to control the garment dimensions. To that end a number of experiments were designed to find the relationship between thread tension, machine speed and thread consumption, to the dimension of the fabric after sewing. For this set of experiments conventional negative disc tensioners were used to feed the threads to the sewing machine. It must be emphasised that the sewing operations were made under carefully controlled conditions, in contrast to the factory situation in which operator handling introduces another variable.

3.2. EXPERIMENTATION AND PROCEDURES

The experiments were conducted on typical knitted material under constant bobbin tension of 50 gr. Static thread tension was set manually and presser foot pressure was kept constant at 1450 gr. as needle tension is considered to have by far the major influence on sewing parameters. Three different needle thread tensions i.e. 50, 105, 185 gr, were used. These were determined by a professional machinist to provide what could be considered the upper, lower and medium tension limits to achieve an acceptable seam appearance. Three different machine speeds, i.e. 2550, 3500 and 4800 spm., were selected for this series of experiments. The dynamic needle thread tension was monitored using an electronic tension transducer developed for this purpose.

Samples of a 5 x 50cm^2 at a 45° of bias were fed to the sewing machine under carefully controlled conditions using guides developed to try to minimise handling variables. The sewn fabrics were relaxed in steam followed by standard humidity environment to simulate the conditions obtained with a typical manufacturing process of the knitted garment. Relaxation measurements were obtained for bottom and top layers, but for the purpose of our discussion average relaxation was computed.

3.3. RESULTS AND DISCUSSION

Figure 19 shows the combined effect of machine speed and static needle thread tension on the length of needle thread (consumption per stitch). The significant effect of needle thread tension on the length of the needle thread (correlation coefficient of -0.92 which is significant at 0.1% level) is in agreement with the published work on lockstitch seams.

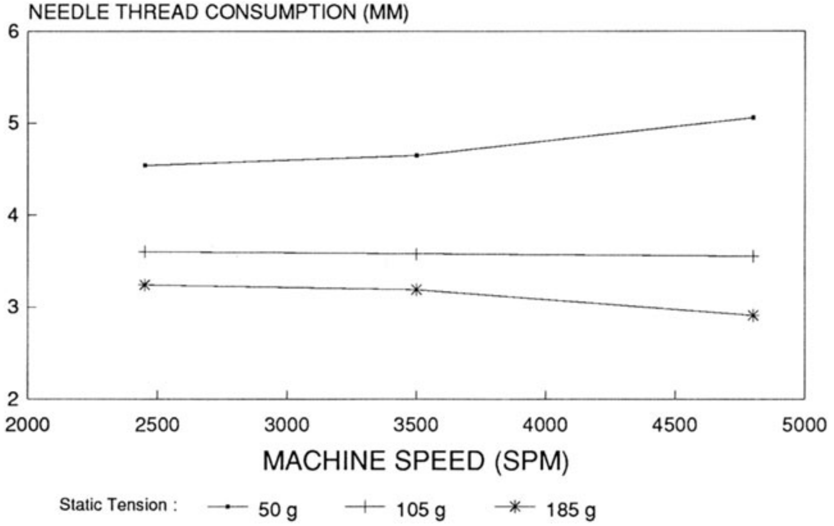


Figure 19. Combined effect of machine speed and static needle thread tension on the needle thread consumption per stitch.

Figure 20 shows the variation of the dynamically measured needle thread tension peak with the machine speed. The trend seems to be different for various static thread tensions. This trend was also observed in more detail with another make of chain stitch sewing machine, where the controller allowed a wider range of speed settings (Figure 21) and can be attributed to the disc type tensioner. This phenomena has also been observed before on lock stitch machines.

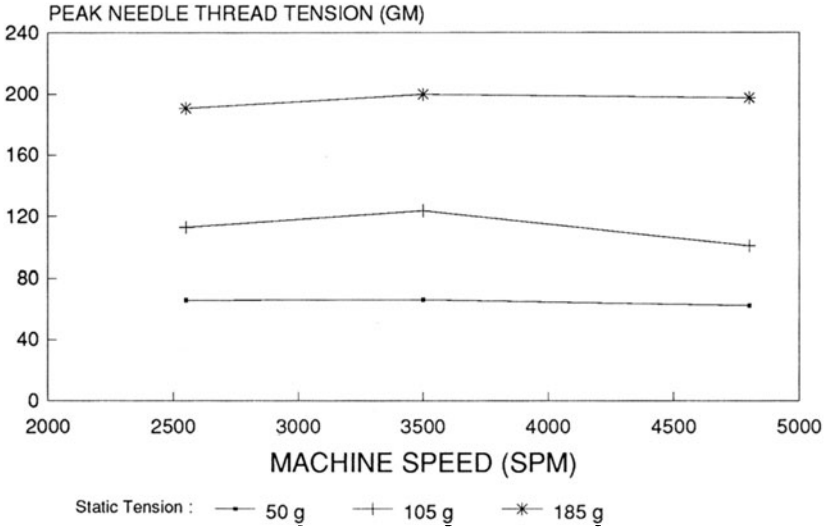


Figure 20. Combined effect of machine speed and static needle thread tension on the dynamic needle thread tension peak.

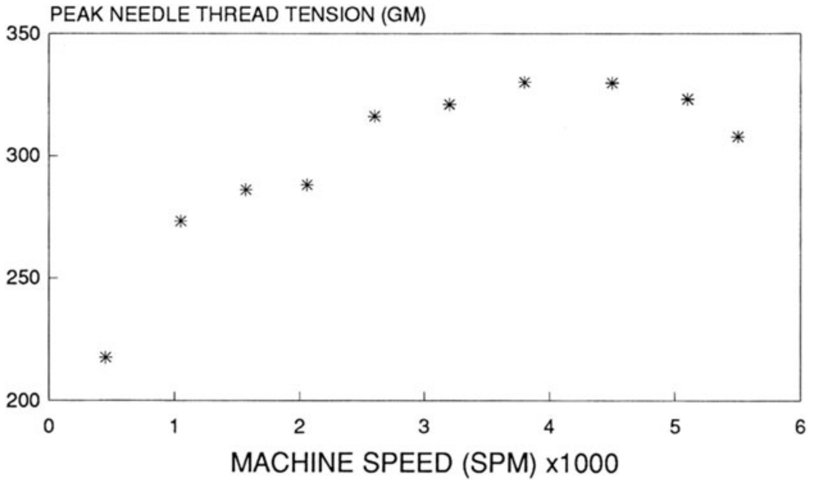


Figure 21. Effect of machine speed on dynamic needle thread tension peak (Union Special Machine).

The most relevant to our work is Figure 22 which shows the variations of shrinkage with the length of the needle thread after sewing operations. The obvious point to be noted is that at a specified machine speed, as the length of the thread increases, the percentage shrinkage reduces, which can be expected at constant stitch density, (the coefficient correlations of -0.78 which is significant at 1% level). It can be noticed that at the same length of thread, different machine speeds result in different percentage shrinkage and hence different levels of stability.

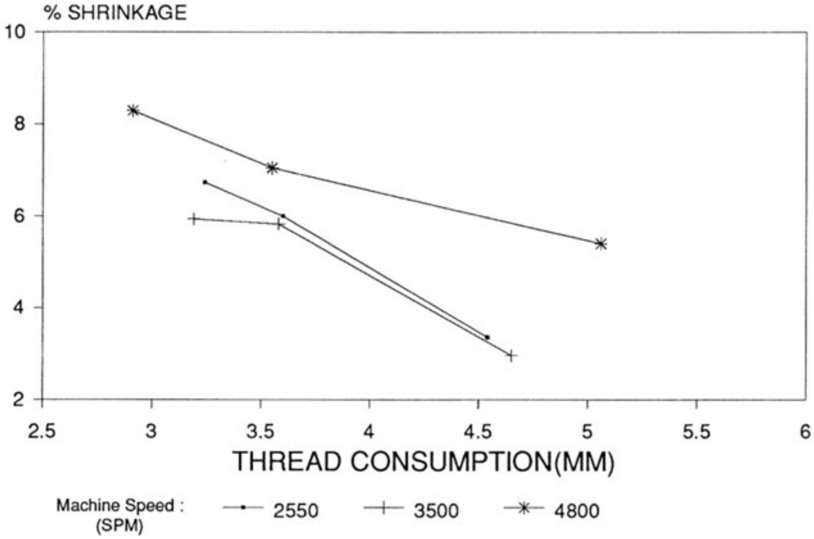


Figure 22. Effect of needle thread consumption per stitch on percentage shrinkage of fabric.

The length of the seam is thus not only determined by the thread length, which was shown to have good correlation with thread tension, but also by the sewing machine speed which changes the effective pressure of the presser foot.

3.4. POSSIBILITY OF SHRINKAGE CONTROL

The previous experiments suggest that for a constant speed and thread consumption it is possible to control the fabric shrinkage after relaxation. In practice however sewing machines work at different speeds during a typical seam construction and therefore it seems that a possible way of achieving constant shrinkage across the speed range is to change the amount of thread supplied at different machine speeds. This point was indeed verified with trials at very low and high speeds, which are illustrated in Figure 23. The amount of thread required to compensate was achieved by changing the static needle thread tension. This phenomena, interesting as it may be, does not enable us to achieve shrinkage control, as it is fairly unclear what the thread length supplied should be. One possibility which may provide a clue is the pressure or height of the presser foot from the sewing table. That may provide clues to the amount of energy absorbed by the fabric and therefore to the relaxation expected. This will form the next stage of our work.

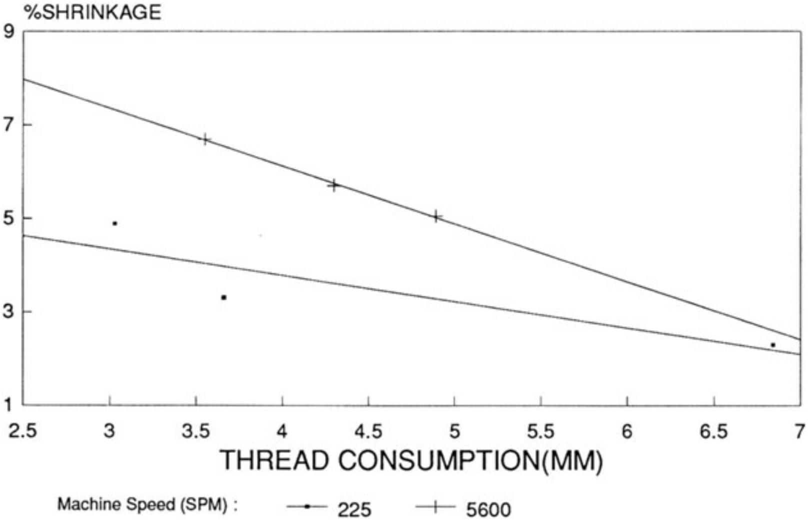


Figure 23. Effect of needle thread consumption per stitch on percentage shrinkage of fabric at very high and low machine speed (Union Special Machine).

CONSTANT BULK FALSE TWIST TEXTURING

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ABSTRACT. The false twist threadline length has been substantially reduced by the use of very small high intensity heaters using hot fluids as the heat transfer medium. The use of rapid response heaters permits a feed back loop to be introduced. Various methods of on-line bulk measurement are discussed and it is shown theoretically that if a tension barrier is deliberately introduced in the second zone of the false twist threadline that measurement of velocity correlates with yarn bulk. Experimental work has verified this approach and a high speed machine, of low cost that can be used in flexible shift patterns of working is described. Substantial yarn quality improvements flow from the use of feed back control to keep the heat flux to the twisted yarn constant, while permitting the temperature of the heating medium to change.

1. Introduction

The first jet texturing process to be commercialised was Taslan and this was followed shortly afterwards by the Du Pont BCF process using jets driven by steam or hot air. The Du Pont BCF process was very successful for deniers of 1000 upwards and so has had a very large impact in the upholstery and carpet markets.

2. Fibre M Process

Below 1000 denier the Du Pont process was not usable due to the production of twist knots in fine dpf fibres. This drawback was overcome in the "Fibre M" process by the work of Foster, Murenbeeld, Ferrier and Berry (Figure 1). Out of the "Fibre M" development came a process using feedback control. The "Fibre M" process was developed as a very high speed process (up to 6,500 m/min) for textile deniers. The process was non-isothermal in that the temperature changed from time to time within a position and was different from position to position. The guiding principle was to keep the heat flux into the yarn constant and so produce yarn of constant bulk and constant dyeability.

M. Acar (ed.), Mechatronic Design in Textile Engineering, 97–106.

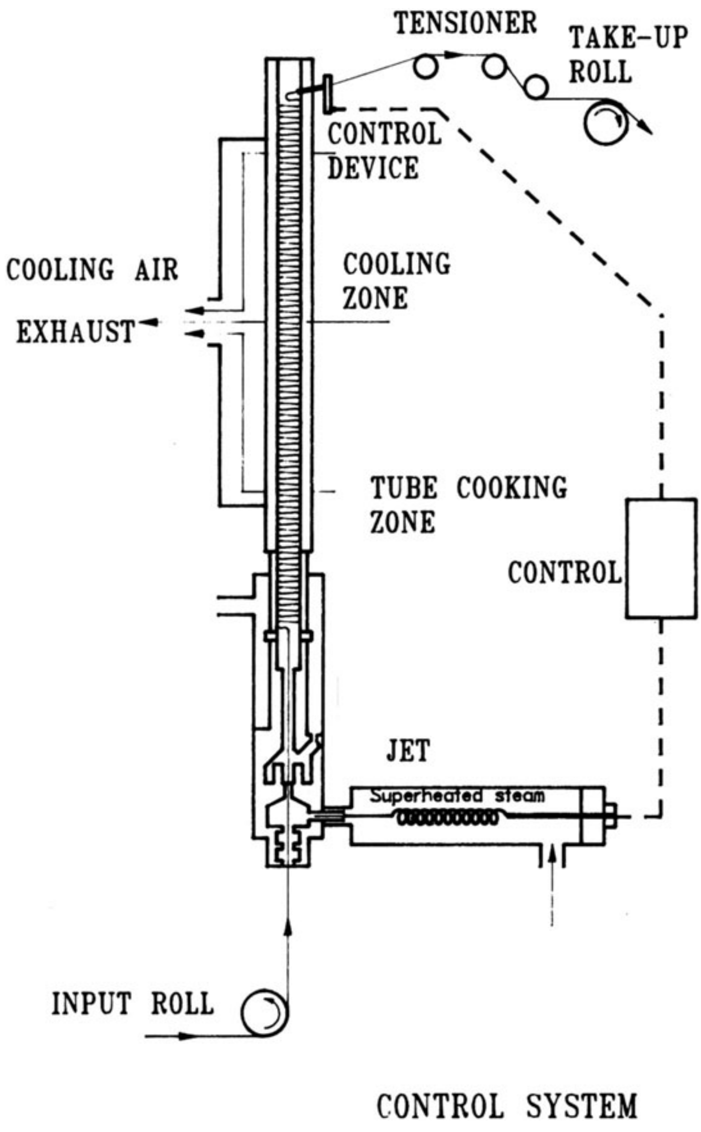

Figure 1. "Fibre M" Process.

3. False Twist Texturing

3.1. CURRENT POSITION

False twisting processes have however, resolutely stayed isothermal in nature. In order to achieve as perfect an isothermal character as possible, heaters have been made as massive as possible so that stray draughts from open doors etc. will have as minimal effect as possible on the temperature of the heater and hopefully on the temperature of the yarn.

At the same time in order to achieve higher speeds and hence better economics, the pin spindle has been replaced with the disc or belt spindle. Current machines have heaters that are 2.5m in length and if the heater is not angled, machine heights of over 6m have been necessary. Such heights mean special and costly buildings and of course the machines themselves become very expensive. On taking stock one finds that with the advent of fine dpf fibres, commercial speeds for processing 150 denier polyester have recently declined to the region of 650-700 m/min. The problem of surging has not been overcome.

3.2. FEEDBACK CONTROL IN FALSE TWIST TEXTURING

The new work described in this paper discusses how to utilise concepts of feedback control in false twist texturing.

3.2.1. Hot Fluid Heaters. The first experiments showed that superheated steam or hot compressed air could in fact be used to successfully heat tightly twisted yarn. On cooling the yarn was heat set and was indistinguishable from yarn made on a conventional long contact heater (Figure 2).

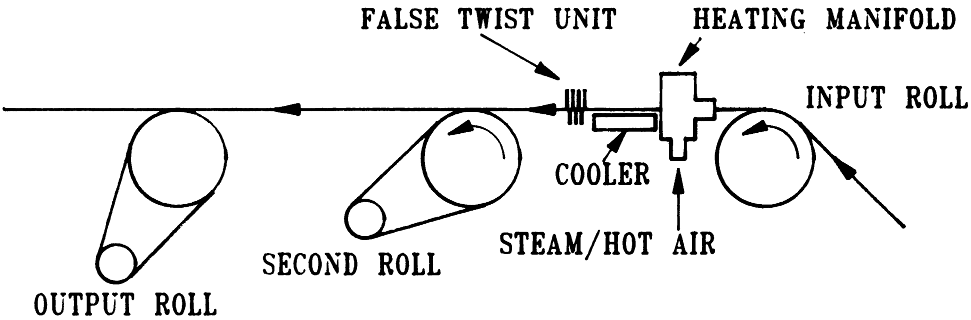

Figure 2. Use of superheated steam or hot compressd air in false twist texturing.

Having established that a heater only 4" long could replace a 2.5m contact heater, the next step was to determine what form of feedback control should be used. The need is to measure the bulk of the textured threadline on the run.

3.2.2. Use of Yarn Reservoirs. Several possibilities suggest themselves. We could use the "Fibre M" approach utilising a yarn reservoir and experiments showed that this route has possibilities. However, making a yarn reservoir purely for measurement of bulk has drawbacks both operationally and economically (see Figure 3).

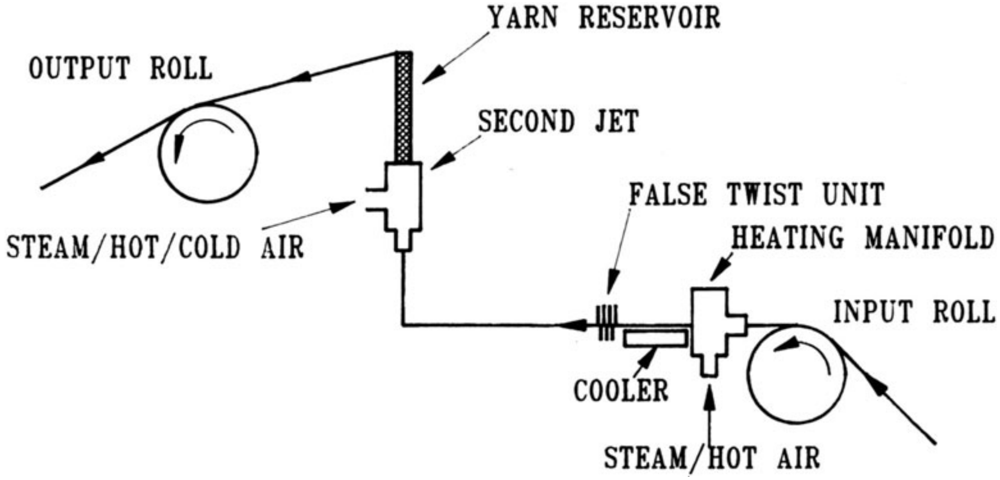

Figure 3. Use of yarn reservoir for measurement of bulk in false twist texturing.

3.2.3. Effect of Tension Barrier in Second Zone. If we deliberately insert a tension barrier into the second zone of the false twisting process then it can be shown that

$$\frac{V_a}{V_1} = 1 - Fe^{-\mu\theta} - C_{max}\,[1 - e^{-\mu\theta}]$$

where V_a = Yarn speed in the feed zone
V_1 = Yarn speed at the intermediate feed roller
F = Overfeed
C_{max} = Maximum value of the crimp contraction
μ = Coefficient of friction between yarn and guide
θ = Angle of wrap round the tension guide

All the variables except V_a and C_{max} are constant machine parameters and therefore V_a can be used as an indicator of the value of C_{max}. If V_a is kept constant then C_{max} will be constant.

When there is no effective guide present, i.e. when $\mu = \theta = 0$ then the above equation reduces to

$$\frac{V_a}{V_1} = 1 - F$$

so that the yarn speed in the feed zone becomes independent of the crimp contraction. In other words it is vital to have a tension barrier in the thread line.

From this analysis we can see that by measuring the yarn velocity of the textured thread line, we can measure the bulk of the yarn in the threadline. If we can measure the bulk of the textured yarn we can create a feed back loop to keep it constant.

3.2.4. Direct Yarn Velocity Measurement. Direct yarn velocity measurement has been achieved by putting a freely revolving roller in the threadline (Figure 4), and the signal developed has been coupled into a feedback loop to a supplemental heater in the superheated steam or hot air supply line. By increasing or decreasing the temperature of the heater we can keep the bulk of the dyeability of the textured yarn constant (see Figure 5).

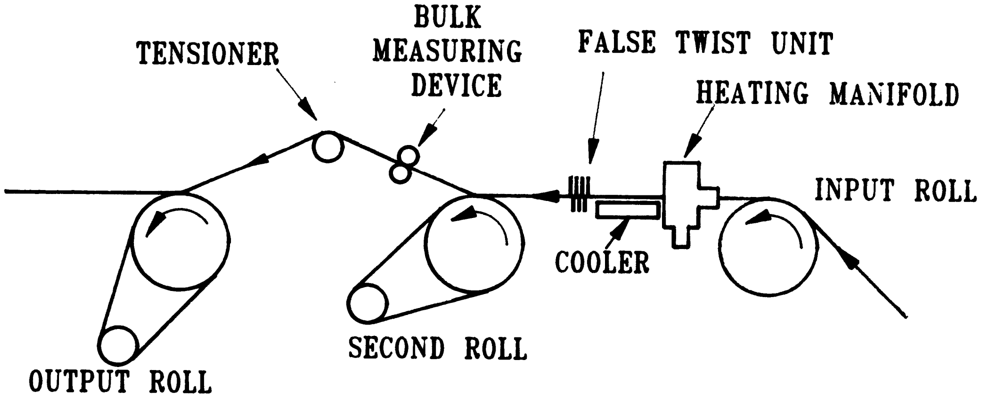

Figure 4. Direct yarn velocity measurement by a freely revolving roller in the threadline.

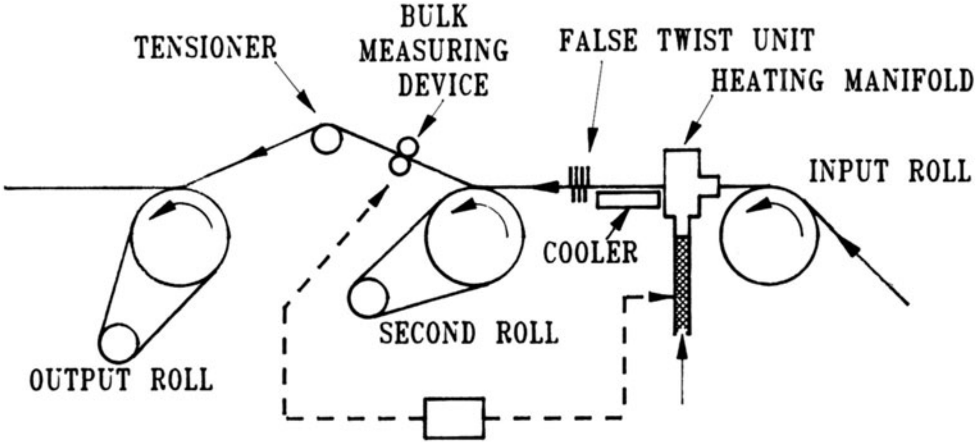

Figure 5. Feedback loop to control the temperature of the heater.

3.2.5. Alternative Feedback Control Routes. The feedback signal can of course be used to control other machine parameters such as

- the twister spindle
- the input roll (Figure 6)
- the output roll
- the intermediate roll
- combinations of the above
- pressure of heating fluid
- specific heat of heating fluid

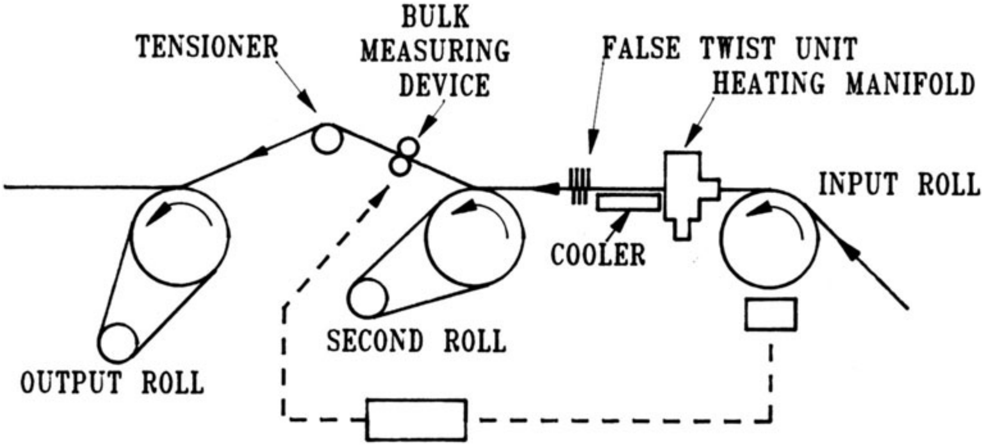

Figure 6. Feedback loop to control the input roll.

3.2.6. Alternative Methods of Signal Generation. Similar analysis allows one to use tension measurements or yarn temperature measurements for generation of a feed back control signal. Other methods of measuring the yarn bulk such as capacitance, direct laser measurement etc. could also be used for generating feedback control signals in addition to the methods described.

4. Results

The results of this work show that because of the shorter heater the machine is only 2m in height, the threadline is short and much higher processing speeds are possible. Yarn quality is improved and machines built incorporating non-isothermal feed back control have the following advantages:

- machine only 2m high, no special building costs,
- lower capital cost of machines (50%),
- shorter threadline, reduced or no surging,
- higher speed (3-4x),
- better quality control within package and package to package,
- flexibility of production, machine can be stopped and started
- permits 3 shift working (as opposed to 4 shift)
- permits 4 day 2 shift working

It would appear that a new dimension to false twist texturing technology i.e. constant bulk non isothermal false twist texturing, is opening up and the heart of it is feed back control, that is mechatronics.

4.1. EFFECT OF STEAM PRESSURE ON YARN TEMPERATURE

Figure 7 shows graphically the effect of steam pressure on the temperature of 167 d'tex yarn as it exits from our jet. It is believed desirable to have a yarn temperature of 200°C or higher, and as can be seen this very small jet achieves this goal quite comfortably.

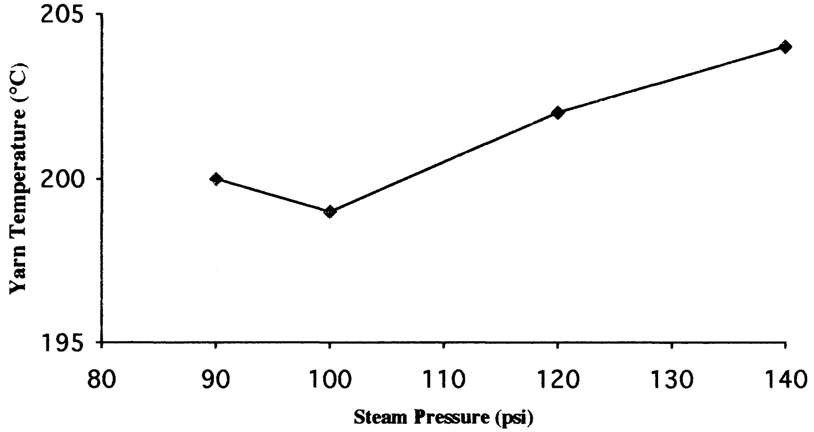

Figure 7. Effect of steam pressure on yarn temperature.

4.2. EFFECT OF JET TEMPERATURE ON YARN TEMPERATURE

Figure 8 shows graphically the effect of the jet temperature on yarn temperature, again as it exits from our jet. It will again be recognised that the desired temperature of over 200°C is comfortably reached.

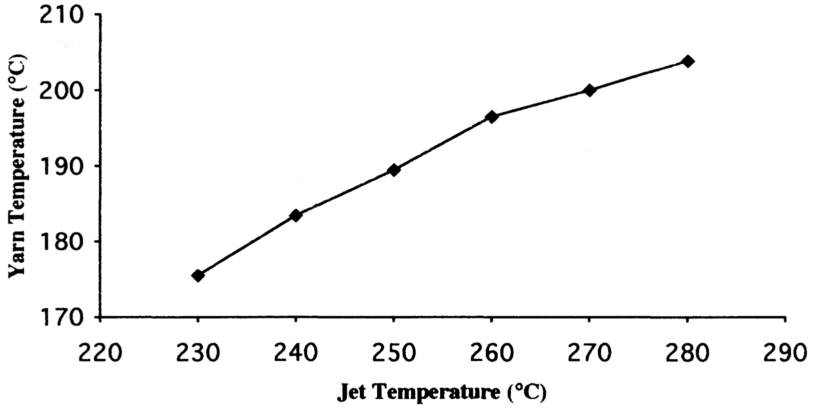

Figure 8. Effect of jet temperature on yarn temperature.

4.3. EFFECT OF STEAM PRESSURE ON YARN PROPERTIES

Table 1 shows the relationship of tenacity, elongation and crimp contraction for 167 dtex draw-textured polyester as steam pressure is increased from 70 to 130 psi. Tenacity and elongation are unaffected, while the crimp contraction of the yarn is substantially increased.

4.4. EFFECT OF TEXTURING TEMPERATURE ON YARN PROPERTIES

Table 2 shows the relationship of tenacity, elongation and crimp contraction for 167 dtex draw-textured polyester as the jet temperature is increased from 200°C to 250°C. As in Table 1 the tenacity and elongation are little altered, but the crimp contraction increases steadily to very high levels.

4.5. DYE UPTAKE AND CRIMP CONTRACTION RESULTS

Table 3 summarises the results obtained when fabric is made from constant bulk yarn, dyed and K/S values measured spectrophotometrically. As will be seen from the two samples quoted the temperature variation in the first samples was 17°C and in the second set 14°C. As would be expected the crimp contraction increased with increase in temperature. However, of particular significance is the fact that the %CV for the two samples, despite the large change in nominal temperature is 0.6 and 0.9%. In other words the yarns are very uniform.

When fabric is made from these yarns, dyed and evaluated spectrophotometrically the K/S values are also very uniform with %CV of 3.0 and 3.2%. In other words despite the nominal differences in processing temperatures, the fabric is very uniform.

Table 1 : Effect Of Pressure

POY Polyester (300f 30 → 167f 30)
Textured at 600 m/min speed and 220° C temperature

Pressure psi.	Tenacity cN/tex	Elongation %	Bulk K%
70	35.5	20.2	31.5
85	34.6	19.0	33.7
100	35.4	18.7	33.0
115	35.2	19.3	40.2
130	35.1	18.9	39.1

Table 2 : Effect Of Temperature

POY Polyester (300f 30 → 167f 30) Textured at 600 m/min speed

Temp. °C	Tenacity cN/tex	Elongation %	Bulk K%
200	34.7	19.6	29.8
210	35.1	19.2	30.4
220	35.4	18.7	32.8
230	35.5	19.2	37.4
240	35.2	19.0	41.5
250	36.1	19.4	41.9

Table 3 : Dye Uptake And Crimp Contraction Results

Nominal Texturing Temperature	Temperature Dye Uptake (K/S)				Yarn Contraction (%K)		
	Variation	No. of Readings	Average Value	%CV	No. of Readings	Average Value	%CV
200°C	± 8.5°C	10	16.2	3.2	10	29.8	0.9
250°C	± 7.0°C	10	11.0	3.0	10	45.5	0.6

MEASUREMENT AUTOMATION AND DIAGNOSIS IN SPINNING

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ABSTRACT. The quality and productivity demands inevitably cause the production systems to adapt to the changing requirements. This adaptation is based on two factors, first the use of on-line sensors with information centralization, and second the automatic processing of this information. Then the decision-making must be automated.

In this chapter, we will look at sensor principles whereby yarn characteristics or production parameters can be measured. Then we shall take a closer look at processing the obtained signals and discuss the difficulty in interpreting these analyses. Finally, we will present a software to analyse and interpret weight regularity.

KEYWORDS: sensor, weight regularity, diameter, twist, hairiness, tension, speed, yarn, expert system, spinning, artificial intelligence, measurement principles, diagnosis, automation, quality, mechatronics, textile.

1. Introduction

Twenty or thirty years ago, when ring spinning ruled in mills, one spindle produced roughly 15 metres of yarn per minute. Today, 300 metres per minute of yarn are produced by one spindle in air jet spinning, and in laboratories astronomical figures go round; in the near future, 1000 metres per minute will be achieved and even much more, for some technologies.

This evolution can take place only if two conditions are fulfilled:

(i) the production must satisfy the client, so on-line checks must be numerous and continuous for a complete control to be effected.

(ii) the profitability of the production must be considered because if we produce 20-100 times faster than thirty years ago, any spindle stoppage costs the firm a lot. For example,

M. Acar (ed.), Mechatronic Design in Textile Engineering, 107–131.

a two-hour shutdown of all spindles in one firm is equivalent to a one or two week strike in a firm thirty years ago.

The quality and productivity requirements inevitably cause the production systems to adapt. This adaptation is based on two factors that cannot be separated; first the use of on-line sensors with information centralization, and second the automatic processing of this information. If the number of sensors and consequently, the amount of information increases, the automation of their processing becomes necessary; and, decision-making must be automated.

In this chapter, we will first look at sensor principles whereby yarn characteristics or production parameters can be measured; some are very well-known, others are being commercialized. Then we shall take a closer look at the treatments effected on the obtained signals and we shall discuss the difficulty in interpreting these analyses. Finally, we shall present a software to analyse and interpret weight regularity.

Before discussing sensors, let's try to define the parameters which permit the progress of a process to be controlled, the yarn quality to be estimated, or the possible applications for a yarn.

It will be interesting to know some yarn characteristics such as weight regularity, diameter, twist, hairiness, tenacity and some production parameters such as tension and speed of the yarn.

All these measurements can be done without sampling, except for the tenacity which needs destructive tests. On the other hand, to measure some parameters, contacts between sensor and yarn are imperative, considering the technologies used; but the tendency to measure without contact is necessary at high speeds.

2. The Sensors: Measurements And Interpretation

2.1. WEIGHT REGULARITY

Studying the weight regularity of a yarn means studying the variation of its count (linear density). It is a factor which conditions the aspect regularity of the fabrics and consequently is a very important commercial quality criterion.

In this field, an HF (high frequency) sensor is used, which makes it possible for the yarn count variations to be measured around a nominal value. So, the number of defects (number of neps, fineness, etc.), as well as the count variation coefficient and the spectrogram can be determined.

This basic sensor which was well designed by Zellweger Uster is the most popular one in the textile world. It is a relative sensor without any contact which makes it very sensitive to various pollutions and to thermal drifts. For example, much is known about the sensitivity of those sensors to hydrometric variations from climatic origin or possibly due to the water content of the material. If this sensitivity is real, the weight sensor without any contact is capacitive and the presence of polar molecules like the water molecules will have an influence. However, it can be noticed that if the frequency of the electrical voltage of the sensor can be made to vary there are frequencies where water does not matter so much. These are evidently the working areas. Yet, such a sensor remains sensitive and in on-line controls, simplified versions are used.

The biggest drawback of this sensor is that it somehow lacks credibility when a fibre blend has to be measured because, in this case, the dielectric within the sensor can vary independently of the captive weight and hence the response of the sensor is not meaningful. This type of sensor prevailed, for it has the advantage of performing an overall sampling for a constant length of measure, whatever the structure and the shape of the yarn.

The information that can be derived from the different data obtained, thanks to this sensor, will be dealt with in more detail later on; this type of sensor has been used to build our automatic analysis prototype.

2.2. DIAMETER

The diameter sensor is appropriate for performing a measurement that is independent of the fibre nature [1]. The diameter is a direct measurement of a parameter which effectively conditions the fabric aspect. This measurement is suitable for monofilaments (metal, glass) but less suitable for staple fibre yarns because these structures are rarely cylindrical, and there are fibres around the compact core where sensing becomes difficult.

The different techniques that can be used to measure the diameter are presently discussed.

2.2.1. *Shadow Measurement.* The shadow of a yarn should be proportional to its diameter. This method gives good results for metallic threads or organic monofilaments dyed in dark colours. In these conditions, the accuracy reaches some micrometers, but for a texturized yarn, for example, differences of over 50 percent of the value obtained by microscope are frequent.

2.2.2. *Measurement Through a Beam Scanning.* An element sets the beam to vibrate so that the bulk of the yarn can be scanned. According to how the sensitivity of this device is adjusted, important differences unfortunately appear. This solution is often used for metallic threads, glass, etc.

2.2.3. *Measurement Through a Picture Scanning.* A big source illuminates the object to be measured, but it is the receptor that scans the obtained image.

When compared to shadow measurement, the latter two techniques bring about a much better analysis in the evolution of the limit of the object to be measured; however, for our structures, the estimation is not always satisfactory since it depends on the threshold value of the adjustment.

2.2.4. *Measurement of the Bulk of the Yarn Through a Diffraction Process with Picture Reconstitution.* The estimation of the limits can be performed by using the phenomenon of diffraction. Using filters in Fourier's plane makes it possible to split the information which is actually responsible for the phenomenon of diffraction. So, the compact core of the fibres gravitating around can be split, based on the differences in their spatial frequencies (HF filter and LF filter). The so-treated picture can be reconstituted and analysed.

2.2.5. *Measurement of the Yarn Bulk Through a Diffraction Process at Fourier's Plane.* Another way to obtain the dimensional information consists in examining the picture of interference obtained in the focal plane of the lens. The distance between two rays depends on the inverse of the yarn diameter.

Among all these techniques, the most sophisticated solutions are those requiring information treatment in Fourier's plane. Such techniques are particularly simple to implement with laser sources. Yet, two remarks are to be made. The first is that measuring the diameter does not really provide any information on the shape and bulk of the fibres. The second is that according to the bulk (small or big), the sensitivity and precision of the measurements are likely to be quite different based on the techniques that have been used for reading the luminous data.

2.2.6. *Our Solution.* Recent research has shown an easy way for measuring interference fringes (Figure 1). This principle combines two identical sensors which have a fixed distance between them, in two perpendicular directions. Each sensor comprises a variable slit. The yarn is shown centred in the middle of that slit. The whole yarn inserted in the slit generates two slits on either side of the yarn, hence producing a system of interferences.

Based on the geometrical quality of the yarn, bands, alternatively bright and dark, are more or less well-defined but their frequency is a function of the inverse of the distance between those slits and hence from the diameter of the yarn. These slits, which are adjustable, make it possible to work in satisfactory conditions for reading the optical data.

The analysis of the fringes can be carried out directly through a scanning process of the interference picture or according to an optical process. The presence of fibres in the loose structure does not really affect the information being sought. Moreover, both sensors which are in two perpendicular directions enable the processing of the shape of the yarn by means of intercorrelation functions. In such an arrangement of the sensor, the shape of the section is assimilated to an ellipse.

These solutions, however promising and already used by some manufacturers, are still insufficient, for we do not really process all the data of yarn shape and volume

2.3. TWIST

A parameter which has not yet been measured on-line is the twist in the yarn. If the yarns were monofilament assemblies, the problem of analyzing linear structures would not be so critical. But, the fibres being entities of a few microns in diameter, have to be effectively combined so that the whole assembly can resist the different transformations and wear; this can be accomplished by introducing cohesion into the fibrous assembly.

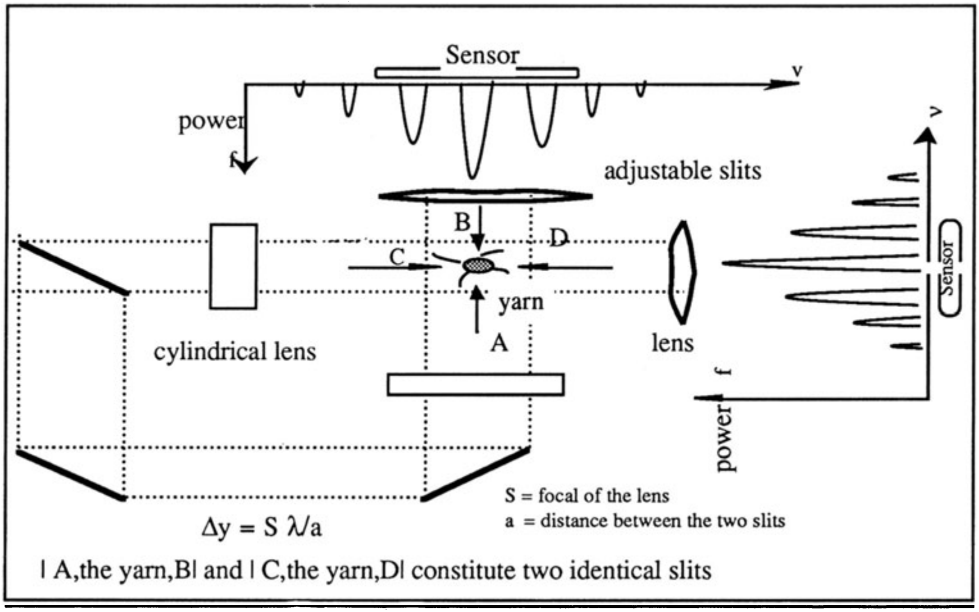


Figure 1 - Principle of the diameter sensor

This cohesion determines the way the fibres are linked and indirectly their structure. Two approaches can be envisaged for measuring the twist [1]:
(i) a mechanical method which requires the destruction of the initial sample and is incompatible with on-line measurement. The other method, an optical one, lies on the hypothesis which states that, what generates the cohesion is maximum at the surface of the compact core and quantified by the angle of inclination of the fibres in relation to the axis of the linear textile. The sample size of the mechanical method can only be reduced below a certain threshold of one centimeter and a real twist is achieved.
(ii) the method of diffraction at low angles is not ideal and does not provide the real twist but it is very significant because of its measuring principle without any contact.

2.3.1. *Low Angle Diffraction.* Paramonov [2] proposes a fast technique to determine α, the helix angle of the fibres. Based on the slow angle diffraction of a laser beam (Figure 2), it orientates a narrow beam at right angles to the yarn. The diffracted light is collected on a device set behind the yarn. The diffraction diagram can be seen in the form of a cross with three branches (Figure 3). One component is due to the yarn, the other two are due to fibre orientations behind and in front of the yarn. According to observations by Paramonov, it seems impossible to attribute the observed phenomenon to the diffraction of the fibres of the compact core. Conversely, the phenomenon helps if one is interested in the fibres which are peripheral to the compact core and these fibres represent only a small proportion of superficial fibres; moreover as they are marginal, it is doubtful that their orientations represent the compacted fibres.

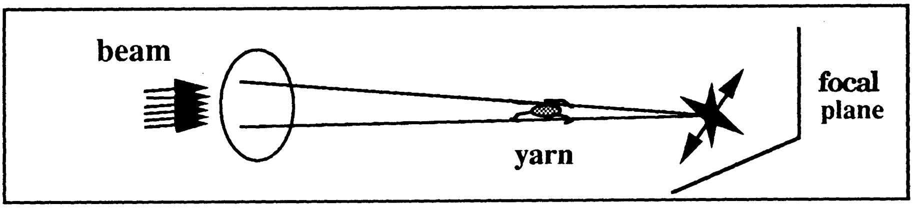


Figure 2 - Low angle diffraction

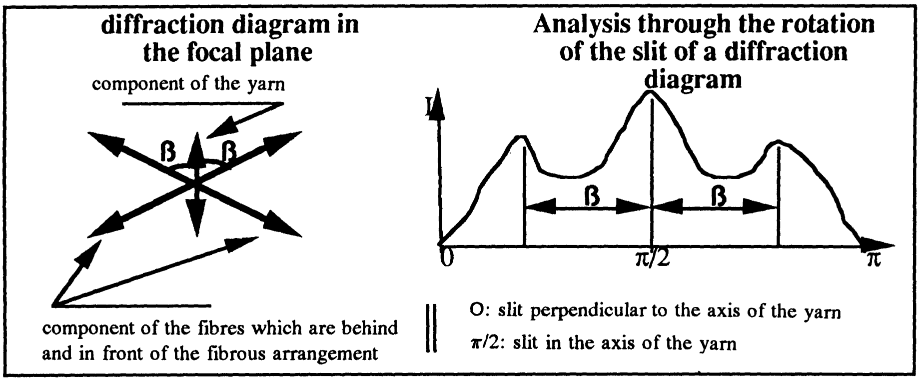


Figure 3 - Diffraction diagram in the focal plane and Analysis through the rotation of the slit of a diffraction diagram

2.3.2. *Our Method.* Our method does not aim at the light going through the fibre arrangement of the yarn but on the contrary to use it as a rough screen. The beam, which is very much focused, falls on the fibres of the superficial arrangement of the compact core (see Figure 4). The beam is narrow enough to light only one or two fibres [diameter of the beam between 15 to 100 µm]. The lit fibre(s) diffract the light which forms a reflection of a spot perpendicularly oriented to the lit fibre(s) on the nearby fibres. Increasing the angle of inclination of this spot also means increasing the angle between the fibre in relation to the axis of the arrangement. The analysis can also be carried out through a circular scanning of the spot, to determine the direction which actually shows a maximum intensity.

Measurements performed in visible light on fibres that have been guided in black, show that even in extreme conditions the slightly reflected light still enables the angle of inclination of the fibres to be read. However, it is better to work in infrared light, for most dyes used in the textile industry are transparent in this field of the electromagnetic spectrum.

The previously defined method makes it possible to read the angle of inclination of the fibres in the yarn but does not make it possible to analyze the assembly which is resulting from several types of operations on yarns, such as simple winding. These assemblies are supposed to be multi-ply yarns essentially used for technical applications (thread, covered yarn) which have the particular feature of a very uniform macrostructure (as opposed to a microstructure) given by the fibres.

It is also important to know this macrostructure that notably influences the estimation of the microstructure and which in itself is a major indicator. This measurement is carried out by the same assembly as before, but, there is only the direct reflection component that is taken into account (Figure 5). The macrostructure generates a reflection which is more or less intense, as a function of the position of the reflection plane. The variations of intensity are analyzed in frequency owing to the speed of displacement of the yarn and the intensity; the uniformity of the phenomenon can be calculated.

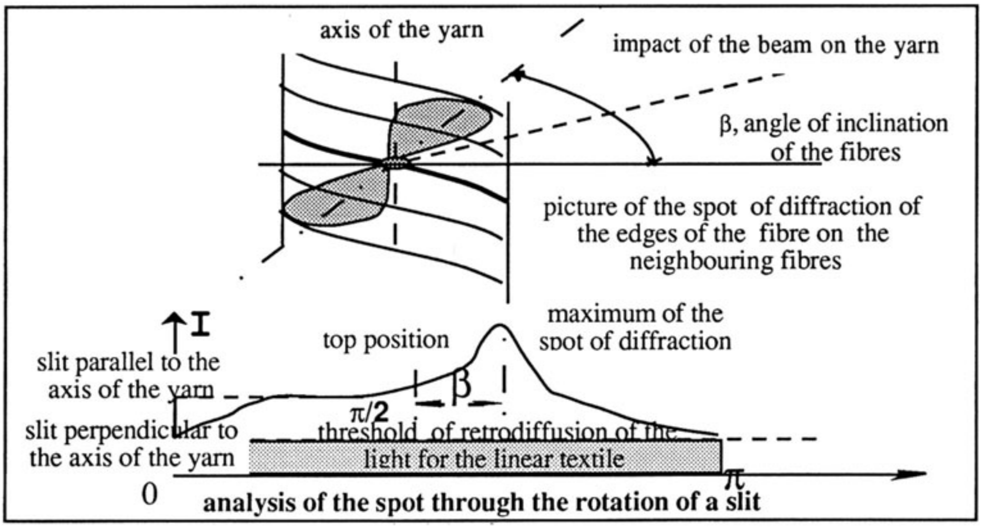


Figure 4 - Principle of a structure sensor

2.4. HAIRINESS

The measurement of hairiness is not new and has not yet been implemented on-line. However, the technique designed by Durand [1,3] and marketed by Uster is a reliable means of measuring hairiness that can be reproduced.

Up until 1950, yarn hairiness was considered to be an insignificant characteristic, it was only in 1952 that the notion of hairiness coefficient appeared; this characteristic will become more significant as newer production technologies appear.

By observing a fabric made of spun yarn under low angle light, it can be noticed that certain numbers of these fibres escape the twisting process and populate the surface of the yarn, and hence the woven surface. If one has to identify these fibres, it can be noticed

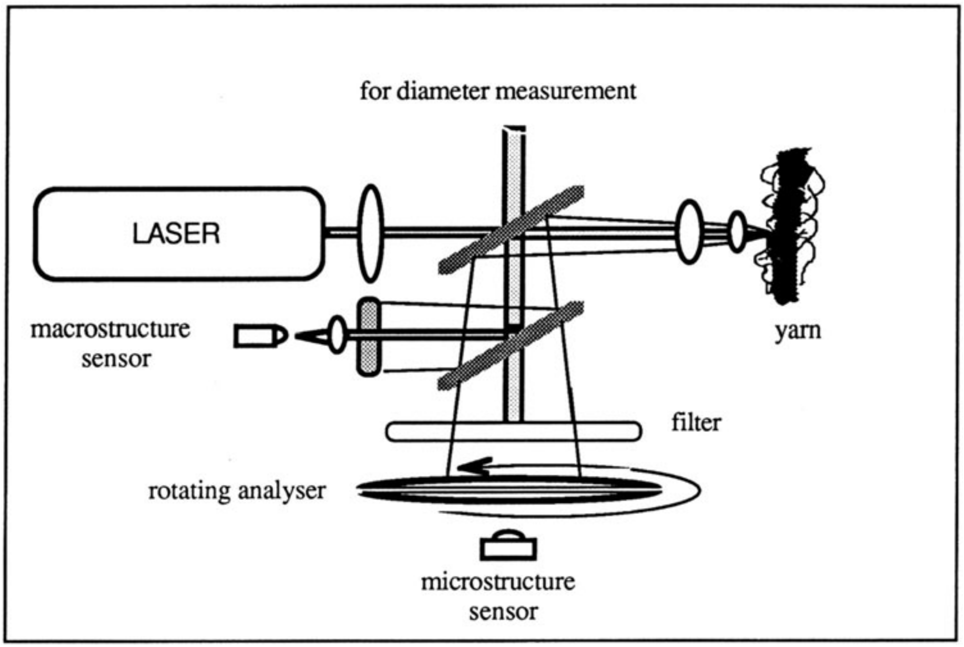


Figure 5 - Structure sensor

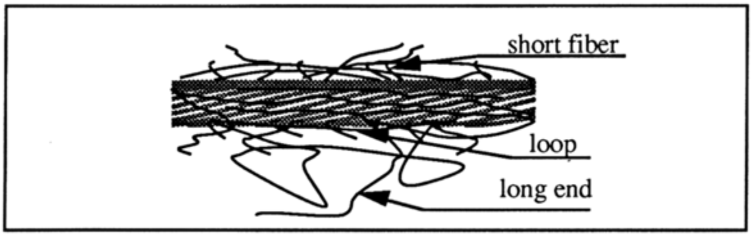


Figure 6 - Picture of a yarn

that some of them are made of long ends of fibres greater than 1.2 millimeters and others of small ends that are smaller than a millimeter, and others yet which form loops (see Figure 6).

The shadow of the hairs on the surface of the fabric brings about an impression of darker nuance according to the lighting system that has been set.

The hairiness irregularity often results in an optical impression of irregular dyeing. This is why different means to evaluate the hairiness of the spun yarn have been sought after through electrostatic, gravimetric and optical methods.

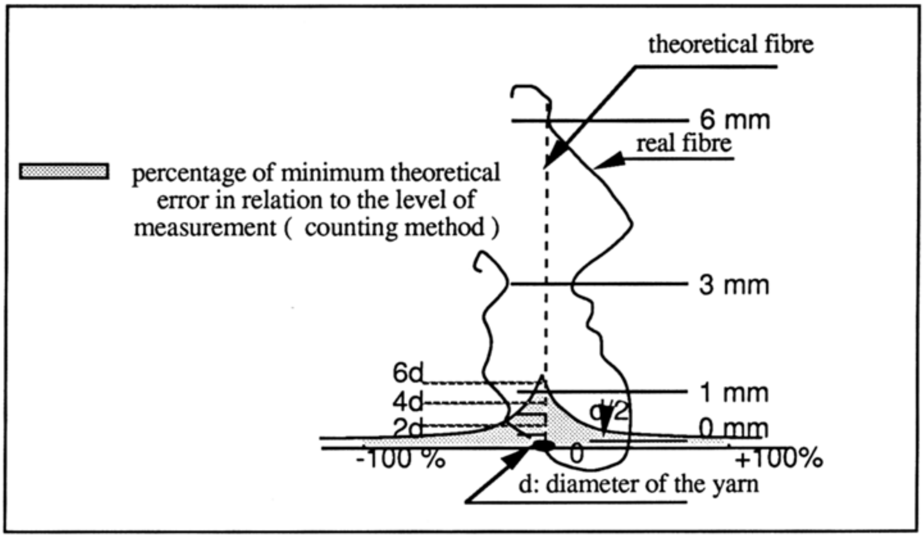


Figure 7 - Error of measurement during the counting operation

2.4.1. *The Sensor.* The ideal sensor would make a distinction between the core of the yarn and the hairiness of the yarn (Figure 7). Now, physically, the function providing the cohesion can be seen through a compact fibre arrangement and the perturbation function by a loose fibre arrangement, the fibres being practically in contact with the air only.

Placed in a luminous flow, the core of the yarn i.e., the compact arrangement, will stop the luminous rays proportional to the projection in that direction of the core of the yarn. Conversely all the fibres belonging to the perturbation function will diffract quite a high proportion of light, while they will only stop a small amount of it. This is why we have opted for placing the yarn in front of a lens in a widened laser beam.

The edges of each emergence behave like secondary light sources while the body of the yarn absorbs all the received luminous flow. By stopping (in the focal plane) the rays that have not been subjected to any interference with the yarn system, it is possible, by only considering the diffracted light, to reconstruct a picture in which only the fibres of the perturbation function will appear. So, the perturbation function and the cohesion function are simply split.

2.4.2. *The Data Processing.* In the picture plane in which only the diffracting elements appear, the limit of length of the yarn samples can be extremely reduced or on the contrary very much widened. Practical conditions, however, limit the length of the yarn in the measuring field which is a function of the increase of the width of the sensor window. These constraints are connected to the spatial differences of energetic distribution of the laser beam, so that the reading can be performed with a good regularity, which implies a reduced reading space that is still sufficiently energetic.

In the measuring field, a given fibre produces a signal whose intensity is proportional to the tightness of the fibre in the assembly. At this stage, the luminous data are transformed into an electrical signal which spatially averages (in x,y) the information (Figure 8).

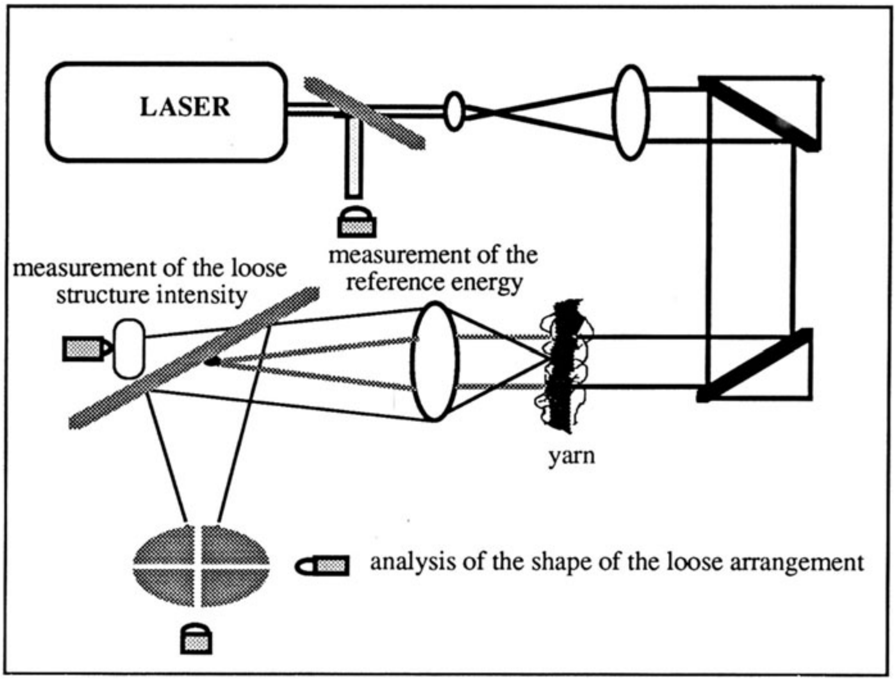


Figure 8 - Loose structure sensor

2.4.3. *Conclusion.* The use of the diffraction phenomenon enables the arrangement of superficial fibres to be well separated from the arrangements of the compact core fibres. This discrimination between the structures finally gives rise to results that are unquestionable and that can be reproduced.

This principle resulted in a patent that has been taken up by a textile metrology equipment manufacturer and which has been sold throughout the world. The reliability of the measurement technique made this quantity credible so that the analysis of the hairiness phenomenon could be made clearer. However, this credibility must not mask that the perception is only global and that many properties may be due to the shape of the fibre arches. Although an in-depth analysis of the structure may be of paramount interest, it is currently out of reach because, except for the global characterisation of structure, the distribution of the fibre length cannot be established. For this, it is therefore necessary to locate the beginning and the end of the fibre arches. Trials are currently being carried out in this direction by studying the angular distribution of the fibre ends.

2.5. STRENGTH

As for the yarn strength, it isn't estimated. We can only know a threshold. Any fragility of the yarn which has a strength lower than the imposed stress brings about breaking, so the weak points must be eliminated.

2.6. SPEED

The speed measurement is classical, but the techniques involve contact with yarns. The measurement is generally performed by a wheel carried by the yarn itself. Speed is limited by problems of breaking, inertia and contacts. New techniques are being developed.

2.6.1. *Speed Measurement by Intercorrelation Method.* The principle that we have used requires two sensors (see Figure 9) which can evaluate the transit time by intercorrelating the random signals stemming from sensors [4].

Generally the sensors can't be specified, a phenomenon with random fluctuations and carried by the yarn is only needed. Two appropriate sensors detect the phenomenon in two distinct places. In these conditions, the random phenomenon fluctuations are supposed to be seen by the first sensor, and then by the second but with a delay that is a function of the transit time.

The measurement problem is to estimate the delay between the two signals x(t) and y(t), that is to say $y(t) = x(t - \tau_m)$.

The estimation $\hat{\tau}_m$ of this delay can be achieved with the intercorrelation function that measures the similarity between two temporal signals.

Precision on the Transit Time Determination: $\hat{\tau}_m$

Consider a stationary phenomenon and so a constant average speed with random variations.

The problem is to estimate: $\tau_m = E[\tau_m(t)]$, so we take a closer look at determining the precision on the estimation $\hat{\tau}_m$ of the true average τ_m.

$$\hat{\tau}_m = \frac{1}{N}\sum_{i=1}^{N} \tau_{mi} \pm \frac{2\hat{\sigma}}{\sqrt{N}}$$ is obtained

Where

$\hat{\tau}_m$	a delay estimator
N	the number of measurements
$\hat{\sigma}$	estimated standard deviation

The limits of this principle are closely linked to the stationary hypothesis, to the necessary acquisition time, to the waveband width of the correlated signals, and to the ratio of the signal to the noise.

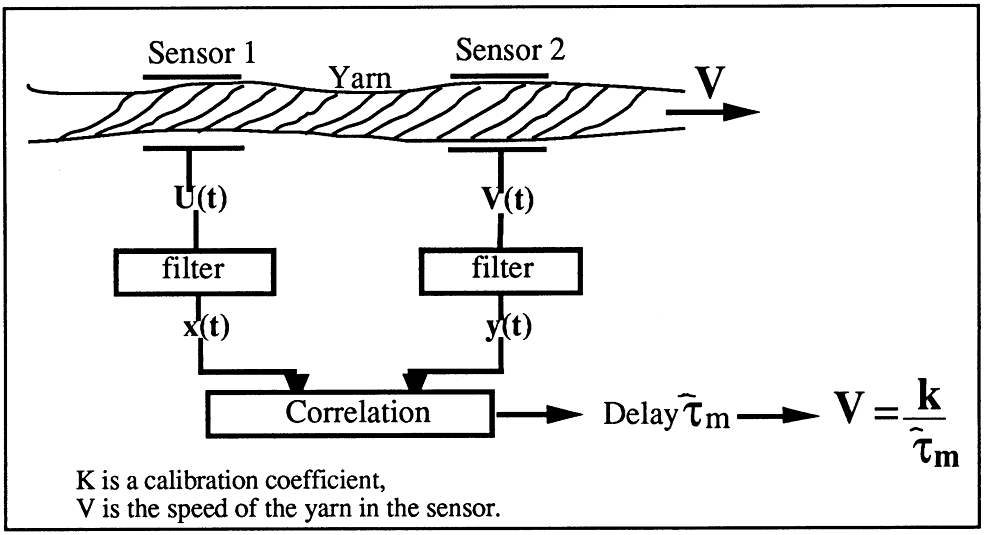


Figure 9 - Speed measurement by means of an intercorrelation method

2.6.2. *Noncontact Speed Measurement On Running Thread Using Spatial Filter.* The basic concept of spatial filtering is to observe the natural irregularity of a moving object through an optical system and a set of parallel slits (Figure 10) [5]. This works as a kind of narrow-band-pass spatial filter that selects a particular spatial frequency component of the irregularity. When the object moves, a narrow-band random signal with a central frequency is proportional to the running speed of the object. The speed of the object is then determined from the central frequency of the output signal.

The error in estimating the central frequency, which is proportional to the speed, is about 2.0 percent for threads which exhibit an optical irregularity; the spatial filtering method is also applicable to the speed measurement of textile materials whose optical irregularity cannot be observed when the materials are sprayed with a substance like water, which do not change the quality of the material.

2.7. TENSION

At present, the measurement of tension seems to be perfectly controlled; however all

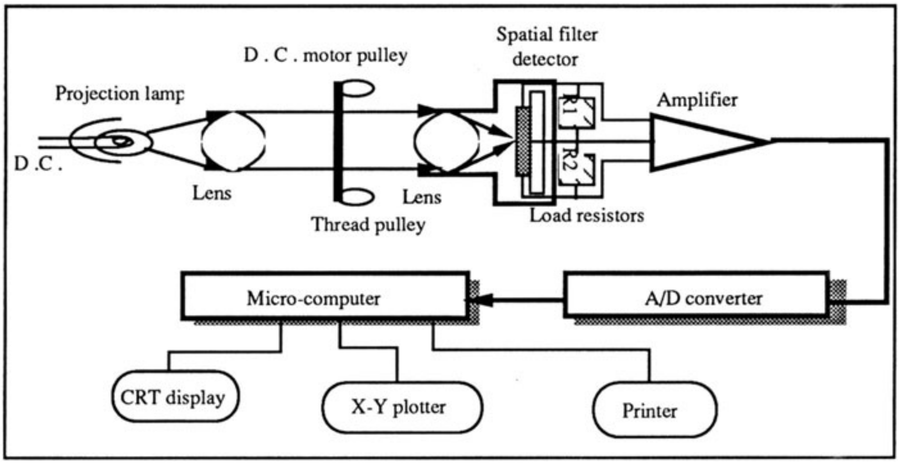


Figure 10 - Noncontact speed measurement on running thread using spatial filter

measures are taken with contact between the sensor and the yarn and in limited spaces. The principles are always the same, a bending strain is imposed on the yarn and the stress is measured. The sampling lengths on the yarns cannot be controlled, and the high speeds, of the order of 1,000 m/min, require very high rotations of the sensor wheels (30,000 revolutions per minute for a wheel with a diameter in the order of one centimeter); this gives rise to limits in sensor utilisation. So it's necessary for these measurements to progress, but not much work has been done so far.

2.8. THE ANALYSIS: Fourier's analysis

2.8.1. ***Principle Of Fourier's Transformation.*** This analysis consists in achieving a Fast Fourier's Transformation (FFT) of the signal. The principle of FFT is as follows: any g function can be analyzed through a family of sinusoids making a convolution between g and each sinusoid with a specific frequency.

$$G = \int g(x)\, e^{-2i\pi fx}\, dx$$

G(f) is a complex whose modulus has the dimension of energy.

The G(f) spectrogram is defined as: $S(f) = 2\,|G(f)|$, pour $0 \leq f \leq +\infty$

When the g function presents a periodic phenomenon of an f_0 frequency, the value of Fourier's transformation $G(f_0)$ has a significant energy, that is to say presents a maximum in $f_{0.}$

Let us recall that in the textile field, spectrograms are not expressed in frequency waves but in wavelengths. The obtained spectrogram in this way shows a peak for the wavelength ot the defect and possibly on the harmonics.

Five major categories of defect can be distinguished, to analyze weight regularity:

C1 - periodic defects with sinusoidal variation
C2 - periodic defects with a non-sinusoidal but symmetrical variation
C3 - periodic defects with non-symmetrical and non-sinusoidal variation
C4 - periodic defects shaped as an impulse with positive and negative components
C5 - periodic defects shaped as an impulse with solely positive or solely negative components

2.8.2. *Limits Of Fourier's Transformation.* The FFT can only detect periodic defects; moreover it cannot locate in time the defect because of the use of infinite sinusoid in its calculation. So for example, if two distinct defects of the same frequency exist with a Fourier's Transformation, one single peak will be obtained with a corresponding frequency, and we cannot say if there are two defects. Although Fourier's Transformation can only treat periodic functions, a yarn comprises both periodic defects and random defects.

3. Interpretation Module

3.1. WHAT'S THE PROBLEM ?

We will now summarize the different problems inherent to the analysis of the spinning data by humans, who have a significant theoretical knowledge in various fields: The treatment of the signal, statistics, etc.

If one is interested in using these parameters in spinning process, one should also have a detailed knowledge of the machines of the different spinning processes. Such a knowledge should also involve the different parts of each machine and even the influence between these parts in terms of defects.

If one is interested in using these parameters in the weaving or knitting fields, one should perfectly master all the characteristics of the manufacturing process so as to be able to foresee the final aspect of one's item from the data of the yarn that one is going to use.

On the other hand, it would be desirable that one should be able to consult the statistics and the standards which can actually evaluate the quality of a yarn in relation to the world production of that category of yarn. These statistics enable the relative quality to be only roughly grasped but one therefore may know if the yarn can be located within the most regular yarns of that category.

Finally, one should spend enough time to carry out this analysis correctly.

At present, this kind of control makes it possible to monitor quality but not to control it.

Because an actual quality control system must not only enable the quality to be evaluated but also to correct, if not in real time, at least relatively quickly, the causes of the off-quality; in our case, this means locating the different parts which have given rise to the variations of a parameter measured on the yarn so as to be able to intervene or foresee the behaviour of the yarn in the subsequent operations.

To conclude this study it can be said that we can develop an equipment which provides interesting data on a theoretical level and it is quite possible for these data to be interpreted, but only after extensive work that cannot be carried out only within the frame of daily control.

In addition, owing to the multiplicity of the sensors, of the methods of analysis, and of the manufacturing processes and the increase of production speeds and to the increasing interest of controls in real time, the analysis and interpretation of all the parameters to be taken into account as well as the diagnosis of a manufacturing process should be effected with greater speed so that the expected quality can be achieved. This implies that all operations should be automated and we shall now see the different computerized solutions which make this possible.

3.2. FIRST SOLUTION: CLASSICAL COMPUTING PROGRAMME (CCP)

This solution consists in replacing the individual by a CCP in which the FFT constitutes the data and the individual knowledge is in fact the body of the programme. Such a programme should propose the same solution as the individual for the same spectrogram. Yet, there isn't one single type of defect nor one single cause for the defect. So one is capable of giving another interpretation or questioning the previous interpretation for another spectrogram. From a data processing point of view, this results in a programme for each interpretation or a programme that takes all possible interpretations into account. In the latter case, the increase of the programme is in 2^n , n being the number of independent tests which are necessary to model all cases.

In this CCP, knowledge being the body of the programme is frozen, i.e., any modification of such a knowledge requires the source code of the programme to be modified, then compiled again.

3.3. SECOND SOLUTION: EXPERT SYSTEM (ES)

There is a second solution which consists in replacing the individual by an expert system [6].

An expert system is a software meant to replace or assist anybody in fields where there is a significant human expertise, subject to be revised or complemented according to the accumulated experience.

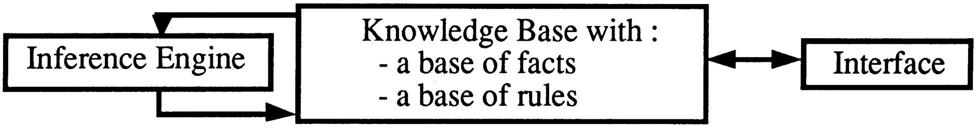
Such a system allows:

(i) to capture easily the know-how units, i.e., to facilitate most directly the expression of the rules in relation to the way they appear in the expert's mind.

(ii) to exploit all the units of know-how, i.e., to combine and/or to chain the groups of rules to infer different types of knowledge such as evaluations, plans, proofs, decisions, predictions, new rules, etc. and often to report how the new types of knowledge have been inferred.
(iii) to enable the whole set of units of know-how to be very easily revised, i.e., to offer facilities for rules to be added or suppressed.

An expert system can be split into three parts:
(i) a knowledge base which groups the knowledge pertaining to a field of application, and which splits up into two parts: a base of facts, which are the actual system data, and a base of rules which comprises the operational knowledge of the considered field;
(ii) an inference engine, which is roughly a didactive computing mechanism whereby the order of execution of the rules which are contained in a base of knowledge can be arranged at will;
(iii) a dialogue interface with the user.

The different parts of an expert system communicate between themselves as follows:



The base of facts and the base of rules constitute for the inference engine both an input and output set of data. However, most of the time, the inference engine only modifies the base of facts.

For such a solution, FFT constitutes a part of the data, the knowledge of the individual another part. The latter constituting then a base of knowledge of the expert system. This system should also propose the same solution as the individual for the same spectrogram.

Each interpretation is modelled by an island of knowledge (set of rules) and the body of the programme (inference engine and interface) cannot be modified easily.

3.4. COMPARISON IN TERMS OF EVOLUTION AND CHOICE

We shall now study the evolution costs of both solutions that have been presented to replace our individual. We shall envisage four possible extensions and compare the advantages and disadvantages of CCP or ES in each case.

3.4.1. *Modification Of An Already Programmed Knowledge.*

Solution CCP: The body of the programme has to be modified. For example, if a solution is added (one independent test) to n others, 2^n tests will no longer be adequate but 2^{n+1} tests will be needed. It can be seen that this modification is costly not only in time but also in money because the evolution of the programme is exponential.

Solution ES: Rules are added or substracted in the existing base of rules without modifying the body of the programme. In this case, a linear evolution of the base of rules can be seen.

3.4.2. *Interpretation Of A New Sensor.*

Solution CCP: A new programme modelizing the interpretation of this new sensor must be conceived as well as a third programme allowing to take this new sensor and the already existing sensor into account. In this case, a problem of memory may arise, for the resulting programme involves $2^n + 2^m$ cases. Some cases which are useless when the modification occurs, can be cut off. But the latter unfortunately may prove indispensable during a further modification which, then, will be more difficult to effect.

Solution ES: The body of the programme remains the same. A new base of rules modelling this new sensor can be created, and so we have two islands of knowledge in the resulting base of rules, one for each sensor. Both islands need not be loaded simultaneously in memory because they can be successively loaded, which doesn't pose any memory problem.

3.4.3. *Intercorrelated Interpretation Of Several Sensors.*

Solution CCP: If the interpretation of two sensors are to be intercorrelated, as the modeleine of each sensor respectively comprises 2^n and 2^m tests, 2^{n+m} cases must be considered. This number may become considerable, and in this case the limits of a CCP begin to appear.

Solution ES: For the interpretation of two sensors to be intercorrelated, an island of knowledge is created which takes the results provided by these islands of knowledge for each sensor into account. Here again the simultaneous presence of three islands is not compulsory, therefore no memory problem arises.

3.4.4. *Discovery Of An Algorithmic Model.* Currently, the interpretation of a sensor is empirical. But a significant progress of the modelling of a textile yarn might lead to an algorithm in the classical sense of the word to interpret a sensor.

Solution CCP: In this case, the knowledge becomes an algorithm and so it is very easy to programme it.

Solution ES: Programming such an algorithm with an expert system is not very interesting because of the complexity of the programming operation and because of the time of execution. Yet, an expert system can use a classically programmed algorithm: the island of knowledge is replaced by a single rule which triggers off the algorithm. In this case, if the expert system is considered to be useful, it is often necessary to adjust some parameters (and such an operation can be done with the help of a new island of knowledge) for the algorithm to work at its best.

In short, it is quite clear in terms of cost of evolution that the ES solution is far better than the CCP solution. The ES solution is extremely flexible without being too expensive. So it is not difficult to imagine that the company which sells this type of system will be able to provide updated copies of the system every year, which in fact are an enrichment of the knowledge base of the ES. Moreover, such a solution makes any sort of knowledge to be modelled: algorithmic, deductive, intuitive, heuristic, quantitative or qualitative. Finally, an ES can also use the data from other fields of artificial intelligence like neural networks or fuzzy logic. For example, it may be possible to grasp the shape of the spectrogram thanks to a neural network and then to transfer this elementary knowledge into an ES.

To conclude, the ES solution seems to be best adapted to carry out a diagnosis of the yarn, from data obtained from the sensors.

4. Knowledge Based System To Interpret The Weight Regularity

An overview of the working of the software is as follows: first, a signal stemming from the weight regularity sensor is received by the software; second, the user must define the yarn manufacturing process, and if necessary, the test conditions (speed of the yarn in the sensor, unknown manufacturing process, etc.); then, the software detects the defects on the weight regularity signal and suggests their possible causes.

At present the defect detection on the yarn is based on Fourier's analysis, but other kinds of analysis can be used.

As shown in Figure 11, the signal treatment module receives the weight regularity signal and, using Fourier's transformation, one class is allocated to each defect. The defect, and some information about the testing yarn and its manufacturing process are passed on to the interpretation module which then proposes possible causes for each defect.

The storage in memory of the signal, the defects and their real causes, is planned for the manufacture.

This software needs to assist humans. This implies two things: the software must contain the present knowledge which permits the evaluation of yarn quality and defects and it must be able to pick up new sets of knowledge.

Human knowledge is varied, it can be intuitive, and it is based on quantitative, qualitative and heuristic notions. Then the software will have to be able to accept all types of knowledge.

In conclusion, the software will have to be more flexible and adaptable in order to accept new sets of knowledge, new sensors and new methods of analysis.

4.1. SIMPLIFIED GLOBAL STRUCTURE OF THE SOFTWARE

The Macintosh Pascal Lisa Object has been used to develop this software to take as much advantage of the graphical resources of the Macintosh environment. In addition, such a language can be well interfaced with the C language which is the programming language of Nexpert's libraries. Nexpert is the expert system generator used for our prototype.

We have chosen to use Nexpert only to process the part devoted to analyzing the defects and using a classical programme for whatever may be introduction or display of the data:

there may be an analyzing signal, a process to be defined, results to be displayed. This has numerous advantages. It is the CCP that controls the coherence of the data used by Nexpert, which considerably alleviates the base of rules. Moreover this solution enables our interfaces to be created so as to use a friendly environment. Our software is therefore a CCP with Nexpert only as a sub-programme.

Object-oriented programming offers several advantages, so that different parts will be functionally well split. Each object has a well-defined functionality and the links between the different objects constitute the framework of the programme. Furthermore, the programme tolerates a lot of signal-type documents, process-type documents, screen result documents if the memory contains enough space to store everything. So, for the same process several signals can be analyzed, or for one single signal several processes can be proposed, and the results of each analysis can be seen in a different resulting document.

Later on, a data base has been planned for addition to the system, so that the history of the defect, signals, statistical data, the characteristics of the machines, and the badly identified defects can be stored.

4.2. SIGNAL TREATMENT

4.2.1. *Characterizing The Defects.* The main difficulty which came up during the implementation of this module has been looking for the fundamental wavelength and the harmonics. First of all a criterion meant to locate the energy peaks associated with a fundamental wavelength had to be defined. Then an algorithm had to be designed with a parameter of degree of tolerance in frequency and energy to detect the harmonics associated with the fundamental wavelength.

However, all the ambiguities have not been removed and when the system hesitates between two types of defects for a detected defect, it creates two defects with the same fundamental wavelength but of a different type. It is up to the expert system to remove the ambiguity.

4.2.2. *The Problem Of Noise.* The weight regularity signal is noisy. This noise can be decomposed into two noises of different origins: a measure noise, and a noise due to the random distribution of the fibers within the yarn.

Currently, the two noises cannot be separated. Models for the theoretical distribution of the fibers in the yarn exist, but it is essential to know which case actually comes up for each test. In this field, statistical studies are to be done. It is possible, when such studies are conducted, to create an island of knowledge which, according to the qualitative and quantitative criteria, will choose the noise model to be applied; the purpose of the system being either to filter this noise by computer, or to evaluate its power in relation to the power of the pure signal of weight regularity.

Because of the noise, the detection of defects is semi-automatic because it is necessary to pre-adjust the various filters to try to eliminate this noise without eliminating too much significant information contained in the signal.

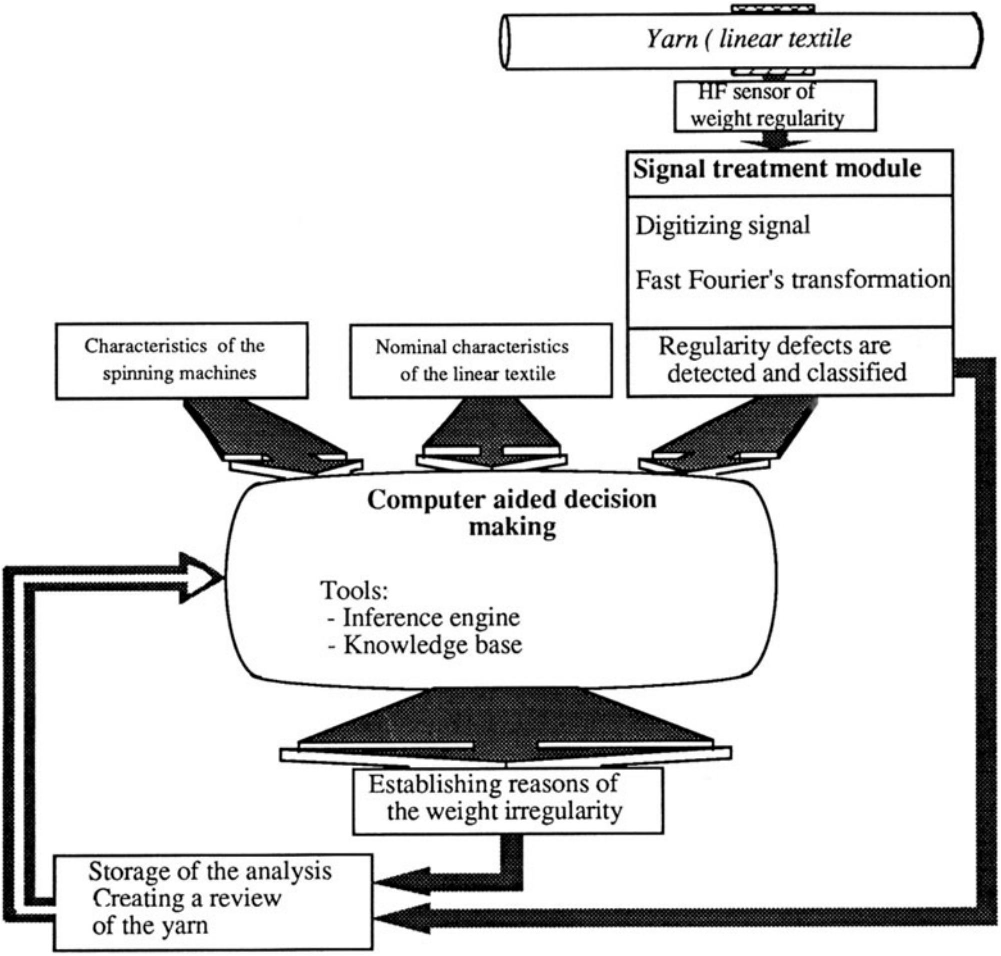


Figure 11 - Classification of yarn defect

4.3. INTERPRETATION MODULE

This module is meant to replace the human in 80 percent of cases. This module consists of an expert system generated with the help of Nexpert Object software and interfaces. We will first see the data in the knowledge base and then the different options which make it possible to achieve this knowledge base for weight regularity.

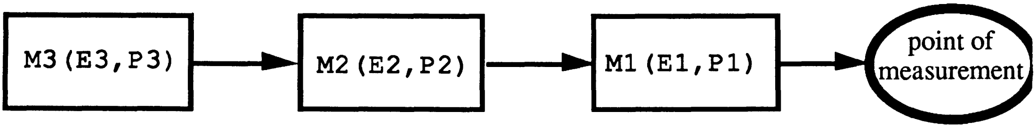
4.3.1. *Description Of The Developed Knowledge Base.* To propose a set of possible causes, that are at the same time coherent and limited, human experts go through successive filtrations to eliminate infeasible solutions. Using the classes of defects that can be identified from the spectrogram as the basis, it is possible to find the possible

causes for a class of defects; then the possible sources in the manufacturing process can be identified based on the existing machines and the wavelength of the defect. These machines constitute a M set which in fact is the intersection of the two following sets:
(i) the set of all the machines which can contain the component which actually generated the defect,
(ii) the set of the existing machines in the manufacturing process of the tested yarn.

At this stage, causes associated with machines can therefore be proposed for a defect.

But the wavelength of the defect has not yet been taken into account. Now this can reduce M set to a M' set of machines whose wavelength intervals of the defect they generate are compatible with the wavelength of the considered defect. To achieve this new filtering operation, one has to know: the intervals of the wavelength of the defect that can be generated for all the spinning machines and for each machine, the draft between the input and the output of the machine so as to successively correct the wavelength of the defect by different drawing operations of the machines that are not concerned.

The following example is an illustration of all that:



Let a process consist of three Mi machines; each machine is characterized by its Ei drawing and its Pi wavelength interval. Pi corresponds to the wavelength interval of the defect that can be generated by the Mi machine on a yarn.

If one considers a defect of a λ wavelength belonging to the C2 class, the M set can be determined. We shall suppose that m contains M1, M2 and M3.

If λ does not belong to P1, M' at least contains M2 and M3.

Now a comparison is to be made between $\lambda/E1$ to P2 and if $\lambda/E1$ belongs to P2, M'contains M2. If $\lambda/E1.E2$ belongs to P3, then M' contains M2 and M3 and the possible causes can be traced to those machines, and only a direct identification of the cause of the defect will be the solution. Conversely if $\lambda/E1.E2$ does not belong to P3, the incriminated machine will very likely be identified.

The following stage consists of a new filtering operation through a dimension or a speed which is specific to a machine component. If the possible causes are known for a defect and the set M', and if the expression of the wavelength of the defect which can be generated by each cause is also known, the characteristic quantities of the components associated with the causes can be evaluated.

In most cases, the expression of the wavelength is of the type: $\lambda = k\,G\,E$, where k is a constant, G is a characteristic dimension or a characteristic speed and E is the drawing undergone by the yarn between the creation of the defect and the measuring point.

Therefore, if the expression of λ nd E are known, G can be calculated. Then G is compared to the known characteristic quantities of the components belonging to the machines of the manufacturing process. So a new set of possible causes is created that way, which contains only the components whose G characteristic quantity can be found in the process of yarn manufacturing.

4.3.2. *How Can All This Be Achieved With The Computer ?*

Nexpert Object is an expert system generator, i.e., it supplies the inference engine, the user's interface and a set of controls, whereby a knowledge base can be created. In addition, the created knowledge base and the supplied inference engine can be integrated is an independent application.

The Knowledge Base is a model of the specific knowledge of the application field. It comprises a base of facts and a base of rules.

The Base Of Facts: facts are a set of assertional knowledge used to describe the considered situation either as established, i.e., true, or to be established, i.e., facts that are looked for which there are hypotheses.

So, the rules to be exploited can be conditioned and achieved. They can be created or destroyed by exploiting the base of rules.

In Nexpert, the structure which groups the set of facts is composed of objects and classes, each object or class having properties. A fact can then be defined as a specific property of an object or of a class. All the objects and classes together are called the world of objects. Nexpert proposes two structures as far as the world of objects is concerned:

(i) either a flat world in which all the objects are independent. This world enables a simple reasoning to be performed but we will see later that the performance is poor.

(ii) or a hierarchical or genealogical world in which each object or class can be the child or the father of one or several other objects or classes. This world has an oriented graph structure.

Various types of inheritances are possible between the elements which constitute the base of facts:

(i) property inheritance: an object can inherit properties of the class or of the object it is the son of;

(ii) value inheritance: an object can inherit the value of a property of the class or of the object it is the child of;

(iii) method inheritance: for each property of a class or of an object, actions can be defined to be triggered off in relation to the value of this property, these actions can be inherited.

The Base Of Rules: rules are a set of operational knowledge which represents the know-how of the considered application field. They indicate which consequences are to be triggered off and/or which actions to be carried out when a situation is established or is to be established. The rules are interconnected by their hypotheses and the whole set of rules builds up a graph which can be displayed. The base of rules has a tree structure. This structure highlights the backward chaining in relation to the forward chaining, but the latter remains possible.

So, suggesting hypotheses and validating values can be proposed for some properties and this makes it possible to operate the inference engine by changing at will the initial state of the base of knowledge and of the pile of hypotheses to suggest.

The Inference Engines. It is a deductive computer system which exploits the knowledge of the previous base by considering them as data and therefore as different types of knowledge which are likely to be changed.

There are three types of actions on the knowledge base;

(i) checking and/or questioning the validity of the knowledge;

(ii) reaching the knowledge;

(iii) triggering off specific actions according to the state of the knowledge; in general this entails modifications of the knowledge base, particularly in its 'facts' part, but sometimes in its 'rules' part.

Nexpert inference engine functions in mixed chaining. It can be noted that the latter also comprises two sorts of forward chaining systems:

(i) A forward chaining which is due to the modifications of the value of the data. When the value of data changes, Nexpert looks for all the rules; this fact is a condition to evaluate them.

(ii) A forward chaining which is pertinent to the hypothesis; when the value of H1 hypothesis has been determined, H2 hypothesis can be evaluated if it belongs to the H1 context even if H1 is not a condition of a rule that leads to H2.

Strategy. The processing modes of the rules, through backward chaining, forward chaining or mixed chaining, have only a partial influence on determining the chaining process of the rules.

In fact, one or the other classical strategies to develop the search can be superimposed on the releasing mode of the rules: in depth-first strategy, in breadth-first strategy, in ordered search strategy.

Nexpert offers different strategies:

(i) according to the case, one can opt to use only the forward chaining or only the backward chaining during the evaluation mechanism sequence of the hypothesis;

(ii) to establish the value of an hypothesis, all the rules leading to it can be evaluated (exhaustive evaluation), or the rules leading to this hypothesis can be evaluated until a true one can be found (non-exhaustive evaluation);

(iii) in forward chaining pertaining to the hypothesis, the value of truth of the hypothesis enables its context to be taken into account.

The developed expert system typically functions as a backward chaining system. This has many advantages: several causes can be proposed for the same defect; and it is not necessary to ask the user the same question twice.

However, forward chaining can be used in two cases:

(i) to question the solutions that have been found with new facts; in this case, it is the user that introduces the new facts and starts the interpretation again. In no case, can the ES question an object solution; this protection has been designed to prevent the ES from looping indefinitely and thus never giving any solution to the user;

(ii) to link two islands of knowledge which model different sensors. This mechanism has been tested on two islands of knowledge. But it is not currently used in this system for

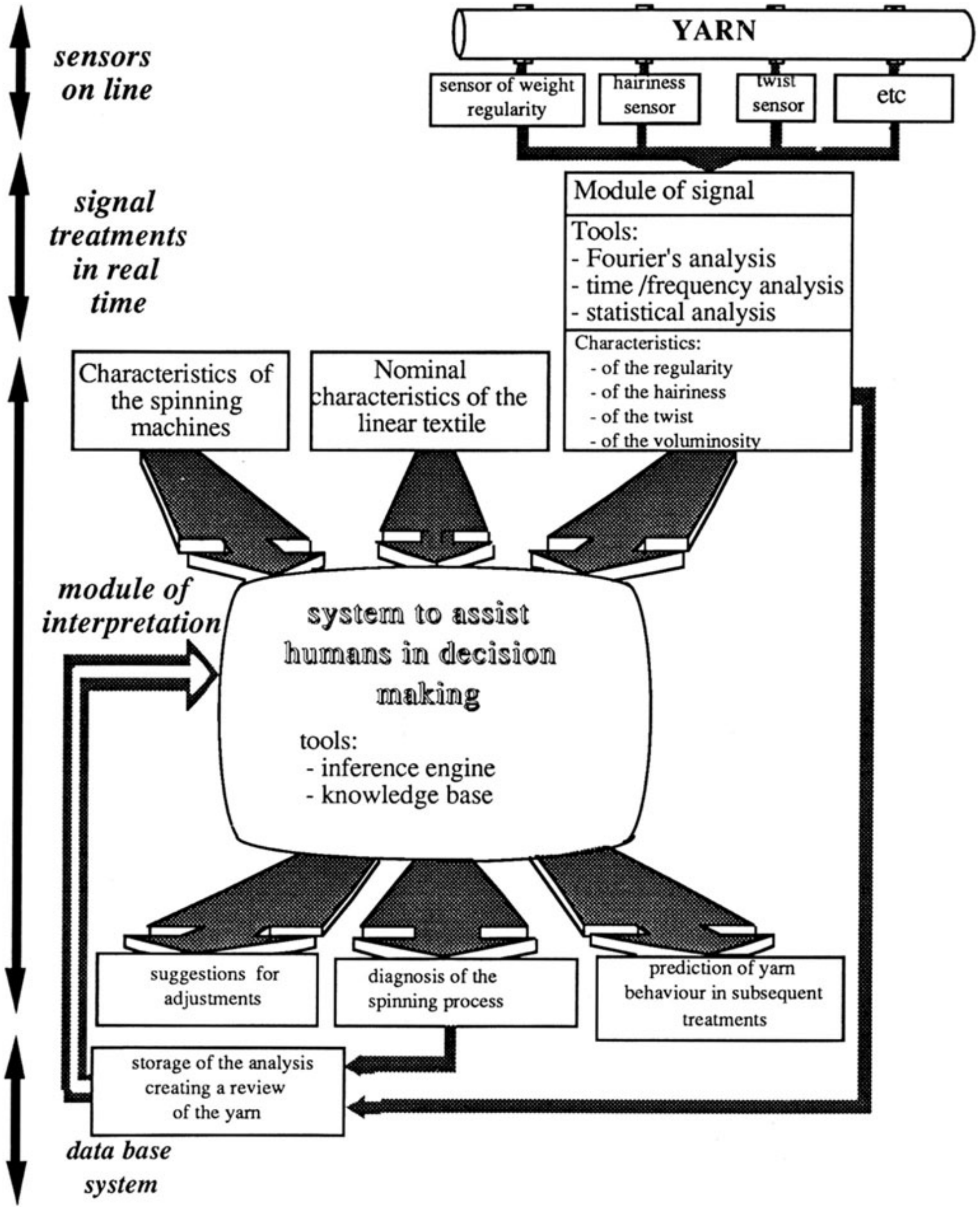


Figure 12 - Future evolution of spinning expert system

only the weight regularity sensor is taken into account.

These options in terms of chaining have led us to use a depth-first search strategy for our reasoning since it was easier to programme.

5. Conclusion

The spinning expert system has been designed with the major concern that it should be user-friendly. It constitutes a core around which other quality estimators (twist, hairiness, diameter, etc.) are built. It can also be used to propose adjustments of spinning machines, or foresee how a yarn will behave. To do so, new islands of rules ought to be created. the possible extensions are summed up in Figure 12.

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MONITORING AND KNOWLEDGE-BASED EXPERT SYSTEMS IN SPINNING

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ABSTRACT. Since the eighties, monitoring systems that control and manage yarn production have appeared in the spinning mills. Different architectures of monitoring systems, sensors and actuators, and their limitations are discussed in the first part of this chapter. The second part of the chapter tries to answer the following questions: What is a KBES? , How does it work? and How is it implemented? Non-exhaustive studies define the different functions that such a system can perform in the area of spinning. An industrial application is presented and discussed.

KEYWORDS. Monitoring, Sensors, Actuators, Data Acquisition, Network, Processing Software, Quality Evaluation, Fibre Preparation, Roving, Sliver, Knowledge-Based Expert System, Forward Chaining, Backward Chaining, Knowledge Base, Inference Engine, KBES Implementation, Spinning.

1. Monitoring Systems

Computer aided-design and computer-aided manufacturing are beginning to make inroads into spinning industries, but, in such industries, the monitoring concept is more developed. In the near future, the control of each production position in spinning and the total control of the entire plant (computer integrated manufacturing-CIM) will gradually emerge. But, KBES (knowledge-based expert systems) which will be able to supervise all the decisions of the plant (technical or management decisions) are awaited.

1.1. INTRODUCTION

Substantial progress has been made since the invention of the micro-processor in 1971 by INTEL Corporation and the invention of the microcomputer a few months later. These computers, from the smallest to the biggest, perform computations at very high speeds

M. Acar (ed.), Mechatronic Design in Textile Engineering, 133–155.

(hundred to thousand Mips). All these machines have "invaded" our industries.

After the mechanical industries, which were the first to use "EDT", some areas in the textile industry are using such advanced technology. Many plants use monitoring systems to control and to manage their production. The latest developments in data control are about KBES. They are used in many industrial fields (process control, system maintenance, planning), but there are only a few applications in the textile industry. Some of them are actually running but others are only laboratory prototypes.

On the other hand, monitoring systems, which are genuine control systems of production, have spread. Some specific ones are integrated in production machines, others, more versatile ones, can be integrated in different kinds of machines on production lines. Before discussing KBES we present an in-depth view of monitoring systems.

1.2. MONITORING SYSTEMS

1.2.1. *The objectives of monitoring systems.* The mill is monitored to rapidly and continuously get the information required for a streamlined management, both in production and quality. The data acquisition has to be automatically carried out to get accurate and reliable data, and to avoid all human errors.

Data regarding the working teams, running machines, machine positions and devices, raw material and product flows and quality are captured by the monitoring system.

Based on these data and information, a production management programme, a quality management programme (detection of defects due to materials or machines) and a provisional maintenance programme can be implemented. While both production and quality management programmes are quite easy to implement, it is quite difficult to implement an efficient provisional maintenance programme. Therefore, it can be said that it is necessary to have continuous information about the yarn being processed. The information collected from the production of a specific machine or a complete plant helps the user to obtain a judgement about materials being processed as well as the conditions and the machine settings, and to derive conclusions about possible deviations or alterations.

1.2.2. *How is a monitoring system constituted ?* Let us take a spinning room equipped with N spinning frames as an example. Each spinning frame (ring or rotor spinning frame) is divided in sections, each section with 4, 6, 8, ... positions.

Each position of the spinning frame is equipped with specific sensors. These individual sensors provide data which are first stored in a concentrator and then sent to a node of the network system. Eventually the information is sent to the supervisor computer. The data are displayed and edited as requested by the user (Figure 1). Thus the three main components of the monitoring system can be summarized as follows: the sensors, the transmission network and the processing software.

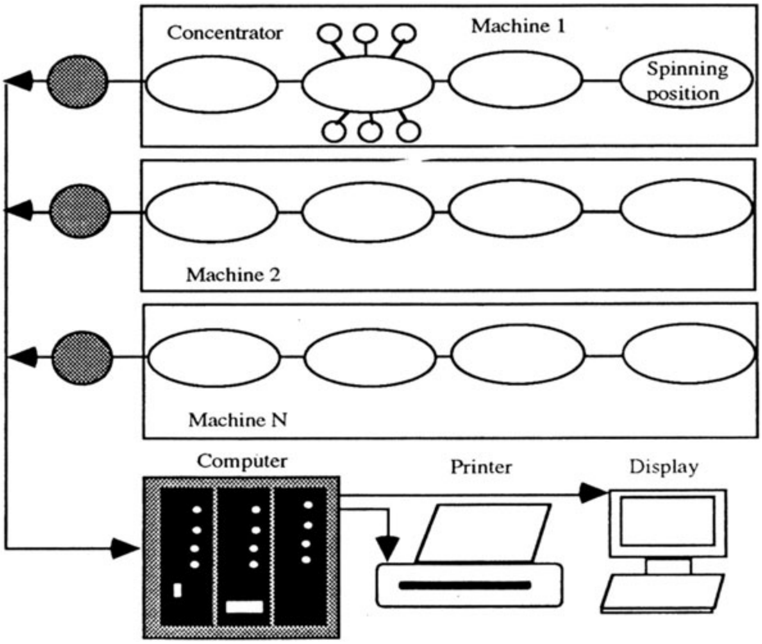

Figure 1. Components of a monitoring system

1.2.3. *What kind of data are to be acquired ?* Before following the monitoring system investigation, information required to control production has to be listed. Based on a spinning frame, the required information can be split into three sets as follows: data pertaining to the frame; data pertaining to the spinning position and data pertaining to the yarn being spun.

Frame data. The machine is running or is stopped. In the case of a shutdown or downtime, the case has to be identified (breakdown, stop for maintenance, etc.)

Spinning position data. The data entities pertaining to the spinning position are many and their acquisition is more difficult. Here are a few examples: rotation speed of rotor; delivery speed; spindle is running/stopped; yarn presence detection; sliver presence detection, etc.

Yarn data. Data entities pertaining to the yarn include: produced yarn length and package weight; quality of produced yarns; number of defects, etc.

1.2.4. *The sensors.* The sensors represent the main point of the monitoring system. In fact, the increase in efficiency of monitoring systems is linked to the development of sensors, particularly for the evaluation of the yarn quality and for determining the appropriate time for maintenance. We briefly review some sensors, from the simplest to the most complicated.

Run/stop sensor. The information is easy to obtain and is given by the state of the power supply of the main electrical motor. The detection of the state of the spinning position is given by an optical sensor.

Rotation and delivery speed. This information is given by the preset value (frequency, tension) given to the position driving motor. The delivery speed is calculated from the speed rotation multiplied by the diameter of the driven cylinder.

Sliver and yarn detection. The detection of the presence of sliver or yarn is given by a switch.

Yarn quality evaluation. The evaluation of the quality of the produced yarn needs more complicated sensors because of the large variety of materials and types of produced yarns. Based on the same spinning machine example, the evaluation of the yarn quality needs the measurement of the following properties: thin places; thick places; moiré and fibre contamination.

The measurement techniques are more sophisticated, such as capacitive or optoelectronic techniques. Consider the example: the "Corolab©" optical measurement device developed by Schlafhorst©.

Corolab sensor developed by Schlafhorst is one of the most efficient ones to improve the quality of the yarn. This sensor is based on an absolute measuring optical system using an infrared light beam. The transmitter sends a beam through the measuring field to the receiver. Simultaneously, a part of the light falls upon a reference receiver. The amount of light which is transmitted in each case is compared to determine the diameter of the yarn (Figure 2).

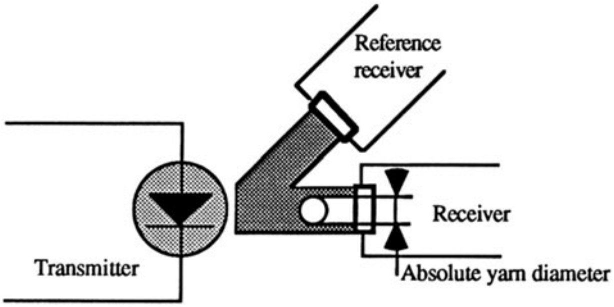

Figure 2. The Corolab sensor

Through continuous monitoring during yarn production, such a system detects all the irregularities in the yarn. If thick places in the yarn occur several times with the same period and with a diameter higher than the allowable diameter deviation, the monitoring system will detect a moiré. So, the spinning position (rotor) has to be stopped for a cleaning operation. In fact, such a complex sensor constitutes the first step in a preventive maintenance programme.

We now present some monitoring systems from fibre preparation to yarn spinning.

1.3. FIBRE PREPARATION

Let us take as an example the Trützschler monitoring system developed for fibre preparation. Such a system is quite interesting because it takes into account the fibre flow from fibre preparation to carding operation. This fibre preparation line consists of a bale preparation station, multiple mixers and cards (Figure 3). Each component of this line is equipped with its own monitoring system and these are connected together through a five level architecture network (Figure 4).

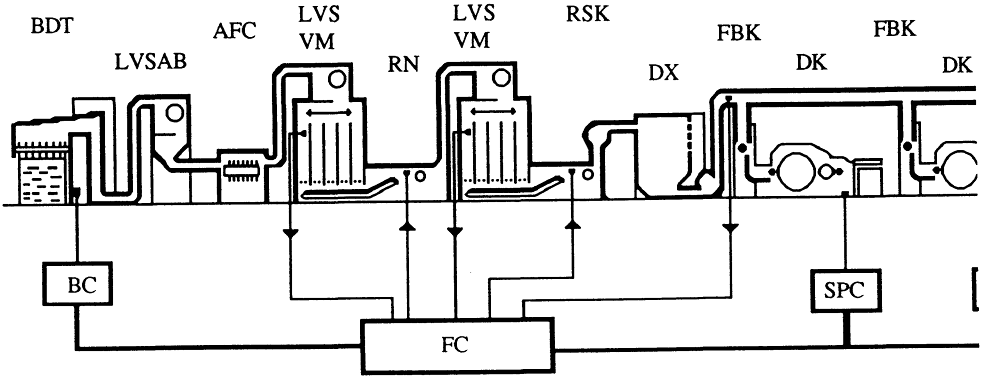

Figure 3. The fibre preparation line (from Trützschler)

Level 0 is the sensor level and actuator level. Sensors are indispensable for the useful application of machine control. In such a preparation line, sensors measure, for example, the sliver count at the card, and the web thickness. They also measure delivery speeds, pressures in chute, distances, the bale height etc. Actuators adjust, for example, the deflector blades and chute walls, control speeds, or stop the machine when the door is open while the process is running.

Level 1 is the machine control level. It consists of individual special controls in a modular system as follows:

Blend commander© for bale preparation. This system requires the following elements for running:

> the working area (right or left), the number of bales, the number of lots of bales, the bale height and the quantity of material taken by the opening rolls at each travel cycle.

Mixcommander© for multiple mixers:

Cleancommander© for cotton. This system controls, for example, the deflector blades in front of the moving knives in order to control the amount of waste and the degree of opening, the amount of air suction for the fibres and the wastes.

Cardcommander©. The following data can be entered in the card monitoring system:

the sliver count, the delivery speed, the total draft, the length of sliver in the can, the pressure in the chute, the deflector blade adjustment and the reference value for autolevelling and control.

With such data, all the functions of the card are controlled including the high speed coiler, the high speed can changer and the autolevelling system.

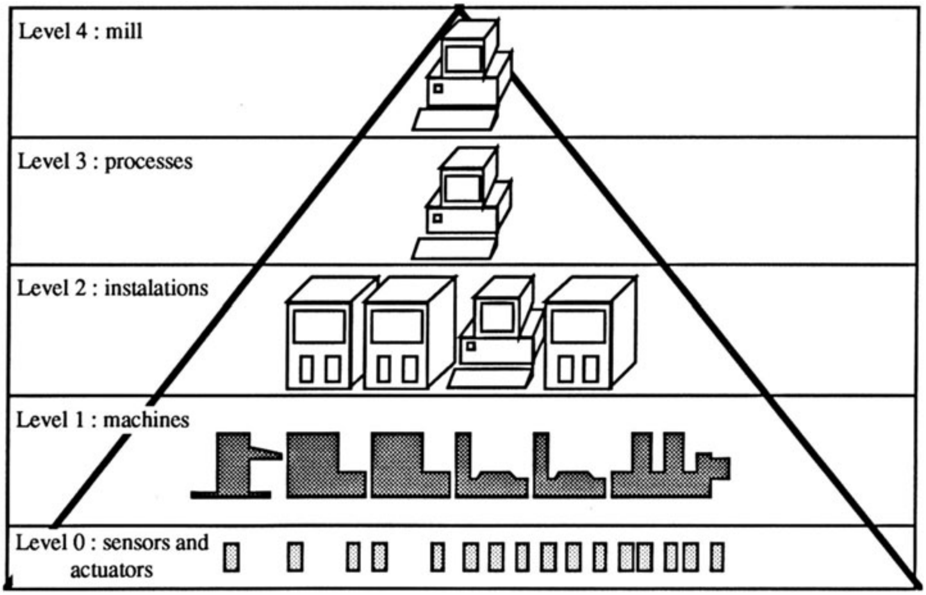

Figure 4. Control levels

On Level 2 there are installation control units as well as production and quality data collection systems. Systems belonging to this level are, for example:

the overall electrical control, the overall electronic installation control, the overall installation feeding control and the carding room control.

For the Trützschler fibre preparation installation, the feeding control is effected by the Feedcommander© system. It requires the following data for running:

the technical specification of the raw material being processed, the material removing vertical step height for the bale, the production of the carding room and the pressure in the chute.

The carding room is controlled by a card information system KIT. By means of a specific network, KIT gives quality and production information about the connected group of cards. It condenses data provided by the cards, establishes spectrographs, makes the length variation curves of the card sliver, compares the real measured values to preset values.

Level 3 is the process level control which represents an important management instrument for the spinning mill manager. This high level system summarizes all the relevant mill, production and quality data for the opening, cleaning and carding sections. The process control system should condense and evaluate the on-line data in such a way that data needed for decision-making are quickly and freely accessible. The system also provides evaluation of selected time periods in the past, so that trends can be detected and analyzed.

Level 4 is the highest control level of the mill. It consists of a host computer giving an overview of all the production of the mill, so that the different kinds of process control systems could be connected (preparation, carding, spinning, winding, etc).

Many sensors, devices, and process controls have been developed to control fibre preparation. But, as far as fibre preparation is concerned, the main functions are: removing the trash card dust, splitting the flocks and individualizing the fibre.

This efficiency of fibre preparation, including these three functions, is evaluated by the degrees of cleaning and opening. The efficiency of a fibre preparation monitoring will depend on the accuracy of cleaning and opening degree sensors. But, today, there is no suitable definition of degree of fibre opening and no efficient and accurate sensors either.

1.4. ROVING AND SLIVER

Many monitoring systems have been developed to track the quality of roving and sliver. They are based on a pneumatic or capacitive count measurement. The data are taken on-line and analyzed. The deviation from a given preset value is highlighted. When the deviation is considered harmful to yarn quality, the machine is stopped.

1.5. YARN

Efficient systems monitor the spinning of conventional and unconventional yarns. These monitoring systems introduce a new concept: the information exchange could be bidirectional. This concept includes the data acquisition from the machine and the data transfer from the computer to the machine. This concept allows an auto-control of the spinning position.

Consider the example: the Informator© system of Schlafhorst Autocoro©. The Informator offers comprehensive data acquisition and data transfers with the following features:

> setting the spinning machine, the automated units, the yarn control device Corolab© and the piecer carriage, acquisition and provision of production data, acquisition and provision of quality insurance data and assumption of machine and handling system control tasks

Each group of 24 spindles is linked to a section computer which is linked to the Informator. Events and signals are exchanged between the section computer and the Informator. The spindles use a wireless communication system for contactless requests of the piecer carriage, package doffer, and for exchanging data with the piecer carriage. Based on the set of acquired data, in the event of dysfunctions, the Informator sets a flag to inform the spinner.

The Peyer CAQ concept is another example of interactive monitoring system applied to winding. Based on a standard IBM computer equipped with standard interfaces, open architecture and conversational mode, such a system has the following performance features:

> setting or modifying the setting of the operations by means of a nodal computer in an individual or grouped way, transferring all the setting parameters to the machine, storing the yarn quality characteristics and
> transferring these data to a higher level in the hierarchy.

Such a monitoring system is particularly suited for producing a variety of yarns. Setting is quickly and efficiently performed without any human intervention.

1.6. HOW TO DEVELOP PREDICTIVE MAINTENANCE

The development of predictive maintenance requires specific sensors which are really complicated. As said before, Corolab can be considered as a predictive maintenance device. Take for example the control of a nozzle in air jet spinning. The quality of the yarn is related to the injection air pressure in the nozzle and especially the variations of this pressure. On-line pressure checking is quite impossible because of the limited accuracy of manometers. But, the variations of pressure in the nozzle induce vibration frequency variations. So, the vibration frequency analysis will be equivalent to a yarn quality analysis. Such an analysis needs the following elements:

> an accurate accelerometer sensor, a high data acquisition speed and an on-line and real time spectrum analyzer.

There is no problem in performing such an analysis in a research laboratory. However, due to the costs of sensors and spectrum analyzer, and the complexity of this analysis, it is nearly impossible to equip each spinning position with such a device.

1.7. THE NETWORK

As no communication network standards are readily available in the spinning mill, the choice of a network is not easy for the spinner. Moreover, the different manufacturers do not use the same network and the same communication protocol. Consequently, buying equipment from several manufacturers forces the spinner to manage different kinds of incompatible networks.

Schlafhorst, Zinser © and Trützschler © have recently created Texnet ©, a standard network for spinning mills.

1.8. DATA TREATMENT AND EDITING

The monitoring system gives the spinner a very large amount of raw data which has to be processed to extract the information that needs to be highlighted. The monitoring system is able to deliver more than 200,000 basic units of information for 1,000 spinning positions. These data have to be written on the same media to be easily interpreted. All data are not simultaneously useful for the management of the spinning mill; so the data has to be sorted before being edited.

Only the few following specific reports have to be created: general production report, exception report and statistical analysis.

Considering the case of a running production, the exception report is the only useful one to move towards the "zero defect" concept. In the production of a new yarn, all information has to be collected and analyzed until the required quality has been reached. Then, exception reports are useful.

1.9. CONCLUSION

The monitoring system is an accurate and reliable tool for spinning mill management. But, as far as these monitoring systems are concerned, the most obvious disadvantage lies in an insufficient predictive maintenance. The gap will be filled by developing new measurement methods and new sensors. The development of such methods and sensors will be very long and very expensive.

It can be considered that the monitoring systems manage currently 80% of the spinner's problems. The addition of new sensors and methods to solve the other 20% shall cost 80% of the total cost of the monitoring system !

Another point has to be highlighted: the amount of data. Considering the amount of data and the complexity of the spinning production, use of a spinning KBES needs to be considered.

2. Knowledge-Based Expert System

2.1. INTRODUCTION

As mentioned in the first part of this chapter, the present management and control devices have increased their efficiency to such a point that a different kind of software is needed. The software must carry out analysis in relation to the different kinds of data (supplied by monitoring devices) so that it can help the expert in his/her own analysis.

The computer scientist has resorted to conventional data processing for a long time; however, limitations of this approach have forced the scientist to explore other techniques, specifically the application of KBES to solve the problem.

KBESs are making inroads into the framework of control and prediction within the spinning process. Before giving examples we define and analyse a KBES.

2.2. WHAT IS A KNOWLEDGE BASED EXPERT SYSTEM ?

Knowledge-based expert systems are sofware, designed to replace or rather assist humans in fields where human expertise is required. Such expertise is important because it is composed of a set of disparate methods; it can also be revised or supplemented with the accumulated experience. They belong to the field of artificial intelligence (AI) which aims at solving delicate and specific problems which require knowledge that is specific to a defined technical area. By simulating, with the help of a computer, what a human being would do where deterministic algorithms cannot be used, or would not be efficient, they make it possible to find a solution that is compatible with the state-of-the-art knowledge according to a strategy which leaves a certain intiative to the machine (heurism: from the Greek heuriskein = to find), Bonnet [1].

This definition allows us to highlight the different functionalities that such an efficient system should possess:

(i) The possibilty to easily acquire the "know-how", i.e., the system of knowledge representation should be as near as possible to the wording expressed by the expert.

(ii) A maximum utilisation of all the elements of the "know-how", i.e., it should be possible to combine and/or link sets of knowledge so that new kinds of knowledge could be deduced as well as new judgments, plans, evidences, decisions, predictions and new reasonings.

(iii) An easy alteration of knowledge and reasoning, i.e., to make it possible to easily alter the knowledge base in case of addition, alteration or suppression of knowledge.

(iv) Provision to explain the reasoning process when questioned.

The list of characteristics of KBES shows how important it is to acquire and represent easily the data derived from the expert and how important it is to be able to modify quickly the knowledge and reasoning. This desire for easy representation and modification led to different studies on the models of representation of reasoning as well as knowledge.

2.3. DATA REPRESENTATION

Within the frame of a KBES, two major types of representation have been developed:

(i) The declarative declaration

(ii) The procedural declaration

Each representation meets a specific question: "to know what" in the case of declarative representation and "to know how" in the case of procedural representation. Each representation has its own specific advantages and disadvantages:

Declarative-type knowledge: it has a simple syntax; it is easy to modify and it needs the procedure type knowledge at run-time. The set of the declarative type structure is generaly called "data structure".

Procedure-type knowledge: it has a rigorous and complex syntax and it is difficult to modify. The procedure type knowledge is used for the interpretation of the declarative knowledge.

2.4. COMPONENTS OF A KNOWLEDGE-BASED EXPERT SYSTEM

Schematically a KBES comprises an inference engine, which is a programme (and possibly an integrated circuit in the future) capable of moving from formal deduction to formal deduction by applying formal rules on symbolic facts and axioms so that a solution can be found (diagnosis or action). It is often independent of any application area.

There are three types of actions on the knowledge base:

(i) checking or questioning the validity of knowledge;

(ii) enriching the knowledge and

(iii) triggering off specific actions according to the state of knowledge; in general this entails alterations of the basic knowledge, particularly in the fact part, but occasionally in the rule part.

The knowledge that can be split into:

(i) a base of facts, comprising observed events entered by the user in response to system questions. Therefore, facts are knowledge which make it possible to describe specific situations either established, that is to say that they can be proved, or to be established that it is hypothetical or are to be reached. In some cases, to describe blurred or uncertain facts, a coefficient of likelihood can be attached.

(ii) a base of knowledge, comprising axioms ("trivial facts") which are always verified, rules and relations which can be applied to these axioms (IF <condition> THEN <action>).

The rules are operational knowledge which represent expert know-how in a specific application area. They indicate the consequences to be deduced and/or the action to be achieved or carried out when one or a combination of facts corresponding to an established situation or situation to be established, is faced.

The rule usually comprises three parts as shown in Figure 5:

a hypothesis denoted by H; a "triggering part" also denoted as "premise" or "left-hand-side"; which consists of P conditions; and a "right-hand-side" also denoted as "Q action part".

From a logical point of view, a rule can be defined as P => Q, i.e., if all the conditions of P are true, then H is true, and the action of Q can be effected.

The rules are generally of a declarative type, i.e., they can be readily understood.

(iii) a consultation module which is used to carry out the interaction. This module is also denoted as "the user interface". Natural language is used as far as possible. It can also integrate a set of sensors (in a case of an industrial application). It also enables the computer to communicate the result of the reasoning as a graphic display on the screen or pulse operating a relay. In most cases a KBES provides the user with the reasoning process, the objective to be reached and the rules that are applied.

(iv) a module of knowledge acquisition. This module is used to update the knowledge of the usable system.

(v) an explanation system, which fulfills the function of the help module.

The structure of a KBES is schematically shown in Figure 6:

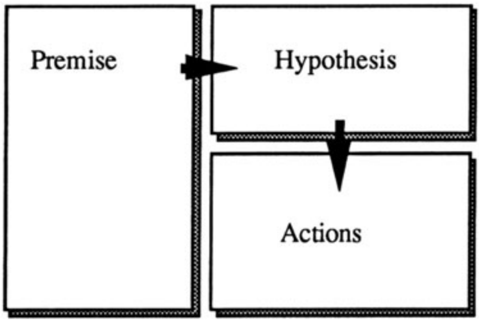

Figure 5. Rule architecture

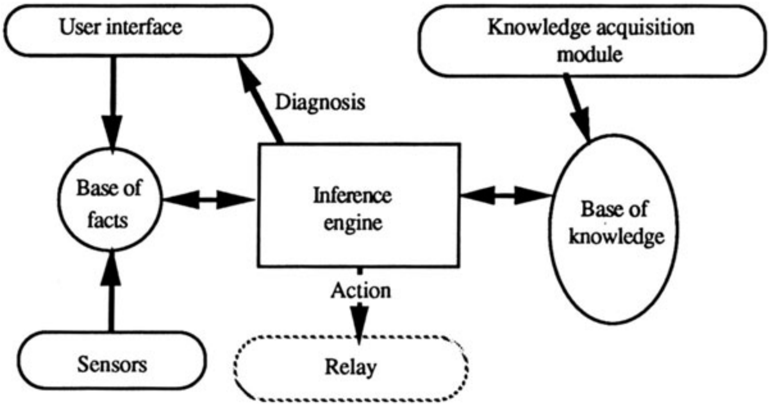

Figure 6. Structure of knowledge-based expert system

2.5. MODE OF REASONING

We now discuss the mode of reasoning in a KBES. The reasoning moves on through successive trial and error tests with a heuristic process, i.e., a non-deterministic partly intuitive process search of solution that might be compatible with the system of knowledge. The qualitative treatment prevails over the numerical calculation and may lead to several responses which are equally valid according to the fact that has been ascertained or the acquired knowledge or none.

Contrary to an algorithmic programme, KBES can

indicate the objective to which it tends (answer the question "why ?");
list the process of reasoning in progress (answer to the question "how ?");
enrich its base of knowledge as new experiments are carried on (learning).

In the same way as an expert is specialized in a specific area, most of the early KBES used to be specialized as well. But the current tendency is to develop KBES "shells" comprising an inference engine, a particular syntax to represent the rules as well as different tools of development so that the user interface can be constructed.

We now take a closer look at how an inference engine works as well as different types of inference mechanisms that define the power and the capacity of a KBES to closely match human way of reasoning.

The different existing inference mechanisms are derived from two principles of first order logic:

(i) the "Modus Ponens" which is based on the following statement:
If P => Q and if P is true, then Q will be true.
(ii) the "Universal Specification" is based on the following statement:
If R(x) is true whatever x may be, then R(a) will be true.

2.6. INFERENCE MECHANISM

The inference engine successively examines the basic rules of the knowledge base. The inference process can be guided either by a fact that has been observed (forward chaining) or through the objective which is being looked for (backward chaining).

2.6.1. *Forward chaining.* A forward chaining (or saturation deduction mechanism) denotes the process which starts from the facts to be reasoned with (the data of the problem) to deduce conclusions (diagnosis or actions to be launched). Most of the time this scanning is effected in depth. As seen before, a rule can be represented by an expression of the type "P => Q" and the inference engine which works in pure forward chaining proceeds along reasoning which says that if P => Q and "if P is true", then Q will be true.

The programme looks for the rule RULE1 whose premises are indentical to the fact; the conclusion triggers off looking for the rule RULE2 whose premises are indentical to the previous conclusion until progressively all the rules contained in the base are exhausted.

"Security software" tracks the rules which are used, so that risks of infinite loops are avoided.

Before all the rules have been explored, the inference engine stops the process and displays the result or concludes with an exhaustion failure.

The different stages during the inference cycle are as follows:

selecting a sub-set of knowledge-base;
comparing the premises of the selected rules with the fact (filtering);
choosing the rule to be effectively applied;
applying the rule, modifying the base based on the conclusion of the rules and deactivating that rule, etc.

The advantages and disadvantages of such a forward chaining system are as follows:

the inference engine cannot question the user during the cycle;

quick response: it does not use a lot of memory, the hypothesis to be checked is not stored;
monotonous: the value of the hypothesis can only be evaluated once;
irrevocable: the choice of releasing a rule is irremediable and if the way that has been covered in the tree does not lead to any solution, another one cannot be covered.

The problem of irrevocability can be resolved by applying a variance of forward chaining called "Strategy by attempts" which allows the system, in case of failure, to use a rule that has been previously discarded.

2.6.2. *Backward chaining*. Backward chaining aims at verifying the hypothesis or target by comparing it to the facts. Typically, the search is breadth-wise.

From a hypothetical conclusion, CIBLE, the programme moves through the base of knowledge to look for the rules whose conclusion is equal to CIBLE. These rules involve CIBLE 1 premises which the inference engine compares to the real facts. The process is repeated until all the premises of the CIBLE N rule and real facts are identical or sufficiently similar. At that moment, the inference engine stops working and displays the results, failing which, it concludes with an exhaustion failure.

The engine therefore tries to establish that a Q hypothesis is true, and so it reasons as follows:

it looks for all the "Q => P" type rules;
it evaluates all the P hypotheses and for those whose true value is not established,
it looks for the "R => P" type rules and then evaluates R and so on and
if R is true, then P is true and consequently Q is also true.

At each level, the inference engine selects the rules depending on their conclusion by covering a cycle whose stages are the following:

selection of a subset of the base of knowledge among active rules;
comparison of the conclusion of the selected rules with the hypothesis to be tested (filtering) and
comparison of the premises with the observed fact (application of rules). If the difference is big, there is an alteration of the target in relation to the premises, the questioning, etc.

It is a mechanism which uses a lot of memory space; the increase of the evaluation tree is exponential. It presents a risk of memory explosion in the case of P =>Q, Q =>R, R=>P type rules. It is revocable and monotonous.

2.6.3. *Mixed-chaining*. An inference engine combining both forward and backward mechanisms works in a mixed-chaining procedure. It is a mechanism which has the same memory problems as backward chaining; it is revocable. Conversely, it is non-monotonous, that is to say, the value of a hypothesis can be questioned again.

The system agrees upon a CIBLE from which it tries to implement a backward chaining; meanwhile it undertakes a forward chaining from the observed fact. The overall process stops as soon as search moves to the same rules or failure.

2.6.4. *The working cycle of an inference engine.* Whatever the type of chaining, the inference engine follows a working cycle which comprises two phases: the evaluation phase and the execution phase.

The evaluation phase comprises three stages:

(i) The "selection" or "restriction" stage, which determines from a stage of the base of knowledge, on F1 sub-set of the base of facts as well as an R1 sub-set of the base of rules which after initial analysis deserves to be compared during the following filtration stage.

(ii) During the filtration stage, the inference engine compares the releasing part of each R1 rule to the F1 set of facts. One of the R2 sub-set collects a rule whose release condition has been satisfactory, owing to the different criteria according to the system through the state of F1. R2 is denoted as "a set of conflict".

(iii) During the last stage of the "resolution of conflict", the inference engine determines a rule to decide which of the R3 or R2 subsets should be effectively released. If R3 is empty, the cycle will not comprise any execution phase. According to the different systems there are different criteria for resolving the conflict. For example, the first n rules of an arbitrarily ordered list are selected, or preferentially the rules that have been mostly used are selected, or those which are assessed to be the least complex (fewer conditions to be checked, few variables to be fixed before releasing the procedure; sometimes, the option is based on criteria which are likely to take into account the meaning of the rules in relation to the application context (criteria of preponderance, reliability or cost).

During the *execution phase* the inference engine controls the implementation of the action defined by the R3 rules. The procedure to be used when R3 comprises more than one rule can be different from one engine to another.

2.7. NOTIONS OF STRATEGY

One of the following classical search strategies can be superimposed on these different types of rule invocations, Rich [3]: strategy in "depth first"; strategy in "breadth first"; or strategy of "ordered research". The set of rules can be shown as in Figure 7:

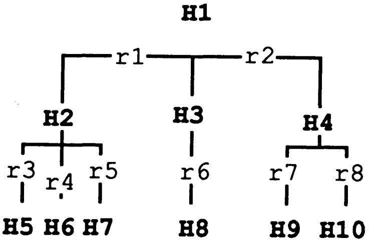

Figure 7. Notions of strategy

The strategy of "depth first" search consists in evaluating H1,H2,H5,H6,H7 then H3,H8 and finally H4, H9, H10. The search strategy in "breadth first" consists in evaluating H1 then H2, H3, H4 and finally H5, H6, H7, H8, H9, H10. The strategy of ordered research consists in evaluating the hypothesis according to a pre-defined order or according to specific criteria.

2.8. THE IDEAL KNOWLEDGE-BASED EXPERT SYSTEM IN SPINNING

We have just seen the contents of a KBES and the different methods of reasoning. Let us now apply these different types of knowledge to formulate what should be the ideal KBES in the spinning area. Let us first define the different sectors in which a KBES can be developed, and see what its functions would be. To do so, two lines can be envisaged, one deriving from a descending analysis of the process (starting with the product one wishes to achieve downwards to its components) the other one an ascending analysis (starting with the raw material up to the final product). Either method is going to highlight the need for KBES at different stages of the process (from the choice of components to manufacturing, from the control of the process to product and its further use).

2.8.1. *Ascending analysis of the process in spinning*. The spinner's reasoning is shown in Figure 8. It is clear that, not one but several KBESs are needed at each decision stage of the spinning process and even of the overall process of transformation.

Knowledge-based expert system 1:
This system would be used to determine the most appropriate spinning process for the fibres, or fibre blend, desired by the industrialist, by providing the different technical adjustments of the process and the resulting physical and mechanical properties of the obtained yarn. Currently, there are KBESs which enable the first defined function to be achieved, and one of them is discussed later.

Knowledge-based expert system 2:
This system will use the characteristics of the produced yarn to indicate the different problems which took place during the spinning process as well as to show the causes and possible remedies. The system is far from being utopic and an application is currently being performed in our laboratory.

Knowledge-based expert systems 3 and 4:
In relation to the characteristics of the obtained yarn, the KBES puts forward the different types of textile transformation (knitting, weaving) and in relation to the characteristics of the transformation (pattern), it defines the characteristics of the final product.

2.8.2. *Descending analysis of the spinning process*. In the case of a descending analysis of spinning process other KBESs come up with many other functionalities (however, quite similar to the previous ones).

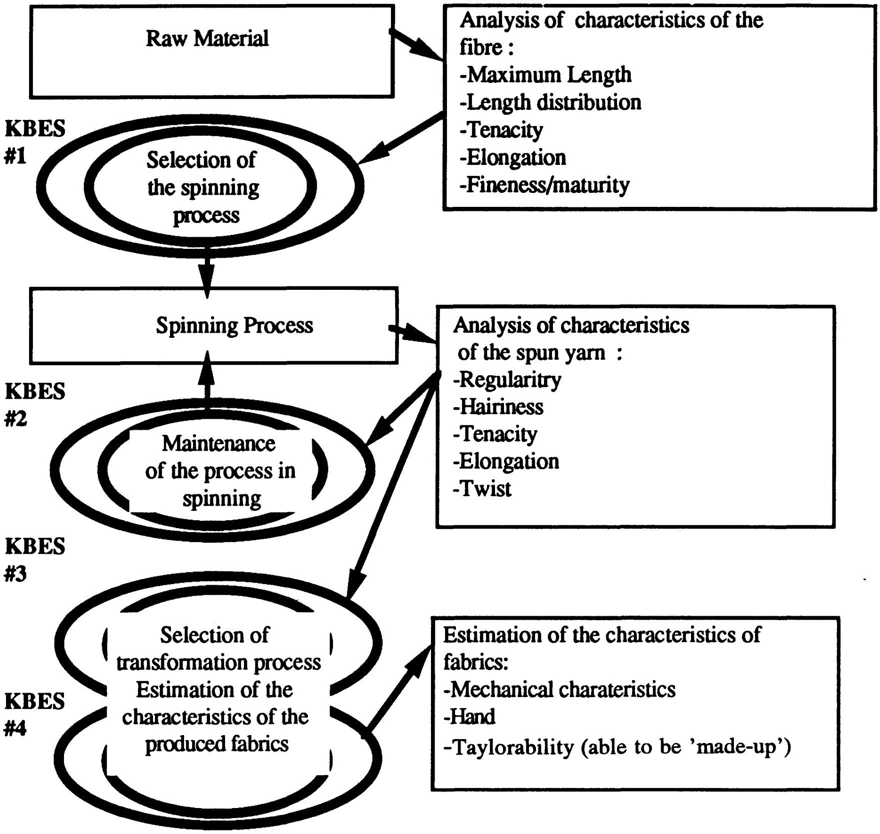

Figure 8. Ascending analysis of the process in spinning

Knowledge-based expert system 1:
This KBES utilizes the characteristics of a product (fabric), to define the spinning process as well as the raw material to be used. For the time being, such a system is more or less an utopia but it would be the most rational approach to the product in terms of product analysis.

Knowledge-based expert system 2:
This KBES utilizes the characteristics of the fibres and of the different spinning processes to determine the adequate spinning lines as well as the different technical adjustments which are to be made to this line.

Knowledge-based expert system 3:
This system is meant to control the quality of the spun product in relation to the

characteristics of the spun yarn. It should be able to determine and locate the different causes of a defect.

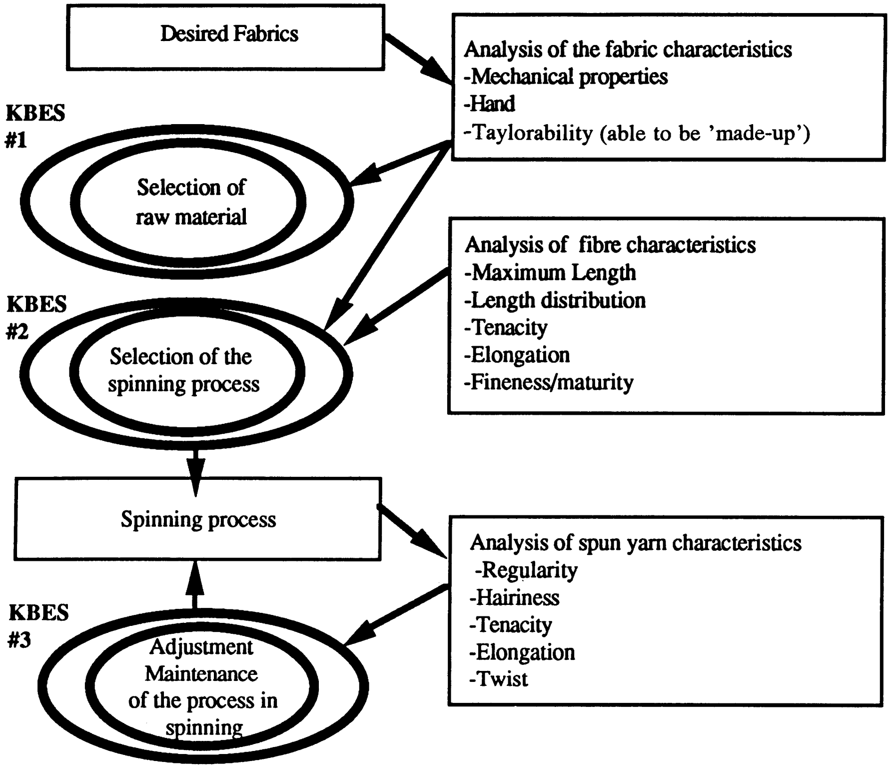

Figure 9. Descending analysis of the process in spinning

We have just seen the different types of KBES which might come up in the spinning process. These analyses are not exhaustive and some other KBESs could be developed in the spinning process. Some of them are still utopia, but others have already been built and validated, and some are already being marketed.

2.8.3. *Other knowledge-based expert system already in industrial use.* It is quite clear that we have moved onto the aspect of manufacturing techniques. Within the frame of CIM (Computer Integrated Manufacturing) a more complex data processing set including production management, cost calculations, material management, product and material management should be found in any firm. This set should obviously include an already-existing KBES. The connection between the different manufacturing and management systems should bring about additional strength to the company. We shall now move onto the question of building a KBES.

2.9. IMPLEMENTATION OF A KNOWLEDGE-BASED EXPERT SYSTEM [2]

Based on the type of system being developed, the analysis of the domain and the construction of a KBES can be entrusted to an individual who is in charge of the expertise and who is sufficiently trained and has modern tools (overall system) at his/her disposal or to a team (an analytical system) composed of: one or more specialists; a knowledge engineer and a programmer specializing in different AI languages and tools

2.9.1. *Overall system.* This is the latest solution and it has been favoured by the appearance of KBGS (knowledge-based system generator software) which are more and more friendly. It is quite clear that a specific and rather good training used to be necessary so as to handle such tools. The advantage of such a system is that it is quite easy to implement; a single individual can perform all functions. Its main disadvantage is the non-optimization of the product implementation as the KBES might not be performing as fast.

In addition, not having a third person (knowledge engineer) working on rephrasing the reasoning mode of the expert may result in not taking a part of his/her reasoning into account and thus depriving the model of a big part of the expertise.

This approach can not only be adopted for building a simple KBES but can also appear as an acceptable compromise for a first approach to the problem, particularly for a small or medium sized company that might be afraid of the cost of developing quite a big KBES and which has a top level specialist at its disposal for a few months on the basis of an industrial contract.

2.9.2. *Analytical system.* Development of an application according to this method means following the steps shown in Figure 10.

Let us analyse the detailed stages shown in Figure 10.

Stage 1:

First of all, the users are to fix clearly the target to be reached. These include:

assisting the expert to carry out his task by supplying him with a first approach (help for decision making);

spreading the expertise (training KBES);

automatically controlling an industrial process;

assisting the expert to work the empirical practices.

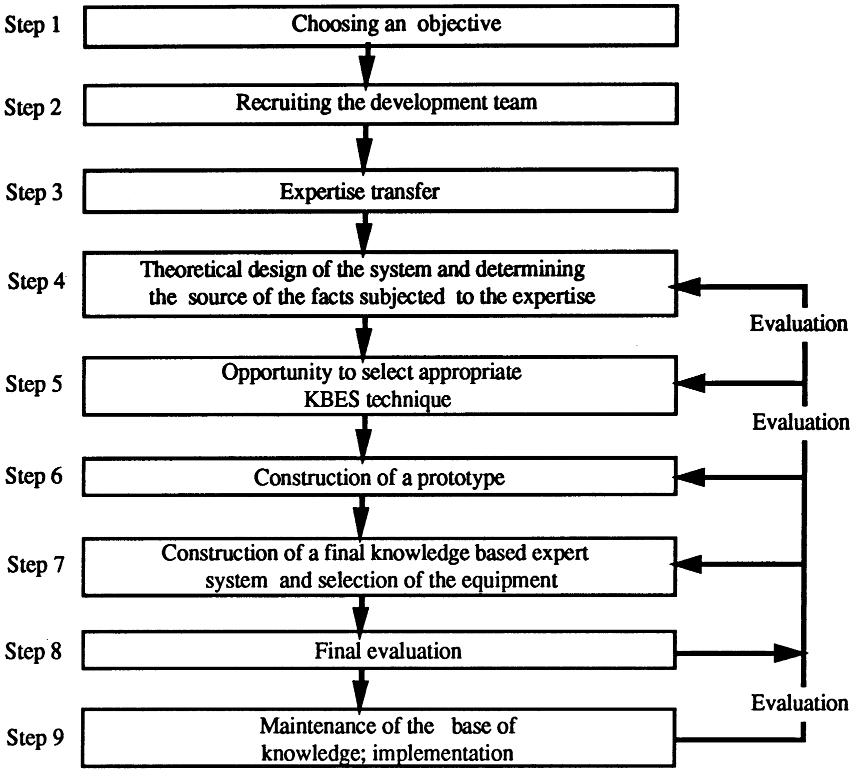

Figure 10. The different stages in designing a knowledge-based expert system.

Stage 2:
Recruiting the development team:

This stage, which proves more and more indispensable, is essential for developing application of a certain volume, and to reduce the total time for the development cycle.

The expert is selected according to his/her know-how (reasoning strategy, selection of adequate questions, etc.) than because of the scope of his knowledge. He/she adapts his reasoning strategy to the problem which is actually posed. He/she reasons logically in spite of testing all the hypotheses. He/she looks for the links of causality between the facts which are certain and not only the plausibility coefficients.

The knowledge engineer is both a psycho-sociologist well-versed in the art of making the expert speak and a computer scientist specializing in AI tools.

Stage 3:
Transfer of the expertise:

This involves the crux of the matter of the expert because he/she is the one that determines the field of the base of knowledge and the key concepts. He/she formalises the rules by focusing on the crucial concept and shapes the conclusion.

It should be noted that the transposition of a specialist know-how in a KBES cannot be reduced to a simple computer knowledge canning. The exchange between the expert and the knowledge engineer is often difficult because of the expert mode of reasoning. The role of the knowledge engineer, during this stage, is to help the expert communicate his know-how. This is one of the most delicate tasks for the knowledge engineer and for the expert: one has to know how to make the expert speak without inhibiting him, the other must analyse his reasoning which is often intuitive, so as that transcription of this one by the knowledge engineer can be possible. The knowledge engineer has the expert to analyse and reword all the sets of his method of reasoning as well as his intuition, innuendo and the different kinds of knowledge which are the bases of his conclusion (diagnosis) or his action.

In this phase, it is highly recommended to follow an expert in order to fully understand his method of reasoning.

Stage 4:

Theoretical design of a system and determining the sources of the fact which are subject to an expertise.

The present stage is that of the transfer of the expert knowledge to its computerized form. This is the role of the knowledge engineer, naturally assisted by the expert. The expert, after a worded interview, describes the nature and the origin of the facts to be reasoned and defines the proper means to acquire them:

the inside of the computer structure (ratio, statistical calculation, etc.);
manual, vocal data acquisition, with the help of a scanner, etc., so that the expertise can be properly captured;
acquisition by the real time system (detection, automatic diagnosis, etc.).

Stage 5:

Test of opportunity to select appropriate KBES methods; from the different types of knowledge described by the expert, the knowledge engineer will be able to determine the type of inference engines to be used by taking into account the expert's mode of reasoning; the structure of the knowledge; the target to be reached and the computer constraints.

Once the inference engine has been chosen, the knowledge engineer translates the processes covered by the expert into the syntax imposed by the chosen sofware. Then he/she tests the validity of his/her option on any simple example.

Stage 6:

Construction of a prototype:

This phase involves the knowledge engineer that decided the type of KBSG or the type of inference engine to be used. He/she builds a prototype comprising a reduced base of knowledge, so that the prototype can be tested. At this level, the selection can be re-evaluated.

Stage 7:

Construction of a KBES and selection of the equipment:

This is the most costly stage, and it cannot be easily started. Once the equipment has been bought, the knowledge engineer builds the KBES. As for the expert, he/she supplies a first set of tests and evaluates the answers that have been supplied by the system.

Stage 8:

Final evaluation:

The final evaluation is meant to see how much the objective initially assigned to system has been achieved. It aims at reducing the gap by improving the system. It is cleverly carried out by groups of human experts.

Stage 9:

Maintenance of knowledge base, implementation:

Implementing a KBES does not put an end to the job of the team whose role is to maintain the base of knowledge. When compared to other computer applications, a KBES has the advantage of being permanently maintained and it is the expert that will be in charge of maintaining it.

2.10. KBES USED IN SPINNING MILL [4]

Only a few KBESs are sold in the spinning area. One of them is the "COROSULT©" system implemented by Schlafhorst.

The system is meant to choose, for the Autocoro© spinning line, the optimum spinning element which allows the industrialist to obtain "good yarn" in relation to the raw material.

The COROSULT system was developed with the IBM software (KBGS) ESE -Expert System Environment and it runs on the 3090 IBM family. The full automation of "Open End" spinning with the Autocoro spinning line has led to an increase in implementation of OE spinning lines in mills.

The characteristics of OE yarn can be determined by few elements as: the inside lining of the rotor; the surface of the rewinding buses and the torque-stop. The influence of the spinning elements on the characteristics of the yarn can be reproduced. Then, with the OE spinning line, it is possible to produce a yarn with specific characteristics in relation to its final use. For these reasons, it is essential to specify the optimum spinning element, to obtain a better quality yarn.

COROSULT can be consulted by means of a dialogue display on a screen. This dialogue is determined by the user's questions and introduction. Although this application is implemented under ESE on the IBM 3090 family, just interrogating the system can be done on an IBM PC family computer.

ESE is a KBSG, comprising an inference engine, a base of rules and a base of knowledge. Schlafhorst's experts fill the biggest part of the base of knowledge and the base of rules; these bases reflect the actual state-of-the-art in rotor spinning area.

A typical consultation session with COROSULT may be as follows:
COROSULT's user identifies himself or herself with: spinning line characteristics (number of heads) and the intended use of the yarn which will be produced (weaving, knitting).

For a specific end use COROSULT indicates what kind of yarn must be produced. In fact, the knowledge base "knows" few of the final uses and the characteristics of the appropriate yarn.

The user can indicate his own yarn characteristics: hairiness; regularity and strength.

The user indicates the raw material: type of fibres; blending ratio; fibre properties (fineness, fibre length) and maximum speed of rotor.
The COROSULT utilizes the user's data to return: the breaker lining; rotor geometry and rotor lining.
The user indicates the mass per length unit of the yarn, COROSULT returns the rotor diameter;

The user gives the mass per length unit of the sliver ribbon, COROSULT computes: the drawing range; number of fibres per area and the critical area and in relation to all these data, COROSULT determines the optimal rotor diameter.
COROSULT proposes three different degrees of quality, once a degree is chosen by the user, COROSULT proposes, based on all the data acquired, a first choice of spinning elements.

This prototype KBES has been working for 250 working hours on the shop floor and it is in its validation period. This validation is being done in Schlafhorst all over the world.

The maintenance of the knowledge base, is done by "COROSULT Redaction", from the Schlafhorst International Expert.

3. Conclusion

It is clear from the earlier discussion that KBES technology has potential in the spinning area; however, one of the systems still remains in its validation phase. The practical example shows that this kind of system and application are in perpetual evolution; this research field is full of promises in terms of product analysis and optimisation of processes.

The future CIM spinning mills will utilize IA tools and knowledge-based systems. The link between all these tools will be carried out by means of industrial networks.

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MECHATRONICALLY DESIGNED MAGNETIC BEARINGS FOR HIGH-SPEED SPINDLES AND ROTORS

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Abstract: Contact-free Magnetic Bearings are a typical mechatronic product, and they have some distinct advantages. They do not generate wear and they do not need lubrication. Therefore, they have a potential for long lifetime and low maintenance costs. These features make them attractive, among other applications, for textile machinery.

This chapter presents the state of the art for the design of an electromagnetic bearing system. It introduces first the main elements and then discusses control and system aspects. The characteristics of such a suspension system are detailed. Several applications will be demonstrated, and future trends are indicated.

Key words: Magnetic bearings, design of magnetic bearings, application of magnetic bearings, mechatronics

1 Introduction

Contact-free electromagnetic bearings are a typical product of mechatronics. Together with mechanical components they contain electronic elements like sensors and power amplifiers, a controller realized for example by a microprocessor and an increasing amount of software, which in the end determines their "intelligent" operation. The growing availability and integrability of these elements make the magnetic bearings more and more attractive for solving classical bearing problems.

The principal advantages of a magnetic suspension are that it works without any contact and that the controlled dynamics of the bearing forces can be adjusted to serve various needs. And, of course, the absence of wear, the potential for a long lifetime and for low maintenance costs are most welcome properties for applications in textile machinery. On the other side, however, the magnetic bearing is complex, still expensive, usually not readily available from the shelf, and up to now only used for some advanced machinery. In the following the state of the art is presented so that future trends can be derived.

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Magnetic forces are generated either by *permant magnets, electrodynamically or electromagnetically*. These physical principles differ in their technical applicability. In the constant field of *permanent magnets* a ferromagnetic body cannot hover in a stable way, which has been shown by Earnshaw and Braunbek already /EARN 42, BRAU 39/. *Electrodynamic forces* are usually too small or still too difficult to generate to be of actual technical interest, and magnetic forces generated by High-Temperature Superconductors are at this time still not yet feasible for actual applications /MOCH 90/.

It is the *electromagnetic field* that is used most efficiently. Using this principle for the levitation of guided vehicles a technology of its own has been developed /GOTT 84, ABE 89/ that basically, of course, has some connections to magnetic bearings for rotors, too. Rotors had been supported magnetically at first for physical experiments. Spectacular 18.000.000 rpm (300 kHz) have been reached while testing the strength of small steel balls under a centrifugal field of 20.000.000 g /BEAM 46/. Since then the electromagnetic rotor bearing has been applied to solve a number of different technical problems, and therefore the construction and the properties of the bearings differ remarkably. Numerous patents in this field have been issued or are pending, surprisingly few, however, with respect to textile machinery. A survey on the actual range of application was given by the First International Symposium on Magnetic Bearings /SCHW 88/, which took place at the ETH Zurich in June 1988. Application areas in aerospace, physics, robotics and in industry have been demonstrated at that symposium. The Second International Symposium on Magnetic Bearings was at Tokyo University in 1990 /HIGU 90/, and the third one is being scheduled for Washington in the summer of 1992. A textbook on magnetic bearings will be published in 1992 /SBLT 92/.

Subsequently, first the functional principle, design goals, and the elements of the bearing will be explained, and in the end some applications will be presented and future trends will be discussed.

2 Functional Principle

Fig. 1 shows the principle of the magnetic suspension: A sensor measures the deviation of the hovering rotor from its reference position, a microprocessor working as a controller uses these sensor information for deriving a control signal. This control signal is amplified by a power amplifier and fed as a control current to the coils of the magnetic actuator, causing magnetic forces to act on the rotor in such a way that it remains in a predefined and stable hovering position. When the shaft for example starts to fall down it produces a measuring signal which leads to an increase in the control current and thus the increasing magnetic force attracts the shaft again. Without the feedback the shaft would either fall down or be attracted by the magnet. The control law has to take care of the stability and of the dynamic properties of the hovering state. By choosing a suitable control law the dynamics of the suspension can be adjusted to a wide range of requirements, concerning especially the dynamic stiffness and damping.

A technical rotor, of course, needs several of these bearing actuators for a full suspension, and they have to be interconnected by a multivariable control. Fig. 2 shows an example for the radial magnetic support of a rotor. For each degree of freedom a magnetic actuator has to be controlled individually. The control signals, however, depend on one another, i.e. each bearing will in general depend on all sensor signals. The axial suspension of the rotor is not shown here, its control is decoupled from the radial one and can be dealt with separately. The basic properties of the magnetic suspension, leading to various dominant application areas, will be discussed in the next section.

3 A Simple Example - Suspension of a Rigid Body

Let us first look at the suspension of a simple rigid body, and how a classical suspension by a spring compares with a magnetic suspension /SBLT 92/. Fig. 3 demonstrates that the restoring spring force f_s increases proportionally to the displacement x_s. The point of equilibrium x_0 is reached when the weight mg is balanced by the corresponding spring force. The magnetic bearing works somewhat different. The magnetic force f_m depends on the displacement x_s and the current i_m through the coils of the actuator. Fig. 4 shows that the magnetic force decreases proportional to the inverse of the square of the displacement, except for very small airgaps, where the magnetic force is limited by magnetic saturation. Obviously such behaviour does not allow a stable positioning of the body, and each child can experience that when playing with a permanent magnet. In our case, however, we still have the current to counteract that destabilizing effect. Fig. 5 shows that the force of the electromagnetic actuator increases with the square of the current, as long as there is no saturation. The slope of the force-displacement function (positive for the spring, negative for the magnet) decides on the stability of the equilibrium position. This slope is called *stiffness*, for an uncontrolled electromagnet we talk about "*negative stiffness*". The equilibrium position is often called "operating point" of the magnetic bearing. Here the airgap x_0 and the curent $i_m = i_0$ are defined as such. For the design of a controller it is sufficient to look at the linearized relations around the operating point A (Fig. 6). In that case we need to define new variables, the deviations from the operating point, for the control current i and the displacement x

$$i = i_m - i_0 \qquad\qquad x = x_0 - x_s \tag{3.1}$$

For characterizing the linear relations two factors are introduced (Fig. 6). The slope of the $f(i)$ function is called *force-current factor* k_i, the slope of the $f(x)$ function is called *force-displacement factor* k_s /SCLA 76/. With these definitions the *magnetic control force* can be expressed as

$$f(x,i) = k_s\ x + k_i\ i \tag{3.2}$$

Of course, the accuracy of the relation decreases with the distance from the operating point. For a practical control design, however, it is sufficient. For limiting cases like a vanishing gap ($x = x_0$), saturation through high current, or for a vanishing current ($i = - i_0$) it will be of no use.

For the beginning let us design the *control* of the magnetic bearing with the properties of a simple, classical spring-damper suspension.(Fig. 7) Therefore, we expect the force to be

$$f = -kx - d\dot{x} \tag{3.3}$$

with the stiffness k, the damping d and the displacement velocity $\dot{x}$. That means that we have to design the controller and amplifier such that the magnetic force has the characteristics of (3.3). Equaling equs. (3.2) and (3.3) leads to the desired relation for the control current

$$i(x) = \frac{(k + k_s)\,x + d\dot{x}}{k_i} \tag{3.4}$$

If everything goes right, i.e. if the model and the parameters are correct, then the two systems of Fig. 7 have the same load charactistics, and the mass is hovering. The behavoiur of the closed loop can be analysed easily. The control plant "hovering body" with output x and input f is described by Newton's law

$$m\ddot{x} = f \tag{3.5}$$

Introducing (3.2).into (3.5) and rearranging we have

$$m\ddot{x} - k_s x = k_i i \tag{3.6}$$

In this expression the negative stiffness is obvious, and therefore for vanishing control current i the solution of (3.6) will be unstable, i.e. any disturbance will lead to an increasing displacement x. By means of the controller the current i is shaped in such a way that the displacement from the equilibrium position will remain bounded even under a disturbance. This can be seen by introducing (3.4) into (3.6) which will lead to the *closed loop equation*

$$m\ddot{x} + d\dot{x} + kx = 0 \tag{3.7}$$

having in our case the same solution as the spring-damper suspension.

The *differences between active and passive bearing* are the following

- the active suspension is with *no contact* at all. It can be realized as shown, stabilizing just the one degree of freedom in vertical direction, the lateral motions are passively stabilized by the attracing magnetic forces
- *"free" choice of stiffness and damping*. If, for the classical case, the stiffness of the spring constant is changed, the equilibrium position x_0 changes simultaneously. This is not true with the active case: the stiffness can be chosen without changing x_0. Damping can be adjusted in a wide range, too, even during hovering, or for example depending on some operating conditions
- the *operating point* x_0 can be adjusted through the control electronics independent of the stiffness

- by a suitable control (PID-control) the operating point can be kept constant even when the *load changes*. This is not possible for a classical suspension
- further advantages are in *vibration compensation* for unbalances of high-speed rotors, in vibration isolation, *monitoring*, *diagnostics*, and integration into overall process control.

The control current (3.4) can be written as

$$i = P\,x + D\,\dot{x} \tag{3.8}$$

with two components, the "Proportional" part P responsible for stiffness, and the "Differential" part D for damping. The parameters P and D for such a PD-controller are determined by the choice of stiffness k and damping d.

It is worthwhile to have a closer look at the behaviour of the control under the influence of disturbances. If the load suddenly changes by some amount Δf_{load} the hovering mass reacts by changing its position by a corresponding amount $\Delta x = k\,\Delta f_{load}$, actually like a spring suspension. This setoff can, however, be compensated by a command-input, which on the other side would not be possible for a spring suspension. With a socalled integrating feedback it is even feasible to continously and automatically compensate the setoff. This *PID control* (Proportional-Integral-Differential) is shown in Fig. 8. The time-behaviour is demonstrated in Fig. 9, showing the transitional displacement after a step disturbance. Using a PID-control the displacement remains zero after the transitional motions have damped out. This can be interpreted as an "infinite" stiffness as the active bearing does not give in to a stationary load, a behaviour impossible for a conventional bearing.

The "infinite" stiffness is obtained with respect to static loads, but for time-varying loads the bearing will behave differently. This implies that the stiffness has to be regarded as a function of frequency, as a *dynamic stiffness*. The actual design of the PD or PID controllers most often are done in the frequency range, leading to a *frequency response* for amplitude and phase.

Before describing the elements of the control loop in more detail, some aspects of the overall design concept /SCHW 90/ will be discussed.

4 Design Concepts

Magnetic bearings contain mechanical and electronic parts and software, being a typical "machine element" of this mechatronic product. To warrant a good interconnection between these elements a modular design, at least conceptually, with well defined interfaces is essential. The elements, as can be seen from the block diagram of the control loop in Fig. 2, are the rotor with the bearing sleeves, the sensors, the signal processing unit and the controller, the power amplifiers, and the magnetic actuator itself. It is useful to conceive each element as an input/output element, as this facilitates the integration into the control loop. And the design of the control law will certainly be facilitated, if the various elements have linear characteristics. A strictly modular approach has several advantages. The design process can be split up into different groups, where specialists can optimize the elements. Error localization, the replacement of faulty parts, and the reliability management is facilitated, too. The adaptability to customer needs will be better and options can be offered more easily. You can increase the advantages of this modularity by using suitable software which can help to interface the modules and which facilitates modifications. And this aspect is closely related to the concept of digital control, that will be discussed next.

The choice betweeen digital and analogue control is part of the design concept. There are a number of positive factors that speak for digital control:

- It is easier to implement sophisticated control, like start-up procedures, disturbance rejection, filtering of sensor signals, or adaptive control.
- Redundancy management, diagnostics, and exception handling can be added as "intelligent" features to increase reliability and safety.
- The software will be structured in modules, and as modifications most often only mean the change of data and not the program itself the design process will be faster, too.
- The interconnection of the magnetic bearing to the whole machine and its process is definitely facilitated. For example, the cutting forces of a milling process, depending on cutting speed, tool, feed and material, can be measured easily in spindles with magnetic bearings, and the data can be used on-line for the process control, optimizing the overall operation of the machine.

The costs for software are high, but they can be reduced by multiple use of it, and the hardware costs for fast microprocessors or custom chips, eventually directly coupled to power amplifiers, will probably continue to decrease in future.

As to future trends an outlook may be permitted. A next generation of magnetic bearings may have a much higher level of hardware integration of the elements of the control loop, thus reducing the degree of modularity. There may be custom-made power elements with integrated control logics. On one side such a development would require large production series, on the other side it could lead to very economic solutions.

5 Elements of the Magnetic Bearing System

The magnetic suspension of a rotor is a wellplanned interconnection of various elements, it is a system /SCHW 88a/. The elements, the rotor, the sensors, the controller, the amplifiers and the magnetic actuators have to be specified with respect to their tasks within the control loop. Their main characteristics will be presented in this section, emphasizing the most prominent element, the magnetic actuator.

5.1 Model of the rotor

The rotor obviously is the central part of the suspension system and it has to be modeled as the plant within the control loop. Let us assume that the rotor is rigid. Elastic rotors will not be dealt with here, their modeling and control exceeds the introductory level /SITR 89, LARS

90, LAST 92/. The rigid rotor of Fig. 10 shall be kept in its reference position by two radial bearings and of course an axial bearing. The axial suspension with one degree of freedom is decoupled from the radial ones, it is quite similar to the example of section 3 and will not be dealt with here. The radial displacements are expressed by the "analytical" coordinates for the translation of the center of gravity x,y and the inclination of the rotor α,β. The geometry is given in Fig. 10, the mass of the rotor is m, the inertia terms of the symmetric rotor are I_x, I_z, its rotation speed is Ω, any unbalance is small. Then the linearized equations for the radial motion z are obtained as

$$M\,\dot{z} + P\,\dot{z} + S\,z = B_f u_f + V_f s \qquad z = [\beta, x, -\alpha, y]^T \tag{5.1}$$

The vector u_f contains the bearing forces

$$u_f = \left[f_{ax}, f_{bx}, f_{ay}, f_{by}\right]^T \tag{5.2}$$

The harmonic disturbances by unbalance are introduced by the vector

$$s = [\sin \Omega t, \cos \Omega t]^T \tag{5.3}$$

The structural matrices for mass, gyroscopic effects and stiffness are

$$M = \operatorname{diag}\left[I_x\; m\; I_x\; m\right] \;,\; P = I_z\,\Omega \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \;, \qquad S = 0 \tag{5.4}$$

The gyroscopic matrix P is proportional to the rotational speed Ω and the axial moment of inertia I_z. It is the only matrix coupling the two lateral directions (x, β) and (y, α) with each other. The matrix S describes all position dependent forces exept the bearing forces, and it contains pendulous forces and small coupling forces to the axial suspension which may be neglected here. Matrix B_f introducing the bearing forces consists mainly of the sign-valued coordinates a and b for the bearing locations. And the matrix V_f for the unbalance effects contains the products of inertia I_{xz}, I_{yz} and the excentricity e of the centre of gravity C from the (magnetic) rotor axis.

$$B_f = \begin{bmatrix} a & b & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & a & b \\ 0 & 0 & 1 & 1 \end{bmatrix} \qquad V_f = \Omega^2 \begin{bmatrix} -I_{yz} & I_{xz} \\ 0 & me \\ I_{xz} & I_{yz} \\ me & 0 \end{bmatrix} \tag{5.5}$$

It is usefull to express rotor displacements z in terms of the measured displacement signals z_s from the sensors by

$$z_s = \left[x_c, x_d, y_c, y_d\right]^T = T\,z \quad , \quad T = \begin{bmatrix} c & 1 & 0 & 0 \\ d & 1 & 0 & 0 \\ 0 & 0 & c & 1 \\ 0 & 0 & d & 1 \end{bmatrix} \tag{5.6}$$

This can be substituted into the equations of motion in order to express them in the measured variables z_S as well. Furthermore for control purposes it is appropriate to use the state space representation

$$\dot{x} = A\,x + B\,u_f + V\,s \quad , \quad x = \left[z_s^T\,\dot{z}_s^T\right]^T$$

$$A = \begin{bmatrix} 0 & E \\ 0 & -T\,M^{-1}\,P\,T^{-1} \end{bmatrix} , \quad B = \begin{bmatrix} 0 \\ -T\,M^{-1}\,B_f \end{bmatrix} , \quad V = \begin{bmatrix} 0 \\ -T\,M^{-1}\,V_f \end{bmatrix} \tag{5.7}$$

In this representation the input of the rotor, i.e. the controlled bearing forces u_f are connected to the output, the measured displacement signals z_S. This state space representation allows to make use of standard techniques for the control design /SCHZ 76, ACKE 83/. More about the dynamics of rotors and its modeling is to be found in /GAPF 75, SBLT 92/.

5.2 Sensor, controller, amplifier

The *sensors* have to measure the rotor motion. The quality of the measurement is essential for the quality of the suspension. The main requirement is that there is no drift of the zero output. The resolution is directly connected to the positioning accuracy of the rotor, i.e. when the rotor has to be positioned within 1 micron the sensor output has to be at least as sensitive as that. The frequency response of the sensor is part of the dynamic properties of the suspension. The sensors should be insensitive to magnetic fields and to temperatur variations. Good results have been obtained with inductive sensors, eddy-current pick-offs and with optical sensors. The socalled sensorless or *self-sensing bearing* will be addressed briefly in the last section.

The *controller* has to process the measured signals. It may consist of filters, of the controller in the strict sense, and of AD/DA interfaces. It may be built as an analogue network, or it is a microprocessor where the different tasks are taken over by algorithms. In our applications we have used microprocessors of the Motorola 68000 family, digital signalprocessors (DSP) of the TM 320 series, and single chip versions. It is important to consider the development environment for the software and the available support, as well as the bus interface for connecting the processor to the outside world. The control law itself has to be evaluated according to the requirements of the specific application, and depending on the application there are simple solutions and quite sophisticated ones /BLEU 84, LAST 92/. The computational load depends on the control task. As an example the control of a high-speed milling spindle /SITR 89/ involved a model of an overall order of about 70, the control rate using a DSP was 12 kHz.

The *power amplifiers* have to amplify the control signals and to feed the magnet coils. The coils essentially represent an inductive load. With their low pass characteristics they are limiting the frequency response and thus the dynamics of the whole bearing system. We distinguish between dc-amplifiers and switched amplifiers. The first ones are applied for small loads below 0.5 kVA (Table 1). The high power of an amplifier would be essential for achieving good dynamic properties. The actual consumption of energy, however, is low, and at high speeds it is an order of magnitude less than with conventional bearings.

Table 1 Survey on Actuator/Amplifier-Combinations a) actuator for generating testforces and for damping b) actuator for supporting a very flexible rotor, c) actuator for the radial bearing of a high-speed milling spindle

		a)	b)	c)
max bearing force	N	1300	140	1800
bearing diameter	mm	190	58	96
bearing gap	mm	1	1	0.35
switching frequ.	kHz	50	dc	max 100
voltage	V	310	± 54	310
power	kVA	1	perm 0.16	2.4

5.3 Magnetic Actuator

The electromagnetic actuator is the element within the control loop, which transforms an electrical input into a mechanical output, the bearing force. Sometimes this actuator is named magnetic bearing already. Fig. 11 represents the magnetic actuator as an input/output element, whereas Fig. 12 already shows constructional details. The actuator exerts forces in positive or negative X- or Y-direction. The force of each magnet is controlled by a control current. The two typical constructions for a radial actuator differ mainly in the path for the magnetic flux with respect to the rotor axis, and as a consequence thereof the magnetic losses are different. The characteristics of an actuator can be derived from geometric and electric data, or they have to be determined experimentally. This will be explained briefly in the following.

For calculating the bearing forces the radial bearing of Fig. 12 is assumed to consist of U-shaped elements as shown in Fig. 13. The nonlinear behaviour of the ferromagnetic material makes the analytical calculation of the forces difficult. Therefore, U-shaped magnets are modeled with a simplified geometry and then the forces are calculated numerically. Fig. 13 shows the relation between the real iron path and the simplified one. The cross-sectional area $A_{fe} = a \; b$ of the ferrous core is constant along the whole length l_{fe} of the iron path. The width c of the pole shoes is used only for the calculation of the cross-sectional area of the airgap l_0 . With the simplified geometry, the measured magnetisation-curve $B = B(H)$, where B is the flux density and H is the magnetic intensity, can be modified to a socalled sheared magnetisation-curve which relates the flux ϕ to the ampere-turns θ. This relation is given by the two equations

$$\phi = B\,A_{fe} \tag{5.8}$$

$$\theta = H\,l_{fe} + B\,\frac{2A_{fe}\,l_0}{A\,\mu_0} \tag{5.9}$$

where θ is the product of the current i and the number of the windings n

$$\theta = n\,i \tag{5.10}$$

With equations (5.8) and (5.9) we can find the flux ϕ for a given ampere-turn θ. From the flux ϕ we can calculate the force f

$$f = \phi^2 \cos\alpha / \mu_0 A \tag{5.11}$$

The four equations connect the input current i, the airgap l_0, and the force f on the rotor with the electrical and geometrical characteristics of the bearing. The variables can be time-varying as well. As long as no saturation occurs, within the iron the force will be proportional to the square of the current i (Fig. 14a) and it will be inversely proportional to the square of the airgap l_0 (Fig. 14b). The deviation between calculated and measured values is mainly due to stray effects which have not been considered in the simplified mathematical model. The influence of stray fields, however, is small as has been shown by numerical flux-line investigations /TRAX 85/.

The experimental results on the forces were obtained by using a piezo-electric dynamometer for static loads and for load vibrations up to 400 Hz. Above that until 1400 Hz indirect measurements have been used by measuring the acceleration of a test rotor in order to identify the magnetic forces exciting the rotor motion. The amplitude and phase response for the force/current k_i of Fig, 15 is flat within the measuring range up to 1400 Hz and has to be corrected only at about 900 Hz where the test rotor has a bending resonance. That means that for this specific bearing the ratio of force to current for small signals is constant at least up to 1400 Hz /TRAX 85/.

6 Characteristics of the Magnetic Bearing System

Typical specification terms for rotor bearings are the maximal load capacity, the specific load capacity, stiffness, damping, frequence response, maximal angular velocity, and losses.

The *maxima lload capacity* depends on the bearing size, the magnetic material and the control current. Examples are given in Table 1. When the actual load is larger than the allowable maximal load the rotor can not hover any more and touches upon the bearing.

The *specific load capacity* relates the maximum load capacity to the cross sectional area of the bearing hole. Characteristic values for usual Fe/Si-alloys with saturation of 1.5 Tesla are 35 N/cm^2. With special Fe/Co alloys up to 80 N/cm^2 can be obtained.

The *stiffness* of the bearing is typically frequency dependent. For static loads - the frequency of the loading is zero - an integrating feedback of the displacement signals leads to a theoretically infinite stiffness. For load frequencies below the cut-off frequency of the bearing control, which usually is between 100 Hz and 1500 Hz, the stiffness characteristics can be shaped according to requirements. This property can be used to counteract disturbance forces. For load frequencies above the cut-off frequency the stiffness gradually decreases and finally becomes very small.

The *damping* that can be obtained by the bearing depends on the control laws and on the available force. This available force is given by the maximal load capacity, and it can be used as a restoring force, as a damping force, for disturbance compensation, for generating test forces or other purposes. Of course any combination of damping and stiffness can simultaneously be generated as long as the total force does not exceed the load capacity.

The *frequency response* characterizes the dynamic behaviour of the bearing. The actuator itself corresponds to a series of R-L-elements. And a harmonic voltage input, with the highest amplifier voltage-amplitude possible, generates a magnetic force with a frequency response as for example of Fig. 16. Most often the power-amplifier is internally controlled as a voltage-current converter. This reduces the order of the overall control loop and reduces the time constant of coil and amplifier by the factor of the open-loop gain of the amplifier. Thus the current of the bearing - and consequently the magnetic force - follows the input voltage practically without delay. Of course this behaviour is only valid within the frequency response of Fig. 16, i.e., the transfer function for amplifier and bearing refers to small signals within the limits of the frequency response of Fig. 16. And within these limits the transfer function of the closed loop itself, determining the dynamics of the rotor suspension, can be shaped almost arbitrarily by a suitable control design.

The *maximal rotor velocity* depends on two factors. One is the strength of material of the rotor. Because of the laminated ferromagnetic sheets on the rotor circumferential velocities of more than 200 m/s are difficult to obtain. Using amorphous ferromagnetic alloys speeds up to 320 m/s have been reached /LARS 90/. The second factor is the power of the rotor drive necessary to overcome rotor braking torques. As shown in the next section these losses are small compared to conventionally supported rotors, and they have to be considered only at high speeds or when the rotor is made of massive material.

The *losses* of the magnetic suspension mainly occur in the rotor, the actuator and the power amplifier /TRAX 85/. The rotor losses are the equivalent to the friction in hydrodynamic- or rollerbearings as these losses have to be overcome by the rotor drive, too. The magnetic losses in the rotor are caused by the modulation of the magnetic flux in the ferromagnetic part of the turning rotor, when it passes the poles of the stator magnets. This modulation is much lower in the bearing of Fig. 12a than in the bearing of Fig. 12b, because the rotor parts pass only poles with the same polarity. These magnetic losses are caused by hysteresis and by eddy currents. Hysteresis losses depend on the material, used for the ferromagnetic part of the rotor in the bearing area. They are proportional to the rotation frequency Ω and the square of the flux density B:

$$P_{lh} = kh\, \Omega\, B^2 \tag{6.1}$$

with *kh* being a material constant. The eddy current losses also depend on the material used. The ferromagnetic part of the rotor should be laminated and built from thin discs or rings to reduce the eddy currents. The losses are proportional to the square of the rotation frequency, and the square of the thickness *s* of the ferromagnetic material and they can be approximated by

$$P_{le} = ke\, s^2\, \Omega^2\, B^{1.6} \tag{6.2}$$

The other rotor losses, the air losses, depend on the geometry of the rotor and its surronding parts. For example the run-down curve of a magnetically suspended rotor has been measured in air and in vacuum (Fig. 17). The braking torques caused by the various effects are shown in Fig. 18.

The stator losses are dominated by the copper losses due to the resistance in the coils. They are proportional to the square of the current *i* in the coils,

$$P_{lc} = kc\, i^2 \tag{6.3}$$

As a consequence the stator losses typically increase proportional with the bearing force *f*. The amplifier losses are the main source for electrical losses. In the conventional analogue amplifiers the losses depend on the maximal output voltage, that has to be kept available for a good dynamic performance even when it is not required by the quiescent load. Switched amplifiers, however, work much more economically as their losses are dependent on the actual load only. In this case the amplifier loss increases proportional to the load.

7 Applications

Subsequently three examples will demonstrate typical properties of magnetic bearings. Other examples can be found in /DUSS 90/.

Actuator for generating test forces and for damping. Design objectives for the actuator shown in Fig. 19 was to generate high forces within a large frequency range, that can be used to control rotor vibrations. The magnet has 8 poles and can generate forces independently in two mutually orthogonal directions. This actuator is used firstly to generate test forces acting on a rotor for identification purposes and then to work as an active damper or as a bearing /BURR 88/. The rotor itself is 2.3 m long, 100 mm in diameter and supported in two oil bearings. These bearings are known to cause coupling effects between the lateral motions of the shaft. The overhung shaft carries disks with a mass of 93 kg. The actuator first exerts sequential test forces on the rotating rotor. The resulting shaft deviations are measured as test signals. They are used in an algorithm to compute control forces which are subsequently applied to the rotor by the same actuator, synchronously with the rotor speed, in order to compensate for the unbalance. This procedure repeats itself while the rotor slowly runs up to its operational speed. Thus the algorithm determines the control forces necessary for minimizing the synchronous rotor vibrations, without *a priori* knowing the unbalance distribution or the hydrodynamic bearing coefficients. This kind of procedure for automatically adjusting the actuator during operation is of special interest, because generally the dynamic characteristics of the rotor in oil bearings can not be predicted from theoretical models in a satisfactory way. This adaptive control is indicating a direction to even more advanced, to "learning" magnetic bearings. First experiments with nonlinear, learning control using a neural network has already shown very promising results.

Magnetic suspension of a highly elastic rotor. The elastic rotor of Fig. 20 is a research model for demonstrating the capabilities of magnetic bearings to support the rotor and at the same time to damp its resonance vibrations when it is passing critical speeds /BLSA 88/. The digital control has been realized on two microprocessors Motorola 68000, the cycle time of the control being about 400 µs. The rotor is running up to 7.200 rpm and passing five critical speeds, and it can operate within the critical speeds even without having been balanced before.

High-Speed Milling Spindle. In collaboration with a Swiss company, we built a magnetically supported milling spindle (Fig. 21), which now is commercially available. The cutting power is about 30 kW, the rotation speed is 40,000 rpm, resulting in a cutting speed for aluminum of 6500 m/s. This high-speed milling offers advantages with respect to the milling process and production costs. An extensive description is given in /SITR 89/.

8 Current Research for Magnetic Bearings

Reliability and safety management: Reliability is not an integral part of a magnetic bearing system, it has to be built-in and designed deliberately. For the electronics there are guidelines on how to choose reliable components and to design the circuitry. The mechanical parts of the system contain one crucial element. It is the reatiner bearing that will have to support the rotor after a complete failure of the magnetic suspension at least for a safe coast down. An analysis of the nonlinear dynamics of a high-speed rotor contacting a boundary, including multiple impacts, chattering and gliding, gave insight into the resulting nonlinear, even chaotic vibrations of the rotor /SZCS 86, FUFE 92/. But still further work has to be done to evaluate asymptotic behaviour of the rotor during touch down, maximal loads and thermal energy dissipation, leading to an optimal construction of such an emergency bearing.

Even more challenging is the reliability aspect of software. For the software and especially for the combination of hard- and software there is little information on how to reliably combine them, on how to decide which ratio of hardware to software would be most reliable, and how to improve reliability by making the software more intelligent. There are suggestions for the computer integrated safety design of magnetic bearings, describing a method to ecomically verify and implement safety measures, as for example redundancy, diagnostics and exception handling /DISC 88/.

New concepts: Especially for low-cost applications there are suggestions and developments that might lead to promising products.

The self-sensing or ***sensorless bearing*** /BLSC 89, VIBL 90/ makes use of the fact that any displacement of the rotor within the bearing gap causes a reaction within the power amplifier due to changes in the inductivity of the actuator. Of course, no control loop can do without some sensor information. In our case there is no explicit displacement sensor, but the current and the voltage within the amplifier are used as feedback signals.

The energy used by magnetic bearings is by a factor of 10 to 20 lower compared to conventional bearings, and this factor can be increased by especially designing ***energy saving bearings***. There are concepts to incorporate permanent magnets in a hybrid design /BODE 88, FREM 88/ or to use a dedicated control /VIBL 90/ for such energy saving bearings.

A particular arangement of windings and control allows to combine the bearing function and the driving function in the socalled ***bearingless drive*** /BICH 91/.

Not yet investigated has been the potential for ***low-cost design by a high level integration***, for example by integrating the various elements of the magnetic bearing system into one controller/amplifier chip.

9 Conclusion

The paper gives an introduction into the design of magnetic bearings. It presents the elements of the bearing system, discusses the characteristics of the magnetic suspension and the achievable specifications and shows some applications. The last section points to current research, and to future trends and new concepts with potentials for low-cost solutions.

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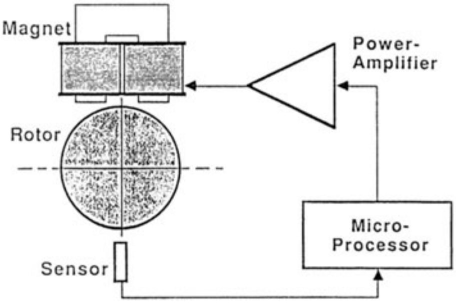


Fig. 1 Principle of the magnetic suspension

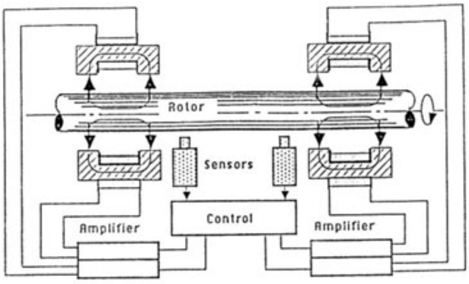


Fig. 2 Radial magnetic suspension of a rotor

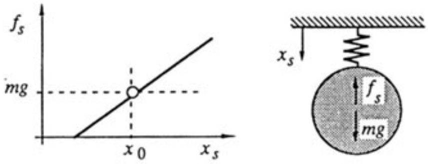


Fig. 3 Classical spring suspension and its restoring force

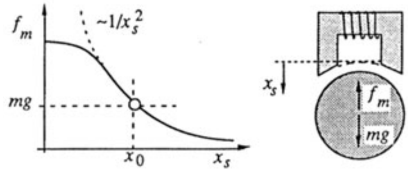


Fig. 4 Magnetic force in function of the displacement x_s, with constant current i_0

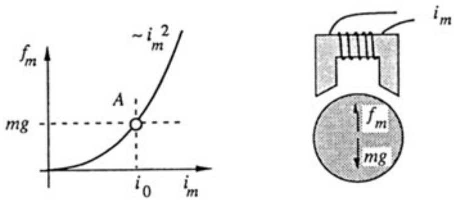


Fig. 5 Magnetic force in function of the actuator current i_m, with constant gap x_0

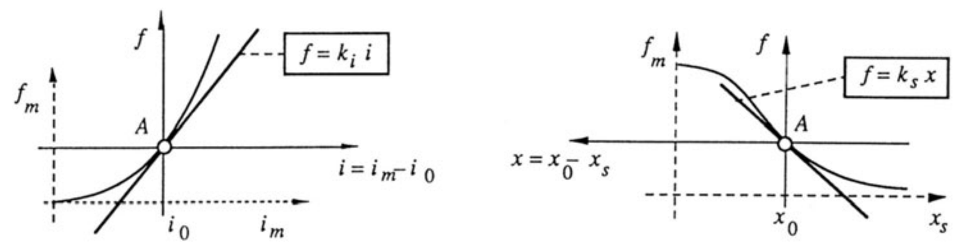


Fig. 6 Linearization of the magnetic force around the operating point, and introduction of the linearized control variables for the control force *f*, the displacement *x* and the control current *i*

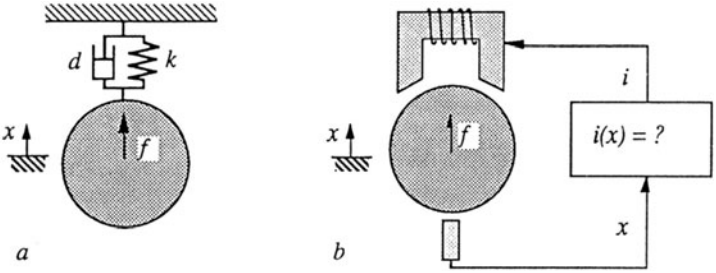


Fig. 7 A first simple controller is chosen in such a way that the magnetic bearing (b) emulates a spring-damper suspension (a)

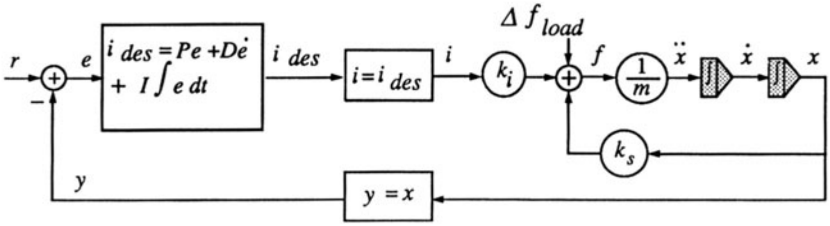


Fig. 8 PID control for the magnetic suspension with current control and disturbance input Δf_{load}. The integrating part of the feedback compensates for the disturbance, the error *e* is the difference beween the command input *r* and the sensor signal *y*

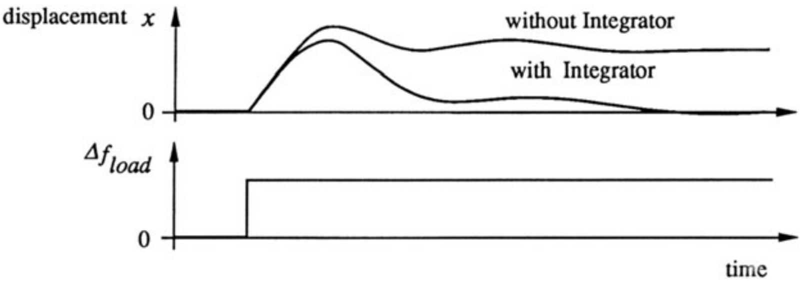
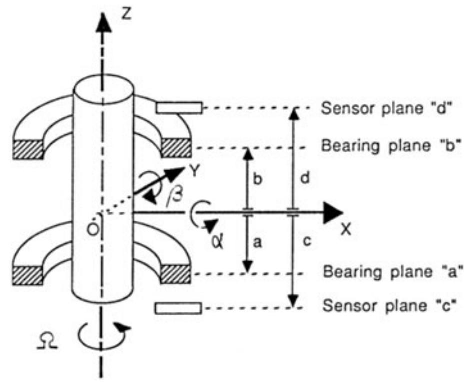
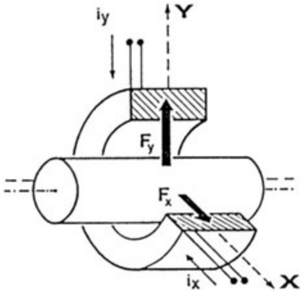


Fig. 9 Step response for the displacement of a magnetic suspension with PD and with PID control

Fig. 10 Rigid rotor model /BLEU 84/





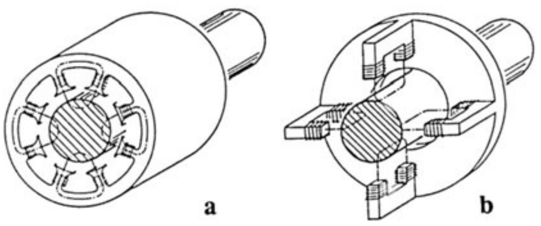


Fig. 11 Radial magnetic actuator as in put/output element

Fig. 12 Two different configurations for a radial actuator

Fig. 13 Single U-shaped electromagnet as part of a radial bearing
a) real geometry b) simplified geometry

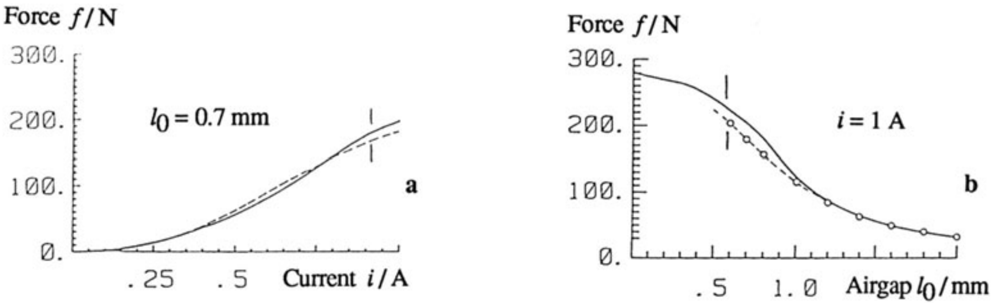
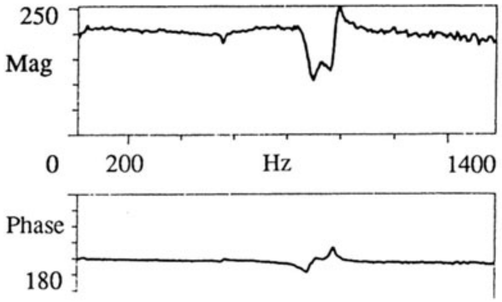


Fig. 14 Calculated (——) and measured (-----, ooo) bearing force of a radial bearing (diameter = 80 mm, a = 40 mm, n = 720)



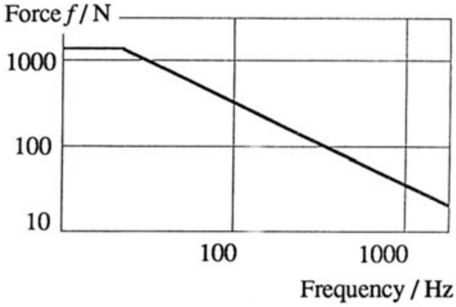


Fig. 15 Measured force/current factor k_i, equ.(3.2), depending on the excitation frequency

Fig. 16 Frequency response of the actuator/amplifier unit, with the specifications of Table 1a

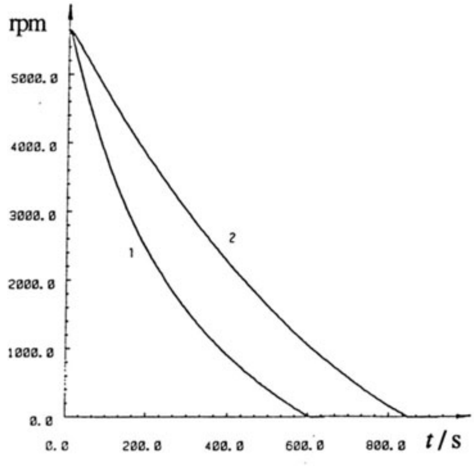


Fig. 17 Run-down curve for a test -rotor (1 - in air, 2 - in vacuum)

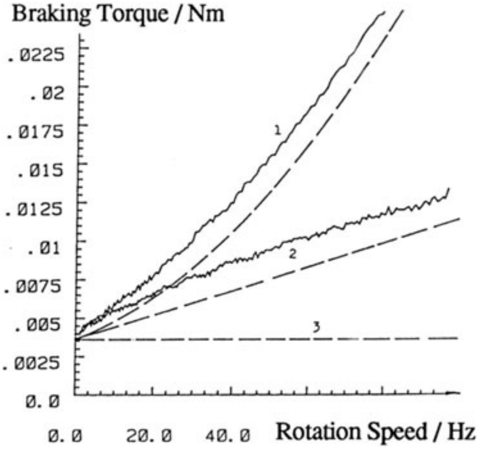


Fig. 18 Braking torques (——— measured, ---- calculated, 1 - in air, 2 - in vacuum, 3 - hysteresis losses only)

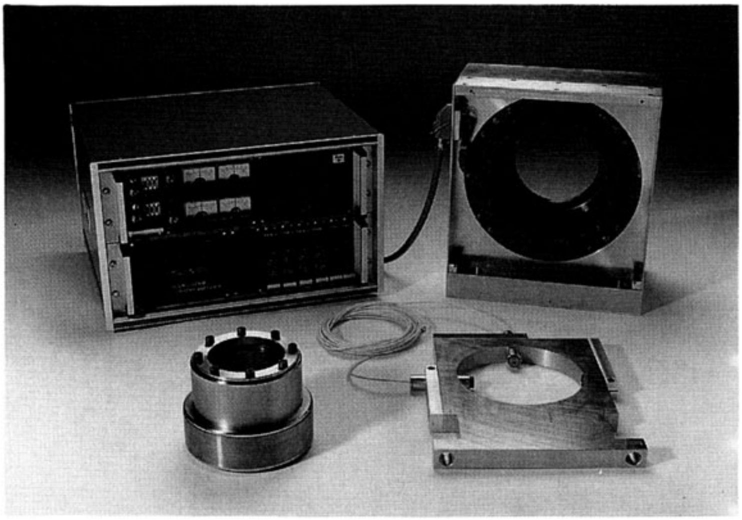


Fig. 19 Electromagnetic Actuator ERH-190/50/1 consisting of the magnet, the power amplifiers, the ferromagnetic laminated sleeve on the rotor, and sensors. Specifi-cations are given in Table 1a

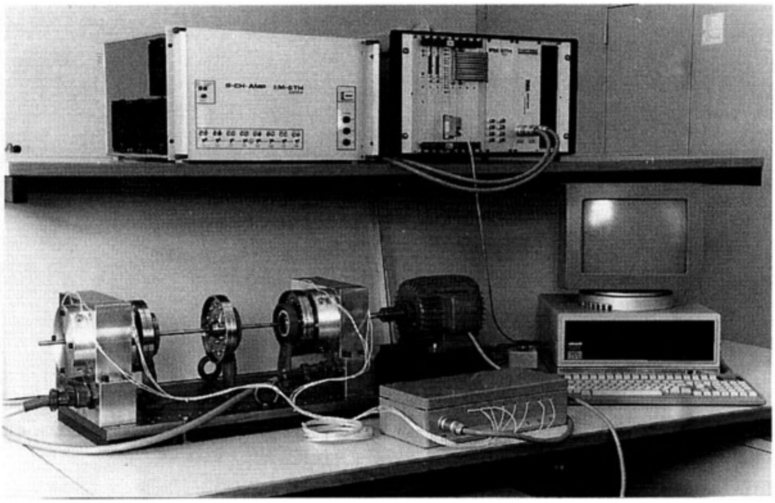
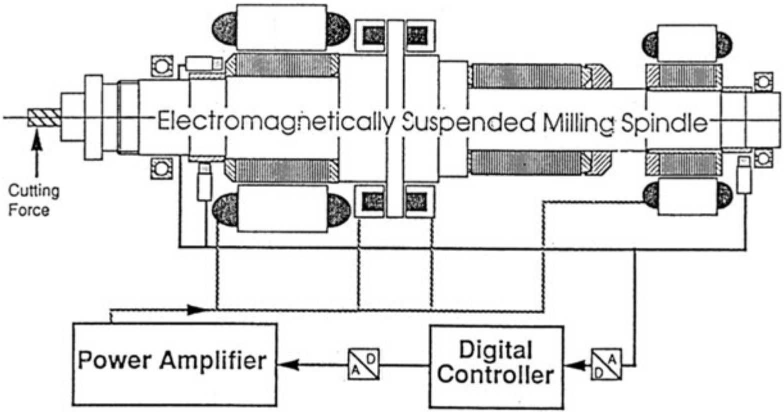


Fig. 20 Highly elastic rotor in magnetic bearings, showing the rotor, microprocessor, power amplifiers, terminal for dialogue and on-line parameter changes. Specifications are given in Table 1b



Performance:

Rotational Speed: 40'000 RPM
Driving Power: 30 kW
Cutting Speed: 6'500 m/min

Rotor:

Length: 486 mm
Weight: 16 kg
Max. Diameter: 144 mm

Fig. 21 High-speed milling spindle with digitally controlled magnetic bearings. Specifications are given in Table 1c

Tension Compensation for Fixed Delivery Cone Winding: A Mechatronic Approach

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Abstract

When winding conical packages from a fixed rate supply, some form of compensation is required to minimise the tension fluctuations resulting from the cyclic imbalance between supply and take-up. For low winding speeds, simple passive mechanical compensators have been used successfully but these are not adequate for high winding speeds. Active mechanical compensators are relatively complex and expensive to manufacture and so it was decided to develop a 'mechatronic' compensator, employing microelectronic control and simple electro-magnetic actuation. This paper describes the design of such a compensator which has proved successful at winding speeds of over 400 m/min, when winding 4°20' cones.

Introduction

Some yarn production methods, such as open-end spinning, produce yarn at a constant delivery rate. Typically the yarn is delivered by a pair of 'pinch-rollers' and therefore any variation of the take-up rate at which the yarn is wound onto the package results in tension variation. When winding cylindrical packages ('cheeses') tension variations can be kept quite small, but for economic reasons it is sometimes desirable to wind directly onto conical packages to avoid an extra winding operation. Figure 1 illustrates this situation.

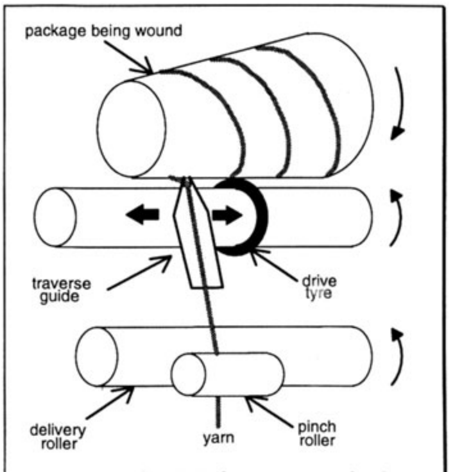

Fig. 1: Fixed delivery cone winding

The package is surface driven approximately half way along its length in such a way that the average take-up rate is slightly higher than the delivery rate, to provide a small positive winding tension. However, as the traverse guide spreads the yarn across the package (at a large helix angle) the take-up rate varies. At the small end of the cone the take-up will be lower than the supply rate, while at the large end it will be higher. Unless some form of

M. Acar (ed.), Mechatronic Design in Textile Engineering, 179–190.

compensator is included in the system the yarn may go completely slack at the small end and/or break at the large end. Even if a package can be wound excessive tension variation will cause a higher frequency of end-breaks during winding, may prevent even dye absorption if the yarn is to be package dyed, and can cause problems in over-end unwinding of the package.

Figure 2 shows a simplified general arrangement of the cone winding system of an OE spinning machine. Tension fluctuation is reduced by a simple passive spring compensator. This arrangement performs adequately at yarn production/winding speeds of up to 150 m/min. It has the important advantage of being cheap to manufacture (there may be 144 compensators on one spinning machine!). At higher speeds the inertia of the bollard disc and its spring prevents it from maintaining adequately constant tension. For high winding speeds a positively driven compensator could therefore be attractive.

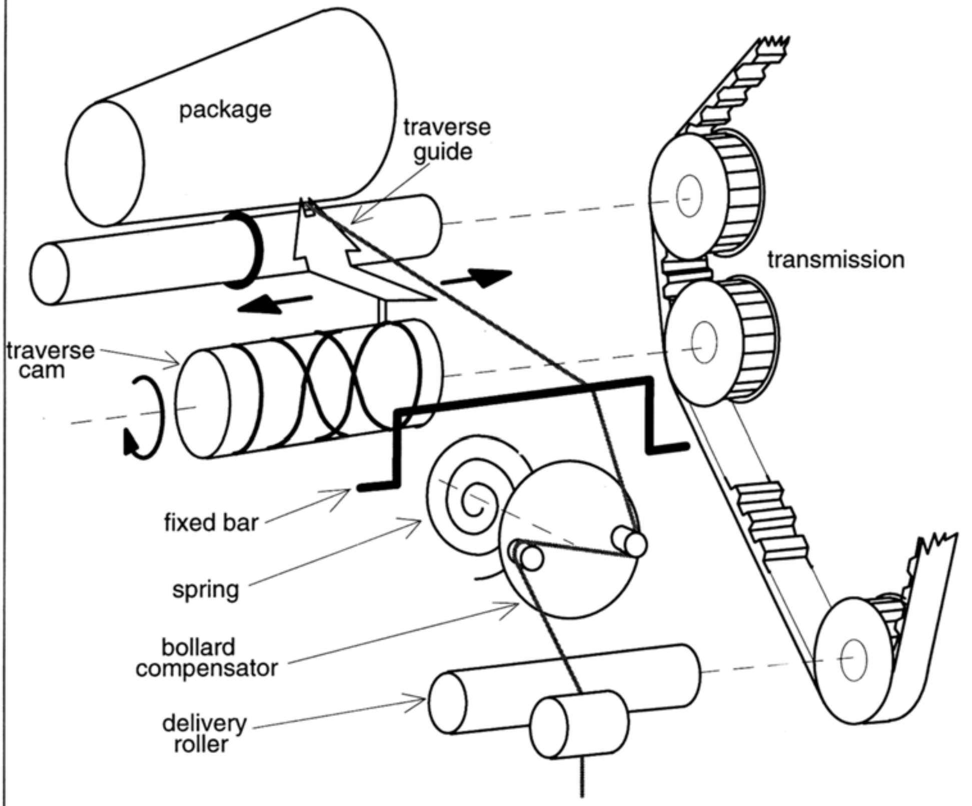

Fig. 2: Winding system with mechanical compensator

Mechanical Positively Driven Compensators

The task of implementing a mechanically driven positive compensator is not as straightforward as might at first be assumed. Although winding a helical path onto a conical surface might be expected to require a compensator motion described by a simple, and hence easily generated, geometric function, in practice this is not the situation. The compensator motion required is made more complicated because of practical requirements of the traverse guide movement. In order to ensure a positive drive to the surface of the yarn package, the winding helix angle is reduced in that part of the package which contacts the drive tyre. This makes the package slightly firmer at that point and prevents the tyre from sinking-in. The practical requirement to keep stresses in the traverse-cam track and follower down to acceptable levels at the reversal points of guide motion also dictates that the winding path is not a simple helix. The actual velocity at which the yarn is wound onto the package therefore varies in a complex way as can be seen from figure 3, which shows the variation in winding velocity during one complete traverse guide cam cycle (two passes back and forth across the package).

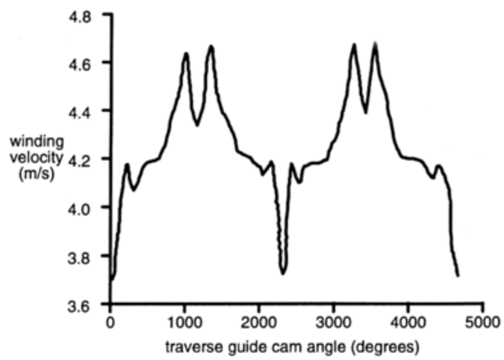

Fig. 3: Winding velocity in one traverse cam cycle

Unfortunately the difficulties of designing a mechanical positively driven compensator are greatly compounded because the compensation required changes as the package builds. As shown in figure 4 the ratio of the diameters of the small and large ends of the package is not constant for differing package sizes. This means that different, progressively smaller amounts of compensation are required as the package builds up.

Despite these difficulties, mechanical positive compensator mechanisms have been built and operated successfully at moderate delivery speeds. Designs employing cams are expensive and difficult to lubricate successfully for use at high speeds in the textile machinery environment. Designs based on linkages, which contain only rotating joints, have also been investigated [1,2]. Although free from lubrication problems and potentially inexpensive if mass-produced, these designs give only approximate compensation and are difficult to optimise. They are also

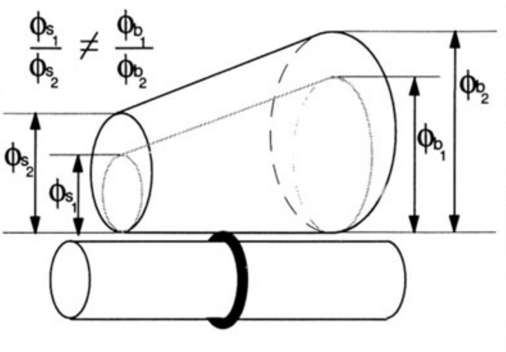

Fig. 4: Changing ratio of diameters

inflexible in that small changes in machine design which affect the yarn path require complete linkage re-design. This is a potentially costly problem since tooling costs for mass-producing the low-inertia links required for high-speed operation would be substantial. Further problems arise with yarn threading since it is difficult to arrange for the drive to be disengaged for 'parking' the compensator in a convenient threading position, an increasingly important consideration now that robotic devices are commonly used for piecing.

Mechatronic Compensators

Providing the manufacturing costs can be kept adequately low, and the reliability and life expectancy high, mechatronic approaches to tension compensation can avoid many of the problems inherent in the mechanical types. Two different mechatronic approaches are evident: open and closed loop systems.

A closed-loop mechatronic tension compensation system in which yarn tension is monitored and compensator position adjusted accordingly would seem ideal. In practice, the difficulty and expense of measuring yarn tension make this approach unattractive at present. The development of a reliable, low-cost yarn tension sensor is a promising area for further work.

The alternative of an open-loop compensation system, in which yarn is taken-in and let-out cyclically according to pre-defined information, in a similar manner to a mechanical positive compensator, has some advantages. It does not require a tension sensor and the compensation motion can be produced by an inexpensive stepping motor which is simple to control and, having no brushes, has a long service life expectancy. A large amount of positional data is required for the compensator/motor position at each stage of the winding process, but this can be pre-calculated 'off-line' so that the computational requirements of the control system are quite modest. An open-loop mechatronic compensator was thus developed.

The Prototype Open-Loop Mechatronic Compensator

Figure 5 shows the general arrangement of the compensator developed. As in the passive mechanical compensator a disc with two bollards is used to take-up and let-out yarn, since this is probably the simplest arrangement possible compatible with a rotational direct drive. The position of this disc is controlled by a small stepping motor (Nippon Pulse Motor PQ40-200C; a style of motor commonly used for computer floppy-disc head positioning and therefore available very economically as a high volume mass-produced component). The motor is a four phase hybrid vernier design, giving 400 steps per revolution driven in half step mode, and is driven by a bipolar-chopper type drive circuit employing RIFA PBL3717 integrated circuits. The use of a relatively sophisticated drive circuit of this type rather than a simpler RL drive is desirable since it provides better motor performance (higher torque at high stepping rates) and consumes less power, potentially easing power supply and distribution requirements for a 144 spindle spinning machine quite significantly.

A number of sensors are required to provide the information needed to control motor/compensator position. Since at switch-on the motor could be in any position, a 'top-dead-centre' reference is required for initialisation. This is implemented by means of a reflective opto-switch (infra red LED and photo-transistor) mounted behind the bollard disc. The back of the bollard disc is coloured half black and half white so that the opto-switch can sense the transition in order to provide a datum position.

The position of the traverse guide also requires a datum so that the compensation cycle can be started in phase with the cam. This is achieved by mounting a small metal target on the traverse guide and sensing its presence at the end of traverse using an inductive proximity detector. Only one such detector should be required for the whole spinning machine, although if traverse cams are run out of phase with one another to minimise machine vibration, as is commonly the case, care needs to be taken in interpreting this datum information appropriately at each compensator.

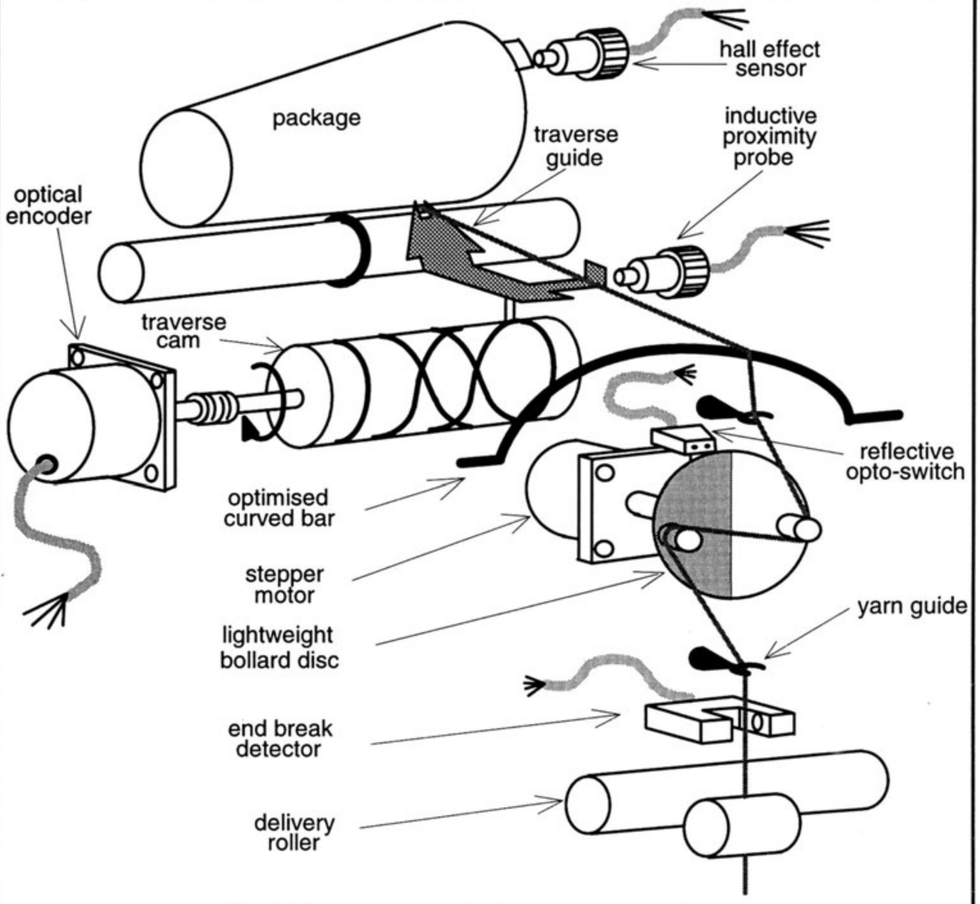

Fig. 5: Open-loop mechatronic compensator

The timing information required to allow the compensator to keep in step with the traverse cam movement is provided by an optical encoder mounted on the camshaft. A high resolution two-track incremental optical encoder was used on the prototype for reasons of availability but a single track 'optical tachometer' disc of modest resolution is all that is required. As the camshaft rotates this device provides the 'timing' pulses which are needed to determine when the compensator's stepping motor should be stepped to its next position.

The method by which the effects of package growth are allowed for will be described later after the basic design and operation of the compensator have been explained.

The process leading to the design and optimisation of the bollard disc was as follows. In order to minimise the task of the stepping motor attention was first given to optimising the yarn path by calculating the profile of an appropriately curved yarn guide bar which nominally removes the path-length variations caused by the varying position of the traverse guide. The next step was to derive the relationship between the amount of yarn stored by the bollard disc and its angle of rotation and bollard spacing.

Figure 6 shows the geometry for the simplest (symmetric) case for which the expression governing the yarn length held, Z_b, is:

$$Z_b = 2\left[\sqrt{(c/2)^2 - r^2} + \sqrt{e^2 + (a+d)^2 - r^2} + r\left\{\frac{3\pi}{2} + \sin^{-1}\left(\frac{r}{\sqrt{e^2 + (a+d)^2}}\right) + \tan^{-1}\left(\frac{e}{a+d}\right) - \theta_b + \sin^{-1}(2r/c)\right\}\right]$$

where $e = \frac{c}{2}\cos(\pi - \theta_b)$ and $d = \frac{c}{2}\sin(\pi - \theta_b)$

A computer program was written to evaluate the yarn storage characteristics for any particular set of bollard disc and guide spacing parameters. This enabled the amount of yarn in the compensator to be computed at each angular step position of the motor. Figure 7 shows a typical result for a symmetric design. As can be seen the compensator angle vs. yarn-length held characteristic is reasonably linear for moderate angles of rotation either side of the bollard mid-position. Although non-linearity presents no problem from the data processing point of view, restricting operation to this central portion of the characteristic is a required to keep the resolution (yarn taken-in or let-out per motor half-step) fine enough at one extreme of rotation and to limit motor

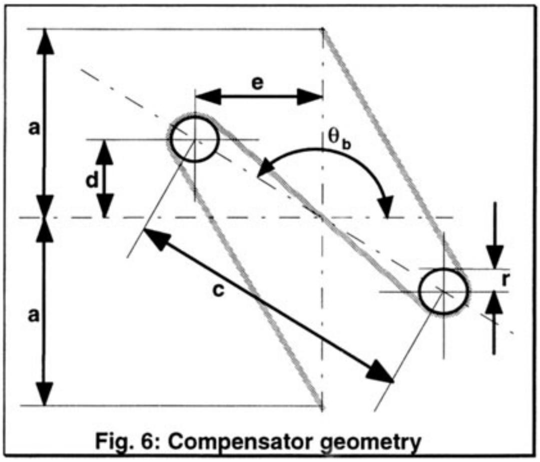

Fig. 6: Compensator geometry

acceleration/deceleration at the other. Analysis of the CAD data for the traverse cam, in conjunction with the geometric data for the empty cone and yarn path allowed the maximum required amount of yarn length compensation to be determined. This enabled a limit to be set on the minimum bollard spacing. The maximum bollard spacing is limited by the 400 step/rev resolution of economically obtainable motors, which limits the smallest discrete increment of compensation which can be applied.

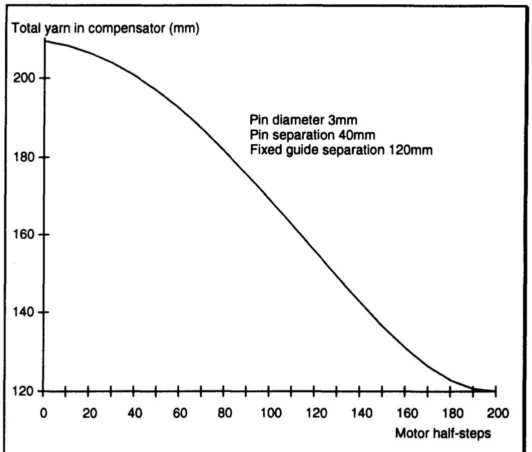

Fig. 7: Yarn Storage Characteristic

An appropriate bollard spacing having been provisionally chosen, the bollard and disc inertia was estimated. The motor torque and stepping rate requirements were then ascertained approximately, using the simplifying assumption that the compensation function would be sinusoidal, to establish that a suitable motor was available (a factor of safety was applied to take into account the effect of higher harmonics in the compensation function).

A further computer program was then written to take the traverse-cam CAD data and the yarn storage characteristics of the bollard compensator and work out the angular positions of the traverse cam at which the stepping motor needs to be stepped by one half-step to give the required compensation. This angular information was then processed into an appropriate form to be used as a look-up table for control of the mechatronic compensator. The look-up table entries are 8-bit values representing the number of traverse cam shaft angular-encoder pulses to be counted before making the next motor step. Information is also placed in the table to indicate direction reversal and cycle repeat points.

The control and sensing circuitry for the mechatronic compensator is shown in fig. 8. An 8031 single chip microprocessor is used to implement the control algorithm. One of the 8031's inbuilt counters (counter 1) is used to determine when the stepping motor should be stepped. The counter is pre-loaded with the current value from the look-up table and counts (encoder pulses) up from this value until it reaches its terminal count. At this point the counter is re-loaded with the next sequential count value from the look-up table and the motor is stepped once in the current direction of rotation. If the new look-up table entry is a 'flag' value, it is not used as a count but taken to signify that the motor direction should be reversed for succeeding steps. In this case the table is accessed once more to obtain the count information. A different flag value is used to mark the end of the table to alert the algorithm to re-commence at the beginning.

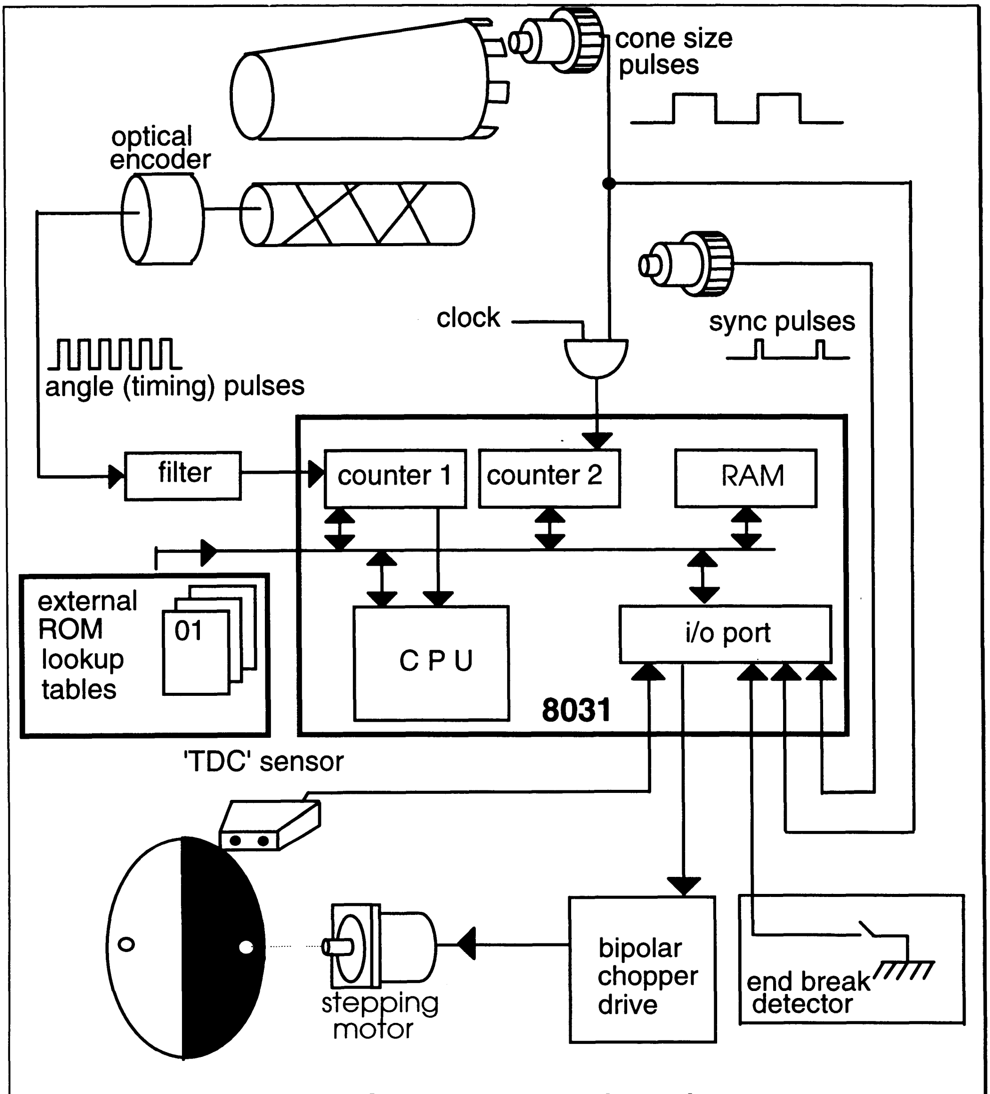

Fig 8: Control system schematic.

Returning to the problem of determining, and applying differing amounts of compensation for, the varying states of package build, the system performs these tasks as follows. Differing degrees of compensation appropriate to different package sizes are applied by working from a set of look-up tables designed for different cone sizes. The look-up table most appropriate to the current stage of package build is used until it is sensed that a switch to the next table (for a slightly bigger package) is required.

A number of ways of determining the package size to provide the control algorithm with the necessary information to select the appropriate look-up table were considered. The most obvious was to monitor the angle of the package arm as illustrated in fig. 9. This approach was rejected, however, for a number of reasons. The angle of rotation of the package arm between maximum and minimum cone size conditions is relatively small. Measuring angular rotation by a directly digital approach would, therefore, require a high resolution absolute encoder, which would be prohibitively expensive. The digital information from the encoder would also be in parallel form and would thus require multiple connections to the controller, entailing further complexity and expense. Use of an analogue sensing technique, such as a potentiometer, could reduce the cost of the sensor but this approach was also rejected as it would require an A-D converter, again increasing expense and complexity quite considerably. The solution adopted was to infer the cone size by measuring its period of rotation. This can be done with very little hardware. A Hall-effect sensor is employed to monitor the presence of target sectors on the cone hub (which is a permanent part of the machine). The output from this sensor gates clock pulses into one of the 8031's inbuilt counters (counter 2). The software can then deduce the rotational speed of the cone by reading (and then re-setting) the count during the inactive period when the Hall-effect sensor output is low.

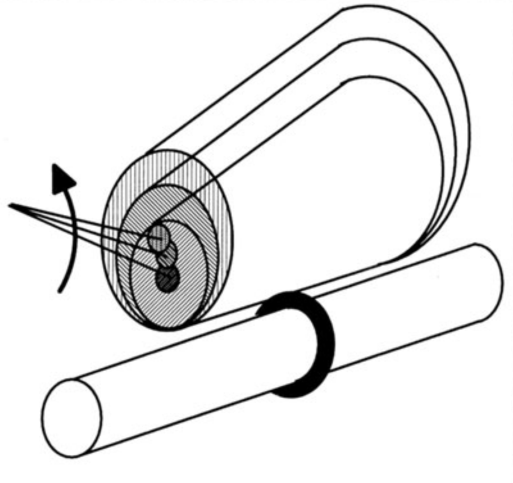

Fig. 9: Monitoring package size

The overall control algorithm commences its operation as indicated in fig. 10. In normal operation the processor's main task is to continually re-estimate the cone size as follows:

- Look for negative transition on cone rotation sensor i/p.
- Clear counter 2
- Look for high level on sensor
- Wait for low level again
- Read counter
- Calculate cone size and set address of correct look-up table into RAM (for interrupt routine)

This 'main' routine is regularly interrupted (more than once per loop through the code) whenever counter 1 reaches its terminal count, indicating that a motor step is due. The interrupt routine performs the following main steps:

- Step the motor one step
- Consult lookup table and get counts to next step (also set direction if changed)

- Load counter 1
- Check end break detector
- Return from interrupt (to size routine)

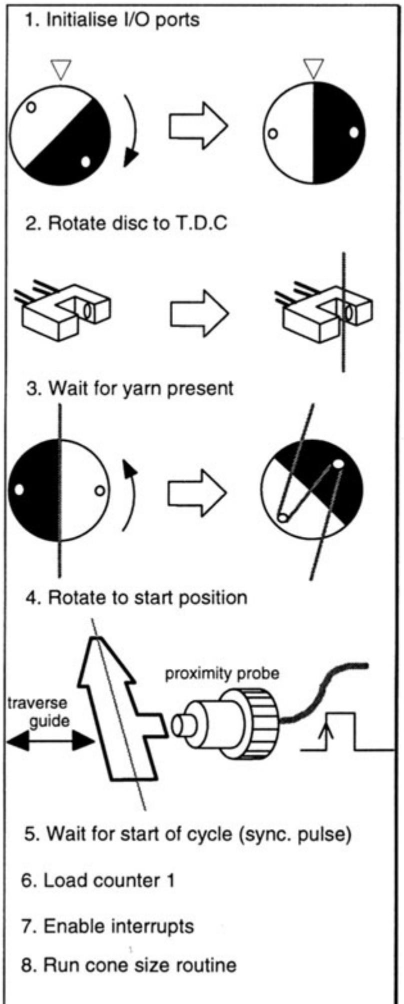

Fig. 10: Initialisation procedure

The system is further complicated in practice by the need to take account of the anti-patterning mechanism built into the winding hardware. This prevents turns of yarn in successive layers from being built up exactly on top of one another and forming ridges on the package. It functions by cyclically varying the speed at which the traverse cam is driven by a small amount. This has a second-order effect on the tension compensation requirements which can be allowed for by providing further lookup table information as illustrated in fig. 11.

Optimising System Performance

One significant obstacle to developing an 'all-digital' system, such as the one described here, lies in the difficulties in 'tuning' the system. Since there are no analogue sensors or actuators in the system it is very difficult to monitor its performance (which must, of necessity, be done in real-time) and hence modify the lookup tables to optimise them to take into account dynamic effects (the lookup table information generated from geometric considerations is all based on static analysis). The development an tuning procedure adopted was as follows:

Using an Intel IPDS 8051 in-circuit emulator, the algorithm was checked for basic performance using a single lookup table designed for initial winding onto an empty cone (the worst case condition from the compensation point of view). This single lookup table could be fitted into the on-board memory of the 8051 (and hence the emulator). Once the basic operation of the program had been established the emulator was replaced by an 8031 CPU and the program placed into external EPROM. This configuration having been verified operational, the EPROM was replaced by an EPROM emulator (a 'Softy-3' EPROM programmer used in its emulation mode). This allowed the contents of the memory to be easily altered by downloading data from an IBM PC compatible computer, thereby allowing easy alteration of the contents of the lookup tables (which were initially generated by software on the PC). Having established a mechanism for 'tuning' the lookup tables without having to re-program the EPROM's, their contents were refined by fitting (analogue) tension monitoring equipment into the yarn path and recording residual tension variation along with appropriate machine timing indications (from the digital sensors) on a digital storage oscilloscope. Painstaking manual data reduction allowed usefully improved performance to be obtained by adjusting the lookup tables. It is quite difficult to see how this difficult development stage could have been improved. Incorporating some kind of analogue feedback (eg a potentiometer to monitor bollard disc position) into the development prototype appears attractive. The imposition of additional friction and inertia would, however, have detracted from the performance attainable (the limits of which were being explored) and taken the system one step further from a potential commercial realisation.

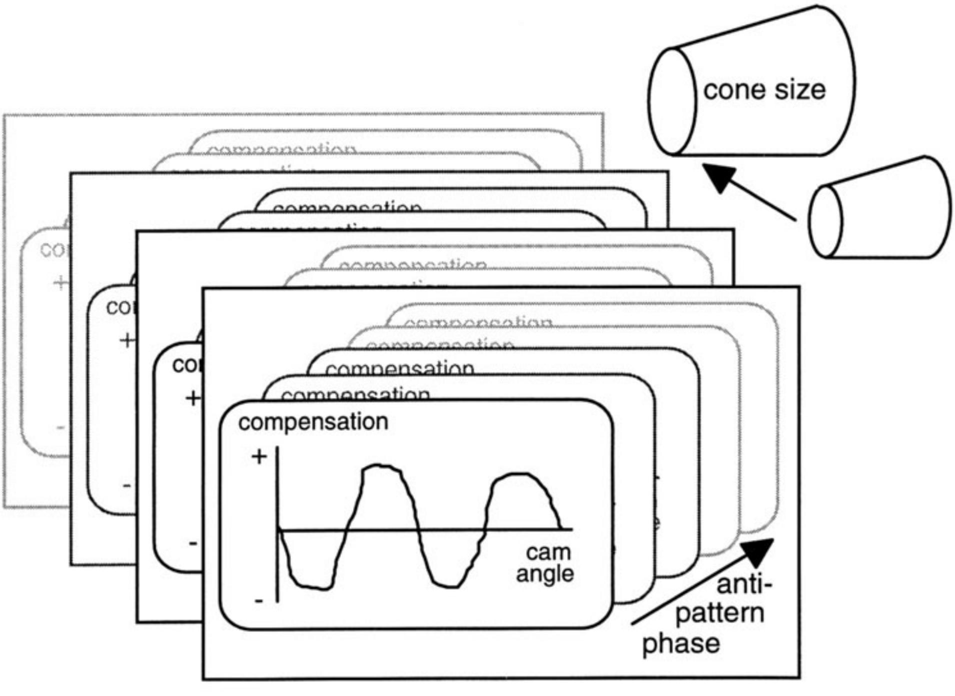

Fig. 11: Look-up Table Arrangement

Conclusions

A mechatronic open-loop compensator using a minimum of moving parts was demonstrated to be a viable proposition in terms of performance. Additionally the mechatronic approach afforded the following advantages in this case:

- Flexibility
  - Easily re-programmed for different cone angles or yarn path changes

  - Applicable to a range of different machine types

- Robot friendliness
  - Able to co-operate with piecing robots after end-breaks
  - Self-parking for ease of threading
- Relatively low cost
  - Inexpensive digital sensors and stepping motor
  - High production volume and low parts inventory because of flexibility of application
- Expandability
  - Spare processing capability (and I/O) available for other functions such as maintaining long-term tension control by adjusting drive-tyre position or assuring reliability by checking the bollard position twice per cycle (using the existing TDC sensor)

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MECHATRONICS IN THE DESIGN OF TEXTILE MACHINES

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ABSTRACT. Textile machines have been rapidly mechatronized in Japan to save labor or improve the productivity and the quality of the fabrics. This trend is also placed in a part of total automation in the weaving factories. In this paper, introducing some examples of the mechatronization of a weaving machine, we consider the problems concerning it.

1. Introduction

The mechatronization of textile machines has been improving very rapidly in Japan. The background of such trends in Japanese textile industry is represented by the following facts. Because most weaving factories are located away from city area due to noise pollution and the working conditions are not so good, the textile industry is always suffering from a lack of hands. Therefore, the mechatronization of weaving machine is much desired in order to try to save labor. In addition, demanding quality of the products is increasing year after year and the inspection of fabrics is getting more strict. In order to pass such strict inspection, fine adjustments of weaving machine are required. Moreover, the trend that new-field products (fabrics) are developed in weaving factories is remarkable. However, traditional full-mechanical weaving machines can not meet such needs. These factors have accelerated the mechatronization of weaving machinery. The weaving machines mechatronized with high performance are mainstream at present in Japan.

In this paper, we introduce some examples of the mechatronization of weaving machines and point out the problems concerning it.

2. Motion of weaving machine

First of all, we briefly address the basic motions of weaving machine. Though we take up Nissan air-jet loom for an example among many kinds of looms, the fundamental structure is common to all of them.

Figure 1 shows a schematic of the traditional air-jet loom. In general, the motion of the loom can be divided into five main-motions as follows:

(1) Shedding motion
(2) Filling motion

M. Acar (ed.), Mechatronic Design in Textile Engineering, 191–198.

(3) Beating motion
(4) Let-off motion
(5) Take-up motion

(1) through (3) are periodic motions synchronizing with the rotation of the main-shaft of the loom. Since one woof is inserted into the warp every one rotation of the main-shaft, the productivity of the loom is usually represented by revolutions of it.

Weaving motion starts with the shedding motion. The warps adjacent to each other are pulled up or pushed down respectively due to the vertical motion of the heddles (Shedding motion). At the same time, the reed swings backward and a space through which the woof passes is taken. Then, the woof of the same length as the reed width, which has been pooled in advance, is inserted into the space between the warp with an air-jet stream (Filling motion). After the insertion has completed, the reed returns forward and thrusts the woof into the cloth-point (Beating motion).

(4) is the motion in which the warp wound on the yarn beam (spool) is unrolled keeping its tension constant. (5) is the motion in which the cloth just woven is wound on the cloth-roller at a constant velocity. These are not periodic but continuous motions.

3. Mechatronization of weaving machine

In the case of the traditional full-mechanical weaving machine, all the motion including the main motions mentioned above were generated by the mechanical coupling with the rotation of the main-shaft by means of gears, cams and links. That limited the movements and caused complicated transmission mechanisms and difficulty in fine adjustment of the movements.

To overcome these limitations, the newest machines are mechatronized to separate some main motions from the rotational motion of the main-shaft, that is, they are composed of several independent devices. Each device has a microprocessor (microprocessors) to control the actuators and sensors to generate exact motions instructed by the operator. Figure 2 shows an example of the configuration of the control system of the mechatronized weaving machine. Though these control devices basically work independently each other, they can make synchronous motions using the signals on the control bus.

In this section, we present in detail the following systems, the let-off motion and the filling motion control systems.

3.1 Let-off motion control system

Figure 3 shows the full-mechanical let-off motion control system and the mechatronized one. In the mechanical system, the rotation of the main-shaft is transmitted to a continuous speed-change gear whose output shaft rotates the yarn-beam using the reduction gears. The change of the warp tension is converted into the displacement of the backrest roller. The displacement is transmitted to the lever of the speed-change gear through the spring and the links. The warp tension is set by varying the weight hung on the lever A.

The speed-change gear is required that the rotational speed change ratio of the input to the output is more than five times which is the same as the ratio of the radius of the yarn beam which is almost empty to that which is fully rolled up. The speed-change gear which is capable of changing the speed with such a wide range is very expensive. In addition, the displacement of the lever of the change gear induces the displacement of the backrest roller, which sometimes causes a serious problem, uneven quality of the fabric. Moreover, the combined vector of the warp tension applied to the backrest roller varies as the radius of the yarn beam changes as shown in figure 4. To resolve the problem, complicated mechanisms to compensate the change of the combined vector is required.

On the other hand, the mechatronized let-off device is driven with AC servomotors using vector control. The warp tension is detected with a force sensor as the force applied to the backrest roller. The strain gauges attached on the sensor-body convert the force into an electrical signal, which is used as a feedback signal by the controller.

The microprocessor mainly performs the following processes:

1) Extraction of the real value of the warp tension from the signal of the force sensor.
2) Computation of the manipulated variable (velocity command to the AC servomotor driver).
3) Compensation for the sensitivity of the force sensor due to the change of the combined force vector.
4) Input of the warp tension value instructed by the operator.

The mechatronization of the let-off system brought the following results.

1) Controllability, especially responsibility and steady state error, were improved and the fluctuation of the warp tension was very reduced.
2) The structure of the machine was simplified because mechanical transmission gears used for driving the peripheral devices were removed.
3) Remote operation comes to be possible.

3.2 Filling motion control system

Figure 5 shows a schematic of the mechatronized filling motion system. The woof is usually supplied in the form of a yarn package. It is impossible to insert the woof supplied from the package directly into the warp or the woof will snap before completing the insertion because the resistance force generated by unwind-motion of the woof is too large. Therefore, to keep the woof from snapping, the woof is rewound on a measurement drum.

When the reed swings backward and a space through which the woof will passes is taken, FDU (Feeder Driving Unit) unhooks the woof to enable the woof to leave the dram for the space. At the same time, TCU (Timing Control Unit) opens the woof-gripper and the main air-valve. The woof is carried with the air-jet stream through the main-nozzle and inserted into the space between the warp. In the case that the machine has a long reed space, the air-stream jetted from the main-nozzle can not arrive at the end of the reed due to reduction. To strengthen the jet-stream, several sub-nozzles are used with the main-nozzle.

FDU counts the turning numbers of the woof which has just left the drum in order to measure the length of the woof which should be inserted into the warp. As soon as the number reaches a value FCU quickly returns the woof-stopper to prevent the woof from overrun. FLU detects the woof arrived at the end of the reed and outputs a signal meaning success in the insertion. After receiving the signal, TCU closes the woof-gripper and shuts all the air valves. In this time, the reed has already been swinging forward. When the woof is thrust into the cloth-point, TCU operates the cutter to cut the woof.

The correct setting these timings is very important to make the woof insertion successfully. The timings depend on fabrics, that is, they have to be changed according to the kinds of fabrics. It is because the flying velocity of the woof varies according to the kind of the woof, the diameter of the woof, weight and so on.

In the case of the full-mechanical machine, it was very difficult to adjust the timings precisely because the timings were adjusted by changing the phases of pairs of cams, so that the setting of the timing had depended on the experience of the operator. As the result, it had taken a long time to find a good condition to operate the machine steadily.

Mechatronization of the filling motion system enables the operator to set the timings easily, quickly and precisely by means of key-input with the operation panel or down-loading the timing data using a LAN system. It also improves the productivity because the timings on which the machine have worked with good record can be utilized.

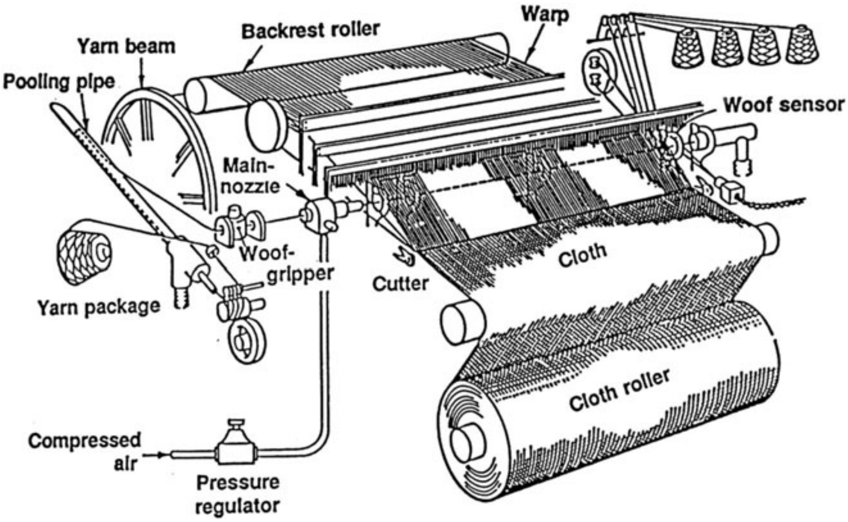
4. Summary

The most important technical issue on the mechatronization is to improve the responsibility, reliability, and durability of the elements as well as the actuators to drive the devices. The operating speed of weaving machines is increasing every year to get high productivity, one of them is more than 1,200 RPM for example. In that case, the driving parts are required very high response frequency.

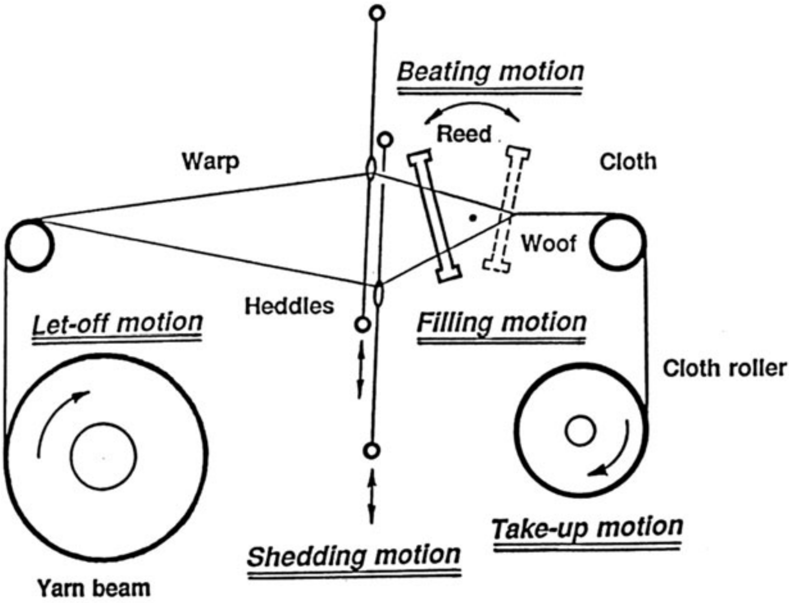
On the other hand, the weaving machine halts automatically in case of failure of the woof-insertion. Since the machine-halt affects the quality of the product (fabrics), allowable times of the halt are usually less than one time an hour at most. In that case, for example, missing the action of the devices is not allowed even one time in 72,000 times when the machine works at 1,200 RPM.

In addition, the almost weaving machines in Japanese weaving factories works for 24 hours. In that case, even if an element has a life of 1,000,000 times, it will break in only 14 hours at most.

At present, it is very difficult to get the parts and the actuators answering such severe specifications, so it is the largest bottleneck of the mechatronization of the weaving machines. Especially, development of new actuators which satisfy the specifications is very important and is much desired.



(a) model of air-jet loom



(b) main motion of loom

Figure 1. Schematic of air-jet loom

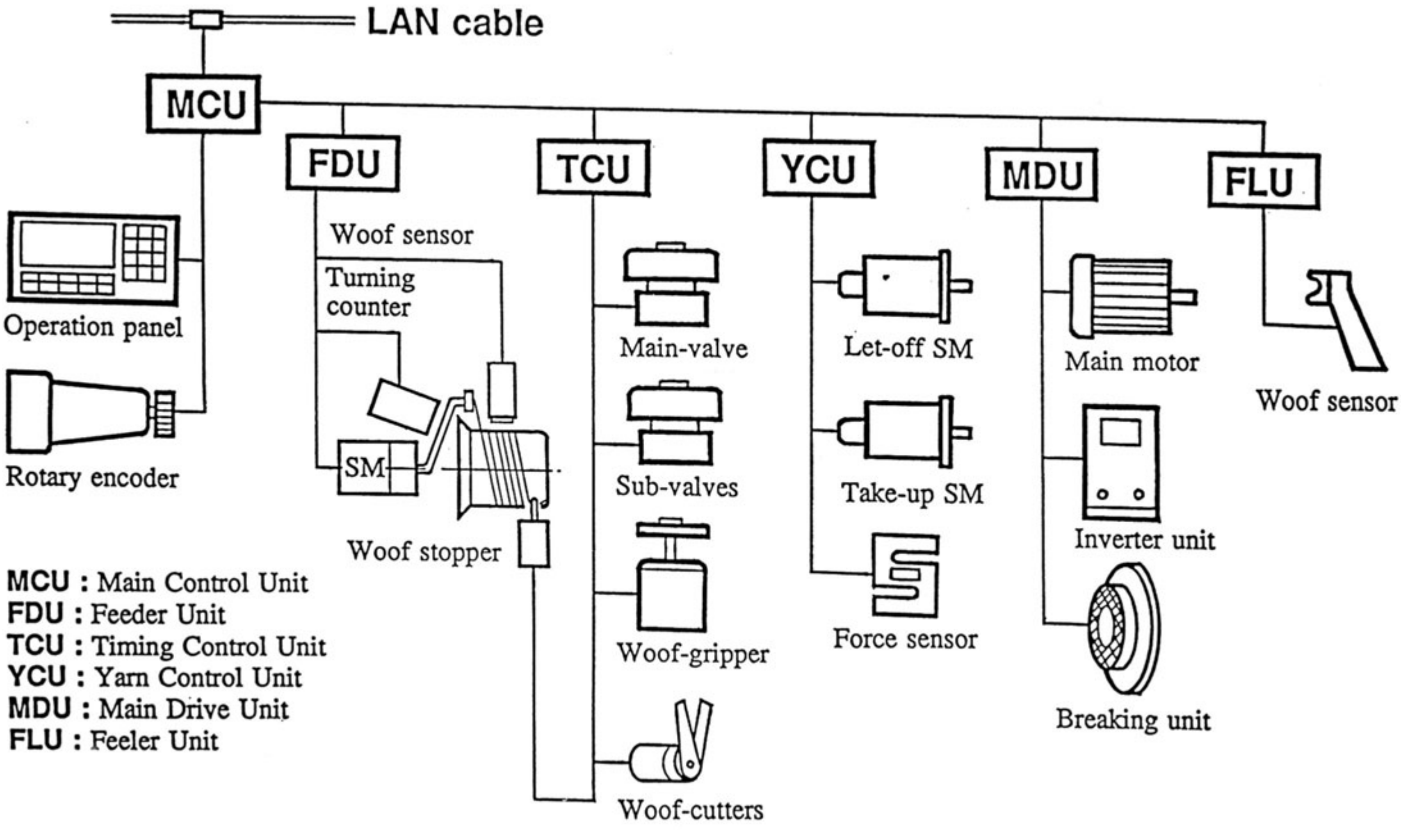
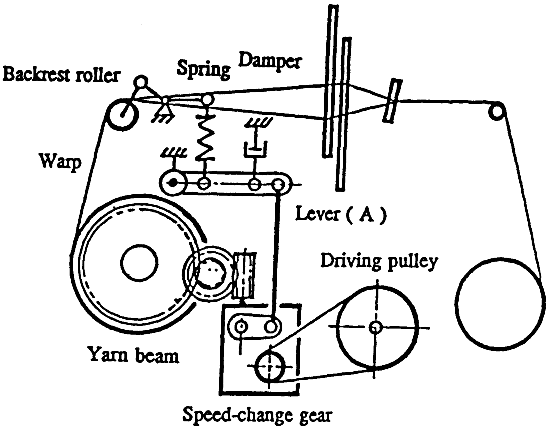
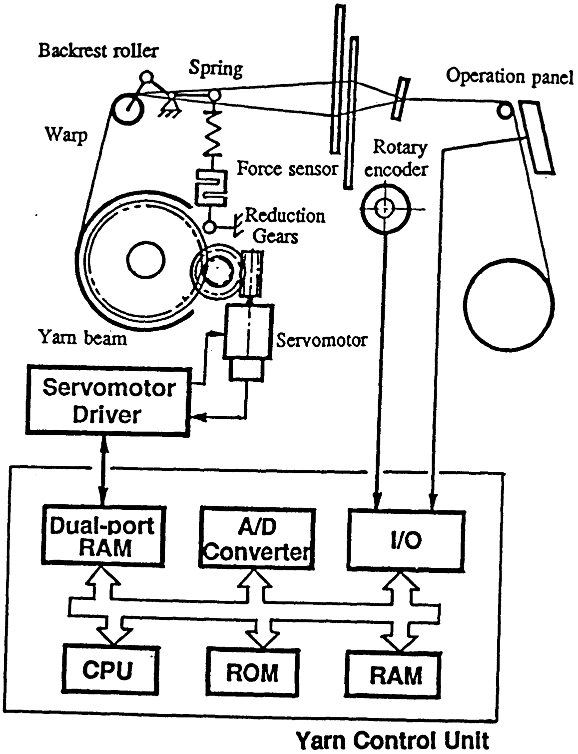


Figure 2. Control system for an air-jet loom

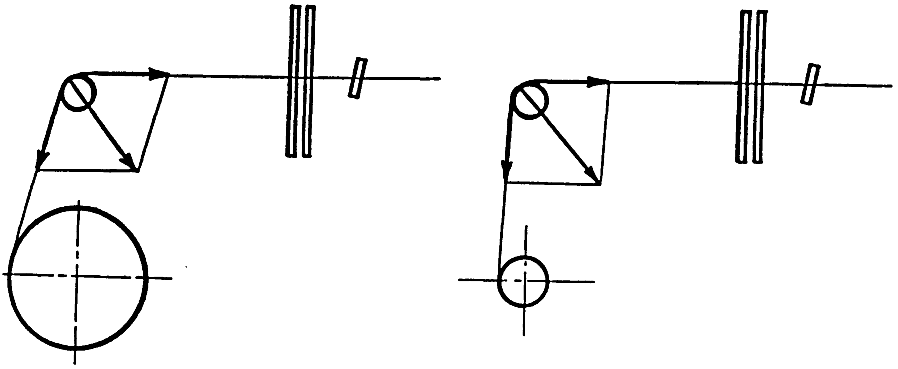


(a) full-mechanical system



(b) mechatronized system

Figure 3. Let-off motion of air-jet loom



(a) fully rolled-up yarn beam (b) almost empty yarn beam

Figure 4. Change of the combined force applied to the backrest roller

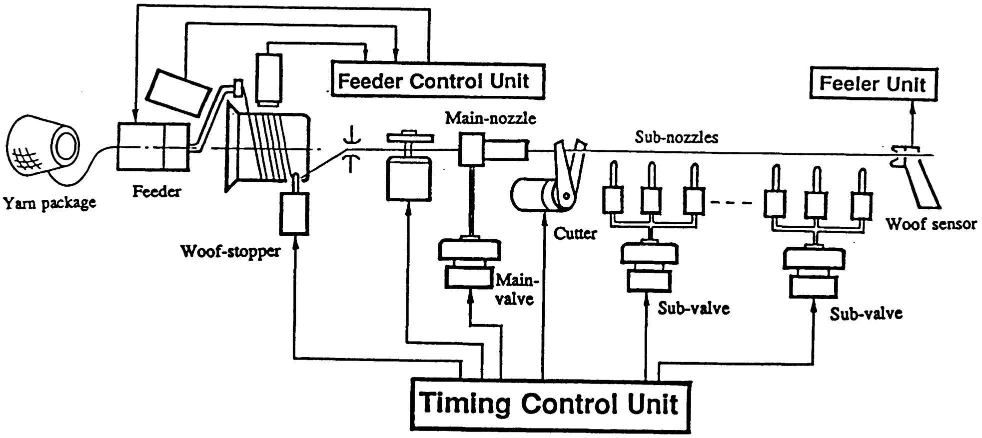


Figure 5. Filling motion system

MECHATRONICS APPLICATIONS IN THREE-DIMENSIONAL BRAIDING

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1. Introduction

This discussion addresses the application of mechatronics to braiding processes, particularly, those processes that afford a measure of flexibility in controlling braid patterns. The ideas presented here grew out of an effort at Clemson University to develop an idealized, three-dimensional braider and which relied heavily on the application of mechatronics. The impetus for the study was the need for complex and variable yarn patterns in textile preforms used for fiber reinforced composite materials [6,11].

These notes also include a brief description of several non-conventional braiding processes that have been proposed as methods of producing three-dimensional structures of the type used for composite preforms. Both the nature of past efforts at developing advanced braiders and the potential for applying mechatronics in such endeavors should be apparent from the discussion. Finally, the recent work at Clemson University will be described.

In most instances the application of mechatronics can be characterized in one of two ways. One category includes those cases in which electronic elements are adapted to an existing, largely mechanical, machine or process as a natural, evolutionary step. The second category consists of those machines or processes in which both the mechanical and electronics aspects of mechatronics are intimately and indivisibly coupled in a compementary way from the start. One of the braiding schemes developed at Clemson is of this second type, where the basic concept is an integration of mechanical and electronic functions and really has no basis other than as a mechatronic process.

2. Braiding Processes

Briefly stated, braiding consists of the interlacing of several yarn to form a structure. Obviously, most weaving processes would be encompassed by so general a definition and no clear, accepted

M. Acar (ed.), Mechatronic Design in Textile Engineering, 199–213.

distinction between braiding and weaving appears to exist. Products having components that are reasonably termed the "warp" and the "weft" are often referred to as woven structures. Others are usually considered braids or knits. Sometimes the classification is based more on the machine than on the process and depends on whether the machines are composed of loom-like or of braider-like elements. Materials produced on conventional looms are readily classified as woven products and materials produced by braiders are referred to a braids. Some definitions have been offered that make distinctions based on the method and/or direction of yarn insertion[6]. However, the distinction blurs when the process evolves into a 3-dimensional weaving process. The semantic dilemma is further revealed by examining a generalized interweaving process. For instance, the general, ideal process could be thought of as a procedure in which the interwoven structure can be produced by the successive exchange of positions of any of many individual yarns arranged in a spatial array. Such a procedure is embodied in the AYPEX process [12], which consists of a series of elementary position changes and has been shown to be capable of yielding any yarn structure. Although the AYPEX process will be discussed more fully later in these notes, it will be instructive to examine it briefly here. The elementary position changes for the process are shown in Figure 1. Interweaving is accomplished by the successive elementary exchanges of positions of adjacent yarns, hence the name Adjacent Yarn Package EXchange. Other braiding (or weaving) processes can be viewed as a less general procedure in which restrictions are placed upon the possible interchanges that can occur and upon the geometric form of the spatial array. A conventional braider, for example, executes a subset of the possible interchanges and this subset is fixed by the mechanical construction of the machine. Conventional weaving consists of a subset of exchanges as illustrated in Figure 2. The shedding operation in weaving is the repeated, simultaneous interchanging of complete rows of yarns. Weft insertion is likewise an exchange of position. A machine capable of executing all of the elemental interchanges would satisfy the definition of a braider that was offered and would be capable of duplicating any of the weaving processes. Loom-like machines are not capable of approaching the general braiding process. However, a machine capable of implementing the general braiding process would likely be an inefficient weaver. In fact it would be an inefficient alternative to produce any materials for which more specifically optimal machines could be dedicated. This is because the flexibility to produce all possible interchanges would result in much redundant capability when applied to the production of a particular material. This complexity can be reduced, however, if the goal is to produce materials having a limited range of variation. For example, ordinary looms are built to yield materials of a certain type but are limited to that type.

3. Three-Dimensional Braiding Processes

As indicated earlier, several non-conventional braiding processes will be described. The examples given here were selected to convey an appropriate overview and to provide a context for discussions to follow.

3.1. ROW AND COLUMN SHIFTING PROCESSES

Several braiders have been developed that involve the sequential shifting of rows and columns of yarns. Some of these processes accommodate both a rectangular array of rows and columns and a circular arrangement having radial and circumferential rows. All suffer from one principal weakness--individual control of a yarn is difficult because entire rows or columns must be shifted as a unit. This problem will become apparent from the examples to follow.

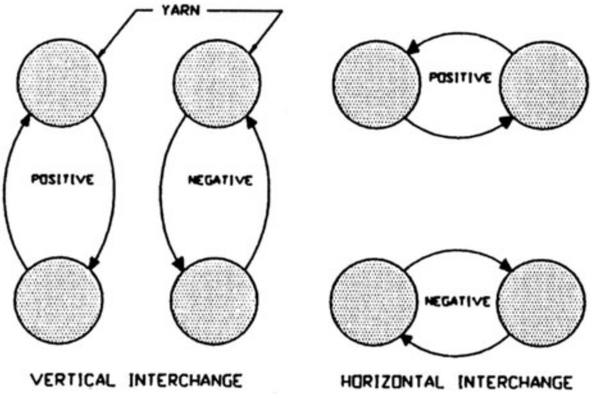

Figure 1: Elementary Position Exchanges in the AYPEX Process

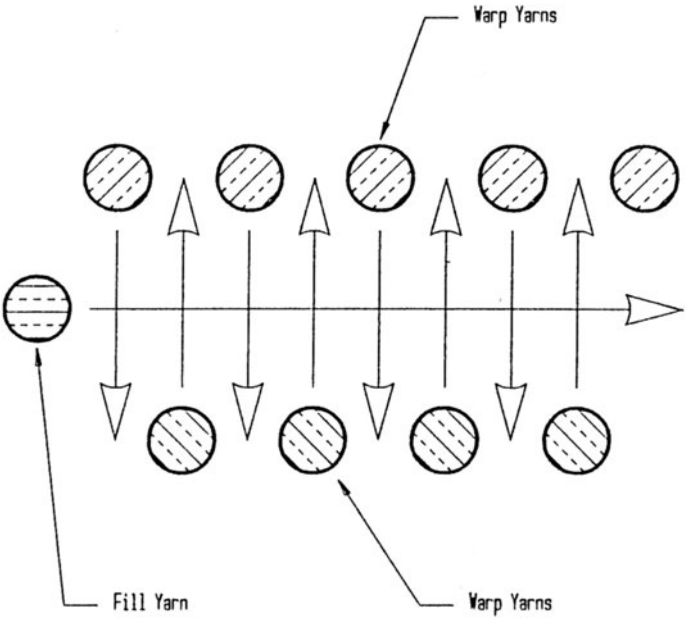

Figure 2: Conventional Weaving as a Position Exchange Process

3.1.1. *The Bluck Braider*[1]--The basic Bluck braider consists of individual yarn carriers arrayed in a rectangular pattern. These carriers are the elements numbered 21 in the patent drawing reproduced in Figure 3 [1]. Elements 27 and 31 are cams arranged and driven so that the rows and columns in the carrier array can be moved back and forth. The timing of these moves is such that adjacent rows are driven in opposite directions followed by a similar shift of adjacent columns. The cumulative effect of these motions results in the individual carriers being driven about in the array causing interlacing to occur. While the weaving process yields a structure that is useful for certain applications, the interlacing pattern is fixed by the mechanical characteristics of the machine and the array of yarn carriers. Large scale machines would also be quite complex. Bluck offered other mechanical schemes for accomplishing the interweaving process. However, they too were limited to one pattern and would yield complex machines.

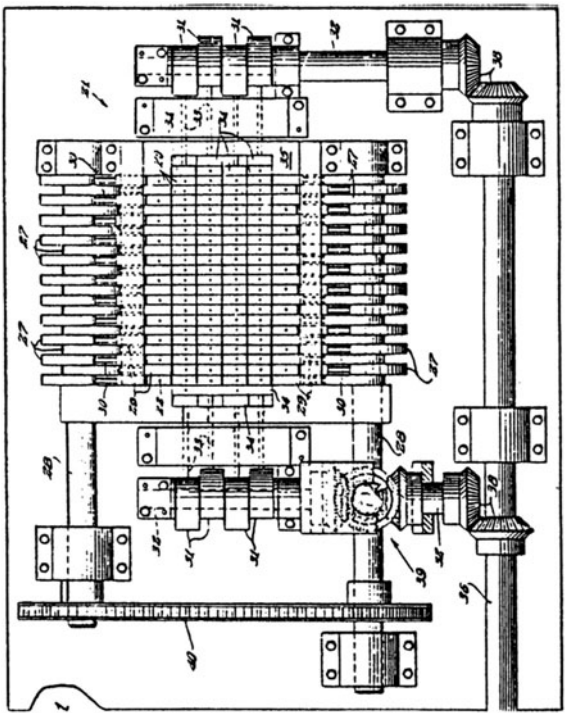

Figure 3: Basic Elements of the Bluck Braiding Process

3.1.2. *The Florentine Approach* [3,4]--Another non-conventional braiding process of the row and column type was suggested by Robert Florentine. It is similar to that of Bluck and can be understood most easily by referring to Figure 4 taken from a US patent [3]. The circular elements depicted represent yarn bobbins arrayed in a rectangular pattern. The items arranged around the array of bobbins (items numbered 44 in the patent drawing) are actuators, possibly hydraulic or pneumatic cylinders, that are used to shift the rows or columns in directions parallel to the rows or columns. By controlling the sequence of column and row shifts, an interlacing pattern is produced that yields a braided structure. The limitation cited earlier is immediately apparent. The destination and path followed by an individual yarn is very difficult to control independently of the paths and destinations of other yarns even though the actuators (hence, the rows and columns) can be individually controlled.

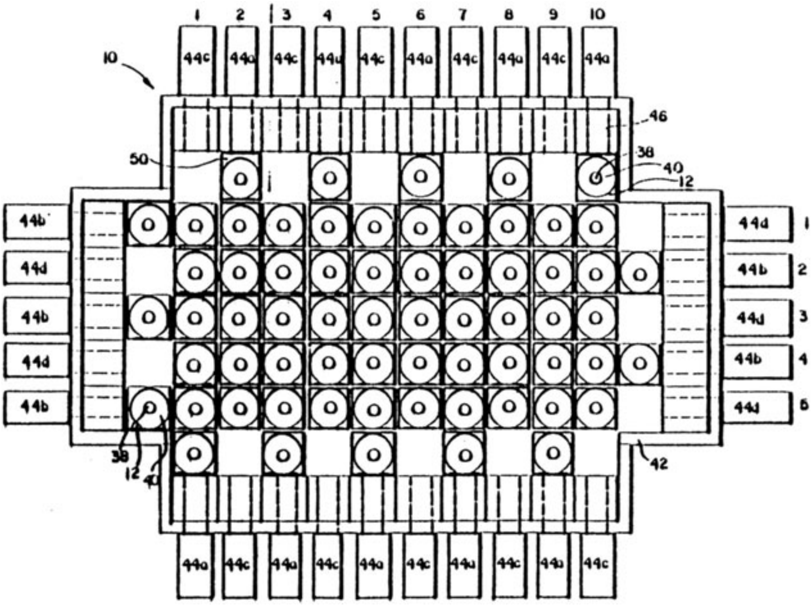

Figure 4: Basic Arrangement of the Florentine Braider

3.2. POSITION EXCHANGE PROCESSES

Processes that shift individual yarns from position to position have also been proposed. Some of the processes afford individual and independent control of yarns and would therefore permit general control of the braid pattern. These processes all require very complex mechanisms if complete generality is to be obtained and therefore have not proved to be practical alternatives.

3.2.1. *The Fukata Process* [5]--The Fukata process results in a braided structure consisting of a series of yarns woven about another series in a perpendicular orientation. Figure 5, reproduced from a US patent [5] for the process illustrates the basic configuration of the structure. The points in the figure labeled Z represent a rectangular array of yarns oriented normal to the plane of the figure. The lines labeled Y_1 and Y_2 and X_1 and X_2 represent the paths of other yarns that weave about the Z-yarns, forming the structure. The braiding yarns are transported from point to point by mechanisms located at each point in the array and that move yarn bobbins individually. The Fukata process requires very complicated machines to accomplish all of the bobbing transfers required. Further, unless the transfer mechanisms are individually controlled, there would be no flexibility in defining the interlacing pattern.

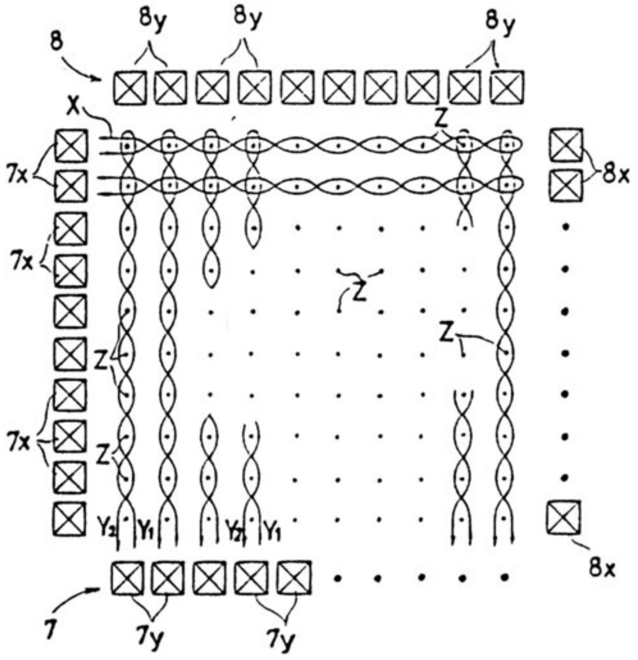

Figure 5: Basic Arrangement of the Fukuta Process

3.2.2. *The APEX Process* [12]--The APEX process was mentioned earlier in the discussion of braiding. The process involves the exchanging of positions of individual yarns in an array. Richard Weller, the originator of the process, has shown that by implementing a combination of several elemental exchanges it is possible to move any individual yarn from any position in the array to any other position. These elemental exchanges were shown earlier in Figure 1. Full implementation of the process would require individually controlled exchange mechanisms at each point in the braid array and would result in mechanically complicated machines requiring complex control systems.

3.2.3. *The Farley Braider*--Gary Farley at the NASA Langley Research Center has proposed a process that would afford completely general control of the braid pattern. It consists of individually powered and controlled tractor units to transport yarn bobbins about the braiding surface. The braiding surface consists of an array of turntables, each capable of indexing 90 degrees. Translation is accomplished by linear tractor moves with the translation direction being controlled by the turntables. The braid pattern is obtained by coordinating tractor moves and turntable rotations. Figure 6 shows the basic configuration of a small prototype machine that was built at Clemson University. While the process has a number of attractive features, it, like several of the other processes, would yield a complex machine when implemented on a practical scale. This process lends itself to mechatronic applications and this aspect of it will be discussed further in later sections.

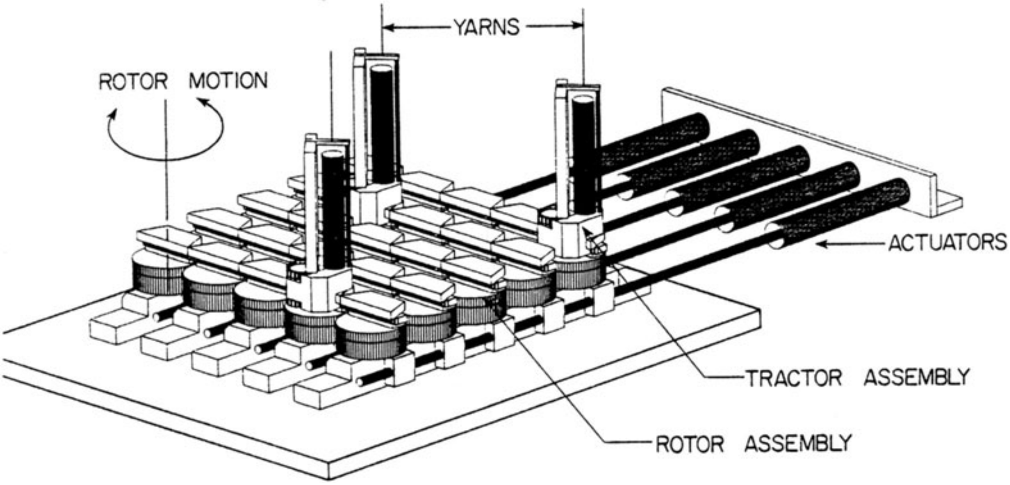

Figure 6: Farley Braider Prototype as Implemented at Clemson University

3.3. OTHER PROCESSES

3.3.1. *The 2-Step Braider* [8,10]--Ronald McConnell and Peter Popper proposed a process that has now become known as the 2-Step process. The process is illustrated in the patent drawing of Figure 7 [8]. It has been implemented in several different locations. Researchers at North Carolina State University have achieved significant success with the process [2,7]. In it a large number of braiding yarns are passed diagonally through an array of axial yarns. The "2-step" terminology derives from the two diagonal directions followed by the braiding yarns as indicated in the figure. The process permits flexible control of the cross-section geometry of the braided structure and is best applied to materials of uniform cross section consisting of many axial, non-braiding yarns.

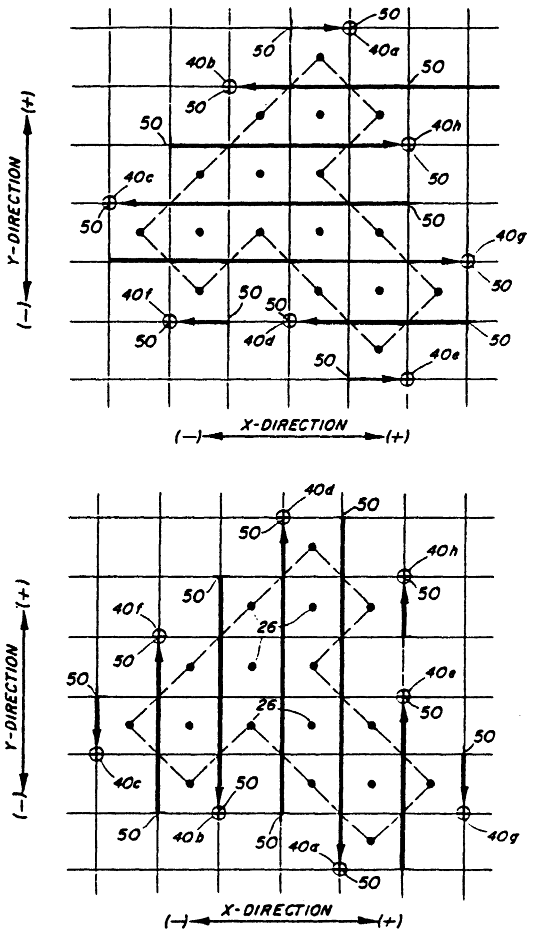

Figure 7: Two-Step Process

3.4 THE IDEAL PROCESS

An ideal braider must satisfy a two-fold, fundamental requirement--it must possess only the mechanical complexity needed to control the braiding pattern, yet be capable of producing generally variable patterns. As suggested by the descriptions above, most 3-D braiding schemes either achieve simplicity by limiting flexibility or seek flexibility at the expense of complexity. The traditional mechanical braiders, the Florentine Magnaweave scheme, and the two-step braider, described above produce braid patterns that are intrinsic to the process. On the other hand, methods such as the AYPEX and the Farley procedures possess the necessary flexibility but suffer from complexity that becomes overwhelming when the process is scaled up to produce large braided sections with full flexibility. Even when the size of the product is modest, the flexibility required to produce a variety of structures requires a great deal of redundant capacity when used for any particular structure.

3.4.1. *Specific Requirements of the Ideal Process*--An examination of the ideal process as considered above yields the following specific attributes that would be embodied in a machine designed to implement the process:

1. A completely general braiding capability, permitting any particular yarn to be moved from any position on the braiding surface to any other position by any prescribed path, must be attained.
2. The mechanical construction and control requirements must be practically feasible, even in machines of large size.
3. A large number of non-braiding, axial yarns, must be accommodated if needed.
4. The braiding action must require a minimum of actively and independently controlled devices.
5. Actively controlled actions should be uncomplicated mechanically.

Concerning item 4, it can be concluded that the minimum number of active yarn transport devices should be no greater than the number of braiding yarns, and that one transport device must be sufficient to drive a yarn completely through a braiding cycle. Also, if individual and independent control of the yarns is achieved, then at any given time the minimum number of actively controlled devices must equal the number of yarns being controlled.

3.5. THE SHUTTLE PLATE BRAIDER

A braiding scheme, referred to here as the shuttle plate process, that approaches the ideal in several respects was developed. A drawing of a prototype machine, also constructed at Clemson University is shown in Figure 8. It depends entirely on the mechatronic synthesis of mechanical and electronic elements.

This braider consists of a braiding surface formed by an array of stationary square sections, each separated from its neighbors by a gap. A flat plate beneath this surface is caused to reciprocate in two perpendicular directions, first in one direction and then in the other. This movement is made possible by openings in the plate that clear short columns supporting the surface segments. Yarns are interwoven as they are moved about the surface by shuttles. These shuttles are caused to engage the reciprocating plate as needed to yield the desired movements. In the first prototype version, both power and control signals were transmitted to the shuttles through electrical contact with the braiding surface. The shuttle plate is the prime mover that supplies the mechanical energy needed to shift all shuttles. The shuttles themselves are very simple devices that employ only a single moving part. This part is a solenoid-actuated plunger that engages the shuttle plate on command. Each shuttle is assigned a unique identity and is controlled independently by directing control commands to particular addresses. The entire process is controlled by a host computer. Figures 9 illustrates the braiding process and shows the prototype braider that was actually constructed.

The shuttle plate device satisfies all of the requirements listed above. Each shuttle is individually and independently controlled. The number of actively controlled devices is equal to the number of braiding yarns (the number of shuttles) plus the shuttle plate--one device more than the theoretical minimum. Should the shuttle plate be made a completely passive prime mover, then the number of actively controlled devices would equal the minimum possible. The mechanical operation of the various components is very simple. For each shuttle the controlled action requires a simple on/off command to actuate a solenoid. Such simplicity is in stark contrast to other methods that require control of actuators, direction control devices, and the like at each surface location that could be occupied by a yarn end. For example, Bluck's braider and the AYPEX process, as originally proposed, require an x-y grid of actuators, all independently controlled and quite complicated in their function. A 100 x 100 braiding grid would require ten thousand such actuators, even when only a few hundred or perhaps a few dozen yarns are being controlled. With the shuttle plate approach, the size of the braiding grid has no effect on the number of controlled devices.

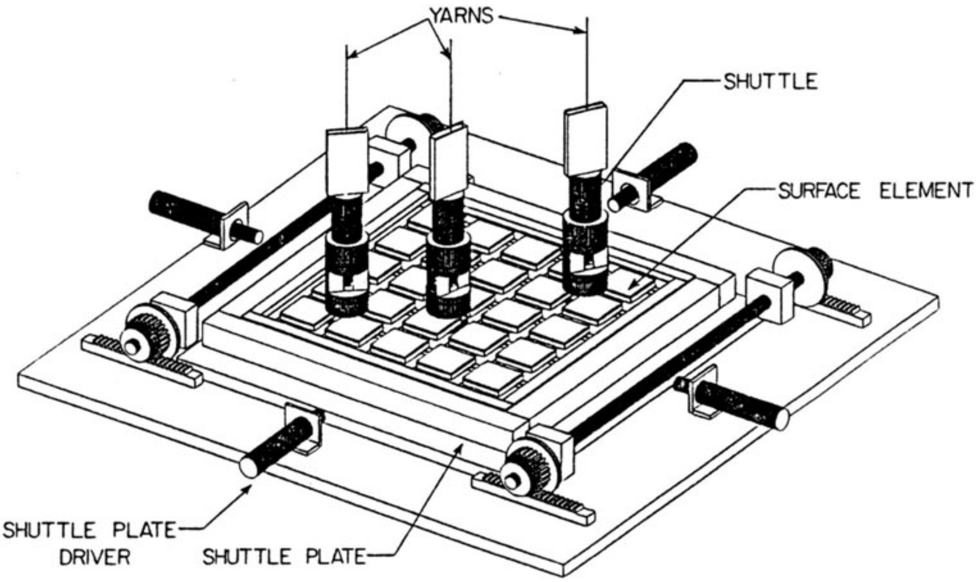

Figure 8: Shuttle Plate Braider Prototype as Implemented at Clemson University

It is possible to make the shuttle plate itself a completely passive device by driving it alternately in one direction then the other at a constant frequency. However, the braiding process can be sped up by independently driving the plate in the two axes in a controlled fashion to eliminate wasted moves when possible. Such control adds one element to the number of controlled devices and promises substantial speed increases for certain braid patterns.

3.5.1. *Mechatronic Aspects of the Shuttle Plate Braider*--As suggested earlier, in this case there is a sort of synergistic relationship between the electronic and mechanical elements, perhaps the essence of mechatronics. Not only are the elements of both types dependent on the other, the integration of the two helps reduce the complexity of both. First, by directly controlling each shuttle the number of controlled devices in reduced to the minimum, as mentioned above. Second, by requiring only an on/off type mechanical operations the electronic control requirements are reduced to a minimum. Obviously, there remains the need to transmit data to the shuttles and to monitor the operation of all components to detect errors, malfunctions and the like. However, this communication is easily implemented using established technology. It is also held to a minimum by holding the number of controlled devices to a minimum and keeping the controlled actions simple.

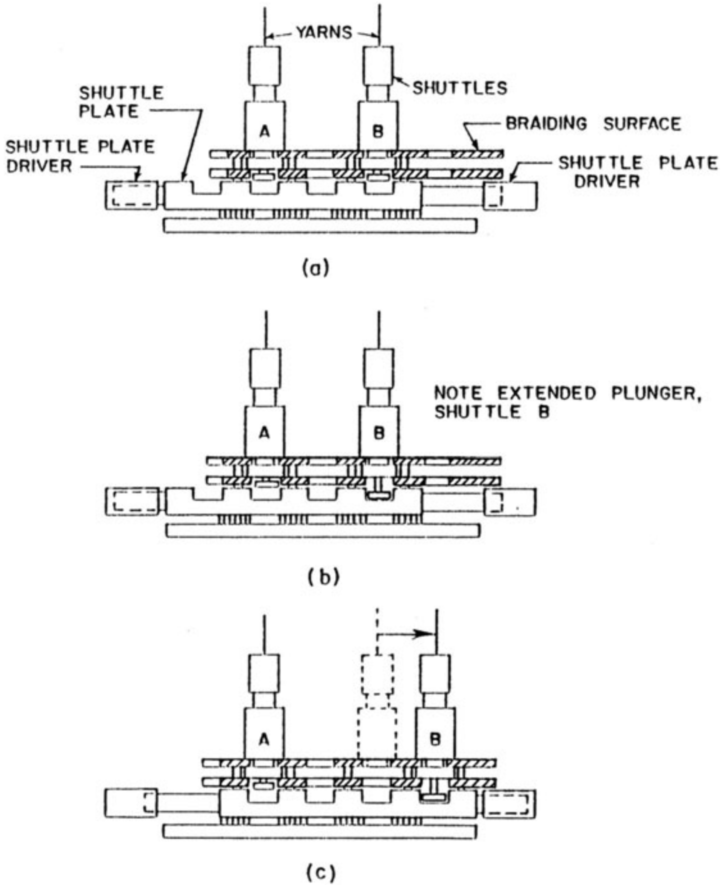

Figure 9: Shuttle Plate Braiding Process

3.6. THE FARLEY BRAIDER

The Farley braider described earlier was also implemented in prototype form. As originally conceived, the Farley braider would consist of a large array of independently controlled rotating turntables. Such independent control of the turntables is desirable but would require an immense number of actively controlled devices when implemented on a practical scale. Consequently, in the prototype, and likely in a practical implementation, the turntables operate in unison and are actuated by a single actively controlled prime mover. The switching action of the turntable array is controlled by a computer with each rotation occurring after a complete set of tractor moves along a given axis. For example, with the turntables set in the X-axis, the tractors are moved as necessary in the X-direction (+ or -). After each tractor reaches its current destination, the turntables are switched to the Y-axis. The next set of moves of the tractors, all in the Y-direction, then take place. The turntables are then returned to the X-axis orientation, and another set of tractor moves occurs. The switching back and forth of the turntables continues in this alternating manner until the entire braiding program has been executed.

3.6.1. *Mechatronic Aspects of the Farley Braider*--Each of the tractors incorporates an electronic control circuit and a small d.c. motor and gear train. Power is conveyed to the tractors through contact with electrically isolated conductors incorporated into the turntables. Control signals are transmitted by frequency modulated optical signals via emitter-detector pairs mounted in the turntables and in the tractors. Directional start signals are transmitted to turntable locations occupied by the tractors. Stop signals are erected at the destinations of the tractors. The tractors, once set in motion, continue in motion until they encounter the stop signals. When all tractors have completed moving, the turntables are commanded to rotate a quarter-turn to align to the opposite coordinate axis. In the current prototype, this rotation is accomplished via solenoid controlled valves and pneumatic cylinders. The rotation completed, the next set of move signals is sent to the tractors and the moves are accomplished as before. Then the turntables are commanded to rotate a quarter-turn, in the opposite direction, back to the original axis orientation. At this time the next tractor move occurs. The sequence continues, alternating between tractor moves and turntable rotations, until the desired braid is completed.

The embodiment of this scheme in the test hardware consists of a 5x5 array, with three tractors. This has proved of sufficient size to test the concepts involved and to allow valid conclusions to be reached. Expansion of the array and the use of additional tractors would be required to scale up the machine to production size. Also, since the tractors are motor-driven and the necessary electrical power is provided through the segmented surface, there is likely to be a practical limit to the number of tractors which can be operated simultaneously with safety.

3.7. A BRIEF COMPARISON OF THE SHUTTLE PLATE AND FARLEY BRAIDERS

The two braiders discussed accomplish truly generalized braiding, both in theory and as reduced to practice, in that they are capable of moving any yarn from any endpoint to any other endpoint by any practical path specified by the programmer. The real significance of this accomplishment is that desired braids which have not been achievable in the past can be made. Comparing the two braiders against each other, as opposed to comparing against other braiding techniques, the following advantages and disadvantages can be cited.

The shuttle plate braider is a very simple design from a mechanical viewpoint, and its control requirements are as simple as they can be made since all that is required are simple on/off commands. Further, all the power needed to move the shuttles is derived from the shuttle plate, and thus little power is needed for the shuttles themselves. The modified Farley braider does not have this simplicity, but it does have the advantage of speed for braiding patterns which require numerous long length moves of the yarn carriers. In addition, while at any given time all the yarn carriers of the modified Farley braider must move along a given axis, some can be moving in the forward direction while others are moving in the reverse direction. Of course, this speed advantage diminishes as the average move length of a yarn carrier becomes shorter in complex patterns.

For the Farley braider there is a concern regarding the timing and synchronization of moves between yarn carriers, especially as the number of carriers increases. This concern could force the use of more complicated devices, such as stepper motors, and proximity detectors to avoid collisions between the tractors. The shuttle plate braider does not have this timing difficult since all shuttle moves are automatically synchronized by the driving plate.

Although both braiders transmit power to the yarn carriers via the braiding surface, the power requirement is significantly different. The shuttle plate braider requires electrical power to engage the solenoid in each shuttle. As currently implemented, this power is held continually to maintain engagement. Activation of several solenoids at the same time would require high currents on the surface. However, there are numerous ways to overcome this difficulty in a scaled up version of the shuttle plate braider. These include such options as using mechanical latching and momentary currents to engage the latch. For the Farley braider, the motors must be powered continually. Thus the power, of necessity, must increase as the number of moving yarn carriers increases. There is no simple solution to this dilemma. The shuttle plate braider scales up readily since the control problem remains the same no matter the size of the braider. The inherently more difficult control of long moves and the timing difficulties discussed above make it more difficult to scale up the Farley. In its favor, it should be noted that the Farley braider might more easily be implemented on an upwardly curved surface. Use of such a surface would reduce the size of the braiding surface needed to control braid angles. However, such an approach would complicate the design significantly. For example, the turntables of of such an arrangement would have to be of unequal size or rotate through unequal angles, depending upon location on the braiding surface. Finally, set-up and operation of the shuttle plate braider is much easier and more reliable, as demonstrated in operation to date.

Either braider could be applied to special or short-run production items, since such situations could not justify the development of special, dedicated machines. Of course, some products, even if to be mass produced, might require the flexibility offered by the approach described for these two braiders.

3.8. SOME OBSERVATIONS

It is risky to generalize on the basis of limited experience. However, several observations have grown out of the experience with the two braiders described above and are offered as food for thought.

1. The promise of mechatronics is greatest where controlled actions are spatially distributed and the actions must be independently and individually controlled. This observation is based on the immense simplification afforded by the shuttle plate process when compared to the AYPEX process or any of the others that would require large numbers of controlled devices.
2. Communication technology and signal processing are likely to be important components of mechatronic systems used in situations such as those described in item 1. The obvious need for either centralized control or coordination of distributed activities gives rise to this observation.

3. When possible, separating control actions from operations that require significant amounts of power should be pursued. A comparison of the shuttle plate and Farley braiders supports this conclusion. In the case of the shuttle plate braider, the gross operating power is derived from the shuttle plate. As discussed earlier, this arrangement avoids the need for significant amounts of power on board the shuttles. In one sense the mechatronic components serve as amplifiers--devices taking in low-power inputs and yielding higher powered outputs. In the case of the Farley braider, motive power is provided by the tractors. Distribution of sufficient power to the mechatronic devices in cases such as this is likely to bring with it some serious problems.

4. Summary

A successful attempt to develop and implement generalized, three dimensional braiding has been accomplished. Two practical schemes for implementation have been designed, built, and tested. Both schemes, as implemented, produce the motions necessary, with a reasonable level of control. Each scheme has its advantages and disadvantages. However, the shuttle plate braider offers the greater immediate promise because of its mechanical simplicity and ease of control, especially when scaled up to practical dimensions. Both rely on the application of mechatronics to accomplish the flexibility of operation that is required without becoming overly complex mechanically.

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Design of An Automatic Weaving Machine For 3-D Net Shapes

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ABSTRACT. This paper reviews existing 3-D weaving processes and presents a new patented process developed at the Mars Mission Research Center of North Carolina State University. The design of an automated machine based on the U.S. patent will be presented. Preforms woven on this prototype machine and the properties of different composites made from carbon fibers for space applications will be discussed. Comparison of the properties of the new materials with existing ones showed superior performance.

INTRODUCTION

The use of high performance textile structural composites is becoming increasingly popular in many engineering applications. Examples include aerospace and aircraft structural components, deep submergence vessels, sports equipment, textile machinery and automotive parts. The rate of growth of composite use is expected to continue to increase rapidly with new developments in fiber and matrix materials and manufacturing technologies.

Fiber reinforced composites basically consist of two fundamental components; the reinforcing fibers and the surrounding matrix. Technologies for the manufacture of the reinforcing fibrous preforms include a number of conventional textile processes as well as several specialty techniques developed mainly for the composites industry. Laminating several layers of a woven fabric, cross-laying of tapes of continuous filaments or filament winding the fibers into the required shape were most common in the late seventies and early eighties. However, because of failure by delamination of the these materials, several systems of producing three-dimensional integral shapes have been developed over the last decade. The new textile systems include 3-D braiding, 3-D weaving and 3-D knitting. Other systems were developed especially for bodies of revolution or for the manufacture of billets which have to be machined to the required shapes after consolidation. Recently stitching multiple layers of multi-axial warp knitted 2-D fabric into 3-D shapes has improved the availability of structures with several fiber orientations as well as enhanced damage tolerance.

Considerable development work is taking place in industry, research institutes and universities to automate 3-D braiding machinery using the 2-step and 4-step processes [1-3]. Developments in 3-D weaving of net shapes have not been given sufficient attention by the industry. This lack of activity was the driving force behind the effort which will be described in this paper. Composites made with 3-D integral structures woven or braided into net shapes offer considerable advantages over laminated composites. The properties which made composite materials so attractive include their high specific strength, high specific modulus and low thermal expansion coefficient among others [4]. However, the high cost of advanced composites has limited their use mostly to space and military applications, where the

M. Acar (ed.), Mechatronic Design in Textile Engineering, 215–229.

performance of these materials has been unmatched by metals.

REVIEW OF 3-D WEAVING PROCESSES

Mohamed [5] reviewed the different methods of producing three-dimensional textiles and their influence on the fiber architectures produced. However, since the main topic at hand is weaving, this review will only deal with the different 3-D weaving processes. In the strict sense, three-dimensional fabrics not only have three-dimensional shape, but also have yarns in three or more directions.

Multi-layer woven fabrics have been used for a long time in industrial applications, particularly in belting and webbing. Multi-layer fabrics are composed of several series of warp and weft yarns which form distinct layers, one about the other [6]. Binding the layers together can be achieved by many ways, either by interlacing warp ends in the structure with the weft of adjacent layers (referred to as angle interlock), or by having ends interlace between the face and back layers (warp interlock). The binding yarns may also interlace with the weft vertically up and down between layers producing an orthogonal weave. This system usually involves inserting the weft one pick at a time, which requires moving the fabric up and down, during beat-up, to achieve the desired thickness. The loom can be adapted to weave three-dimensional shapes by the proper arrangement of the warp. However, it is very difficult to maintain all yarns in the structure straight. Only straight yarns contribute their full strength to that direction.

An integrated 3-D structure is produced by the process invented by Fukuta, et.al [7], shown by Figure 1. This method comprises three steps: 1) inserting a number of doubled weft yarns (Y direction, across the width) between layers of warp yarns (X direction, axial), 2) inserting vertical Z yarns between the rows of the axial warp yarns perpendicularly to the weft and warp directions, and 3) packing the yarns together using a reed. The structure produced is 3-D orthogonal. The density of the structure is limited by the need have sufficient distance between the yarns to accommodate the means of inserting the weft and Z yarns. The patent described the production of structures with rectangular cross section only and did not describe the formation of 3-D net shapes.

King [8] invented a different method of forming three-dimensional structure. In this method, shown by Figure 2, the Z axis yarns, which are rigid rods made of a self-supporting material, are vertically oriented and positioned passing through holes in the upper frame and resting in mating recesses in the upper surface of the lower frame. The X and Y axes filament feed units are essentially identical. They insert the X and Y filaments by advancing parallel, equally spaced needles alternately. The X and Y yarns are doubled and are inserted leaving a loop at the far outside edge of the Z axis filaments. The selvage (fabric edge) is formed by pins which hold the X and Y axes yarn loops during insertion. The pins may be removed as the filament layers build up. After sufficient layers have been formed, it is suggested (but not necessary) to compress the fabric along the Z axis by lowering the upper frame. Again, this method is used to produce only structures with rectangular cross sections. The patent also describes a different method to produce cylindrical shapes.

THE NEW 3-D WEAVING PROCESS

Mohamed et.al. [9] developed a new process for forming variable cross-sectional shaped three-dimensional fabrics. This method of weaving 3-D net shapes utilizes different weft yarn insertion from at least one side of the warp layers for selectively inserting weft yarns into different portions of the fabric cross-sectional profile defined by the warp yarn layers. If inserted from both sides of the warp yarn layers, the weft yarns may be inserted simultaneously or alternately from each side of the warp yarn layers. The vertical yarns, which are part of the warp, are then inserted into the fabric by reciprocating a plurality of harnesses which separate the vertical yarn systems as required by the shape of the three-dimensional fabric being formed.

Based on the system used for moving the harnesses, the structure could by either 3-D orthogonal, angle interlock, warp interlock or combination of all three in the same piece. Mohamed et.al. [10] used this process to produce thick panels and structural elements with different cross sections such as T and I with fairly thick walls in all directions.

THE AUTOMATED 3-D WEAVING MACHINE

Mohamed et al. [11] described an automated, computer controlled machine designed to weave 3-D orthogonal structures according to the method described above. Warp yarns taken from bobbins on a creel are separated into layers to allow for weft insertion. In this case there are more than one layer, and thus more than one shed. These warp sheds are fixed open. Multiple weft yarns are inserted through the sheds by needles. The Z yarns are fed into the machine parallel with warp yarns and separated into two layers controlled by harness. When the top Z yarn layer is moved to the bottom and the bottom Z yarn layer is moved to the top (achieved by crossing the harnesses) a vertical component of yarn is added.

The weaving process can be described as follows: several needles containing doubled weft yarns are inserted horizontally through the sheds in one motion, as shown by Figure 3. The weft yarns (Filling I and Filling II in Figure 3) can be inserted simultaneously or alternately and from one or both sides according the cross-sectional shape. The weft yarn loops are temporarily held on the opposite side by a vertical "selvage needle", as shown by Figure 4. The insertion needles are then withdrawn to their original position leaving behind a set of doubled weft yarns. A reed is brought forward (beat-up) packing the yarns into a tight structure, as shown by Figure 5. While the reed is forward, the harnesses are crossed thus placing the Z yarns, as shown by Figure 6. The selvage needles are lowered and the formed structure is then "taken-up", that is, moved a distance corresponding to the required spacing of the weft yarns.

The reed is then moved back and the entire cycle is repeated. This process lends itself to continuous production of long structures.

MACHINE DESCRIPTION

The yarn supply is from bobbins on a creel behind the machine. The tensioning of the warp and Z yarns is achieved by weights applied to the yarns individually. The layers of warp yarns are drawn through the reed in a formation similar to the shape being produced. Weft yarn tension is controlled both passively and actively and varies throughout the weaving cycle. Figure 7 shows a photograph for the yarn arrangement on the machine while weaving a double stiffened panel (double T).

All the motions are pneumatically actuated, with the exception of the take-up action. This simplified the design of the machine and eliminates the need for drive motor which could have a high risk of being shorted when weaving carbon fibers. Double acting air cylinders controlled by solenoids are used for weft insertion, reed, harness and the selvage needle movements. The reed movement is controlled to be linear and perpendicular to the insertion direction. The linear motion is necessary to ensure the vertical placement of the Z yarns. A step motor is used to turn a threaded rod causing the linear motion effecting fabric take-up. A microprocessor using a simple program, written in BASIC controls the timing of all the movements and the amount of take-up.

To control the neatness of the edges, the selvage yarns are knitted through the weft loops.

MICROPROCESSOR AND COMPUTER CONTROL

The control system of the 3-D automatic weaving machine consists of a microcomputer, a control board which is connected to the computer with an interface card, solenoid air valves, a step motor, and pneumatic cylinders. Any microcomputer should be able to accomplish the control job, because of the availability, an IBM compatible 386/16 personal computer is used for the machine. An AC5 parallel interface card is used for digital input and output. This card enables the PC to communicate with OPTO 22's PB24 mounting rack, which can accommodate up to 24 single channel I/O modules. One channel is used for checking on/off status of the control switch to cause the machine to run or to pause. Two channels are used for the operation of the step motor. The rest of the channels are for controlling the solenoid air valves. A flow chart of the control system is shown in Figure 8.

The control programs are written in BASIC language and are stored in either a floppy disc or a hard disc. Figure 9 shows a flow chart of the control program. Depending on the dimensions and the cross-section of the preform to be woven, an appropriate program can be loaded to run the machine. The parameters and the programs themselves can be modified to meet different weaving requirements. The machine speed could be controlled by changing the corresponding parameters in the programs.

Control of the pick density is by means of the number of steps made by the take-up motor. Increasing the steps decreases the pick density.

MANUFACTURE AND PROPERTIES OF COMPOSITES

Dickinson et.al. [12], Mohamed et.al. [13] and Brandt el.al. [14] produced several composite panels using a variety of preform structures produced by the new 3-D weaving process. Carbon fibers and three types of epoxy were used as well as commingled carbon/PEEK. The epoxy was infiltrated using different techniques, whereas the carbon/PEEK was consolidated using heat and pressure.

Tensile, bending, compression and compression after impact are some of the properties investigated. Comparison between composites made with the new and old types of reinforcement showed, in general, superior performance to the new materials. One of the main reasons for the superior properties is the ability to control all three yarn sets to remain straight in the structure. Another major advantage for 3-D integrally woven preforms is their lack of sensitivity to the presence of voids. In laminated composites, voids represent areas of stress concentration at which usually delamination failure starts. Table 1 shows a summary of some of the properties obtained for the above mentioned composites.

CONCLUSIONS

A new method of 3-D weaving of net shapes has been successfully developed and patented. The combination of electronics and mechanical actions (mechatronics) has been utilized in the design and operation of the 3-D weaving machine.

Different composite materials using the new preforms have been produced and compared favorably with the state-of-the-arts technologies.

ACKNOWLEDGEMENT

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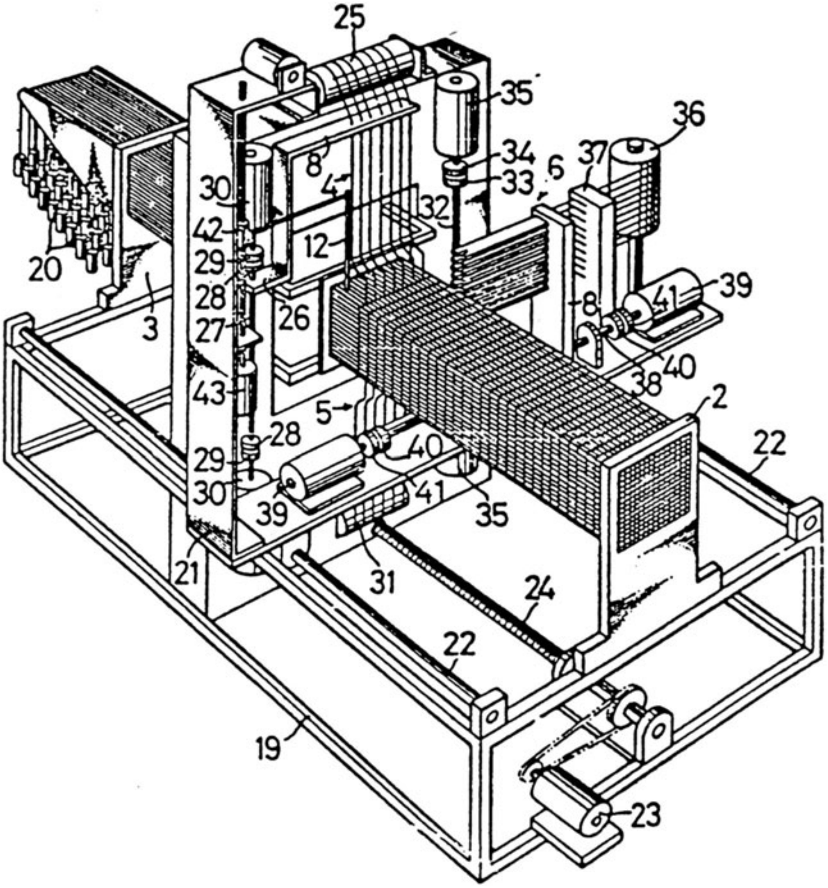

Figure 1. Fukuta's 3-D Billet Manufacturing Machine

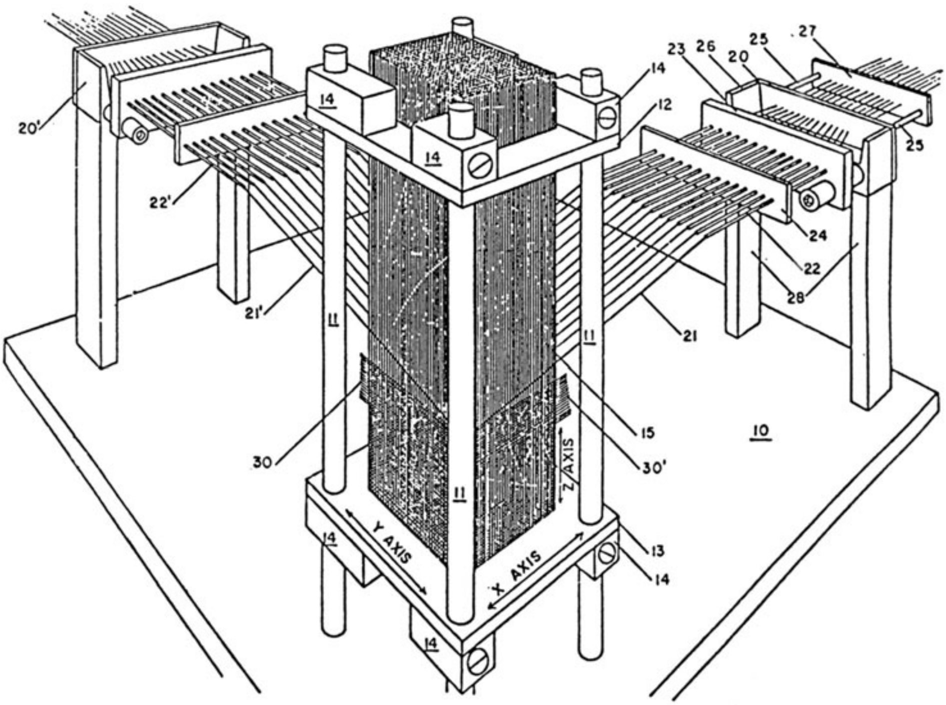

Figure 2. King's 3-D Billet Manufacturing Machine

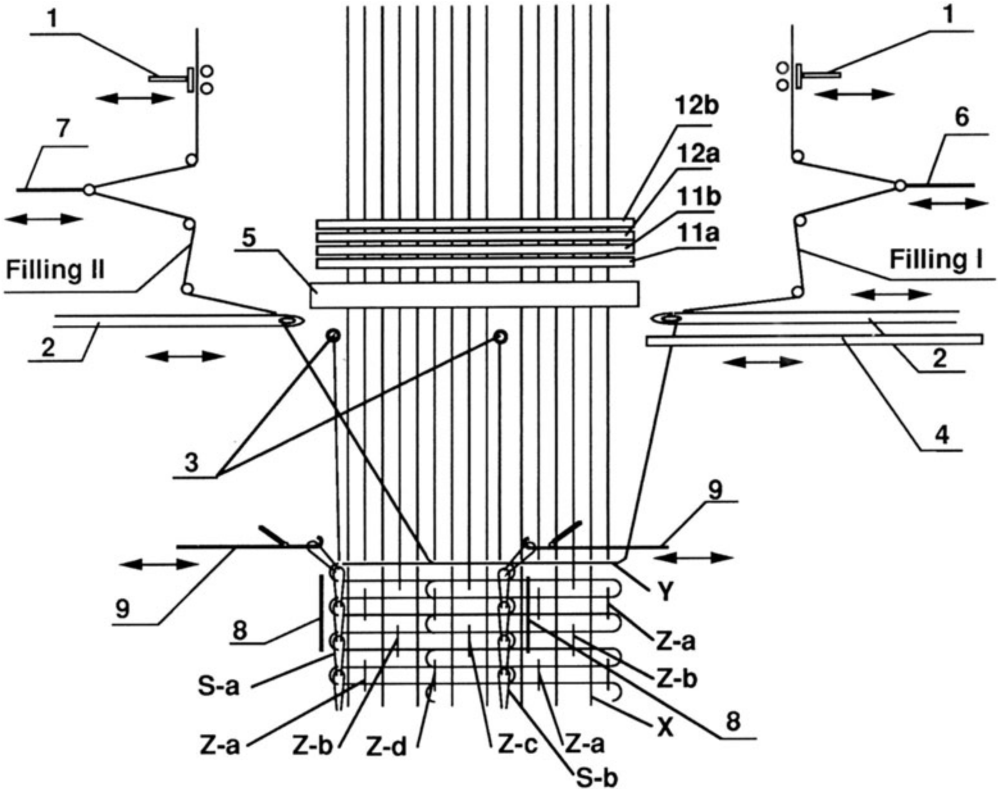

Figure 3. Filling Insertion By Needles from Both Sides

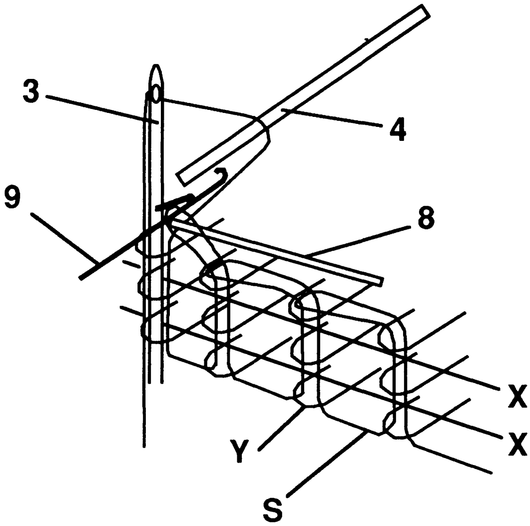

Figure 4. Knitting of Selvage Yarn

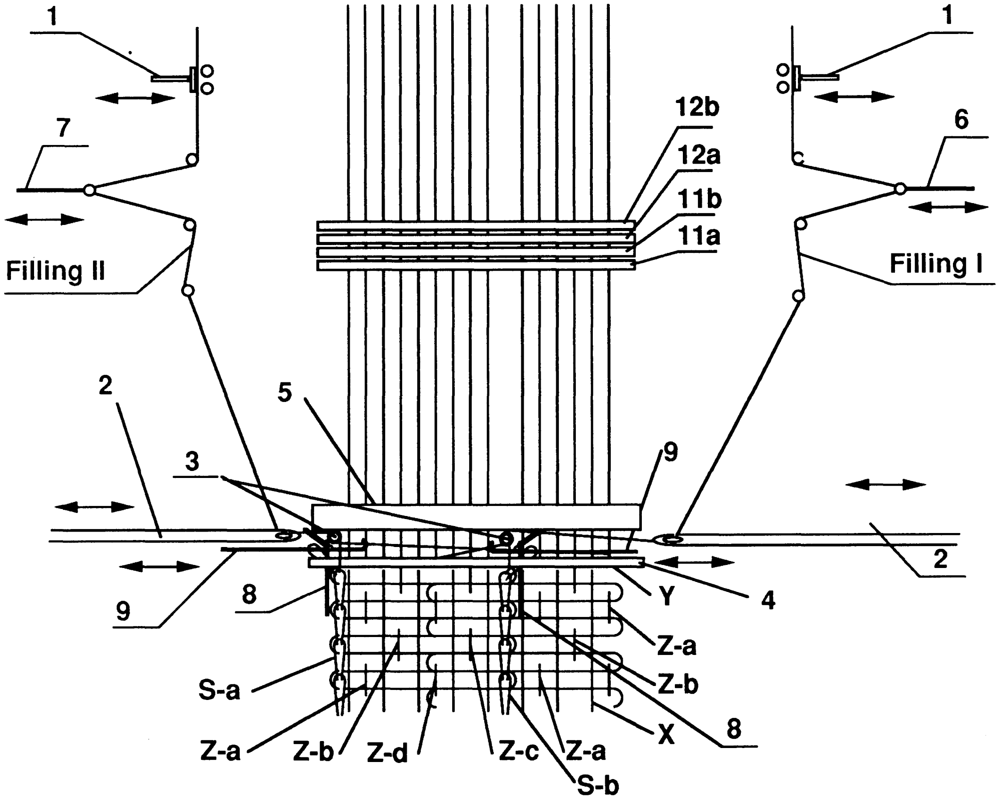

Figure 5. Beat-up Position

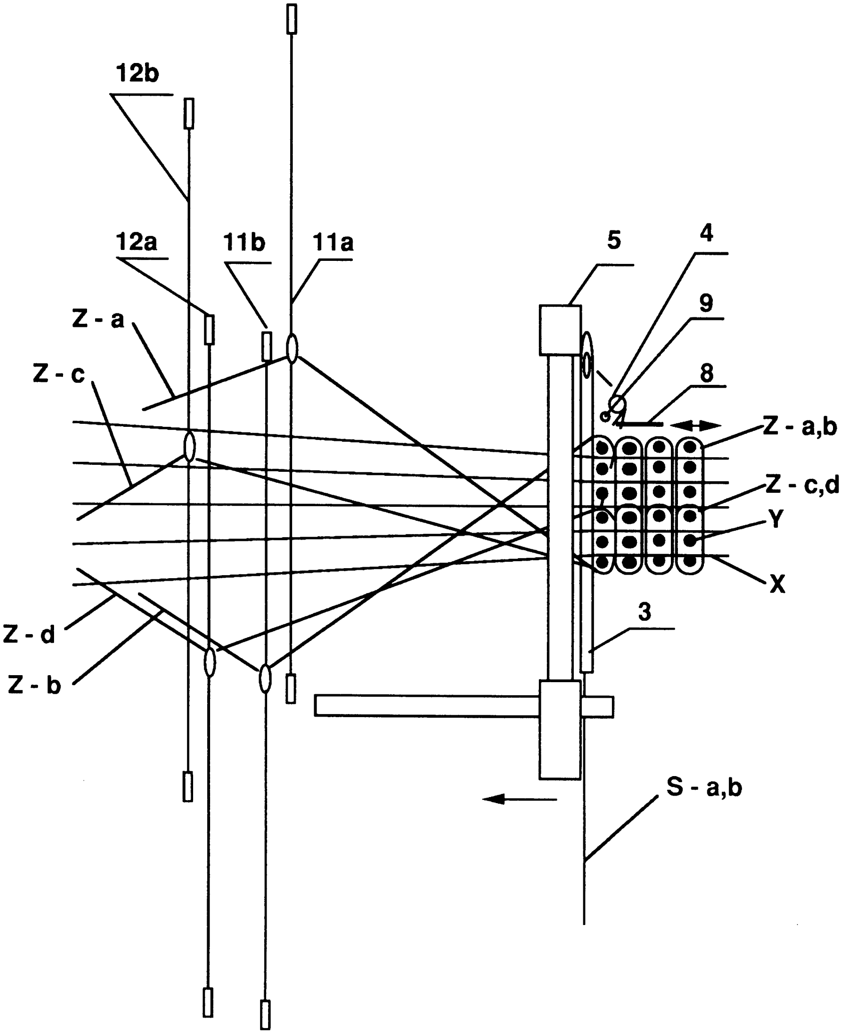

Figure 6. Crossing of the Z Yarns by Harness Movement

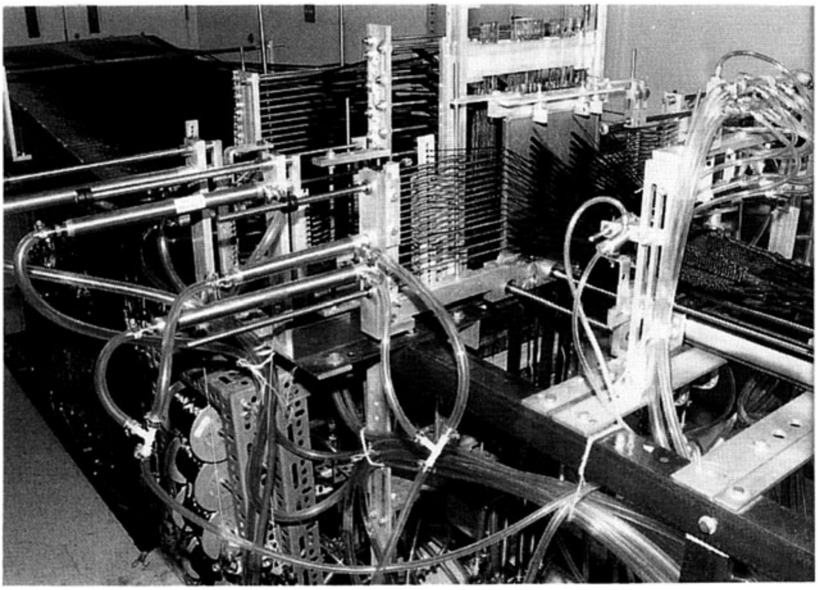

Figure 7. View of the Weaving Machine

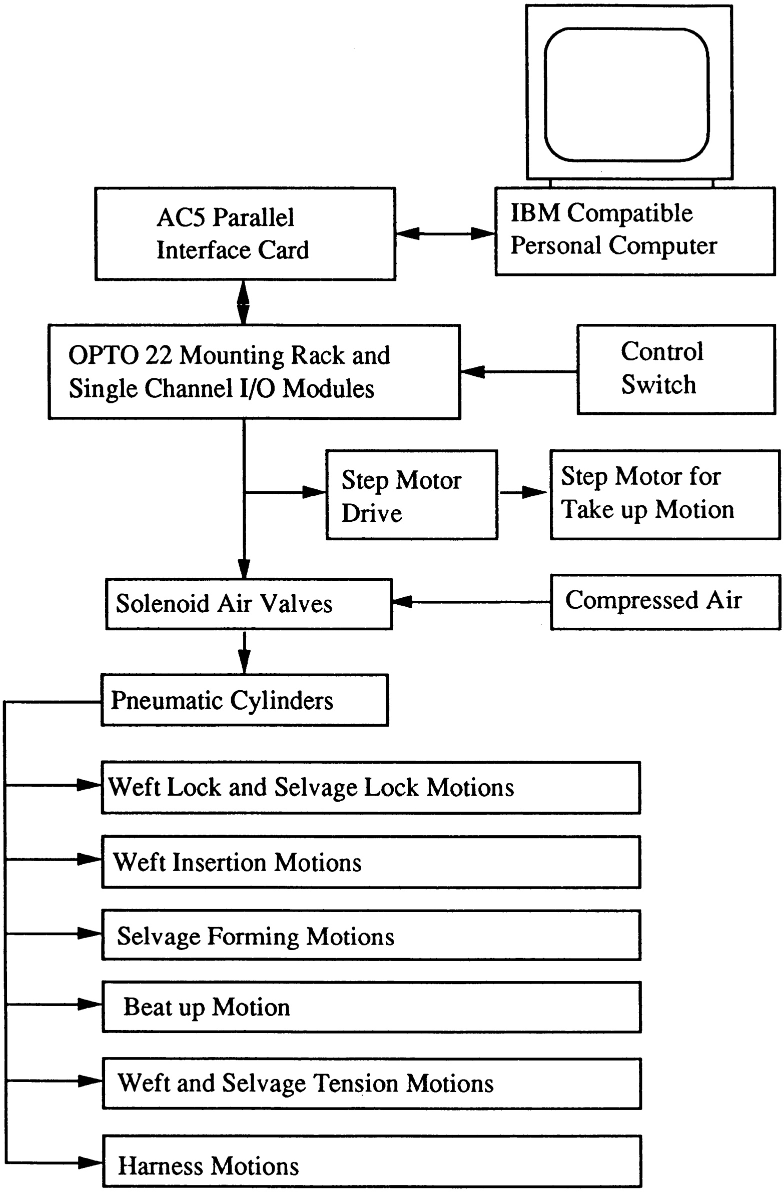

Figure 8. A Flow Chart of the Control System for the 3 - D Automatic Weaving Machine

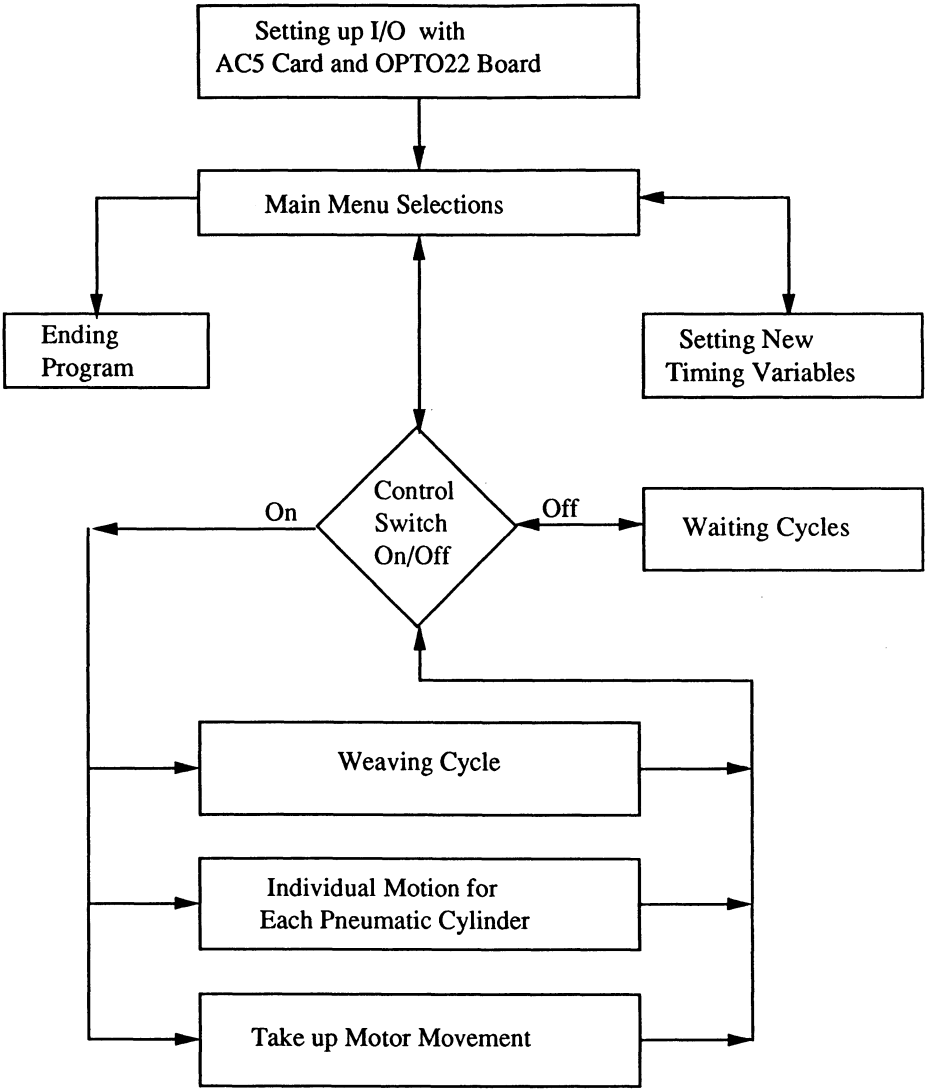

Figure 9. A Flow Chart of the Control Program for the 3 - D Automatic Weaving Machine

Table 1. Properties of 3 – D Woven Composites [14]

	Warp	Weft
Tensile Strength (MPa)	674	629
Tensile Modulus (GPa)	72	55
Compression Strength (MPa)	535	500
Compression Modulus (GPa)	64	55
Flexural Strength (MPa)	580	–
Flexural Modulus (GPa)	51	–
CAI (MPa) (3.3 J/mm)	350	–
CAI (MPa) (6.7 J/mm)	301	–
Energy Absorption (J)	81	

DEVELOPMENT OF A LAN SYSTEM FOR WEAVING FACTORIES

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ABSTRACT. The productive method in weaving factories has been changing from mass production to small scale production of various kind of textile fabrics. To keep high productivity, new production management system suitable for weaving factories has been much desired. In this paper, introducing the Nissan LAN System, one of the most widespread LAN system in Japanese textile industry, we consider the essentials of the management system for weaving factories.

1. Introduction

In recent years, the productive method in weaving factories has been changing from mass production to small scale production of various kind of textile fabrics to keep up with the diversification of the consumers' preference. The production of many kinds of fabrics frequently requires change of the warp on weaving machines. Generally speaking, it takes a lot of time to change the warp on the weaving machine, so that frequent changes of the textiles cause the productivity to lower. Therefore, it is getting more important to reduce the preparation time for changing the warp on the weaving machine. In order to keep the productivity from lowering, the development of a new monitoring system (total production management system) suitable for weaving factories has been much desired.

As compared with general production lines such as TV assembly lines, the textile production in weaving factories has some peculiarities as follows:

1) There are many causes of forcing weaving machines to stop working. Since the time necessary for restarting the stopped machine depends on the causes, it is difficult to precisely predict the time on which the textile on the machine will be finished.
2) The quality of the product is approximately proportion to the number of times the weaving machine stopped. In other words, the machine halt affects not only the productivity but the quality of the products.
3) There are many old factories in which the installation of LAN system is not taken into account.
4) The installation cost of LAN system per weaving machine must be as cheep as possible because weaving factories usually have many weaving machines.
5) There are many old machines without capability of communication with external equipments.

Taking these circumstances into consideration, we need a flexible management system

M. Acar (ed.), Mechatronic Design in Textile Engineering, 231–238.

suitable for many weaving factories. Nissan Motor Co. Ltd., one of the Japanese manufacturers of weaving machinery, has developed a LAN system for weaving factories to improve the textile productivity. In this paper, introducing the Nissan LAN System (hereafter referred to NLS), we consider the essentials of the management system for weaving factories.

2. The outline of the NLS

The NLS has some kinds of configurations according to the scale of the factories. One of the general configuration of the NLS is shown in Fig.1. The NLS is divided into three parts, LTB, NWC and DPB. The LTB, which stands for *Loom Terminal computer Block*, is attached to each weaving machine and many LTBs are connected to the NWC (*Net Work Controller*) using RS-422 interface. Since the main function of the NWC is a communication server, it is seemed that the LTB directly communicates with the DPB (*Data Processing Block*, that is the host computer of this system). The LTB plays the role of an equipment for communication between the weaving machine and the DPB, providing information on the machine's state, product's quality and so on, and controlling the weaving machine according to many commands given by the DPB.

The DPB, which is usually installed in office away from the factory, collects various data from each LTB and outputs many kinds of reports, for example, an analysis of the causes of the machine halt, the prediction of the time on which the product on the weaving machine will be finished. In addition, various data to control weaving machines are stored in the DPB and they are provided for operators in field as well as in office by means of the LTB. The software on DPB is written with a database language, MUMPS, so that various databases can be constructed very easily. The operators of the weaving machine can access and update the databases in field using the LTB.

2.1. LTB (Loom Terminal computer Block)

The function of the LTB differs with the weaving machines to be connected with. Since the machine which is not mechatronized has no means of communication, the LTB inputs raw signals of the machine by interception and directly controls the weaving machine. On the other hand, in the case of mechatronized weaving machines, the LTB communicates with the micro-processors, which is originally installed in the weaving machine to control the devices, through another serial port. The hardware of the LTB is the same in both cases and the difference between the weaving machines is adapted by software.

Figure 2 shows a schematic of the LTB. The LTB is connected with a LAN cable using RS-422 serial port. Because cheep 3-wired shield cables are used as the LAN cable in order to lower the costs, the flow-control of the communication is performed by software. The LTB has a operation panel with keypad used by the operator of the weaving machine and LED to show him / her the status of the machine.

The LTB is basically connected to the weaving machine by means of DIO (Digital Input / Output) port. In addition, if the machine has a communication port, the LTB communicates with the machine and performs input / output of various information. In this case, the micro-processor of the weaving machine becomes a server and processes the commands and the requests given by the LTB. In the case that the weaving machine has no function for communication, the operator can use the serial port of the LTB to connect with a portable terminal and get more detail information about the weaving machine besides the information which can be obtained from the operation panel on the LTB. An example of the signals linking between the LTB and the weaving machine is shown in Fig.3.

One of the important role of the LTB is measurement of the cloth-length produced by the weaving machine. As a general process of the product, the following operation is repeated in weaving factories. That is, when a desired cloth-length is produced by the weaving machine, the operator stops the weaving machine from working, cuts the cloth off, and sends it to the inspection process. To measure the cloth-length, a mechanical counter as shown in Fig. 4, which basically measures the rotational angle of the friction roller was used in the past. This device could hardly measure the cloth-length precisely due to slip motion between the cloth and the friction roller. Therefore, the operator set the counter value taking the slip quantity into account empirically. However, that value can not use for a new textile product. The counter value for the new product must be set to larger value because a shorter cloth than standard can not be accepted in Japan. Such operation had caused several meters of loss cloth.

LTB counts the number of woof and calculates the cloth-length L by the following equation.

$$L = n / D \tag{1}$$

where

n : number of woof
D : woof density [/inch]

One pulse of the picking signal generated by the weaving machine corresponds to one woof, and it also equals to one rotation of main driving shaft of the weaving machine. The microprocessor of the LTB is interrupted by the pulse and performs a measurement procedure. The interruption does not affect the performance of the CPU so much because its interval time is long enough, for example, it is 100 ms in the case of weaving machine at 600 RPM.

In addition, the LTB controls the machine halt caused by the failure of an insertion of woof into the warp. Usually, in case a failure of woof-insertion occurs, the weaving machine automatically stop running or it makes a flaw in quality like a lateral line in the cloth. Then, the operator (weaver) manually inserts a woof into the warp and restarts the weaving machine. However, there are some waiting time for restarting it because the operator usually covers many weaving machines.

By the way, there are some textile fabrics of which quality failures seldom occur in weaving. In such textiles, a few lateral lines caused by the failure of woof-insertion does not affect the quality grade of the textile. Therefore, in that case, user can use a function of the LTB which the LTB intentionally ignores the signal of the failure of woof-insertion not to halt the machine. By using this function, user can improve the productivity without lowering the quality grade. The allowable times depend on textile. Such data is statistically obtained referring to the results of the quality inspections. The data is stored in the DPB, and it is loaded to the LTB when textile on weaving machine will be changed.

If the weaving machine has capability of communicating with the LTB, many data for optimal adjustment of the weaving machine, which has been determined in advance, are transferred to the micro-processor on the weaving machine through the LTB. The detail will be described the following section.

2.2. NWC (Network Controller)

The NWC plays the role of a communication server. Approximately one hundred LTBs (that is one hundred weaving machines) are connected to one NWC. In order to avoid contention, the polling method is used for data transmission. As an actual condition, the polling method, which is easy to maintain the network system, performs enough because the traffic on the network of NLS is not so heavy.

Since a 3-wired cable is used as the LAN cable, the communication is performed by using software-flow-control. The communication protocol is a simple re-sending sequence using ACK / NAK codes.

2.3. DPB (Data Processing Block)

The DPB collects many kinds of data from all the LTBs through the NWC and performs prediction of the time needed to finish products, analysis of causes that weaving machines were forced to halt, and so on. Then the DPB outputs various kinds of reports as the results. These functions falls under the category of general monitoring system.

In addition, DPB works as a database management system handling the following data:

1) The production management data
2) The quality control data
3) The machine-adjustment data
4) The textile management data

These data are linked closely each other and are updated on real time using information such as working rates of weaving machines, the results of quality inspections.

The software on DPB is written with a programming language, MUMPS. MUMPS is a database-oriented language including the function of the operating system such as multi-user and multi-task system. Using this language facilitates the organization of the databases which the NLS needs. Since MUMPS is also a general purpose language, the system software like a program for communication is also written with MUMPS.

3. A case of operation of NLS in weaving factories

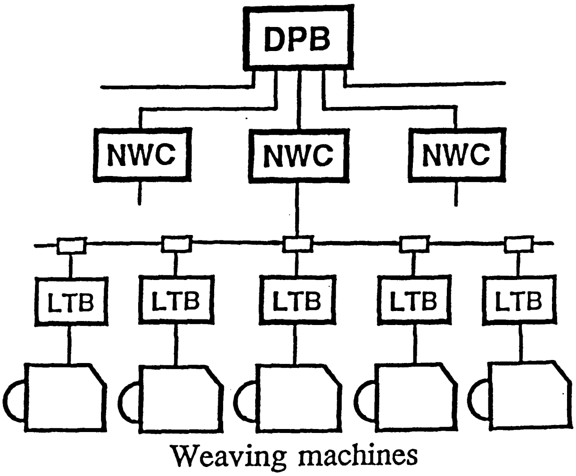
Figure 5 shows a flowchart of the products. First of all, a production schedule for each weaving machine is made according to a general production schedule. As mentioned before, the operator in field can refer to all the databases including the production schedules. The operator first asks the LTB the production schedule for the weaving machine. The LTB shows the next scheduled textile to be produced by accessing to the production management database. The operator then obtains the machine-adjustment data for the textile. According to the data, the operator adjusts the weaving machine and begins running it.

The working rates of the weaving machine is monitored by the LTB and sent the DPB one by one. The operator can refer to the working record of the machine by accessing to the data of the machine operation on the DPB using the LTB. If he realizes that the working record of the weaving machine is poor, the operator retries to adjust the machine and inputs to the LTB what he tried. This data is very important to confirm whether his adjustments is proper or not. This process enables the operator to find a optimal condition of the weaving machine for the textile.

As soon as the cloth was finished weaving, it is sent the quality inspection process. In the inspection process, the quality grade of the cloth is stored to the quality database on the DPB. The operator can access the database in field and check whether the machine is producing fine cloths or not. It prevents the weaving machine from continuing to weave the defective products.

4. Summary

Introducing the NLS (Nissan LAN System), it was presented what the total management system suitable for weaving factories in which many kinds of textiles are produced in small scale should be. The centralistic monitoring system is not suited for the small scale production method and it can hardly operate the factory efficiently. It is very important to make a field-oriented flexible system suitable for weaving factories.



DPB : Data Processing Block (Host Computer)
NWC : NetWork Controller
LTB : LAN computer Terminal Block

Figure 1. Configuration of Nissan LAN System

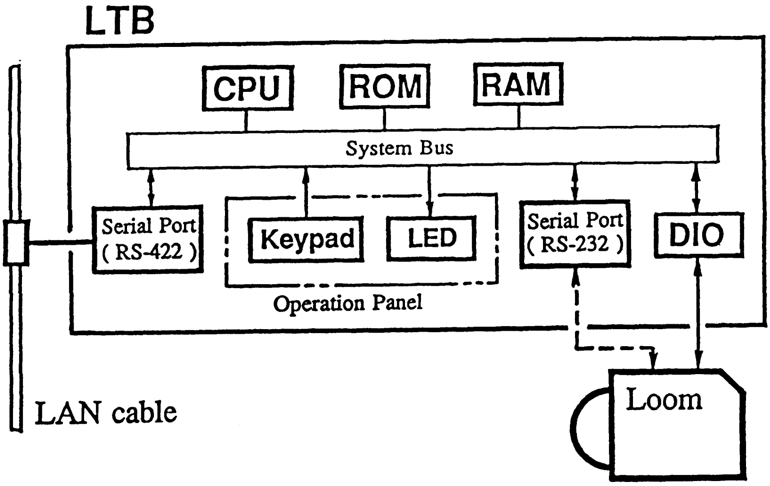


Figure 2. Schematic of LTB

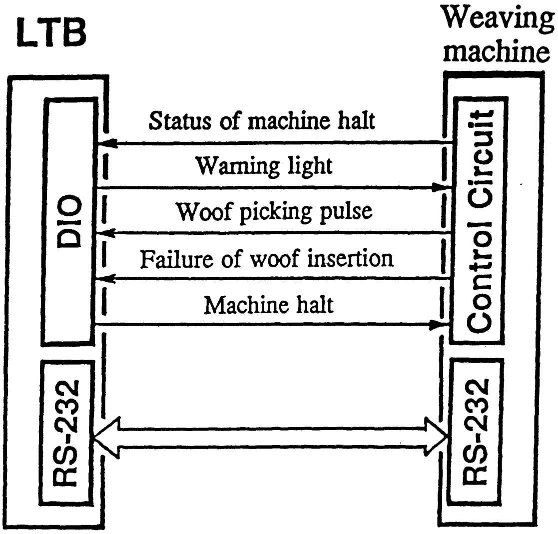


Figure 3. Interface between LTB and weaving machine

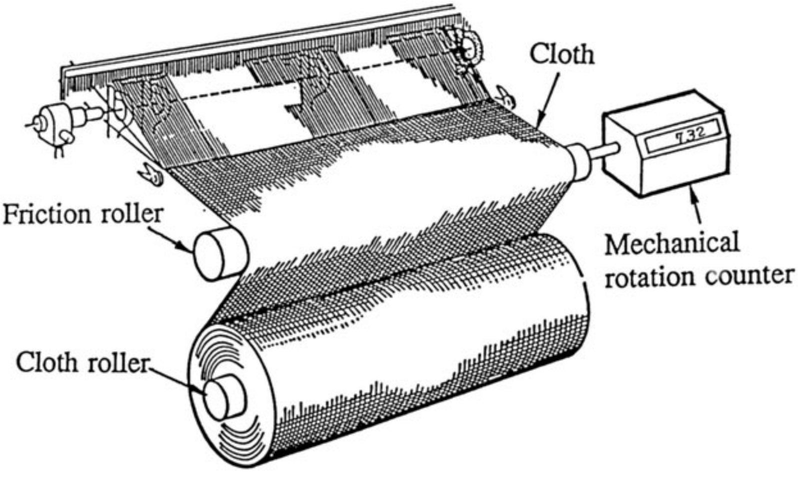


Figure 4. Conventional measurement of cloth length

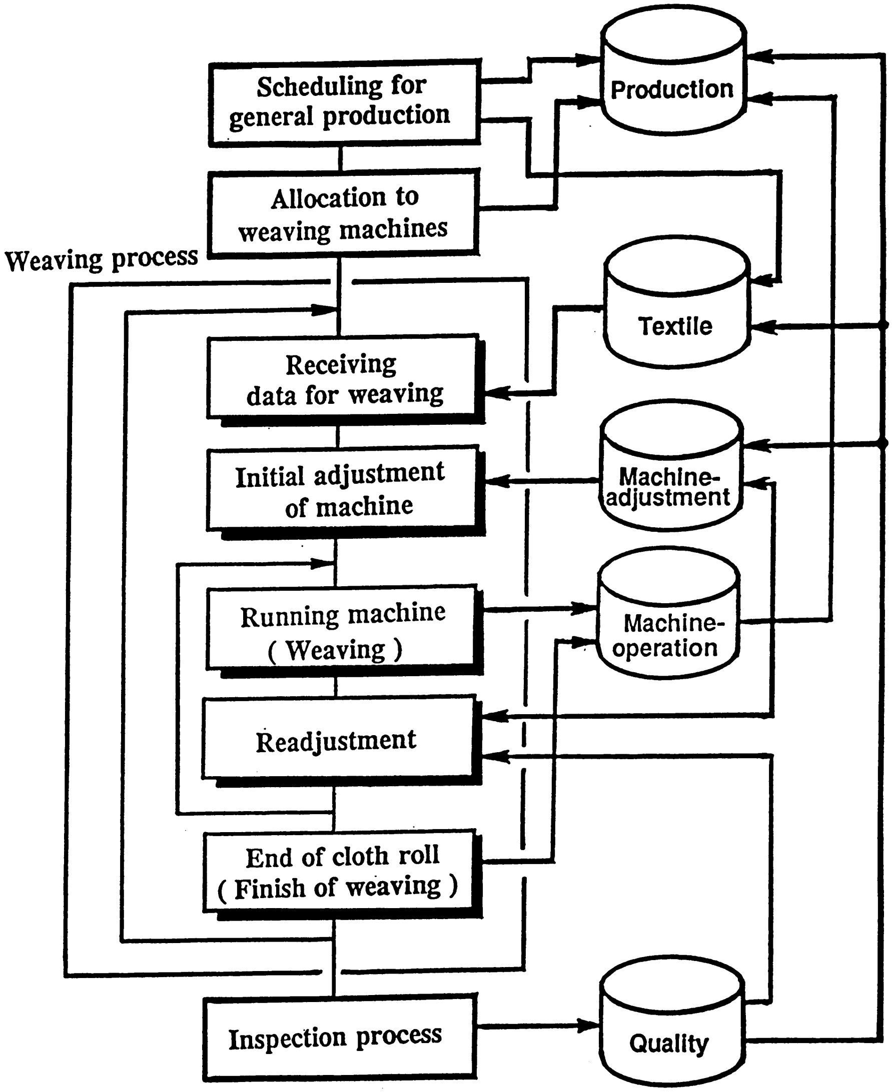


Figure 5. Flowchart of weaving process

COMPUTER-AIDED DESIGN AND MANUFACTURING: A TEXTILE-APPAREL PERSPECTIVE

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ABSTRACT. Today's textile-apparel industrial complex is characterized by a multitude of conflicting demands: smaller lot sizes, increased product flexibility, higher product quality and decreasing delivery times. The textile/apparel industry must deploy state-of-the-art manufacturing and information management techniques to operate successfully in such a demanding and highly competitive global market. In this context, the role and scope of mechatronics in textile-apparel production systems are discussed with specific examples. The need for techniques and tools such as information engineering, electronic data interchange and knowledge-based systems technology is established and their relevance to the textile-apparel complex is discussed. An overview of major research endeavors including the development of an enterprise architecture, knowledge-based systems and product data standards is presented. Finally, some topics for further research in areas ranging from distributed design and manufacturing to the development of product data exchange standards are proposed.

1. Introduction

Today's textile-apparel industrial complex is characterized by a multitude of conflicting demands: smaller lot sizes, increased product flexibility, higher product quality and decreasing delivery times. To operate successfully in such a demanding and highly competitive global market, the textile/apparel industry must deploy state-of-the-art manufacturing and information management techniques; the major techniques are Computer-Integrated Manufacturing (CIM), Concurrent Engineering (CE), Design for Manufacturability (DFM), uniform product representation standards, Just-in-Time (JIT) manufacturing, Quick Response (QR) and Total Quality Management (TQM). The tools or means for successfully applying these techniques throughout the life-cycle of the textile/apparel domain are automation, robotics, computers, electronic data interchange (EDI), knowledge-based systems (KBS), information engineering, and structured analysis and design tools (SADT). In other words, the key lies in successfully integrating mechanical (or physical) elements of the system with the electronic (or information) components.

M. Acar (ed.), Mechatronic Design in Textile Engineering, 239–269.

1.1 MECHATRONICS AND THE TEXTILE-APPAREL COMPLEX

Mechatronics, a term coined by Japanese researchers, is commonly defined as the efficient integration of mechanical and electronic engineering to create an optimum product. The ultimate objective of any enterprise is to produce the *right* product, of the *right* quality, in the *right* quantity, at the *right* price and at the *right* time (the five *R*s of a manufacturing enterprise) [7]. The application of the mechatronics philosophy, viz., the effective utilization of state-of-the-art technology (be it mechanical or computing) in all facets of its operation -- design, development, planning, production, distribution, marketing and business -- will enable the enterprise to achieve its goals in the highly dynamic and competitive global market.

1.1.1 Integration and the Textile-Apparel Complex: An enterprise that effectively integrates the various functions through a common information/knowledge base is generally referred to as a Computer-Integrated Enterprise (CIE) [9]. The key to achieving a computer-integrated-textile-apparel complex lies in a careful study and adoption of the principles of mechatronics by the industry. Moreover, to achieve true integration, the traditional lines that have separated the major components or building blocks (fibers, textiles and apparel) must disappear.

The word *integration* is used in a broader context than just physical proximity or co-location. Figure 1 shows the three major functions associated with a typical scenario in the textile-apparel life-cycle. The *product design* activity may be physically located in any of the major fashion centers of the world, viz., Milano, Paris or New York; the plant to carry out the *product manufacturing* function may be located in Greenville, Hong Kong or Biella, and *product marketing* can take place in retail stores around the world from London to Tokyo. As lead times become shorter and demand for product variety increases, coordination and control -- or *conceptual integration* -- of the three major activities become critical. It is therefore clear that mechatronics has a vital role to play in the textile-apparel complex.

In this Chapter, the state of the textile-apparel industrial complex vis-a-vis the mechatronics philosophy is examined. In Section 2, specific applications of mechatronic elements in textile-apparel production systems are discussed. In Section 3, the roles of information engineering, electronic data interchange and knowledge-based systems technology in developing mechatronic solutions are discussed. Ongoing research activities and scope for further research efforts are covered in Section 4. Finally, some concluding remarks are presented in Section 5.

2. Mechatronics and Textile-Apparel Production Systems

Figure 2 shows a detailed view of the interrelationships between the three major functions in the textile-apparel complex. Two major types of entities flow through, and are processed by, the functions. They are *physical* entities such as fabrics and garments, and *information* entities such as design specifications and market trends. The flow of physical entities is predominantly in a single or forward direction (denoted by thick lines in the figure). In contrast, the flow of information entities is bidirectional (thin lines in the figure). In fact, as the industry becomes increasingly driven by what the consumer wants and demands, i.e., consumer-driven design and manufacturing (CDDAM) becomes the accepted norm in the industry, the information flow in the reverse direction (from the consumer to the manufacturer and designer) will assume greater importance. And the ability of an enterprise to successfully utilize this and other information to rapidly reconfigure itself -- change designs, fabrics, styles, production and marketing

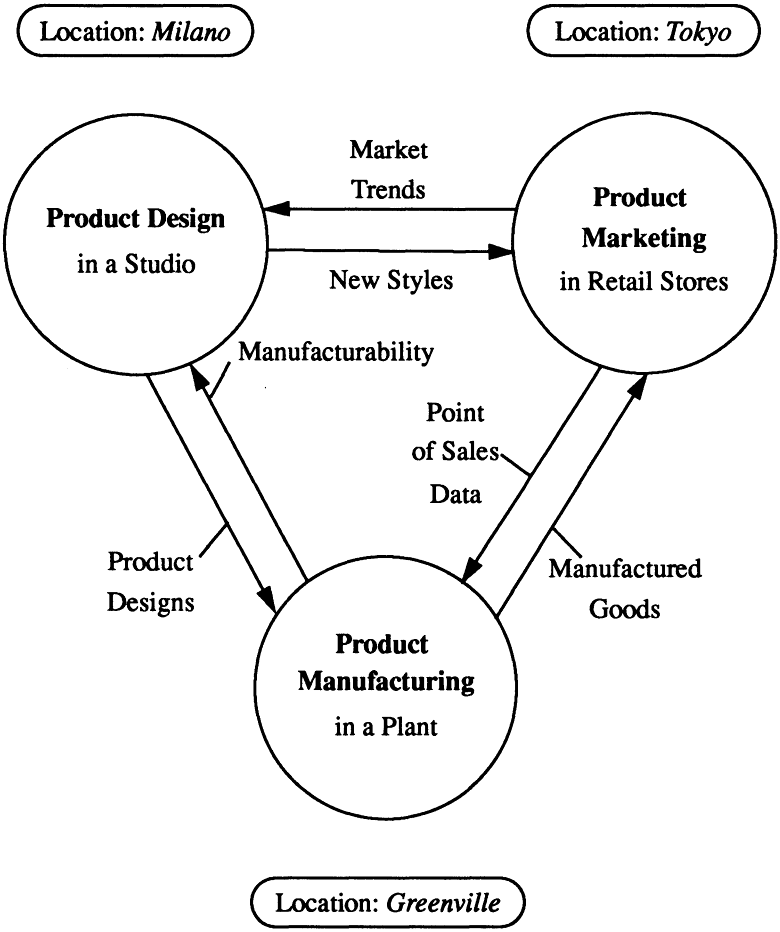

Figure 1. Primary Functions in the Textile/Apparel Complex.

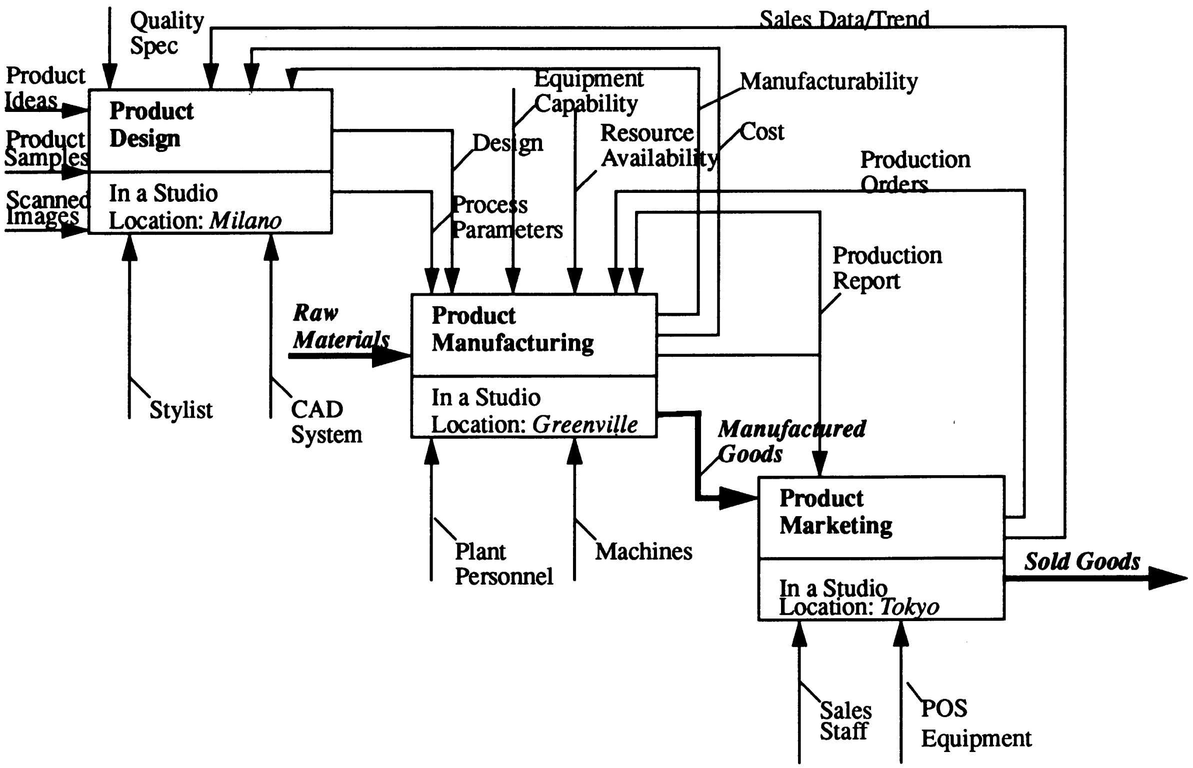

Figure 2. Detailed View of the Primary Functions in the Textile-Apparel Complex.

techniques -- will largely determine its success or failure in the global market.

However, efficient harnessing and processing of information alone, without regard to the handling of physical entities, is inadequate. What is needed is a well-balanced control and coordination of physical *and* information handling activities in an enterprise. The handling of physical entities, viz., manufacturing, is largely carried out by mechanical elements of the enterprise system (e.g., machines, robots); information entities are processed by electronic elements (e.g., computers). Thus, there is a need to effect synergy or integration between the two sets of tasks -- mechanical and electronic -- making the application of mechatronics the logical route to be adopted by the textile-apparel industrial complex. The applications of mechatronic elements in textile and apparel production systems are presently examined.

2.1 MECHATRONIC ELEMENTS IN A TEXTILE ENTERPRISE

Figure 3 shows yet another view of the principal functions in a textile manufacturing enterprise. In the ***textile design*** function, the designer is responsible for producing a design that meets both the aesthetic and functional demands placed by the consumer. In addition, for a design to find its way into the marketplace, the designer must consider the manufacturability of the product. In other words, design for manufacturability (DFM) and concurrent engineering (CE) principles should be followed by the designer so that the designed product can indeed be manufactured by the enterprise. For example, a fabric that calls for intricate woven patterns cannot be manufactured if the weaving machines in the plant are not equipped with Jacquard heads. Similarly, if the equipment cannot handle very fine fibers in yarn production, the proposed product will not see the light of day. Thus successful textile product design calls for a careful synthesis of the various elements of the domain, viz., material characteristics, processability, production capabilities, and consumer-driven product aesthetics and functionality. The predominant activity in textile design is information handling which is denoted by the rounded corners of the box in the figure.

2.1.1 Computer-Aided Design. Computer-Aided Design (CAD) systems, the first of the mechatronic elements, are rapidly proliferating in the textile enterprise. A typical CAD system consists of a personal computer or workstation equipped with input devices, such as an image scanner and a video camera, and output devices such as a color monitor and a color printer. With the advancements in printing technology, often it becomes difficult to visually distinguish between the design on the paper and the fabric. The CAD system can generate processing information for weaving machines, such as lifting of the harnesses, that can be directly sent to electronic dobbies and jacquards. The engineering design of woven textile structures is a complex task and makes extensive use of empirical knowledge accumulated over time. Table 1 illustrates the interrelationships between major design parameters and functional characteristics of woven structures [1]. Computer-Aided Engineering (CAE) software tools such as finite element methods, equation solvers, visualization tools and 3-D modeling help the designer balance the functional requirements of the product with the aesthetics.

The database associated with a CAD system consists of a library of designs created in the enterprise. This library typically includes color schemes, fibers, yarns, fabrics and their characteristics and performance metrics. The CAD system needs to access the database of process sequences, machines and equipment capabilities maintained in the enterprise. Another vital input source for the designer is the marketing database that captures the consumer's profile along with information on past performance of the product in the market. In other words, the

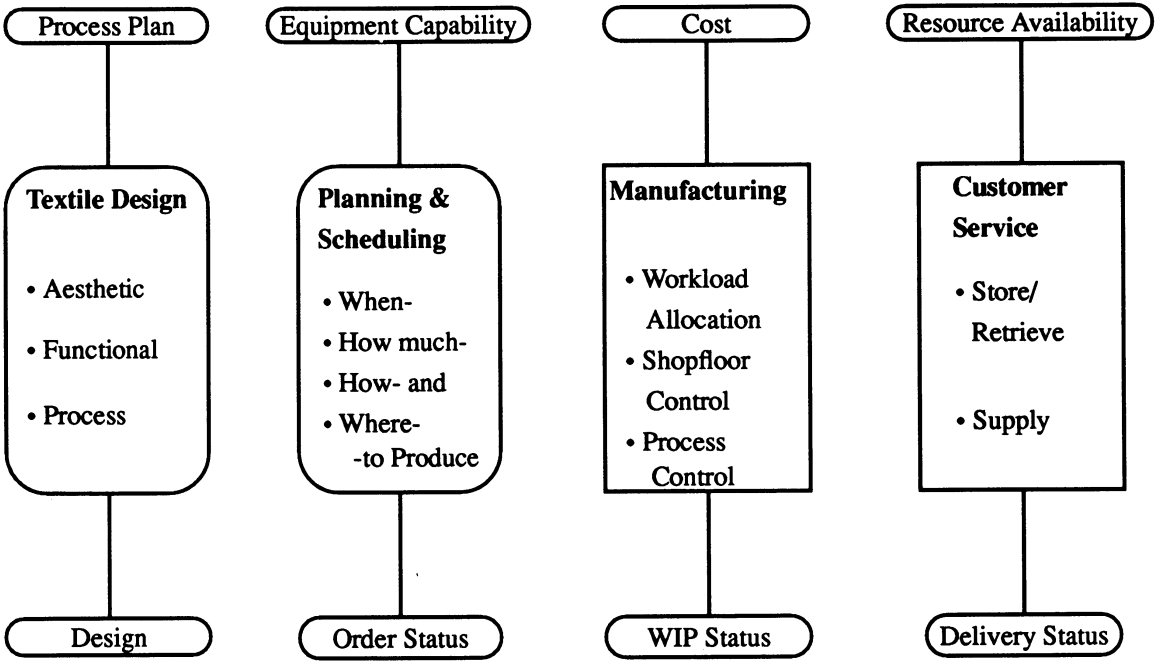

Figure 3. Distributed Databases in the Textile-Apparel Complex.

Table 1. Engineering Design of Woven Structures (from [1]).

Increase Only	Tensile Strength	Initial Modulus	Tearing Strength	Bending Stiffness	Air-Per-meability	Abrasion Resistance	Shear Resistance	Flexural Endurance	Thickness
Fiber Linear Density (Cross-Sectional Area)	—	—	—	↑	↑	↑	—	↓	↑
Yarn Linear Density	↑	↑	↑	↑	↓	↑	↑	↷	↑
Yarn Twist	↷	↓	—	↑	↑	↷	↑	↷	↓
Threads/inch	↷	↑	↓	↑	↓	↑	↑	↓	↑
Interlacings per Unit Area (Weave Pattern)	↓	↓	↓	↑	↓	↑	↑	↓	↑

CAD system should provide the designer with access to its own database in addition to those distributed in other functions of the enterprise. A key requirement therefore is electronic data interchange (EDI) between the various functions of the enterprise. Rather than have a physically centralized or single database with all the enterprise information, a distributed database with each function owning the data pertaining to that activity would be a more desirable solution for ensuring data integrity and data currency.

Advantages of CAD Systems: A CAD system provides QR capabilities to an enterprise by compressing the design-manufacturing-marketing cycle time. Designs, stored in libraries, can be recalled, modified and quickly evaluated. The number of prototypes or samples to be physically produced prior to acceptance by the customer is greatly reduced, thus resulting in cost and time savings. The enterprise can respond faster to changes in the market based on point-of-sale (POS) information generated by the marketing department. Since the CAD systems can directly download process information (e.g., machine settings, lifting plan) to the shop-floor, designs can be quickly brought to production. Moreover, since human intervention is being minimized or even eliminated, information translation errors are greatly reduced leading to a better quality product. For example, when the lifting plan is directly sent by the CAD system to the electronic dobby, operator errors in key-punching or programming can be avoided. Thus, by applying one of the principal mechatronic elements, the textile enterprise can design products to effectively respond to market needs.

2.1.2 Computer-Aided Process Planning and Scheduling. As shown in Figure 3, the *process planning and scheduling* function is the next major function in a textile enterprise. As with design, this function is essentially an information processing operation in which answers to the following important questions are determined: (i) how to produce? (ii) when to produce? (iii) what product mix to produce? (iv) how much to produce? and (v) where to produce?

In process planning, the correct set and sequence of operations required to manufacture the product are determined. In production planning and scheduling, the objective is to optimize the utilization of scarce resources while producing a quality product that meets market demands. This function becomes especially critical in the context of JIT manufacturing philosophy. In such a scenario, the apparel company expects shipment of fabric to arrive *just in time* to be spread in the cutting room. A real-world example is the existing relationship between Swift Textiles, a major denim producer in the U.S., and Levi Strauss, the leading jeans manufacturer. Even the arrangement of fabric rolls in the delivery trucks matches the order in which the fabrics will be spread and cut by the apparel manufacturer. When such fine coordination and control are necessary, planning and scheduling of production become extremely critical in the textile-apparel life-cycle. Carrying the JIT philosophy further upstream, if the fabric manufacturer is procuring yarn from outside sources, the planning and scheduling function provides the necessary information to forecast and order raw materials so that they arrive just in time to be taken to the production floor. Likewise, the planning function in a yarn manufacturing operation helps to order fibers, and the link continues further upstream in the chain. In short, as the textile-apparel complex moves towards JIT manufacturing, the planning and scheduling function in the textile enterprise assumes a pivotal role in maintaining the link. The use of the computer in this function not only simplifies the task, but also improves the quality of the results.

The information required by the planning and scheduling function includes plant equipment capabilities, available capacities, inventory levels (stock and work-in-process), order sizes and due dates. The database associated with a computer-based planning and scheduling system will typically contain information on plant equipment capabilities and available capacities. Moreover, as with CAD systems, the planning system should be able to electronically access other databases in the enterprise (see Figure 3) containing inventory information, order information (order sizes and due dates) and process information (process sequences and times). Materials Requirement Planning and Manufacturing Resources Planning Systems (MRP, MRP II systems) are the commonly used tools for this task. A simulation tool can be effectively used to evaluate various production scenarios prior to scheduling production. Operations Research techniques and tools (e.g., Linear and Dynamic programming, PERT/CPM) can also be used for this activity in the textile enterprise.

Advantages of Computer-Aided Process Planning and Scheduling: The use of computer-based planning and scheduling tools can help to produce the right mix of goods, eliminate bottlenecks in manufacturing and reduce production times. Consequently, the cost of producing the goods can be reduced. Moreover, the organization can be geared to meet market demands and operate successfully under the JIT manufacturing philosophy.

2.1.3 Computer-Aided Manufacturing on the Shop-Floor. As shown in Figure 3, the next logical function in the textile enterprise is *manufacturing*. In this function, the raw materials are physically transformed into finished goods. For example, in a yarn manufacturing facility, fibers are opened, cleaned, carded, drawn and spun into yarn using the appropriate technology, viz., ring, rotor, air-jet or friction spinning. In the case of a woven fabric manufacturing facility, one-dimensional yarns are converted into a two-dimensional fabric through a sequence of steps, viz., winding, warping, slashing, drawing-in and weaving using the appropriate weft insertion technology. In either scenario, handling of physical entities (fiber, yarn or fabric) is the primary function; however, the processes themselves are governed by the information entities generated in the design and planning functions.

Computers are rapidly becoming an integral part of the shop-floor operations in a textile enterprise. Coupled with the proliferation of automation and robotics, a truly computer-aided manufacturing environment is emerging. In other words, the mechatronics philosophy is being applied on the shop-floor. The inroads made by mechatronics can be grouped into two major categories: process control and materials handling.

Process Control and Flexible Manufacturing: Figure 4 shows the hierarchical flow of information in a textile enterprise. The different levels of control in the plant are also shown in the figure. At Level 0, sensors mounted on different parts of the machine transmit the information that is used by the *machine* controller at Level 1. Likewise, the controllers at Level 2, regulate individual *lines* such as opening and carding, and those at Level 3 control *departments* (e.g., spinning, weaving), and so on. Thus, by adopting the *distributed process control* philosophy, the manufacturing process can be monitored and finely controlled at the desired level. For example, the quality of the card sliver is controlled by the autoleveller on the carding machine, while the computer in the weaving plant monitors all the weaving machines and provides appropriate information to the weaving room manager.

At the heart of changes taking place in process control and monitoring on the shop-floor is the expanded role of the machines themselves. The machines are no longer just processing the physical entities, but also are serving as nerve centers or nodes in information acquisition and utilization on the shop-floor. For example, in Rieter's concept of Computer-Integrated Spinning (CIS), the Spin Control Center can download yarn and machine settings directly to the machines in the spinning line. This feature -- rapid reconfiguration and increased flexibility in products produced -- would greatly facilitate quick changeovers in yarns produced in a plant operating

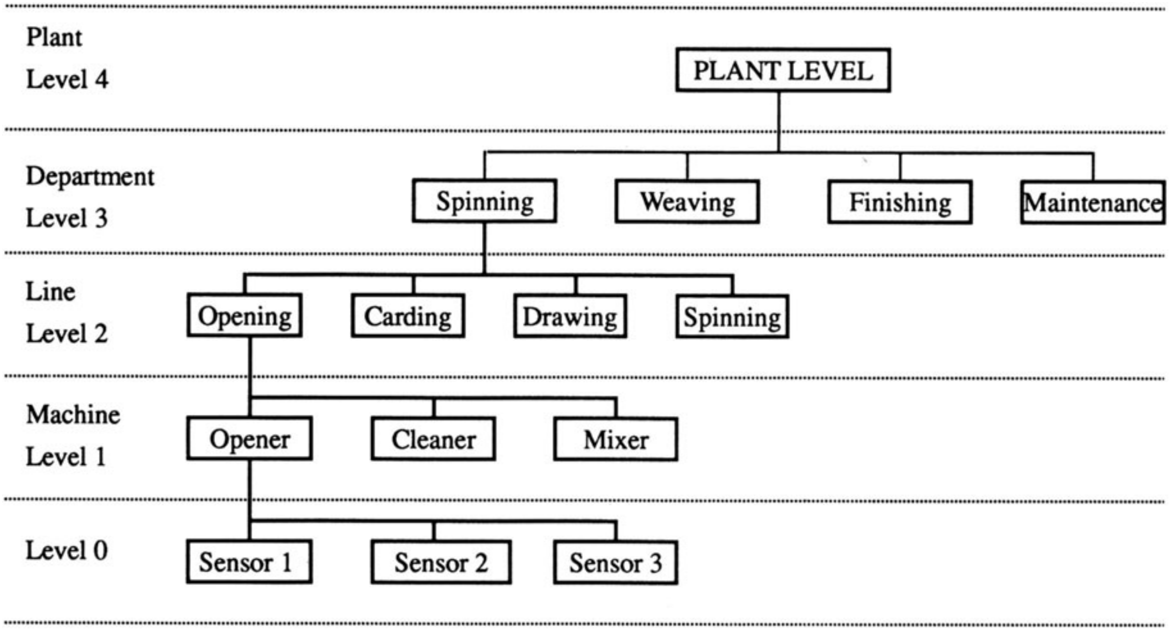

Figure 4. Information Flow and Control in a Textile Enterprise.

in a QR mode. Likewise, Murata, the Japanese textile machinery manufacturer, is a leader in the real-world application of mechatronics to yarn manufacturing [15].

Today's weaving machines are equipped with features such as on-board intelligence, touch screen and graphic displays, and bi-directional communication capability. As the fabric pattern or fabric sett changes, the appropriate pattern data and machine settings can be directly downloaded from the computer to the machine. Maintenance and trouble-shooting instructions can also be displayed by the operator on the machine. Machine performance parameters (e.g., running time, picks inserted, types of stops, downtime and efficiency) are gathered by the machine and sent to the department-wide monitoring and control computer. Thus the weaving machine is an excellent example of the synergy characteristic of a mechatronic production system: it produces a physical entity, viz., fabric, while effectively processing vital information in the plant.

In short, process control in a textile enterprise -- which requires the integration of mechanical and electronic elements of the manufacturing system -- is no longer bound by its traditional definition of making corrections to an out-of-control process. Instead, its scope has been expanded to include customization of the process to provide the necessary flexibility associated with small lot production sizes coupled with frequent changes and shorter lead times for products. A flexible manufacturing system (FMS), or a textile version of it, is slowly emerging.

Materials Handling and Process Linkages: Materials Handling (MH) can be defined as the use of the *right* method or technique to ensure the availability of the *right* material in the *right* form in the *right* amount at the *right* place and at the *right* cost [8]. This definition clearly shows the importance of proper materials handling for attaining the enterprise objective and the five Rs, especially in the context of QR and JIT manufacturing. While MH is typically associated with the movement and handling of physical entities in the plant, a crucial element in the proper functioning of the system is the associated information. If the material on the shop-floor is misdirected due to information errors, bottlenecks might occur. More importantly, consumer demands cannot be met on time resulting in economic and business consequences for the enterprise. Thus there is a need for the application of mechatronics to the domain of MH in the textile enterprise.

In addition to the use of Automated Guided Vehicles (AGV) and Automated Storage and Retrieval Systems (AS/RS) for materials handling, the current trend in textile manufacturing is towards process linkages, i.e., automatically routing material from one processing machine to the next without human intervention. One of the first, going back several decades, was transportation of opened and cleaned fibers directly from the last machine in the opening room to the cards using chutes. However, this linkage or process integration has gone further. The roving bobbins are transported on an overhead rail directly to the ring frame. The bobbins from the ring frame are directly transported to the winding machine; an example of such a system is Murata's Mach Coner. Such systems can also handle several different types of yarns providing a greater product flexibility to the plant. Robotic arms doff the cones from the winding machines and transport them to an inspection station. A vision system inspects the package for defects and good quality cones are transported to be packaged, palletized and rendered ready for shipping. This type of process integration not only minimizes human handling of material (consequently, fewer opportunities for mishandling, yarn mix-ups and soiling) but also greatly reduces the processing time in the plant, a factor that becomes critical in a QR operating environment.

Moving further downstream in the textile process, winding and warping operations are being linked. The cones from the winder are directly transported to the warping machine on an overhead rail. At the warper, a warper creel robot automatically supplies the package to the creel. The fabric on the weaving machine is automatically doffed and transported to the inspection station. At ITMA '91, ELBIT Vision Systems of Israel demonstrated a vision-based fabric inspection system [15]. The fabric is scanned by eight videocameras at 100 m/min. Initially, the system, working on greige goods only, "learns" the fabric pattern on a 3" x 3" sample. The observed defects are classified into spot, vertical, horizontal and area defects. This system is another illustration of how information processing in textile operations has been greatly aided by the rapid advancements in computing technology.

In short, process integration, robotics and vision-based systems used in the textile enterprise illustrate the synergistic functioning of the mechanical and electronic elements in the system.

Advantages of CAM on the Shop-Floor: By utilizing appropriate technologies, including the computer, to effectively integrate the mechanical and electronic systems on the shop-floor, the textile enterprise is better positioned to produce a quality product that meets the requirements of the consumer. For an enterprise operating in a QR mode under the JIT philosophy, CAM on the shop-floor becomes even more critical. In fact, CAM along with EDI are often the prerequisites for achieving such an environment.

2.2 MECHATRONIC ELEMENTS IN AN APPAREL ENTERPRISE

The major functions shown in Figure 3 are also applicable to an apparel manufacturing enterprise. In the interest of brevity, only issues that are unique to the apparel sector and not found in textile manufacturing will be discussed here.

2.2.1 Computer-Aided Design and Marker Making. CAD systems used in apparel design have features similar to those used in textile design. In addition, the systems allow the designer to graphically simulate the drape and appearance of the garment on 3-D forms. Attempts are being made to integrate data on fabric characteristics from the Kawabata Hand Evaluation System (KES) with the design software. This type of link will help the designer better visualize how the garment being designed will drape on the human form.

CAD systems are also used for grading and marker making. In grading, the garment's base pattern parts are used to generate the pattern parts for the various sizes in that specific style. Grading rules are built into the software. The *marker* specifies the desired layout of the garment's pattern parts on the fabric to be cut. The purpose of the marker making process is to pack the pattern parts so that fabric utilization is maximized. Since fabric accounts for a significant proportion of the garment cost, it is important to maximize fabric utilization. Heuristics are being built into the software to achieve this objective. The CAD system also generates the path coordinates for the NC fabric cutting machine; this data is then directly transmitted to the NC cutter thus creating a true CAD-CAM link.

2.2.2 Computer-Aided Process Planning and Scheduling. A unique issue in the apparel industry is the large number of operations involved in making a garment. Also, the operation times, required machine features and operator skills vary with the operation. Therefore, process planning is a complex task requiring the use of computers. Moreover, the process planner needs to access the various databases in the enterprise and also draw upon experiential knowledge. Further downstream, the production planning and scheduling process is complicated by the number of sizes, size distributions and colors associated with a single garment style. Software systems known as *cut order planning* software incorporate optimization algorithms;

these packages enable manufacturers to better control their manufacturing costs and be competitive in the marketplace.

2.2.3 Computer-Aided Manufacturing. Analogous to the weaving machines in a textile plant, sewing machines are being equipped with data terminals that are connected to a monitoring and control system on the shop-floor. Machine settings can be downloaded from the central computer. In an experimental system exhibited at the 1990 Bobbin Show, a Juki sewing machine was using fabric property information based on the KES system to adjust its sewing parameters. This is an excellent application of mechatronics: Fabric-related information is used to change the mechanical processing of the part on the sewing machine so that a defect-free garment can be produced. The ability to rapidly reconfigure the sewing parameters -- based on fabric properties -- will enable a plant to quickly respond to changes in fabric and garment styles. The MITI program in Japan and the Singer company have focused on automating the garment assembly operation, i.e., automatically moving the parts from one operation to the other using mechanical robot arms. However, they have not yet become commercially viable.

2.2.4 Materials Handling. In the area of materials handling, viz., the movement of garment parts in the apparel enterprise, studies have shown that MH and related tasks occupy 60% of the operator's time, whereas the actual sewing accounts for only 20% of the operator's time [28]. Thus, reducing the MH time could greatly contribute to increasing the productivity and profitability of the organization. A MH system known as the *unit production system* (UPS) is making inroads into the apparel industry. The underlying philosophy of the UPS is the processing of a garment in a lot or bundle size of one, as opposed to 36 or 72 units in the more commonly used *bundle system* in the industry. Consequently, the UPS is ideal for producing smaller lot sizes requiring quick turnaround with minimum work-in-process (WIP) inventory levels. In the UPS, an overhead conveyor moves hangers between the workstations; each hanger contains the parts for a single garment. At each workstation, the relevant sewing operation is performed on the parts which typically don't have to be removed from the hanger for sewing. The bar-coded hangers are automatically routed by the control system to the sewing station for the next operation; consequently, the WIP levels can be continuously tracked by the UPS. Thus the UPS is another good example of the application of the principles of mechatronics: Mechanical elements guide the hangers to the appropriate station based on the operation to be performed, availability and skill level of operator, and machine availability and capability.

Having discussed the role of mechatronics separately in textile and apparel operations, issues at the textile-apparel-retail interface are presently examined.

2.3 MECHATRONIC ELEMENTS AT THE TEXTILE-APPAREL-RETAIL INTERFACE

A critical element in achieving a truly integrated textile-apparel complex is the link between the various components, viz., the textile manufacturer, apparel producer and the retailer. Essentially, at each interface, there is the movement of goods (physical entities) controlled by the associated information. Consequently, there is a need to apply mechatronics to ensure a seamless transfer of goods and information.

2.3.1 Role and Importance of Point-of-Sale Data. The POS data gathered in the retail store is transmitted electronically by each store to its headquarters. In turn, the collated information is used by the company to place orders with apparel suppliers. This information is also used by the apparel producers to track the performance of goods in the market and to forecast production. The POS data plays a critical role in a QR operating environment where the apparel producer needs to quickly alter production practices to respond to the market. An excellent case study in the effective use of POS data is the GAP retail chain in the United States. GAP tracks product performance on a continuing basis and typically has a complete turnover of inventory in approximately two weeks.

The apparel manufacturer uses the POS data (furnished by the retailer) and past history to forecast fabric requirements. Orders are placed with the fabric manufacturer as late in the production-retailing cycle as possible so that the quantity ordered closely matches the anticipated consumption. Moreover, the fabric and other materials must arrive in time to be cut and sewn, thus necessitating a JIT environment at the textile supplier.

2.3.2 The Quality Chain. The burden of maintaining quality is being gradually shifted to the supplier. Thus, when a roll of cloth is shipped to the apparel manufacturer, it typically carries a defect map (location and extent of defects) along with other fabric-related information. The defects marked at the fabric inspection stage in the textile plant can be detected by sensors on the spreading machine and appropriate action taken. Further upstream, similar linkages need to exist between yarn and fabric producers, and fiber and yarn producers, respectively. Since information plays a critical role at each interface, the proper transfer and processing of information are of utmost importance in the textile-apparel complex.

In summary, the principles of mechatronics are being applied in all facets of textile-apparel production systems ranging from design to marketing, thus laying the ground for realizing CDDAM. Moreover, the underlying theme behind mechatronics is to bring about true integration between the various functions of an enterprise by tearing down the *walls* separating them; this is slowly, but surely, becoming a reality in the textile-apparel complex. Major tools necessary for successfully applying mechatronics in the textile/apparel industry are presently discussed.

3. Mechatronics, Information Engineering and Knowledge Processing

The successful application of mechatronics in the textile-apparel complex implies the effective control of physical and information entities in the enterprise. Two broad classes of tools and techniques are needed for this purpose: one dealing primarily with physical entities and the other with information entities. Note, however, that this classification only facilitates the discussion and does not diminish the need for -- and importance of -- the two sets of tools working together seamlessly. The focus here is on the tools for information and knowledge processing.

3.1 INFORMATION ENGINEERING AND THE TEXTILE-APPAREL COMPLEX

Having the right information, in the right format, at the right place and at the right time is critical to realizing the five Rs of the enterprise: to produce the *right* product, of the *right* quality, in the *right* quantity, at the *right* price and at the *right* time. Information engineering -- the process of identifying, analyzing, synthesizing and structuring information entities and their flows -- is a powerful means or tool to help an organization effectively utilize its enterprise-wide information resources. In fact, information engineering is the first step toward the successful implementation of CIM systems in an enterprise.

3.2 ENTERPRISE ARCHITECTURE AND STRUCTURED ANALYSIS AND DESIGN TOOLS

As with any engineering activity, the result of applying information engineering concepts is a detailed knowledge and understanding of the functions and information associated with the enterprise. For example, it is important for the product design function to have timely access to various pieces of information such as product functionality and equipment capability (see also Figure 3). The first step in setting up an information system for design activity is a detailed analysis of the function and its associated information entities. A systematic function-by-function modeling of the enterprise activities results in a definition of the enterprise known as the *enterprise architecture*. However, to develop such an architecture or model of an enterprise, modeling methodologies and tools are necessary. Such tools are also known as structured analysis and design tools or SADT. Several diagramming and flowcharting techniques have been proposed in literature [20]. For modeling manufacturing systems, the important methodologies are the IDEF methodology from the U.S. Air Force [29], the ESPRIT CIM-OSA [16] and Zachman's Information Systems Architecture [32]. The relative merits and shortcomings of the three systems have been discussed in [19, 27].

3.2.1 Electronic Data Interchange. Figure 5 shows the flow of information between the major building blocks of the fiber-textile-apparel complex; it also illustrates the interdependency and tight linkages between the components. For example, POS data will eventually (through the retailer - apparel manufacturer - fabric manufacturer - yarn manufacturer path) influence the type and quantity of fibers bought by the yarn manufacturer. For the information to be of value, it must be transmitted quickly and accurately. An effective medium is electronic transfer, commonly referred to as electronic data interchange or EDI. Such electronic transfer is both essential and critical, especially if the textile-apparel complex is to operate in a QR or JIT environment (e.g., the relationship between Swift Textiles and Levi Strauss).

EDI is commonly defined as the computer-to-computer exchange of business documents between organizations in a standard electronic format. Even within an organization, EDI between the functional units (see Figure 2) helps streamline processes that are critical for efficient operation. EDI eliminates the paper shuffle and enables an organization to satisfy its customer's needs by providing instantaneous information on both orders and quality problems (including trouble-shooting).

As with any chain, the textile-apparel-retail chain is as strong only as its weakest link. Thus, if the information flow between the fabric manufacturer and the auxiliaries supplier in Figure 5 breaks down, the short-term impact will be felt by the apparel manufacturer; however, in the long-term, all the nodes in the chain will be affected. As organizations increasingly rely on EDI, data security and correct interpretation of data, viz., what is perceived is what was meant, become critical. Inasmuch as EDI is efficient, powerful and fast, a recent incident in the New

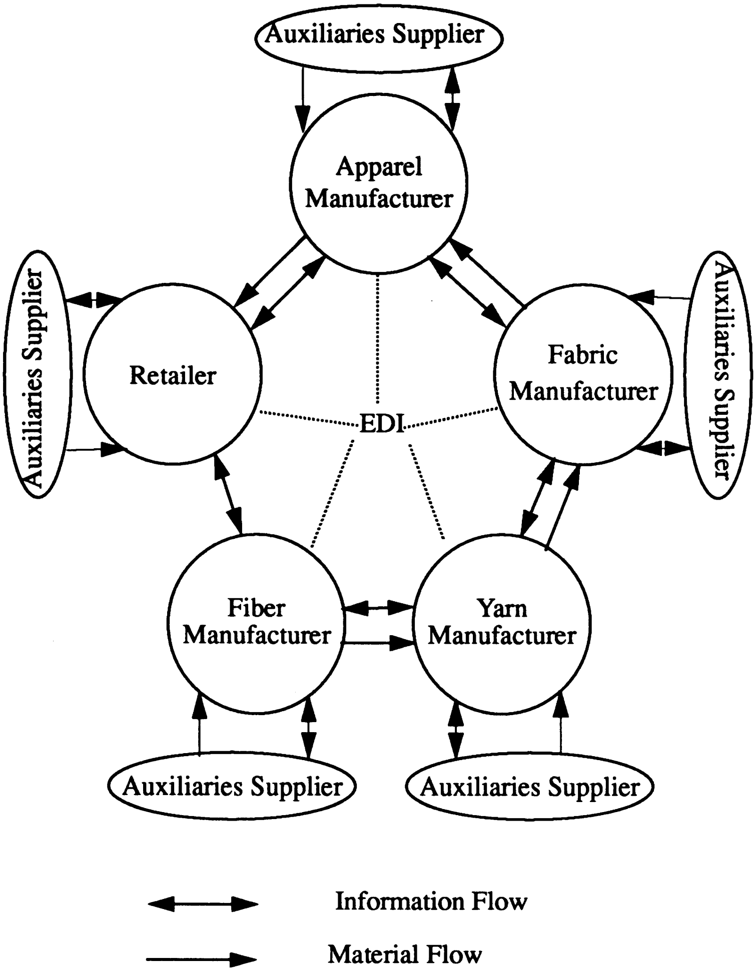

Figure 5. EDI in the Textile-Apparel Complex.

York Stock Exchange[1] illustrates the vulnerability of EDI and underscores the need for proper safeguards and security standards.

3.2.2 Information Exchange Standards. The textile-apparel complex deals with different types of data in the product's life-cycle, viz., design, manufacturing, performance, quality, testing and marketing. As shown in Figures 3 and 5, such a CIM database for the enterprise is likely to be physically distributed across the various functions of the enterprise. The databases may be on different hardware platforms; each function may store and access the data in a certain format; the same data may be *interpreted* or used differently by another function. Some of these systems may be full-fledged database management systems, while others might only permit file transfer. Therefore, for implementing EDI within an enterprise and across companies, some common rules or *standards* for representing and exchanging information are required.

For example, the internal representation of pattern data in the marker making system depends on the system developer. For example, the data format in the Gerber system is different from that of the system marketed by Microdynamics. If an apparel manufacturer has a different system at each of its multi-plant operations, pattern data cannot be directly exchanged electronically, thus precluding true EDI. A similar problem (of larger magnitude) is faced by the U.S. Department of Defense (DoD). DoD is typically forced into issuing *hard* patterns at bid solicitations for apparel procurement. If a common data format were adopted, the industry could implement EDI and derive its benefits: (i) No information will be lost when data is interchanged between systems; and (ii) No complex and expensive coding and decoding protocols will be required at the sending and receiving systems, respectively.

Standards for Product Life-Cycle: A long-term approach to developing such standards is to examine the total life-cycle data of the textile/apparel product. An international initiative, known as PDES, Product Data Exchange using STEP, will facilitate the exchange of a complete product data model with sufficient information as to be interpretable by advanced CAD/CAM systems without human intervention. These concepts are currently being investigated by the hardgoods industry, viz., mechanical parts, mechanical assemblies and electrical printed wiring board products [23]. STEP (*ST*andard for *E*xchange of *P*roduct Model data) is an international standard (defined by International Standards Organization) to represent product data in a neutral format that can be used throughout the life-cycle of the product. Both these initiatives are slowly making their way into the softgoods or textile/apparel world [17]. The information architecture of the enterprise provides the necessary foundation for developing such standards necessary for the design and implementation of an integrated enterprise information system.

DoD Computer-Aided Acquisition and Logistic Support (CALS): CALS is a DoD and Industry initiate to enable and accelerate the integration and use of digital technical information for weapon system acquisition, design, manufacture and support. The CALS program facilitates the transition from paper-intensive processes to a highly automated and integrated mode of operation, thereby improving productivity and quality of acquisition and logistic support

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[1] On March 25, 1992, an order to sell $10 Million worth of shares on the New York Stock Exchange, was misinterpreted and processed by the data entry clerk at Salomon Brothers -- a brokerage firm -- as an order to sell 10 million shares; this error caused the stock market to drop sharply during the closing minutes of the day. The large sell-off was quickly traced to the source and immediate steps were taken to minimize the consequences.

processes [3]. Among the associated benefits of this initiative are: (i) Reduced acquisition and support costs through elimination of duplicative, manual and error prone processes; (ii) Improved responsiveness of the industrial base by development of integrated design and manufacturing capabilities and by Industry networking and communication among manufacturers based on digital product descriptions; and (iii) Improved quality and timeliness of technical information for support planning, reprocurement, training and maintenance, as well as improved reliability and maintainability of weapon system designs through direct coupling to CAD/CAE processes and databases.

Based on the objectives of the CALS program and its related benefits, the CALS strategy could very well be adopted by the textile/apparel industry to be responsive to the needs of the consumer by delivering a quality product in a timely manner while reducing the manufacturing and distribution costs.

3.2.3 Information Exchange and Communication Networks. A prerequisite for effective information sharing is a well designed and implemented communication network (collection of hardware and software) within the building blocks of the textile-apparel complex and between them. For example, the CAD system can access the equipment capability database over a local area network (LAN) if the two databases are maintained within the same physical facility. Otherwise, wide area networks or communication through modems are the means to achieve this information sharing. Likewise, weaving machines in the weave room can be nodes on a LAN with the central computer keeping track of production information, machine settings and patterns. In such a system, the settings from a weaving machine operating at high efficiencies can be electronically transferred to other machines on the shop-floor. Such electronic transfer of settings was demonstrated by Picanol at ITMA '91.

Various communication protocols have been established for information exchange [30]. The Open Systems Interconnection (OSI) Reference Model provides a generic seven-layer framework for the development of standardized communication systems from the physical layer to the application layer. The Manufacturing Automation Protocol (MAP) is based on the OSI Reference model and is extensively used in the manufacturing sector (e.g., automobiles). TOP (technical and office protocol) is a set of standard protocols used to provide a functional network for distributed information processing in technical and office environments.

The ISDN (integrated services digital networks) architecture supports the simultaneous transmission of data, video and audio. This technology opens up some exciting avenues for information sharing in the textile-apparel complex. For example, concurrent design and engineering can be practised more effectively: product designers, consumers and manufacturing personnel located in different cities can work as a team to design a product and improve its chances of success in the market. Likewise, the technology can be used to develop multimedia systems to train operators in plants, provide shop-floor trouble shooting instructions and develop product presentations for marketing.

In summary, advancements in information technology can be applied to design and implement newer ways to present, utilize and share information in the textile/apparel complex.

3.3 KNOWLEDGE PROCESSING AND THE TEXTILE-APPAREL COMPLEX

Information, a meaningful representation of data, is important to an enterprise. Equally critical, if not more valuable for an enterprise to meet its objectives, is *knowledge*, the ability to effectively utilize information. Experience and expertise acquired over time in an organization -

- be they in product design, production planning, shop-floor control or sales forecasting -- need to be captured, preserved and disseminated throughout the enterprise. The role of artificial intelligence in providing tools for this purpose are presently discussed.

3.3.1 Artificial Intelligence and Knowledge-Based Systems. Artificial Intelligence (AI) has been defined as the part of computer science concerned with designing intelligent computer systems, that is, systems that exhibit characteristics associated with intelligence in human behavior -- understanding, language, learning, reasoning and problem-solving [2]. Early research in AI was aimed at developing domain-independent reasoning systems such as the General Problem Solver (GPS). GPS could prove theorems and solve a wide variety of problems, but proved to be inadequate for larger real-world problems. Subsequently, research efforts were directed at developing efficient schemes for representing domain-specific knowledge, and the term *knowledge engineering* was born along with the concept of a knowledge-based system [5].

Knowledge-Based Systems: A knowledge-based system (KBS), commonly referred to as an *expert system,* is a software system that solves complex problems in a specific domain that would otherwise require extensive human expertise. Waterman [31] provides a basic introduction to the field of KBS from a practitioner's standpoint, while Hayes-Roth *et al.* [6] is a good reference text for system developers.

A KBS essentially consists of three major components: At the heart of the system is the *Knowledge Base* which is the repository of domain-specific knowledge. This knowledge comes from the domain expert and other sources such as domain literature. The domain knowledge is stored in the form of facts and heuristics. The *Inference Engine* contains the problem-solving strategies and applies the knowledge to the solution of actual problems based on the specific data currently in the *Working Memory.* The two major inference paradigms or solution strategies are *forward chaining* and *backward chaining.* The user of the KBS interacts with the system through the *User Interface.*

The various steps in the KBS Development Life-Cycle, viz., planning and domain selection, knowledge acquisition, knowledge representation, system testing and system deployment are discussed in [12]. The applications of KBS in various facets of the nonwoven industry, viz., product design, production planning and scheduling, shop-floor control and marketing have also been discussed in [12].

Fuzzy Logic Systems: Fuzzy logic is a discipline that lets the computer deal with shades of grey. Rather than make decisions based on just one input, several variables are integrated over time to ensure better control over the process being monitored and regulated. This technology embodies the principles of mechatronics, viz., to effectively integrate the mechanical and information components of a system. It is being extensively used in the design of elevators, information retrieval systems and stock trading programs. The technology has the potential to be applied in the textile/apparel industry for the development of better process control systems.

In summary, the design and development of information and knowledge management systems are essential for applying mechatronics successfully in the textile-apparel complex. Figure 6 attempts to pictorially represent an integrated view of the relationship between the enterprise functions and the relevant data elements. Central to accomplishing such an integrated environment are the various information and knowledge processing technologies discussed in this section. Some specific research endeavors involving the application of these tools to textile-apparel production systems are presently discussed.

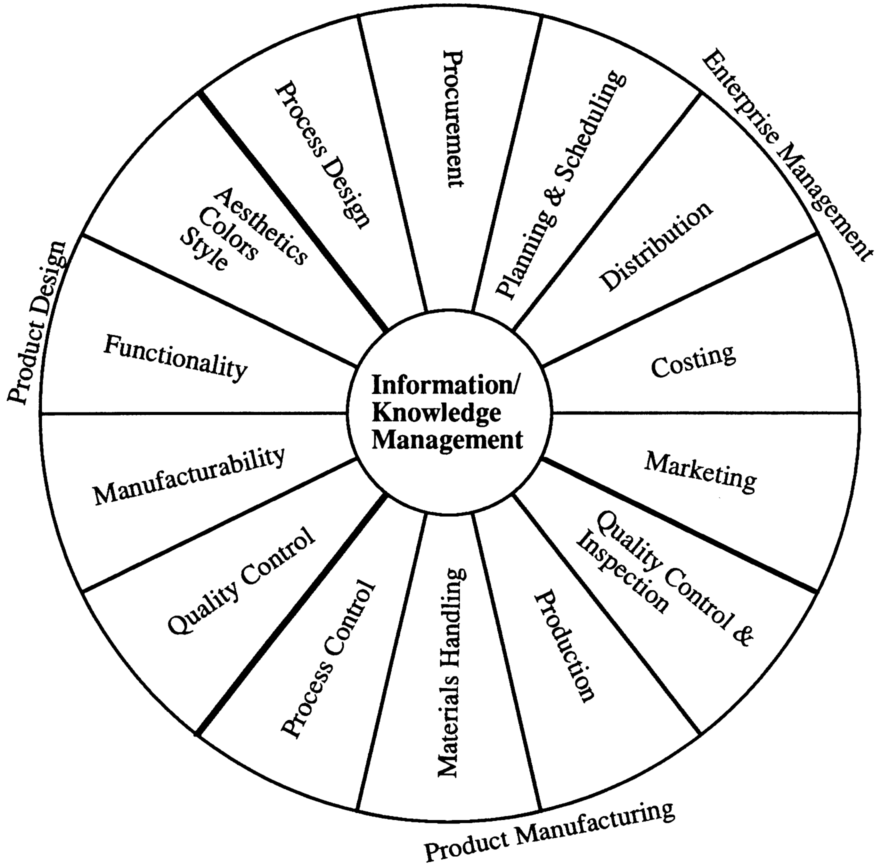

Figure 6. Information and Knowledge Management in the Textile-Apparel Complex.

4. Research in Textile/Apparel Mechatronics

Around the world, there are several research endeavors aimed at applying the principles of mechatronics to the textile-apparel complex. In this section, the focus is on a few major initiatives in the area of information and knowledge processing.

4.1 MANUFACTURING ENTERPRISE ARCHITECTURE

The manufacturing enterprise architecture (MEA) is proposed as the framework that captures, represents and integrates the three major facets of an enterprise, viz., function, information and dynamics [7]. The ultimate objective of MEA research is to design and develop an integrated modeling methodology and software framework that can be used for modeling and effectively running a manufacturing enterprise. Once the modeling software framework is developed, the need for appropriate software tools or *agents* for carrying out each of the functions in the enterprise will be identified; the available tools will then be integrated into the framework. Otherwise, such tools will be developed leading to the creation of a single integrated software environment. Currently, research is aimed at developing a modeling methodology and software modeling tools necessary for the development of an enterprise architecture.

Need for MEA: The architecture, developed by adopting a systems approach to manufacturing, can serve as a blueprint for the effective implementation of new technologies, including computers, which are central to the successful operation of the enterprise. The architecture can be used as a communication vehicle in an enterprise both during the analysis of the enterprise operations and subsequently during the implementation of changes resulting from the analysis. The architecture can also provide the necessary foundation to develop specifications and standards for the seamless integration of the various islands of automation in an enterprise [7].

Structure of MEA: MEA consists of three models, viz., the entity model, the activity model and a model to represent knowledge and beliefs about a manufacturing enterprise [26]. The entity model is a representation of the enterprise entities and their relationships. The activity model is a representation of the various functions performed in operating the enterprise. The object-oriented framework is being designed to overcome one of the major shortcomings of the IDEF methodology identified during earlier research on developing an architecture for an apparel enterprise: the lack of seamless integration between the function (activity) and information (entity) models [7, 27]. Two of the major long-term objectives are to integrate enterprise dynamics with the activity and entity models, and to generate executable models.

4.1.1 Apparel Manufacturing Architecture. Under a DoD-sponsored research effort, the architecture for an apparel manufacturing enterprise has been developed. This architecture is an example of a domain-specific MEA. Based on a set of evaluation criteria developed for the selection of the modeling methodology, the US Air Force's IDEF methodology was selected and used in the development [10]. The architecture is based on extensive modeling and analysis of the operations of a major apparel manufacturing enterprise and subsequent participation of other apparel companies.

The apparel manufacturing architecture (AMA) is a comprehensive set of specifications for a computer-integrated apparel enterprise [11, 18]. AMA consists of a set of models the core of which is the *information* model which defines the schema of the shared information base for an apparel enterprise. The *function* model component of the architecture specifies how the activities carried out in an apparel manufacturing enterprise interact with each other through the shared information base. The third component of AMA, the *dynamics* model, describes how the interactions among the enterprise activities take place over time. AMA encompasses activities spanning product development to distribution of finished goods. The activities at each level have been decomposed to the desired level of detail so that issues related to automating or computerizing the process can be investigated. Thus an architecture encompassing the textile-apparel complex can serve as a blueprint for implementing CIM in the textile/apparel industry.

4.2 KNOWLEDGE-BASED SYSTEMS FOR DEFECTS ANALYSIS

Defects in textile products significantly impact the profitability and image of the textile/apparel industry. As the consumer becomes increasingly quality conscious, better tools must be developed to effectively control defects and improve product quality. KBS technology can be applied to develop computer-assisted tools for use in the textile-apparel complex.

4.2.1 Fabric Defects Analysis System (FDAS). Research has been conducted to investigate the use of KBS technology for analyzing defects in textile and apparel manufacturing. Two systems have been developed, one for fabric defects and another for apparel defects. FDAS is a KBS for analyzing and diagnosing defects in woven textile structures. Based on information furnished by the user, FDAS identifies the defect in the fabric and the causes of the defect, and suggests suitable remedies to avoid defects. FDAS is intended for use on the shop-floor of the textile plant [24].

Figure 7 shows the framework of FDAS for the classification of defects [25]. The defect is essentially characterized by its *type* (point, line or area), *direction*, *lengthwise pattern* and *widthwise pattern.* The primary advantage of this novel classification scheme is that it is based only on the visually observable attributes of defects and, unlike traditional schemes, does not require prior knowledge of the defect. Consequently, the scheme can be used as an underlying framework for an automatic (vision-based) fabric inspection system. In addition to being a tool for analyzing defects, FDAS can be used as a valuable training tool for new fabric inspectors. FDAS has been implemented in Nexpert Object, an expert system shell, and runs under both Unix and MS-DOS environments. FDAS is linked to Oracle, the relational database management system, to record defects and to generate quality reports in the enterprise [14].

4.2.2 Sewing Defects Analysis System. SDAS (sewing defects analysis system) is a KBS for the identification and diagnosis of defects encountered in the manufacture of utility denim trousers [14]. The classification of defects is centered around the location of the defect and the nature of the defect; these are the two visual cues an inspector derives during garment inspection. An object-oriented class hierarchy has been used to represent the classification framework of SDAS. Like FDAS, SDAS is implemented in Nexpert Object and is also linked to Oracle.

4.3 KNOWLEDGE-BASED SYSTEM FOR CONTRACTOR EVALUATION

One of the major functions in the textile-apparel complex is selection of vendors for the supply of products, viz., fibers, yarns, chemicals, fabrics, buttons, zippers, or apparel. Since there are multiple sources for each of these products, the buying organization solicits bids and eventually awards a contract based on several criteria. However, the process of selecting the bidder that is most likely to deliver the best value (i.e., the required quantity, at the right time and of the

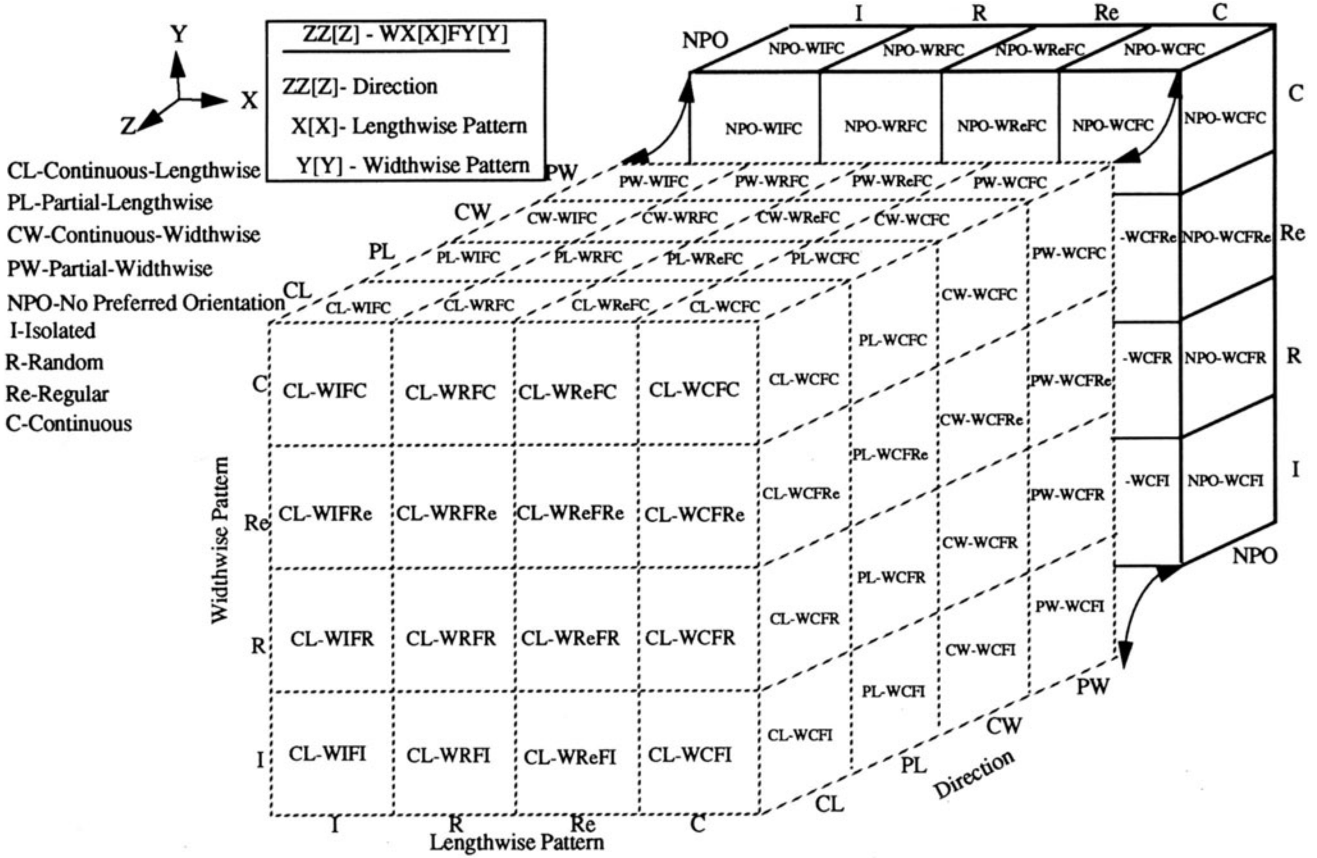

Figure 7. Classification of Fabric Defects According to Key Characteristics.

specified quality) is complex and involves extensive human judgement and experience. If an appropriate tool can be developed to carry out this task, the vendor selection process can be computerized, thus freeing the human to make creative decisions.

4.3.1 Bid Evaluation Software Tool (BEST). DoD is the single largest consumer of apparel items in the western world procuring approximately $1 billion worth of apparel every year [4]. The ultimate objective of the procurement process is to ensure the greatest value for DoD, i.e., all other conditions being met, the total cost is the lowest. With this underlying objective, research has been carried out to develop a knowledge-based decision support system for use by contracting officers at DoD to assist them in their evaluation tasks.

An Apparel Enterprise Evaluation Framework (AEEF) has been designed and developed using the KBS development methodology. In the resulting tool (BEST), the overall capability of the bidder to perform on a contract is determined based on the quality, production and financial capabilities of the bidder (see Figure 8). An object-oriented representation scheme has been used to represent AEEF. As shown in Figure 9, these top level classes are further decomposed until the value for the lowest level object can be directly obtained from the bidder [22]. AEEF is implemented in Nexpert Object and runs under both MS-DOS and Unix operating systems. To obtain the necessary information for evaluating a contractor, a set of forms known as BESTForms has been created. BESTProcess, the problem-solving engine in BEST, utilizes the data in BESTForms and comes up with a rank (on a 0-4 scale) for the bidder.

4.3.2 BEST and EDI. BESTForms represents a modest step in paving the way for EDI between DoD and its apparel suppliers [13]. Bidders can submit the necessary information on disks that can be loaded at DoD and used with BEST. Such an approach will reduce the large amounts of existing paperwork and will contribute to fewer errors in data transfer. Data integrity can be easily ensured prior to the award of a contract. Additionally, once a bidder's information is present in a database at DoD, the bidder will be required only to update the information (on subsequent bids) and there will be no need to resubmit all the data. Moreover, in the event of a mobilization, DoD would have a database of contractors' capabilities that could be quickly tapped. In the long-term, DoD can set up a network or a dial-in facility and bidders could enter the information directly in DoD's computers thus speeding up the response process on a solicitation. This concept of EDI between DoD and its contractors can be easily extended to vendors in the commercial world (see Figure 5) so that a truly responsive and JIT manufacturing textile-apparel complex can emerge.

4.4 APPAREL PRODUCT DATA EXCHANGE THROUGH STEP

The National Institute of Standards and Technology (NIST) has begun work on applying PDES concepts to the apparel industry. As the first step, an Apparel Pattern Information Model (APIM) has been developed to illustrate the feasibility of extending STEP to include apparel pattern data. A neutral file format for exchanging two-dimensional apparel pattern data between different marker making machines has been developed [17, 21]. Efforts are now being directed towards a full-fledged APDES (Apparel Product Data Exchange through STEP) effort that will include three-dimensional garment models, linkages to textile, anthropometric and other data related to the life-cycle of the product. AMA is being used for developing APDES application protocols.

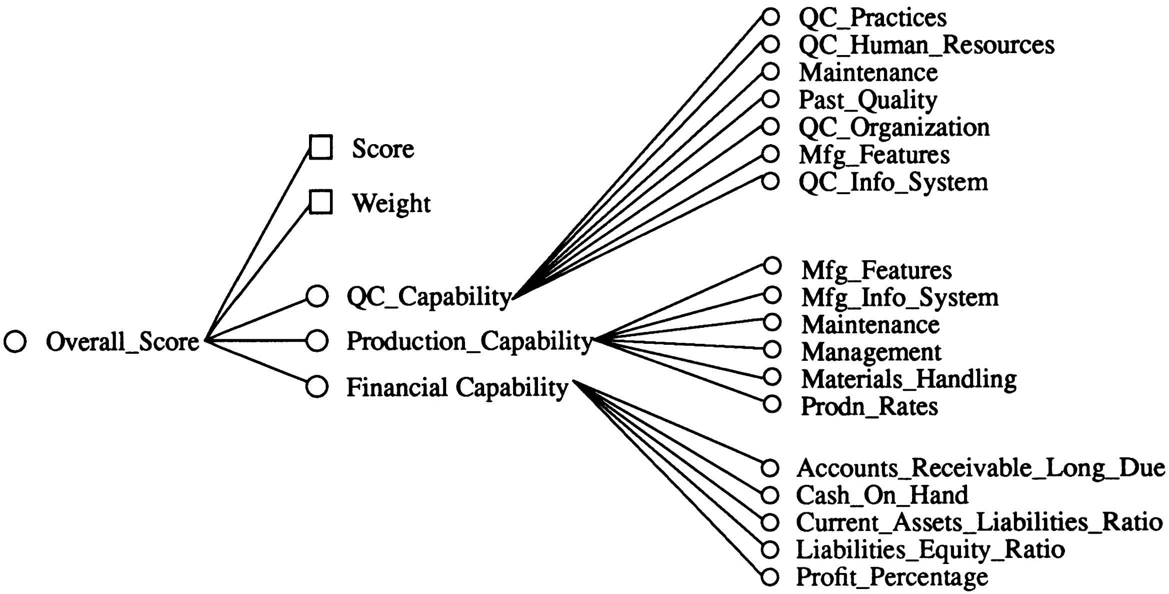

Figure 8. Decomposition of the Class *Overall_Score*.

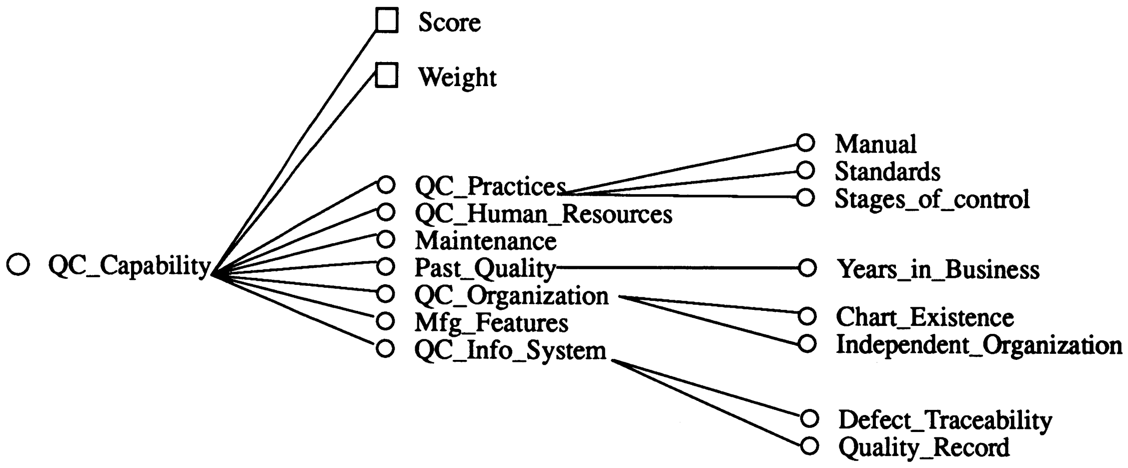

Figure 9. Decomposition of the Class *QC_Capability*.

4.5 POTENTIAL AREAS FOR FURTHER RESEARCH

In this section, areas for further research and exploration to effectively utilize mechatronics in the textile-apparel complex are identified.

4.5.1 EDI and Distributed Design and Manufacturing. By embracing and applying EDI and advancements in communications technology, the textile-apparel complex can explore the concept of *distributed design and manufacturing.* In such a framework, companies will each specialize in one facet of the product life-cycle, but will work together in a conceptually integrated environment even if they are located in different geographic locations. For example, a design house can invest in state-of-the-art technology and develop design expertise (technical and human) that can be shared with several manufacturers. Since resources will be directed to a single area, expertise and market share can be quickly built by the design house. The design house may further choose to focus on one market segment.

For the manufacturer, the proposed framework will provide the ability to pick and choose from a range of design houses. This flexibility in accessing a range of product designs will enable the manufacturer to effectively respond to the changing needs of the consumer and also to cater to a wider segment of the market. Likewise, by concentrating its resources on manufacturing, the company can afford to invest in state-of-the-art technology on the shop-floor, thereby improving the productivity and quality of the product. Issues related to hierarchical distribution of enterprise activities such as feasibility, logical divisions and economies of scale can be explored further.

4.5.2 CALS and Quick Response. As the textile/apparel industry embraces CDDAM philosophy, application of the CALS approach, viz., elimination of paper-based transactions and standardized data interchange throughout the product life-cycle, will become critical. Issues related to the creation of such a truly electronically integrated complex using the CALS methodology can be investigated.

4.5.3 Product Data Exchange Standards. The successful application of the concepts of DFM, CE and CDDAM necessitates the availability of a product's life-cycle date to all functions of the enterprise from design to marketing. This calls for the development of standards for representing product data so that any ambiguities in the design, manufacturing or other operations can be avoided -- the final product delivered will indeed be the product that was designed to be produced.

As mentioned earlier, AMA can serve as a good starting point for the apparel component of the product life-cycle data. The scope of AMA should be expanded to include the textile component of the life-cycle data. Once such an integrated information architecture is developed, the PDES/STEP methodology can be used to develop the appropriate application protocols and product data standards.

4.5.4 A Closed Loop Fabric Defects Recognition and Analysis System. As mentioned in Section 2.1.3, the fabric inspection system from ELBIT Vision Systems identifies defects on the fabric using a system of videocameras. At the other end, FDAS analyzes a defect, determines the cause for the defect in the upstream processes, and suggests appropriate remedies to prevent the defect from recurring. Since the classification schemes for the two systems are nearly identical, issues related to integrating these two systems can be investigated. The ultimate objective will be to develop a closed loop fabric inspection and diagnosis system. Such an effort will further the concept of using sensory information from a process to effect changes on the machines electronically and without human intervention. Although the existing time scales in the process sequence (spinning and weaving) will not currently accommodate a learning and self-correcting system in practice, the area is worthy of further exploration and research.

4.5.5 Knowledge-based Systems for Process Planning and Scheduling. Process planning is a complex activity and the expertise of the process planner is invaluable to an organization. Since such expert planners are scarce, this area of enterprise activities is a potential domain for the application of KBS technology. An intelligent process planner that also effectively utilizes the distributed databases in the enterprise can be developed.

Traditionally, optimization tools such as linear programming have been used in the production planning and scheduling functions of the manufacturing enterprise. However, such purely algorithmic approaches to optimization, do not account for some of the realities of the manufacturing shop floor operations. Constraints are not always linear, and schedules are frequently modified to accommodate changing product demands and availability of resources (operators, materials and machines). The individual's experience and expertise greatly influence both the way the function is carried out and the resulting schedule. While the task itself is fairly well-defined, there is generally a shortage of experienced planners, thus making this task but one of many suitable candidates for the development of a KBS.

4.5.6 Fuzzy Logic Systems. At ITMA '91, Tsudakoma demonstrated a prototype *Fuzzy Logic Expert System* for the air-jet weaving machine. In this system, the main nozzle pressure setting is regulated based on integrating the information monitored on filling arrival time, loom stop data and fabric quality data. This type of integrated control leads to better accuracy and reproducibility. There is potential for similar applications of fuzzy logic concepts in the textile-apparel complex.

For example, in dyeing, the expert's opinion that the fabric has been dyed to the *right* shade is the outcome of a complex knowledge processing task that cannot often be encoded in black and white. Adjustments to the dyebath to ensure the right shade involve a multitude of interacting parameters and the resulting control decision (e.g., to add a certain amount of a specific color to the bath) is based on an integrated view of these parameters. Thus, there is scope for applying the principles of fuzzy logic to develop controllers for monitoring and regulating the shade during dyeing. Product design, production forecasting and style projections are other potential areas for the application of fuzzy logic in the textile-apparel complex.

In summary, the textile-apparel complex is a fertile area for the application of the principles of mechatronics.

5. Conclusions

The key to operating successfully in the global market lies in the effective management of physical and information entities in the textile/apparel enterprise. From the earlier discussion it is clear that mechatronics is being applied in the textile-apparel complex, albeit under different names, for ensuring a smooth and controlled flow of products and information in the enterprise.

The role and scope of mechatronics in textile-apparel production systems have been discussed. Specific examples have been presented to illustrate the applications. Concepts of information engineering, electronic data interchange and knowledge-based systems technology and their relevance to the textile-apparel complex have been discussed with specific examples. Major research efforts including the development of an enterprise architecture, knowledge-based systems and product data standards have been discussed. Finally, potential areas for further research and exploration in areas ranging from application of CALS to fuzzy logic have been presented.

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MECHATRONICS IN AUTOMATED GARMENT MANUFACTURE

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ABSTRACT. Automated garment manufacture can be split up into various types of handling and joining operations once the fabric panels have been cut into various shapes. Each type of operation is studied and various possible solutions described from a mechatronics point of view. Problem case studies are then given showing why particular solutions are favoured in certain circumstances.

Such automation has greater potential if a series of automated modules can be integrated to solve a larger problem, e.g. a complete assembly or sub-assembly. Problems can then arise from the cumulative effects of uncertainties as the assembly proceeds. These can be dealt with using sensory perception and error recovery techniques. Modules may have to accommodate different sizes, styles and fabrics in order to be as flexible as possible to market needs. These concepts are illustrated by the Hull project on the automated assembly of briefs.

1. Introduction

There are, at present, three important aspects of the British garment manufacturing industry which require immediate attention:

a) The cost of assembling a garment is estimated to represent between 20% and 30% of the total manufacturing cost [Nicholson]. This can be reduced by taking the assembly abroad, where the labour costs are less, but a report on the attitudes of United Kingdom consumers towards clothing made in different countries [Bannister] indicates that goods made in Britain are thought to be of a higher standard than those made elsewhere. The cheap labour factor will also become less important as wage rates rise in other countries.

b) The consumer is looking for quality in the goods bought and is becoming more critical and selective when purchasing. It is therefore necessary for the industry in general to set and maintain standards as with the use of the Wool symbol [Brown].

M. Acar (ed.), Mechatronic Design in Textile Engineering, 271–289.

c) The garment manufacturing industry must be able to respond quickly to incoming orders, design, material and size changes. This can be accomplished by reducing the work in progress and using 'Just in Time' or 'Quick Response' systems.

At present, the advanced equipment being introduced into factories is being used to de-skill operations or carry out some of the simplest tasks by hard automation. A major advance has been made through the use of computers in the design and cutting stages in order to reduce the amount of wasted material. Sewing machines have also been upgraded by the addition of digital displays and pneumatic actuators to alter settings. Thereby allowing the operator to concentrate on manipulating the material. Some hard automated systems have also been introduced, for example auto-sergers for the hemming of skirts. These machines perform automatic edge following during sewing, but are primarily limited to use on dimensionally stable woven fabrics.

The only way to improve the production rate and to reduce labour costs in the long term is to automate the handling and manipulation of fabrics. This involves developing techniques to orientate, pick, place, and fold fabric panels in a cheap and reliable way, whilst being able to cope with size, colour and style changes. The major problem when automating garment manufacture is the flexibility of fabric. This was highlighted by Aisaka [Aisaka] who considers "the action of taking up a handkerchief from the table." The point Aisaka uses is "The shape of the handkerchief is different according to the holding method - holding it by one hand at one corner, or at the centre, or by two hands at two corners.". Another problem to be considered when looking at this simple case is the variation in the properties of the cloth itself, since these affect the way the handkerchief folds and creases.

There are six basic areas for automation.

1. Ply Separation
2. Transportation
3. Ply/sub-assembly position and orientation
4. Pick and place
5. Joining
6. Manipulation

Many techniques have already been introduced to achieve the above, but it is important to observe that there is no 'ideal' solution to each problem. Instead a selection of solutions have been designed and implemented, dependent on the task and the properties of the fabric. This paper will introduce some of the solutions to these six areas which have been developed at The University of Hull and elsewhere, but first a brief overview of fabrics and their properties is given.

2. Overview of fabrics

It is important to note that every fabric is unique and that its properties can change along a roll. It is, therefore, possible only to make sweeping generalisations about the different fabric types. The range of fabrics in common use for garment manufacture range between heavy denims and single knit Jersey. The properties of the fabric depend both on the yarn being used and the construction technique, for example, knitted or woven.

There has been a relatively large amount of research into the properties of woven fabrics as used in shirt and suit manufacture. This work, for example Kawabata [Dhringra], has produced a whole range of tests for woven fabrics, primarily to predict the quality of garment which will be produced for a given material. This objective measurement is very important when producing a suit, but not as critical for underwear. The most important of the properties measured are Friction, Bending Length, Shear and Buckling. The emphasis has been on properties important to the feel or 'handle' of the garment.

As will be seen there are many properties important to handling which are not covered by these 'traditional' tests. Relatively little work has been carried out on knitted materials where problems such as curling of the edges can be extremely important in the design of automated handling equipment. Work in these areas is now being started by various researchers, [Cassidy], [Clapp '90], with the specific aim of relating fabric properties to automation problems.

3. Ply Separation

The production of garments starts at the laying up and cutting of the fabric into panels. Although single ply cutters are commercially available, this task is usually carried out by laying up multiple plies and then cutting the fabric into stacks. The stacks are then removed and transferred to the sewing machinists who have to take off panels one at a time, or sometimes in twos. The starting point for many automation projects has been the removal of this single panel off a stack, and many techniques have been developed. The separation means has to grip the top most ply and restrain the plies beneath during the removal process. There are two main problems. The first is that during the cutting operation the stacks are compressed resulting in cohesion between the two plies. The second is the intertwining of fibres (linting) along the edge caused by the action of the cutting blades.

There is, however, no single technique which can cope with the whole range of fabric types. A range of different techniques are therefore required so that the appropriate one can be chosen for the specified fabric.

Clapp [Clapp '88] summarises a number of different techniques ranging from pins to freezing systems. Three destacking techniques have been developed at the University of Hull.

1. The Sensory Air Jet Gripper
2. Electroadhesion
3. Glue

3.1 THE SENSORY AIR JET GRIPPER

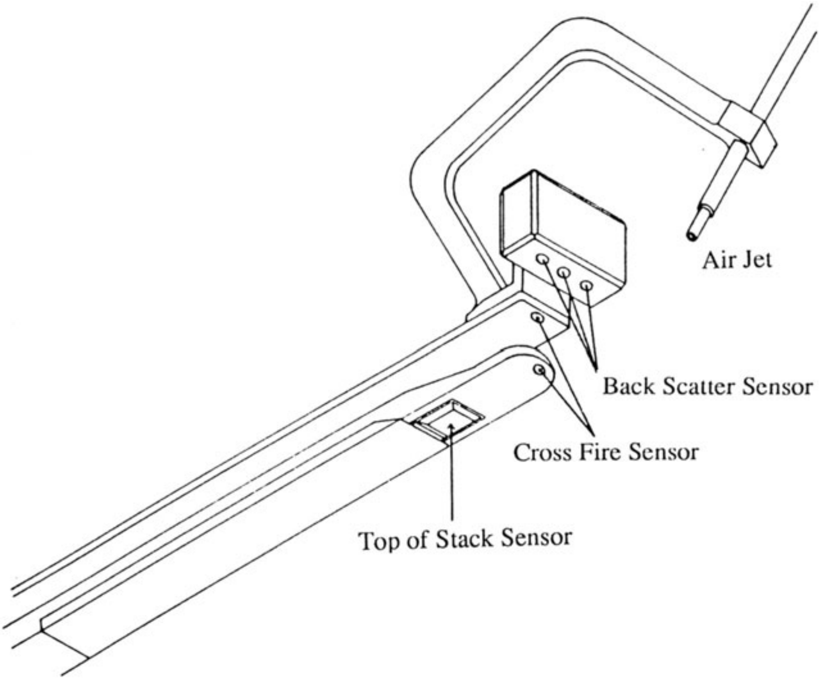


Figure 1 - The Sensory Air Jet Destacking Device [Kemp]

This gripper uses air blown onto the top of the stack to vibrate the top panel [Kemp], as shown in figure 1. A key feature in this technique is the creation of bubbles of air under the top most ply and their propagation towards the stack edge, thereby breaking any linting which may have occurred. The vibration causes the topmost ply to flip over the lower finger. Simple infra-red sensors are used to detect the number of plies between the jaws. Further infra-red sensors along the finger allow alignment of the fingers with a straight edge prior to clamping and removal of the panel. Once the edge has been located, the jaws of the gripper are closed and the panel peeled off. Sensors are also required to position the finger relative to the top and edge of the stack to ensure that the panels are consistently destacked. This technique works best with porous lightweight fabrics such as knitted cottons, which also have low bending stiffness .

3.2 ELECTROADHESION

If a dielectric is polarised, by means of a charged metal surface, any other dialectic it comes into contact with which is electrically polarisable will experience a force of astriction [Taylor '88]. This is a high shear, but low cohesive force and is a surface only effect which allows fabric panels to be destacked. Flat plate grippers could be implemented to destack fabric panels in theory, but in practice the linting between panels reduces their effectiveness. An alternative is a roller which, when passed over the panel both attracts the panel and breaks the linting at the edges by bending the fabric.

Electroadhesion is not suitable for 'fluffy' fabrics, but works well on most woven fabrics. which generally have a relatively high radius of bending thereby allowing rollers of a minimum of 25mm diameter to be utilised [Taylor '88].

3.3 GLUE

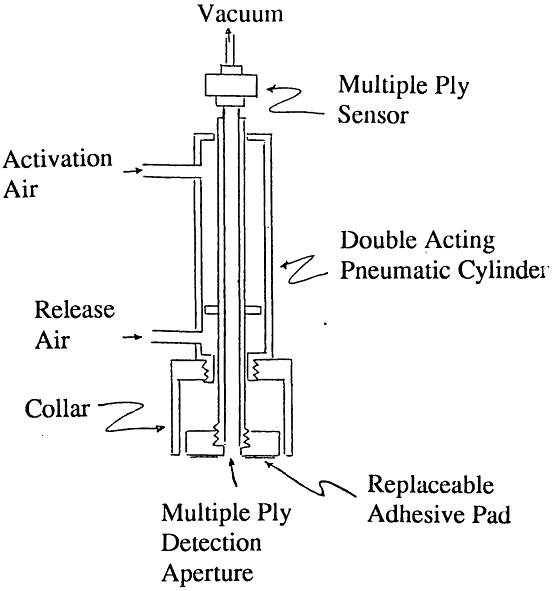


Figure 2 - The Glue Gripper [Monkman]

Glue based grippers have been available for many years, although they have always been prone to dust building up on the surface, reducing their effectiveness. The most common method of improving their reliability has been to use a 'typewriter' style cassette to increment the adhesive area used after each pick. This becomes expensive, as the cassettes are disposable items. An alternative is the use of water washable adhesives. Monkman [Monkman] used several including MAGNATAC™ as the basis of his grippers. The adhesive gives a much stronger general purpose grip then electroadhesion, allowing more vigorous destacking methods to be employed. Unfortunately, the releasing of the panel is not as easy. One method presently employed is to push an adhesive covered plunger through an aluminium tube to pick up the panel. The panel is then released by placing the tube onto the working surface to hold the fabric, while the plunger is removed (see figure 2).

An alternative method is the use of rollers. Fabric prehension is given by the front roller which is coated with adhesive. Movement of the gripper over the fabric as shown in figure 3a ensures enough fabric is wrapped around the front roller to secure it. To carry the fabric once prehension has been performed, the gripper is rotated by 90°, as shown in figure 3b. To remove the ply the picking up motion is reversed. In

this case the rear roller holds the fabric in place whilst the front (adhesive coated) roller forces itself free by rotation over and off the fabric. Two such grippers may be used to handle large fabric panels (see figure 3c).

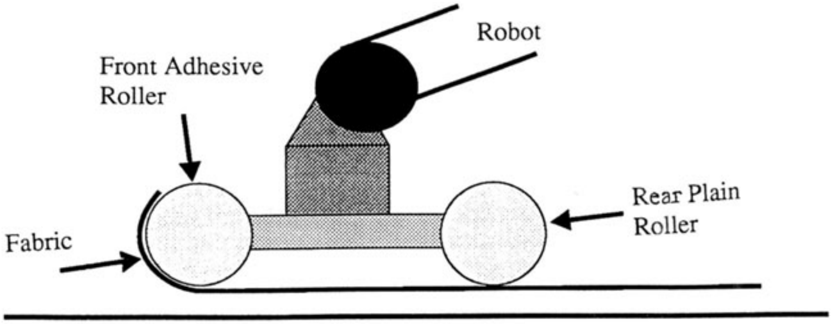


Figure 3a - Picking Up

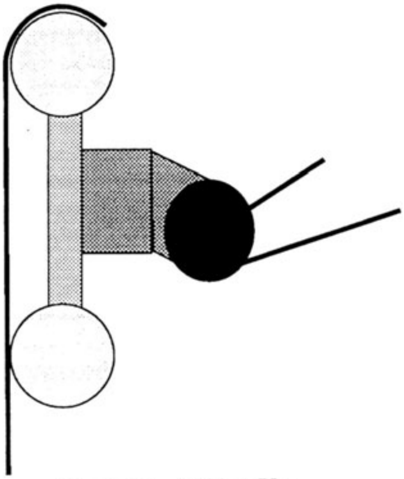


Figure 3b - Lifting Up

Figure 3c - Picking Up Large Panels

Figure 3 - The Glue Roller

These may be mounted on robots or on a single platform similar to that used by Koudis for gusset construction [Koudis]. It is essential that two rollers per gripper are utilised - one coated and the other plain - otherwise it is virtually impossible to maintain positional integrity of the fabric after the first roller has become free.

The adhesive gripper works on a large variety of materials, and is only affected by the build up of dust on the surface. Periodic wiping of the surface by water allows continual use. Various strengths of adhesive are available to suit the nature of fabric.

3.4 PINS AND PINCHING

Pins can be pushed through the top panel, and then tensioned to hold it [Nicholson]. This technique is dependent on the thickness and the planar stiffness properties of the fabric but, unfortunately, delicate fabrics can be damaged.

If two pegs are pushed down onto the top of a piece fabric and then moved together then the fabric will bunch up and be pinched between the two pegs. The effectiveness of this technique depends on the friction coefficient between pegs and fabric and the bending stiffness of the material.

3.5 PLY SEPARATION SUMMARY

It is clear that there are many methods of single panel destacking. Each technique relies on different fabric properties, as shown below in table 1, so care must be taken to define the range of fabrics to be used before selecting a particular method..

Technology	Technique	Main Fabric Properties	Suitable fabrics
Air jet	Vibration of panels by air	Air permeability and bending	Single and double knitted cotton
Electro-adhesion	Surface static attraction	Bending, dielectric and fluffiness	Light weight wovens
Glue	Surface adhesion	Dust content and fluffiness	Most but not delicate fabrics
Pinch	Mechanical clamping	Bending and surface friction	Most but not delicate fabrics
Pins	Mechanical	fabric thickness and planar stiffness	Light weight wovens

Table 1 Ply Separation Techniques and Fabric Properties

The reliability of all of the techniques can be improved by the addition of sensors. Sensors which can detect none, one or multiple plies are vital to all of the systems. Other sensors may also be necessary, for example, top of stack and/or edge of stack sensors if there is uncertainty in the exact location of the stack.

4. Transportation

In typical garment assembly factories garments are moved from operator to operator using bundles or on moving hanger systems which are ideal for the operators but cause problems for automation. Operators can cope well with the 'handkerchief problem' described in the introduction, simple automated systems cannot unless special hangers are used as described below. The alternative, removal of panels and subassemblies from stacks (bundles) can be automated but remains a highly sensor, time and computational dependent task, and should be kept to a minimum.

Conventional mono-rail hangers, such as the Gerber Mover™ [Gerber], allow fabric panels to be hung in totally random ways, usually from one point. Work is now in progress at the University of Hull and Leicester Polytechnic on the CIMTEX project to interface automated systems to such systems. To aid the automated removal, the panels are held along one edge, thereby giving a more consistent position. Removal is achieved with a robot which locates and grasps this held edge.

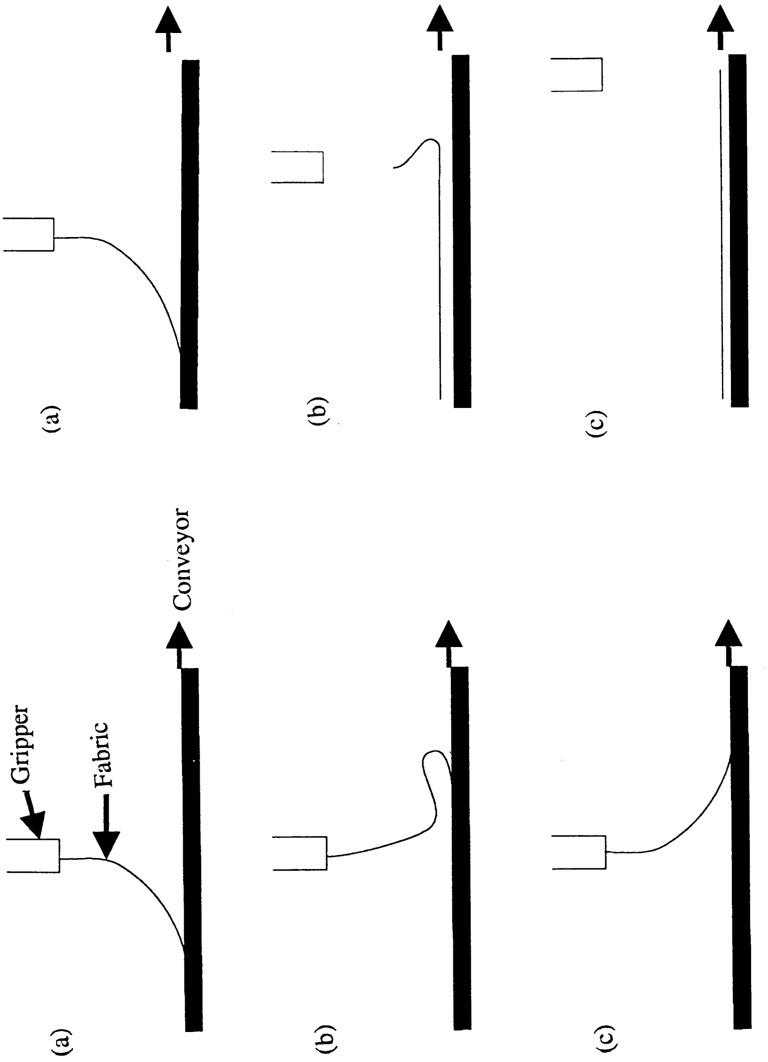
Conveyors are also used to transport fabric between work cells. Some operations can be performed while the conveyor is moving, for example, sewing of a straight seam, and others while the conveyor is stationary, such as the addition of other panels. Problems can occur when placing panels onto moving conveyors [Gunner]. If the panel is moved onto the conveyor in the direction of travel, there are two basic methods which can be used, depending on the speed of the conveyor. The 'furl-on' method, shown in figure 4a, is used if the conveyor is faster than the manipulator. The panel can be fed onto the conveyor by the manipulator and held stationary. The free end of the panel will then be pulled along by the conveyor due to friction, until the panel has been pulled out and can then be released. If, however, the conveyor is the slower, then the handling device can be used to pull the panel over the conveyor. Once the panel is completely on the conveyor, it can be released. This is the 'Pull-on' method and is shown in figure 4b.

Both of these methods are dependent on the bending and frictional properties of the fabric. These can be related to the minimum height the panels can be held above the conveyor, as well as the relative speeds of the conveyor and manipulator [Gunner]. The shape of the fabric panel used can influence the effectiveness of the system as non-symmetrical shapes will skew due to uneven forces across the panel.

Removing fabric panels from conveyors is a less trivial task compared to removing rigid components as care must be taken to ensure that the panels are not creased, distorted or damaged. If the conveyors can be stopped during the cycle, then the surface is effectively a stationary flat surface and in these instances many of the pick and place methods discussed in section 6 can be employed. If the panel has to be removed from a continually moving conveyor, then alternative methods can be implemented. One such method is the use of a 'scoop'.

A scoop is effectively a low friction plate, onto which the fabric panel is dropped or pushed. There are two basic types of scoop: The 'Lower scoop' is held at the end of the conveyor, allowing the fabric panel to drop onto it (see figure 5a). The lower scoop is ideal for removing fabric panels with high bending stiffness, such as woven shirt collars. It has the additional merit of accurately locating the leading edge of the fabric panel against the end of the scoop. With lower bending stiffness fabrics, the lower scoop has to be placed at a very sharp angle in order to catch the panel. Thereby causing the panel to deform.

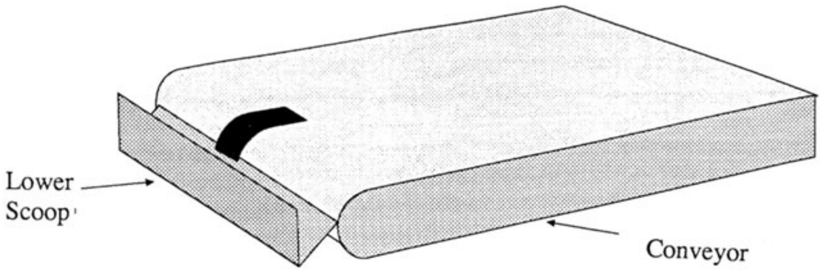
The 'Upper scoop' consists of a plate on top of the conveyor. As the panel moves along the conveyor, it runs onto the plate (see figure 5b). If a free running roller is placed just before the upper scoop, it ensures that the fabric momentum is sufficient to push it completely onto the scoop. This technique works even for low bending stiffness such as single and double knitted cottons.



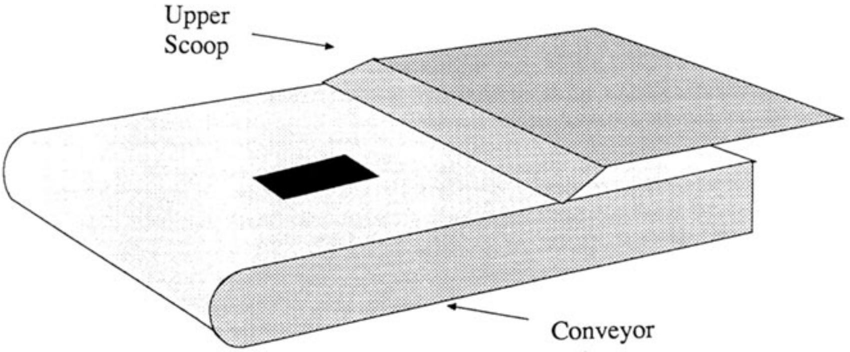
a) The Furl-on Method

b) The Pull-on Method

Figure 4- Methods of Pulling Fabric onto Conveyors



a) The Lower Scoop



b) The Upper Scoop

Figure 5- Scoops

Again the type of scoop used is dependent on the frictional and bending properties of the fabric. Simple optical sensing can be used to detect the presence of a panel on the scoop. If the fabric panel position and orientation are required then a further process must be implemented.

5. Position and Orientation

As components enter an automated process, it is usually vital that their position and orientation are known. The accuracy of location of a panel varies with the operation to be performed but normally +/1mm will suffice. There are two fundamental ways of locating objects. The first is to observe an large area in which the panel is placed on to observe a number of smaller areas whose feature such as edges or corners are expected. The panel's position and orientation relative to an origin can then be calculated (passive location). The second technique is to move the object to a preordained place, where its position and orientation is known (active location).

Camera systems can be used to passively locate panels, as well as identify them. This can be achieved using a area scan camera or a line scan camera if the component is introduced on a moving conveyor. The use of cameras is described by Gilbert [Gilbert]. The main problems with cameras are that they rely on the colour, and texture of both the fabric and its background, as well as the lighting conditions.

Two examples of active systems used at the University of Hull are air and vibrating tables. The air table relies on a laminar airflow across a flat surface to lift the panel off the surface. The system implemented uses an industrial fan mounted inside a box with aluminium gauze as the work top (see figure 6) covered with a layer of fabric. The angle of the gauze to the horizontal is then altered to move the panel. The air flow is crucial to the operation and is dependent on the fabric's air permeability. If the air flow is too low, then the piece will not float, and if too great, the panel 'balloons' causing the edges to fold back on themselves. If any part of the panel moves off the air top, then it sticks irreparably and removal from the table while the air is on is very difficult.

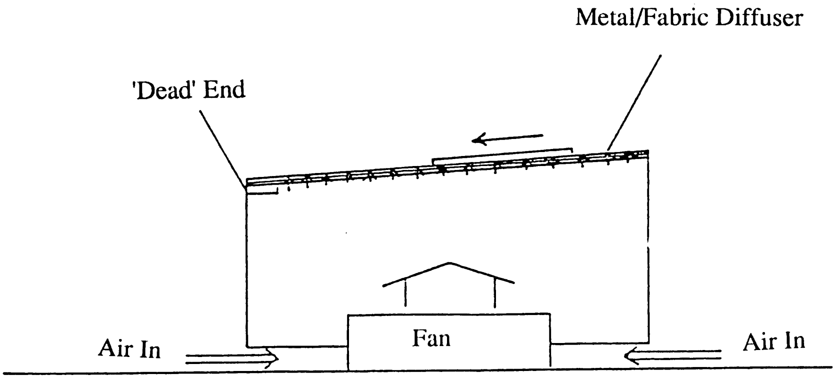


Figure 6 - The Air Table

The vibration table is easier to implement. A standard industrial linear vibrator is bolted to a desk and an A4 by 10mm sized aluminium sheet attached to its top. The top is then covered in acetate to create a low friction surface. When the table is switched on, the fabric moves in the required direction and speeds of up to 30mm/s can be achieved. The speed of movement appears to be related to the coefficient of friction between the fabric and the acetate, and research is underway at the University of Hull to establish this relationship. Again a barrier is used to locate the edge of the fabric panel. A second direction of travel is also obtained by altering the angle of the top to the horizontal. This means that the panel moves down the slope under gravity, and hence align itself against the barrier.

Once the panel is successfully moving on the surface, alignment can be achieved by allowing it to run against a barrier. It can then be moved along the barrier by altering the angle of the table top, or by the addition of air jets. A simple reflective sensor is used to record the position of the corner, given that the edge is against the barrier, and the vibrations are then stopped.

These systems rely on the physical properties of the fabric. In the case of the air table, the air permeability of the fabric is predominant, although panels with low stiffness tend to be more susceptible to ballooning. The vibrating table is very sensitive to changes in the frictional characteristics of the fabric, and so the selection of the surface is of the utmost importance. There is considerable mechatronic difference in the two basic philosophies given above. The camera systems are complex sensors and are dependent on the visual properties. The air and vibration tables are dependent on the mechanical properties and require minimal sensing.

6. Pick and Place

With all automated handling systems, there is a need to move objects around in space. The movement of fabric can be simply classified as 2D and 3D, where 2D operations involve the movement of the fabric in a plane, and 3D movements take the fabric out of the plane.

Various gripping technologies have been developed. In simple 2D grippers, pins, glue electroadhesion, vacuum or even simple friction have been used to move fabric panels across planar surfaces. An example of this is the Hull University friction gripper which moves knitted underwear panels from a stainless steel upper scoop to a vibratory orientation table. The biggest problem to be encountered here is that the surface of the vibrator is not horizontal and so compliance is built into the gripper in the form of a foam damper (see figure 7). The gripper surface is constructed out of

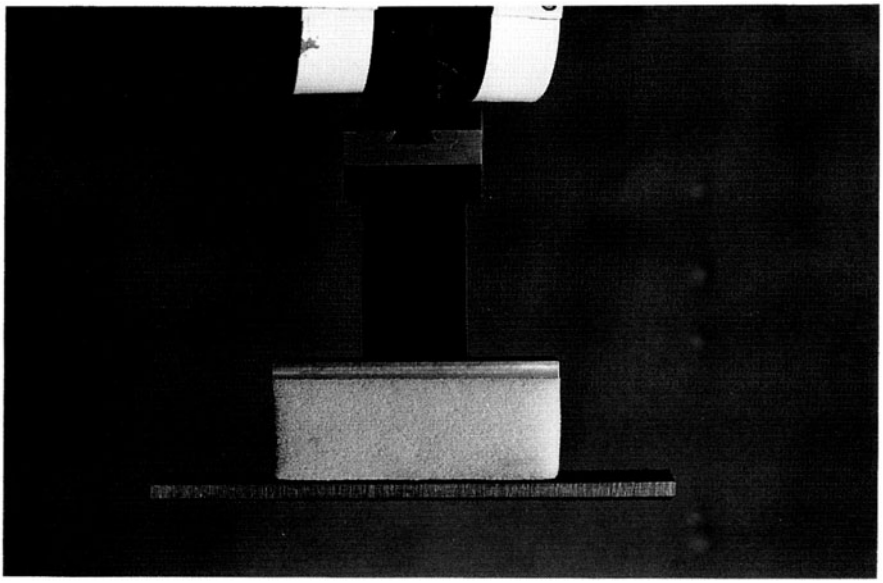


Figure 7 - The Friction Gripper

perspex and coated with the brush side of Velcro™. By ensuring that the gripper is always in contact with the panels, it can be used to move them over the surface, assuming that the coefficient of friction between the gripping surface and the fabric is suitable. Care has to be taken as high friction surfaces can also exert high cohesive forces, which can lift the fabric panel off the surface, when the gripper is removed.

Again many of these fundamental technologies can be used to move fabric panels through space. Some novel ideas have been introduced, for example, freezing, where a moist gripper surface is placed on to the fabric and then frozen [Schultz]. The relevant fabric properties here are probably absorption and thermal conductivity. A cycle time of 3 seconds has been claimed for this technique.

One of the simplest technologies used at Hull University is mechanical clamping. There are two main types:

6.1 CLAMPING GRIPPERS

In the first type, fabric is sandwiched between two parallel clamps or jaws. Getting the fabric between the jaws prior to clamping may be achieved in a number of ways, for example, insetting part of the gripper into the work surface, or allowing the fabric to be pushed over a knife edge and between the jaws. An example of this can be seen in the Pegasus RMC-200 Cuff maker [Pegasus].

6.2 PINCH GRIPPERS

The second technique utilises two 'pegs' which are placed onto the fabric, distance *d* apart. When the pegs are brought together a loop of fabric is formed between the pegs and the fabric can be secured. This requires the coefficient of friction between the pegs and the fabric to be greater than the coefficient of friction between the fabric and the surface. The initial distance between the pegs, *d*, appears to be dependent on the bending and friction properties of the fabric. Research is underway to find the exact relationship.

Each technology is reliant on certain fabric properties, which can be categorised as summarised below in table 2.

Technology	Fabric Properties	Suitable fabrics
Friction	Coefficients of friction and cohesion	All fabrics
Freezing	Thermal conductivity and absorption	Most fabrics
Mechanical clamping	Bending and surface friction	Single and double knitted cotton

Table 2 Pick and Place Techniques and Fabric Properties

Other technological considerations must also be assessed when selecting a gripper. Examples of these include the need for reconfiguration of a vacuum gripper to cope with different panel sizes, or the requirement of glue grippers to be washed regularly. The use of sensors in pick and place grippers is essential to detect successful pick up of the appropriate panel, and similarly correct, release and/or positioning.

7. Joining

There are two basic joining methods employed in factories today:

7.1 FUSING

Fusing involves the placing together of fabric panels which have been coated in glue. They are then transferred to a fusing press which melts the glue and presses the panels together. This technology is used primarily in the manufacture of woven garments, for example, shirt collars and suits. The transportation of the panels through the press is achieved by its own internal conveyor belts, so guidance of the panels through the process is not necessary. The picking and placement of the panels prior to fusing can use most of the technologies described in section 6. The accuracy to be obtained must be typically of the order of +/-1mm.

7.2. SEWING

All of the sewing machine manufacturers have invested a lot of resources into the development of sewing aids for the operator. These include automatic cutters, ply sensors, computer controlled motors and edge following devices. These are helping to implement automated sewing.

The accuracy of placement of panels prior to sewing is dependent on the type of seam being sewn. Overlocking sewing machines have built-in fabric trimmers which trim the edge of the fabric as it is sewn. This allows a placement tolerance of 2mm to be acceptable, whereas chain stitch machines which do not trim require an accuracy of 0.2mm.

The automated transportation of fabric panels through a sewing head is primarily dependent on the number of plies to be sewn, and the seam to be sewn. Most commercial systems for sewing simple straight line seams use conveyor belts with an additional top belt feed. These clamp the fabric and guide it past the head with a velocity matched to that of the sewing mechanism.

Alternatives used at the University of Hull include the use of jigs. A jig comprises of a simple plate attached to a linear actuator which has both position and velocity control. A clamp is used on the jig to secure the fabric plies to be sewn to ensure that the do not move during the sewing operation. This is ideal for simple straight line sewing, but can also be modified for some curved seam operations. In the case of the elastication of underwear legs, the legs can be straightened using flexible curves [Taylor '91]. which are placed onto the curved assembly and then straightened. The seams can then be clamped and sewn. Variation in the size of garment produced requires the curves to be adjustable. Sensing also needs to be added to ensure that the straightening has been successful. This is similar to the action an operator performs on the garment on an incremental basis. This is only possible because of the low stiffness of knitted fabrics, and the concave nature of the seam.

When sewing more complex seams, edge following devices, such as the Zyppy device [Profeel] can be used to good effect. At first sight commercial sewing systems are readily adaptable to automation. Sensors are available to stop and start the machine, thread cutters remove the excess thread, motors are easily computer controlled, and speed information is accessible from the tachometers. However, problems are still encountered when automatically setting the machine variables, for example, thread tensions, and monitoring the seam formation.

8. Manipulation

Some operations such as folding or the sewing of tubular garments are too complex to do in the plane. Three examples of complex manipulation which have been automated at the University of Hull are now given.

8.1 COMPLETING THE ASSEMBLY OF BRIEFS

Once a gusset formation has been completed with its legs elasticated, the last three operations are to close one side seam, elasticate the waist, and finally to close the other side seam, as shown in figure 8.

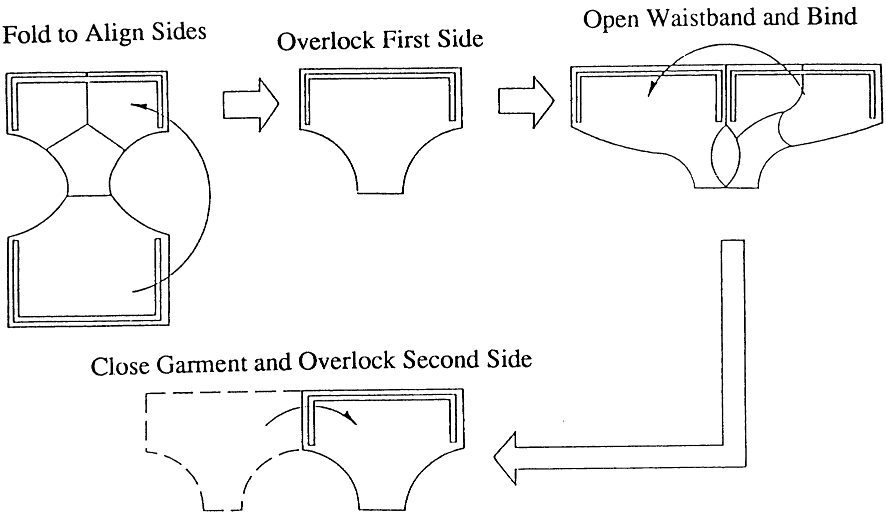


Figure 8 - The Last Three Brief Construction Operations [Taylor '91]

This sequence is performed in the factory by three operators, who rebundle the garments after each operation [Taylor '91]. This is not feasible in an automated system due to the complex nature of the shapes formed in these final processes. It would be expensive to emulate this and accuracy problems would arise. It was, therefore, decided to make a gripper which would hold the key points of the assembly throughout these last stages. This was achieved by a multi-axis gripper shown in figure 9. Simple pinch grippers are used to hold the key points, as relatively high forces are imposed on the fabric during the manipulations. The gripper is used to pick up the flat completed gusset assembly, fold it over and present the first side seam to be sewn. It then opens the garment to 90° and presents the waistband to the elasticator. It can not be opened greater than 90°, otherwise the garment would be stretched. Once the first part of the waistband has been sewn, the garment is rotated through 90° to allow the waistband to be completed. Finally, the gripper is closed, and the final side seam presented for sewing.

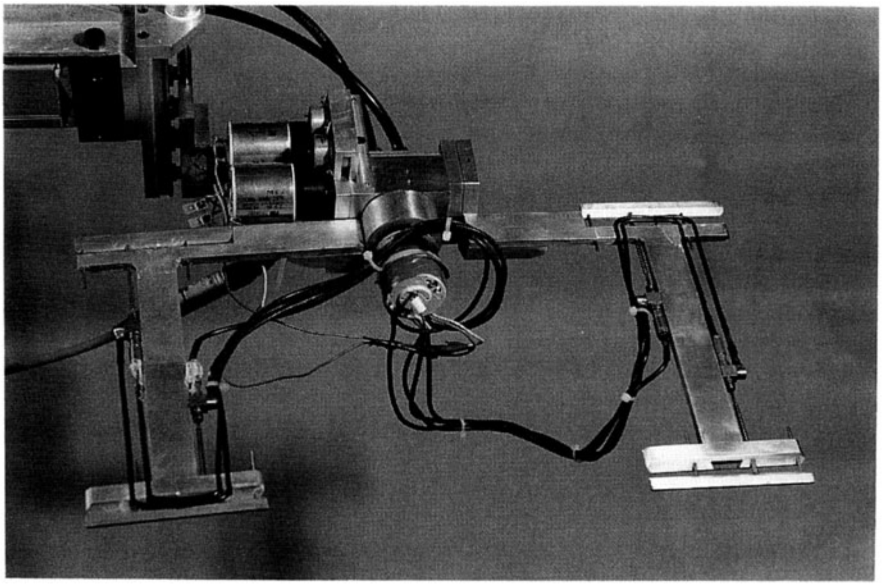


Figure 9 - The Multi-axis Gripper

This form of manipulation is only possible due to the extensibility of the fabric, and hence works very well with knitted fabrics. The general principle of holding all the key points to be operated on during the sequence can, however, be applied to many complex manipulation problems and reduces the need for sensors between tasks.

8.2 FOLDING OF LEISURE TOPS

Leisure tops are usually produced in the UK by constructing the front and back panels, joining them at the shoulders and adding the neck. Raglan, curved or straight sleeves are then added. The next stage is to fold the garment in half ready to sew the side seams. The key points to align are at the cuffs, arm pits, and waistband. A gripper to perform this folding operation of the type described above would be very large, and so an alternative solution was sought. The system used at the University of Hull [Taylor '92] folds a garment approximately into two with a metal plate between the two halves. Stepper motor driven conveyors both above and below the plate provide independently controlled movement of each half. The conveyors can then be moved to align the key points. A bank of optical sensors is used to feedback positional information to the conveyors to give accurate alignment as the garment is removed. This system has been implemented and has been found to work with a wide variety of fabrics, from denim to knitted cotton.

8.3 ADDITION OF CUFFS

The problem of adding tubular cuffs has been aided by the development of the Pegasus RSC cuff attacher [Pegasus]. This uses a spiral to stretch the cuff to the size of the sleeve and pull it under the foot while sewing. Thus, the automation problem is reduced to loading the cuffs and the sleeves on to the machine. Each sleeve or cuff is fed in as a flat tube which is opened out, as shown in figure 10, ready to load onto the machine.

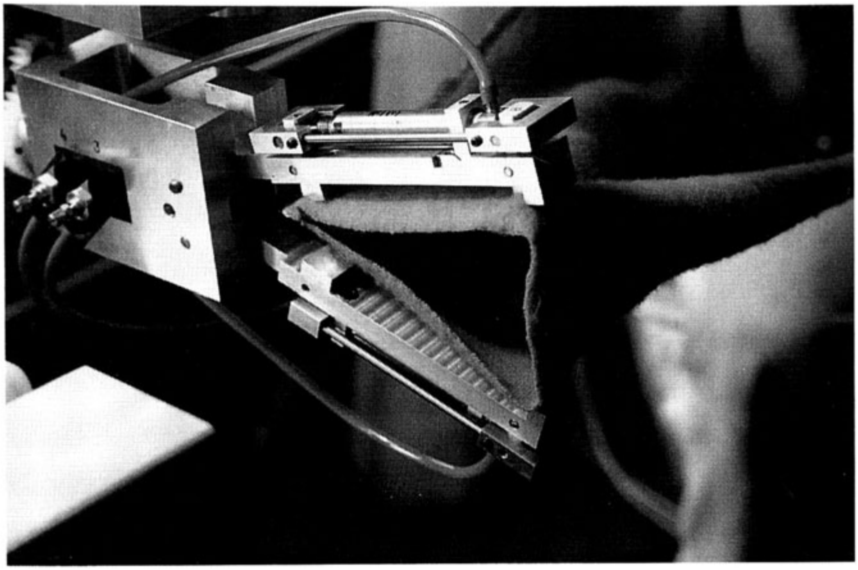


Figure 10 - Triangulation of the Sleeve

Pins are used in the gripper to maximise the retaining gripping force whilst the sleeve/cuff is pulled onto the sewing machine.

9. The Future

The expertise required of the operator has been reduced by the addition of fabric independent devices to sewing machines. This has led to the development of 'one operator-two machines' systems, where the skill of the operator has been transferred from the act of sewing to the loading of the machine. It is becoming increasingly clear that the next stage is to link multiple sewing machines together. Such linking of these systems is difficult due to the fabric dependency of the handling devices. When designing an automated handling system, it is therefore necessary to define the range of fabrics to be used. From this a list of relevant handling techniques and technologies can be derived. Once the these have been short listed, the sensors to be used and where they are required can be outlined. This information can then be fed back into the technology consideration and the process repeated as necessary.

The handling methods given above by no means form a complete list, but they represent some of the wide variety of techniques which have been developed. In order to be able to select different techniques for different operations easily, work is underway at Hull and elsewhere to develop experiments which quantify fabric properties in a form which can then be directly related to the handling techniques. It is this work which will prove to be the turning point in the automation of garment assembly tasks.

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SENSING IN GARMENT ASSEMBLY

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ABSTRACT. Sensing demands in the automated assembly of garments differ considerably from those encountered in rigid materials handling. Attempts to automate in an 'open loop' manner, assuming knowledge and consistency of all relevant fabric properties, are usually doomed to failure because such properties are likely to vary from batch to batch, with time, environmental conditions, and can be dependant on the handling history. Sensory feedback can provide information for the selection of appropriate corrective action. Various sensing strategies have been proposed for the detection of presence, position and orientation of fabric stacks and individual panels, with the aim of preparing parts for joining. These are discussed in some detail with particular emphasis on the practicalities of different means with respect to the relevant properties of the materials and the environment. The applications of sensors during sewing operations, for error recovery and for inspection purposes are also described.

1. Introduction

The aim of this paper is to describe the types of sensor systems which are suitable for use at all the major stages involved in the assembly of a typical garment. Due to the flexible nature of the materials used in garments and the limited understanding of their physical properties, it is virtually impossible to achieve reliable automated handling and processing without some form of sensory feedback. As greater degrees of automation are sought in the garment industry, so the need for appropriate sensing increases.

Part of the problem of automating garment assembly is that the properties of the materials used are different from those used in areas of manufacturing where automation is already well established. This applies not only to the handling but also the sensing of materials and so certain material characteristics used for sensing in other industries are of little use in fabric handling. One of the most frequently used sensors in general automation is the inductive proximity switch. Due to the lack of metalic content in the majority of fabrics such devices are of no use in this area. Having said this there are a wide range of sensor technologies which have been successfully applied but the selection of the most appropriate technology is a non-trivial problem. In this situation, the most suitable sensing method is closely related to the handling method being used (and indeed, situations arise in which the handling method is selected on the basis of the possibility of achieving useful sensory feedback). This calls for a mechatronic design philosophy since the selection of sensors cannot be divorced from the selection of handling mechanism but rather the two must be designed in parallel.

Although many diverse sensor types are applicable to fabric handling problems,

M. Acar (ed.), Mechatronic Design in Textile Engineering, 291–308.

the level of sophistication in the sensors is not necessarily high and, in some specific cases, highly sophisticated sensing schemes do not perform as well as simpler systems. This paper describes the sensor schemes which have been considered and attempts to illustrate their areas of suitability and those applications in which they are less appropriate.

The range of sensors which have been studied is wide, due to the diverse range of operations involved and, not suprisingly, the most appropriate scheme is closely related to the type of operation being undertaken and so the sections of this paper refer to generic operations common in garment assembly. Specifically, the way in which fabric is being held or manipulated frequently imposes restrictions on the type of sensing which can be used. The following sections are arranged in the sequence in which the operations are typically undertaken. Thus, section 2 considers the problem of establishing the presence or otherwise of a fabric ply or stack of plies while section 3 looks at the problem of distinguishing between single and multiple plies.

Section 4 begins from the assumption that a single ply or subassembly has been obtained and looks at the subsequent problem of determining its position and orientation ready for joining or other processing. Sensing which may be used to assist in sewing operations is also considered in this section.

A further, major, area of sensor application is in inspection, both of the raw fabric and of the finished garments for quality control purposes. A number of methods are used in both of these situations and so the general subject of inspection is discussed in section 5.

2. Detecting the Presence of Fabric

The determination of the presence or otherwise of a number of fabric plies is a required element of a wide range of operations. One of the first stages in a garment assembly cell is to ascertain whether the material has been delivered and hence whether the process may begin. The fabric may be presented as a single ply or as a stack of plies and this will have some influence on the sensing system used but often equally important is the mechanism by which the ply or plies are delivered. If, for example, the plies are presented on a patterned or irregular background then an optical or visual system may be less suitable than a tactile method.

The sensors described in this section are of a relatively simple nature, with little processing required to extract the information sought. This does not however mean that the choice of sensor is always straightforward.

2.1. FORCE BASED PROXIMITY SENSORS

Perhaps the most simple methods of detecting the presence of material, particularly when a stack of plies is expected, is to use a microswitch which is gradually lowered until the switch lever contacts an object and the circuit is completed. If this occurs at a position above the level of the base then it is reasonable to assume that a stack of cloth has been detected [Kemp,89]. This assumes that a gradual lowering of the sensor is achievable but, since the subsequent action is likely to involve the removal of the top ply of a stack, the destacking device must be positioned correctly, relative to that top ply and the required movement must therefore be achievable. The problem may be inverted with the stack moved up to the sensor, as described by Monkman [Monkman,89].

A potential problem with this system is that a trade-off is reached between the resolution of the sensor, which in the ideal case must be able to detect a single ply, and the force required to operate the switch. Most switches requiring low activation force also require a large travel and give poor resolution. A partial solution to this problem has been presented by Kemp [Kemp,89] who describes a method whereby a lightweight lever is arranged so that when a small upwards force is applied to one end, as a result of contact with the fabric, the opposite end breaks a light beam. This light beam is delivered by a fibre optic cable connected to a remote LED and detected by a photodiode which is again placed remotely and connected via fibre optic cable. The remote placement of the LED and sensor allows the sensor to be placed in the thin, lower jaw of a de-stacking gripper (see figure 1).

A similar arrangement, but with the sensor embedded in a table, may be suitable for detecting single plies, provided the weight of the ply is sufficient to activate the sensor.

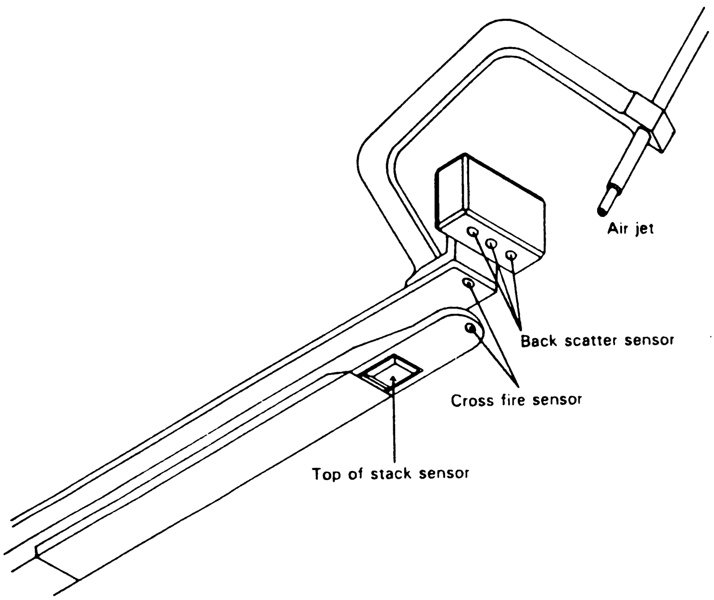

Figure 1. Ply destacking gripper showing top of stack sensor and crossfire sensor

2.2. OPTICAL PROXIMITY SENSING

Optical sensors are extremely common in a wide range of manufacturing environments and are equally important in the garment assembly industry. There are a number of modes of operation which may be used, each of which has some merit in specific applications. The simplest scheme involves the use of a photo sensor, embedded in a flat surface, which is covered when a fabric panel is placed on the surface, thus eliminating any ambient light. This requires a reasonably constant level of ambient light and a material which does not transmit light. To eliminate the former requirement, a dedicated light source is often provided above the sensor. This source must be of sufficiently high intensity to eliminate any effects from varying ambient light. Alternatively, an infrared source and sensor may be used since the ambient infrared levels are far lower than typical ambient visible light levels.

If a through beam system of this type is not suitable then it may be possible to use a reflective optical sensors in which a source and sensor are typically mounted side-by-side. Provided the optical characteristics of the fabric and the underlying material are sufficiently different, the level of reflected light can be used to infer the presence or otherwise of the material. This can present problems if a wide range of material colours are used and so the reflection from the background may have to be modified to make it more easily differentiated. This can be achieved by using polarised light and a retro reflective background, or by removing the area of the background which reflects the light. Such methods may be used to detect the presence of a single ply or a stack but cannot easily be used to determine the position of the top of a stack.

In addition to this rudimentary application of reflective opto sensors, more detailed information may be derived from the sensor output. Koudis [Koudis,87] describes experiments in which the radiation from an infrared LED is reflected by a piece of fabric onto a phototransistor sensor positioned beside the LED. As the distance between the source/sensor pair and the fabric sample is altered the sensor output is monitored. The resulting output has a single peak at a distance of approximately 4mm from the fabric and is reduced when the sensor is closer or further away. This allows the position to be infered to within approximately ±6mm from a single measurement or, by taking a sequence of measurements as the sensor is lowered, a higher resolution may be obtained. Unfortunately, there is a difference in the response for the various colours of cloth investigated but this corresponds to a position error of only ±1mm for a wide range of colours and fabric types.

2.3. PNEUMATIC SENSORS

Air suction is frequently used to grip fabric during manipulation or to hold panels to a surface, for example during cutting. Allied with this, it is possible to detect the presence of the fabric on the gripper or surface by monitoring the air pressure in the vacuum supply. If the air ducts are not obstructed by a piece of cloth then the vacuum pressure will be approximately the same as atmospheric. However, if a piece of cloth is present this will result in a lowering of the air pressure. Clearly for this scheme to operate successfully, the fabric must be reasonably impervious to air and, in some cases, the difference in permeability between the fabric and the surface from which the fabric is lifted must me significant if the two are to be differentiated. The design considerations for pneumatic sensors are described in more detail in section 3.3 in the context of single ply discrimination.

2.4. ACOUSTIC (ULTRASOUND) DETECTION

The high acoustic absorbance of fabric may be utilised in a sensing system in which an ultrasonic transmitter and receiver monitor the absorbance of any material placed on a surface. Provided the background material is sufficiently acoustically reflective, a clear difference in recieved power occurs when fabric is present. Such a system may also be able to monitor the position of fabric provided it is moving in a known direction and the type of panel is known. Early results for such a system suggest that a position resolution of 0.5mm may be attainable. The sensor is not immune to background noise but, by using high frequency ultrasound, this problem may be minimised.

3. Single Ply Discrimination

In the previous section, methods of detecting the presence of plies were considered. Having established that there are a number of plies in the required area, the next stage is frequently to check that the number is one. Several techniques have been established to achieve single ply discrimination relying on a variety of fabric properties. These techniques are the subject of this section, while a number of apparently reasonable approaches are also considered and the reasons for their unsuitability discussed.

In many instances the single ply discrimination process is best considered as part of the separation process since it may not be possible to recover from an attempted separation if sensing is left until the attempt is completed. In accord with this, several of the sensing techniques are described in the context of the separation method to which they are most suited, or in which they have been developed.

3.1. OPTICAL PLY DISCRIMINATION

The vast majority of garment fabrics do, to some extent, allow the transmission of light and the amount of light transmitted will depend on the number of plies present. This forms the basis of a 'cross fire' sensor described by Kemp [Kemp,86] in which an infrared LED is mounted in the lower jaw of a fabric gripper opposite a photodiode, as shown in figure 1. By measuring the photodiode current the amount of light, and hence the number of plies in the jaws of the gripper, may be determined. The processing electronics provides three outputs corresponding to none, one and more than one ply. Due to the variation in fabric properties, the thresholds for these outputs must be variable and are reset for each new batch of fabric.

3.2. ELECTRICAL/MECHANICAL SENSING

Some fabric ply destacking units use a pinching technique to hold the fabric once it has been removed from the stack [Kemp,89]. Similarly, pick and place grippers often transfer material by holding one or more edges [Taylor,91]. To detect the presence of fabric in the jaws of such a gripper, a conductance test can be used. If the jaws of the gripper are electrically isolated, and are pivoted around a common point, then shutting the jaws will complete a circuit if there is no cloth present. However, since most fabrics have a high electrical resistance, the presence of the fabric acts as an isolator and prevents the circuit from being completed (see figure 2). The electrical resistance of any ply is very fabric specific and alters with humidity. This makes resistance measurement unsuitable for the detection of multiple plies.

One of the simplest methods of differentiating between one and multiple plies is to measure the thickness of the fabric. This can be achieved by keeping one jaw fixed, pivoting the other and measuring its position when the fabric is clamped with known force. By elongating the movable jaw away from the pivot, the movement is effectively magnified, resulting in a more easily detected movement which depends exclusively on fabric thickness. A possible implementation is shown in figure 2. The extension of the jaw is moved between a simple slotted opto emitter and receiver pair. The position of the sensor can then be laterally adjusted so that it is uncovered when there is one or no plies present and covered when more than one ply is present. By implementing this technique with the resistive measurement, a fast, reliable and inexpensive fabric ply discrimination system can be achieved.

A more sophisticated ply discrimination sensor consists of a tactile array attached to gripper jaws [Paul,90a]. This is sufficiently sensitive device that it is able to detect the presence of a single ply held in the jaws.

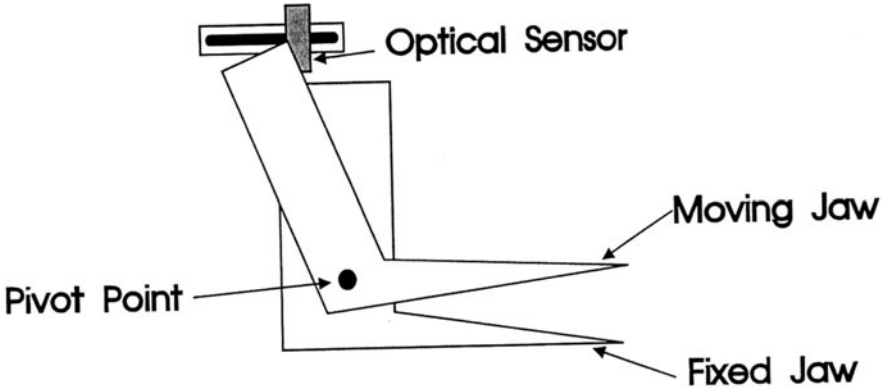

Figure 2. Cross section of electro-mechanical sensing gripper

3.3. PNEUMATIC PLY DISCRIMINATION

Pneumatic suction is of little use in itself for effecting separation of fabric panels from freshly cut stacks owing to the permeability of most cloths and the subsequent tendency to pick-up several plies. However, as a sensing mechanism it can prove most useful both in top of stack sensing and in the determination of the number of panels held by a gripper. As an example, Permatack adhesive grippers [Monkman,91] now manufactured by a UK company [EDA], are available in two forms. The basic model simply consists of an adhesive pad raised and lowered by a pneumatic cylinder and is intended for use with materials which either separate easily or are not stacked. For the automated ply separation of fabric, a model which includes a pneumatic sensor is available. Figure 3 represents a cross sectional diagram of the gripper showing the pneumatic path through the adhesive pad and the rod of the pneumatic cylinder. By drawing a small volume of air through this path the relative permeability of any material held by the gripper may be found. This is achieved by detecting the change in air pressure using a very sensitive differential pressure sensor situated at the top of the gripper, as shown in figure 3. The electrical output of the sensor provides the information necessary to determine whether one, none or several plies have been secured by the adhesive pad.

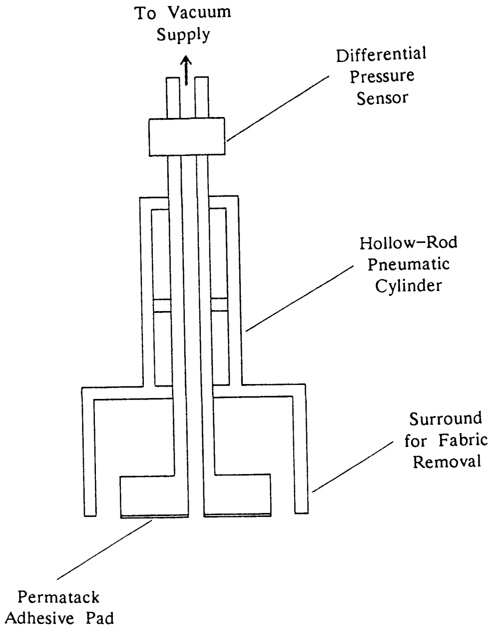

Figure 3. Cross section of a Permatack adhesive robot gripper

Permatack adhesive grippers must make physical contact with the material to be lifted. This allows such pneumatic methods to be used to detect the top of a stack of fabric whilst the gripper is incrementally lowered, by a robot for instance. As the top of the stack is approached, the air flow rapidly diminishes until it is almost totally choked off when the gripper surface is pressed firmly against the top panel.

In addition to the simple air flow/no air flow detection, which may be suitable for top of stack detection, some means of determination of threshold levels of air flow is required. At least three levels of output are needed to determine the acquisition of one, none or several panels. Furthermore, these must all be adjustable to take into account the use of materials having different pneumatic permeabilities.

Unfortunately, the changes in voltage output from the differential pressure sensor corresponding to the different permeabilities between one and two panels, is very small. Consequently, the measuring circuit must be very sensitive and free of drift. The circuit on the experimental prototype gripper has four adjustable outputs which may be set independantly.

To ensure the circuit is free from interactions between each threshold sense during adjustment, only extremely high input impedance operational amplifiers may be used. In the commercially available model of this gripper, a remotely situated venturi vacuum generator is used while the sensor PCB is housed within a small enclosure as part of the gripper.

3.4. INDUCTIVE AND CAPACITIVE SENSORS

Capacitive and inductive sensors are frequently used to detect the presence of, the distance to or the thickness of various materials. Inductive sensing cannot usually be applied to fabric but capacitive sensing of the number of plies can be achieved by sandwiching the fabric between two metal plates, thus forming a capacitor whose capacitance varies with the thickness and permitivity of the material. Unfortunately, the low relative permittivity of most textile fabrics makes the implementation of capacitive sensors difficult. For example, given a sense plate of 1 cm^2 at either side of a sample of 0.3 mm thick fabric, then the total capacitance will be given by:

$$C = \frac{\mu_0 \mu_r A}{d} \qquad \{1\}$$

where: μ_0 is absolute permittivity (8.85×10^{-12}F/m)
μ_r is relative permittivity (say 4 for polycotton)
A is plate area (10^{-4} m^2)
d is distance between plates (0.3×10^{-3} m)

From {1} we can expect a total capacitance of about 12 pF with one ply between the plates, reduced to 6 pF with two plies. These values of capacitance are extremely small, so small in fact that the capacitance of the connecting leads and their proximity to other objects is likely to be a problem. Furthermore, the reactance of such a sensor will be very high for frequencies below 1 kHz. Frequencies in the 10kHz to 100kHz range are required to make effective use of this arrangement.

Improvements would result from making the sensor plates larger or by building the sense circuitry directly onto the capacitor plates. It is also assumed that the jaws of the gripper used are always parallel to one another during gripping, regardless of fabric thickness. Furthermore, in view of the lower surface area requirements and cost effective availability of optical devices which perform this task adequately, such efforts have little prospect of economic success. Nevertheless, high frequency fields can be useful in determining the position of cloth edges, as will be discussed later.

4. Positioning and Orientation.

When a material panel is prepared for some proccess it must in general be positioned correctly or at least the position must be known. The mechanical positioning may be performed by a variety of means and the flexibility of the handling mechanism affects the sensing techniques which are appropriate. For instance, a camera system which specifies the position of a panel is of little use if the handling mechanism cannot recover from a mis-alignment.

4.1. AREA CAMERAS

Area scan cameras are probably the most commonly used form of camera in automation. Several researchers have studied the use of area cameras to determine the position of panels. In all applications of vision, good control of lighting is essential and, when determining the position or outline of an object, a high degree of contrast between the object and the background allows more rapid and reliable processing. The provision of sufficient illumination is not generally a problem in the garment industry but, equally important is the positioning of the light source. Top lighting is generally easy to achieve but, to operate reliably, it requires a clean base plate of a contrasting colour and is less suitable when patterned fabric is used. Backlighting provides good contrast but requires a clean, transparent or, preferably, translucent background plate.

Initially, we will consider situations where a single camera views the entire panel area. Paul [Paul,90b] describes the use of a camera system to determine the position of a shirt collar at three stages of the assembly (after destacking, after turning and after pressing). Jones et al [Jones,92] describe a system in which fabric panels are placed on a light box viewed by a CCD camera. The backlit image is used to derive details which confirm that the correct panel is in view and then determines the location of the panel to within 1mm and 0.3°. A robot manipulator is then instructed to pick up the panel from this location and place it on a sewing conveyor. A vision guided robotic loader for an NC sewing machine has also been studied by Necchi Spa.

Kemp [Kemp,89] used a Vidicon camera mounted above a rotation table as part of a fabric destacking and motif placement cell to verify the presence of a single motif and then to determine its orientation. A 64x64 pixel binary image of the motif is extracted from the camera and the image is checked for the presence of just one motif, which is the correct way up. If not, corrective external action is taken, as required. The table is then rotated until the alignment is known to within 1° and the translational position found to within ±1mm.

In the general case of determining the position and orientation of a fabric panel, a single, area camera may be used but consideration of the system requirements often reveals problems with this approach. Consider a situation in which the edge of a panel is to be located to within ±1mm. If the item in question were the back of a pair of mens briefs, this could be up to 400mm by 250mm (small compared with the panels used in many garments). If the initial position is known to within ±10mm then an area of 420mm by 270mm must then be scanned. In the absence of noise, and taking the worst case orientation, the camera must have a resolution of approximately 420 by 270 pixels if a very simplistic edge detection algorithm is considered. Although cameras with this resolution are readily available, the cost of the camera and the processing equipment required to attain an acceptable speed of operation is high.

From the preceding discussion it will be apparent that, although a single area camera is often suitable for determining the position and orientation of small items, it may be less appropriate for larger panels. In this case a system involving several area cameras detecting the location of significant points on the outline of a panel may prove more effective. This has the dual advantage of requiring low resolution and hence low cost cameras and allowing more rapid processing due to the low resolution and simple feature identification involved. It does however suffer from a lack of flexibility, in that the cameras must be moved when a different shape or size of panel is considered.

An example of this approach [Taylor,86a&b] involves the use of two low cost, low resolution cameras attached to a gripper so that the two points of a shirt collar panel are in view when the gripper is correctly positioned. This has been demonstrated to allow location to within ±1mm using two 128x256 pixel binary images which are immediately compressed to 64x64. A similar system dedicated to the assembly of underwear panels is also described.

4.2. LINE SCAN CAMERAS

In some instances, it is possible to use line scan cameras instead of area cameras [Batchelor,85]. Typically, this would be used when the component is travelling along a conveyor. The line scan camera may be mounted above the conveyor, taking in a series of linear scans perpendicular to the direction of conveyor belt travel and so building up an area image as the components pass. This has the advantage that line scan cameras are available with resolution along the scan greater than that available on a single axis of an area cameras of similar cost. However, a limitation on this method is the speed of the camera, which affects the resolution of the camera in the direction of component travel. The resolution, r is given by:

$$r = V/S \quad \text{(m/scan)}$$

where

V is the velocity of the conveyor (m/sec)
S is the scan rate of the camera (scan/sec)

The scan rate of the camera is controlled by the number of pixels and the light sensitivity of those pixels. The rate can be improved, to some extent, by increasing the level of illumination but this does not always result in a sufficiently fast sensor system. Hence a trade–off is found between resolution in the direction of travel and the conveyor speed.

If the resolution is not adequate, then an alternative can be implemented for certain panel shapes provided the size and shape of the panel being observed is known [Do,89]. A fast, single element optical sensor may be used to detect the leading edge of the component on the conveyor, and cause the line scan camera to take a single scan (see figure 4). If the scanned line is a fixed distance w from the leading edge, then the scanned line can be compared with a look up table, which can be pre–computed to give the position and orientation of the panel.

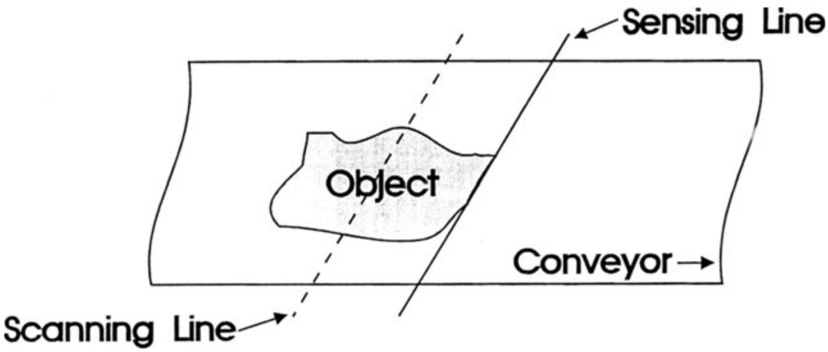

Figure 4. Fast position sensing using a line scan camera

4.3. OPTICAL ARRAYS

Linear arrays of photo detectors may be used, with a lens arrangement, as line scan cameras but in this context we will consider the situation when no lens is used and the sensors may be thought of as omni–directional. In other words, we will look at the situation where fabric is placed between the optical array and a single light source, blocking the light to some or all of the array elements. Since the sensors are omni–directional, control of ambient light becomes an important consideration. In addition, the system must be made immune to changes in material, seams etc.

This sensing scheme has been used, in the CIMTEX automated sweatshirt assembly project at Hull, with a Zyppy air jet system to align the edge of fabric travelling along a conveyor. The 22 element, 1mm spaced photo diode array is set into the table next to the Zyppy device (see figure 5) and the output from the array is processed and sent to a proportional air valve which alters the air flow to the Zyppy. This system is able to position the edge of the fabric, including parts where a seam runs perpendicular to the edge, to within 2mm of the desired position, starting from an initial error of up to 40mm. This is achieved at a speed of approximately 70mm/s.

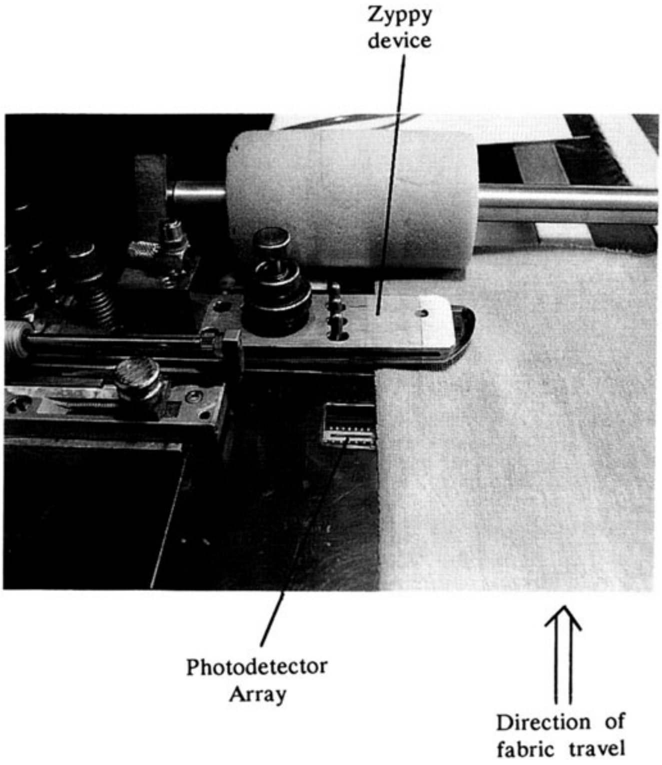

Figure 5. Linear photo detector array and Zyppy device

The reflective optical sensors described above rely on lighting conditions and the colour and texture of the fabric and background being constant. Unfortunately, the colour of fabric can vary enormously, even when considering one fabric type. Some of these problems may be aleviated by the use of the infra red spectrum, thus minimising the effect of ambient light. An addition advantage is that different colours of cloth are less distinct under infrared light than under white light.

4.4. SIMPLE OPTICAL PROXIMITY SENSING

In the previous section, edge sensing in situations where a piece of fabric is moved in one direction was described. There are instances in which the position of the edge of the fabric may be controlled by some mechanical means and only the movement in a direction parallel to the edge needs to be sensed. This may be achieved using a single reflective or diffuse optical sensor located at the required final position of the panel. An example of this involves the use of a rubber wheel, mounted on a motor, which slides a shirt collar part along a smooth plate until a reflective sensor beam is interrupted. Similarly, a system in which an underwear panel moves across a vibrating table until a sensor embedded in the table is uncovered has been described [Taylor,86a]. These schemes have the advantage of simple sensors and processing but are very specific to particular applications.

4.5. CAPACITIVE POSITION SENSING

In addition to cameras and other optical systems, it is also possible to detect fabric edges capacitively. This is particularly relevant on electroadhesive surfaces used for the retention of fabric where high electrostatic field intensities exist. A small area, electrically isolated from the main charged area, as shown in figure 6, may be used as a sensor. When a piece of cloth lies across the charged surface and the sensor pad it acts effectively as a parallel resistor and capacitor, the characteristics of which are different from those for air. By detecting these differences, the presence of a ply may be determined.

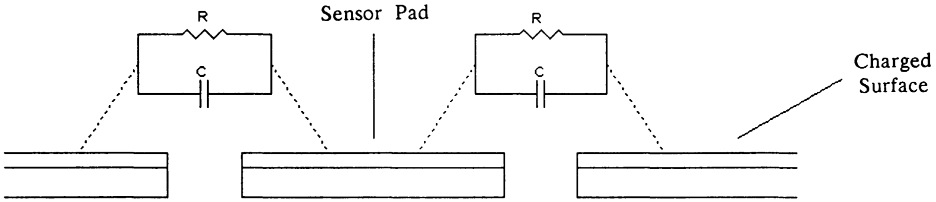

Figure 6. Capacitive edge sensor and equivalent circuit

Alternatively, the sensor arrangement of figure 6 can be used as an analogue device, the collected charge on its surface being proportional to the area of the sensor covered by the fabric. Using an array of such sensors allows the position and orientation of a fabric panel to be determined.

For example, a ply situated exactly in the middle of a gripper surface, with equal lengths of fabric covered each sensor, will result in a null output from a differential amplifier connected between the two sensor outputs. Conversely, a ply covering a greater area of sensor 1 than of sensor 2 will yield a negative analogue output voltage proportional to the ply offset distance from the centre of the gripper.

Due to the very low capacitance between the charged surface and sensor elements, a high voltage is essential. A switching stage between the sensor elements and the differential amplifier inputs, as shown in figure 7, allows the charge on the sensor pads to be dissipated periodically.

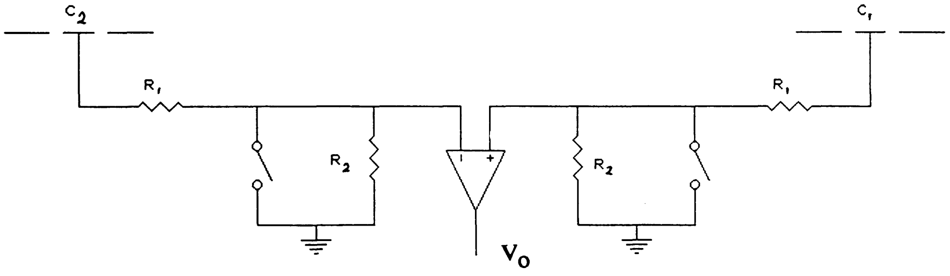

Figure 7. Switched differential amplifier circuit

The frequency of switching is chosen such that the capacitance formed between the charged and sensor surfaces cannot fully charge even when totally covered by fabric. As this capacitance is very small, the duration t, during which the switch is open must be correspondingly short. The voltage from the differential amplifier is of the form:

$$V_0 = \frac{R_2 V}{R_1 + R_2} \left(e^{-\frac{t}{C_1(R_1 + R_2)}} - e^{-\frac{t}{C_2(R_1 + R_2)}} \right) \qquad \{2\}$$

where C_1 and C_2 are functions of the location of the fabric.

The voltage given by {2} may be filtered to give a steady state DC voltage corresponding to the difference in sensor areas covered by fabric.

4.6. SENSING DURING SEWING OPERATIONS

The problem of sensing at the sewing machine has been addresssed to some degree by most of the major sewing machine companies. Most motor controllers for sewing machines may be fitted with a reflective photo sensor which prevents the operator from starting the machine before putting the fabric under the presser foot. These sensors can also be used to initiate cutters which help to reduce operator activity, save time and reduce the amount of thread wasted. Reflective sensors can also be used for the detection of fabric edges. A typical method of aligning edges before sewing uses 3 sensors in a line perpendicular to the edge and a mechanical alignment device which moves the fabric to ensure that only 2 of the sensors are covered at any one time [Pegasus].

Cross fire sensors have been implemented by Pegasus [Pegasus] to ensure that when the operator is sewing multiple plies, they are aligned correctly. Mis-alignment of plies (known as non-inclusion) is detected when fewer than the required number of plies are present between light source and sensor. Similar methods have also been used, when sewing tubular garments, to check for multiple fabric thicknesses.

Besides checking for the presence and position of fabric during sewing, sensors have also been applied to check the process of stitch formation and hence detect mis-stiching. Catchpole and Sarhadi [Catchpole,89 & Catchpole, 90] describe the use of strain gauges to detect irregularities in the mechanics of the sewing machine. Similar systems have also been developd by Pfaff [Pfaff].

The sensing of seam quality, and in particular determining the presence of pucker, has been investigated by Stylios [Stylios,92]. The system tested consists of a CCD camera or laser system and a processing algorithm which aims to derive an objective measure of pucker.

5. Fabric and Garment Inspection

The inspection of fabric for stains, marks, weave flaws etc has traditionally been carried out by human eye during garment assembly. However, with the gradual increase in automation in other areas of the apparel industry, a need for automatic inspection has arisen. This may be tackled when the fabric is removed from the roll on which it arrives at the garment assembly plant or during the assembly process. In the former case, a line scan method is most suitable while, during assembly, either area or line scan techniques are used.

5.1. AREA INSPECTION

A number of area inspection methods have been investigated with the aim of identifying either fabric faults such as stains and mis-weaves or faults resulting from sewing operations. Certain techniques have been applied to both these situations but we will begin by considering methods which are intended for use with uniform material as it might be removed from the supply roll, before being cut, sewn or folded. The types of problem which occur at this stage include weaving faults such as thick weave, knots, mis-weaves and foreign fibres and marks which are made after weaving. It is not possible to detect automatically all of these faults at an economically viable speed but the most frequently occuring problems can be found. Large flaws such as holes can be detected easily with standard cameras and image processing techniques. A slight variation of traditional vision techniques has been developed in which a light stripe is incident at a low angle to the fabric surface and the resulting line viewed using an overhead camera. Any un-eveness in the fabric surface appears as a distortion of the straight line. This technique has been applied to checking for pilling and creasing [Laird,91]. A similar method for locating the seam in trousers in preparation for pressing is described by Kelley [Kelley,91].

A major problems with inspecting fabric as it is taken from a source roll is that some of the flaws, such as ladders or missing threads, can be produced as a result of the cutting process and therefore cannot be detected at this stage. Similarly, the importance of flaws may depend on their position, which is not known until cut. In certain areas of garments, such as collar points, critical flaws can be very small, at single thread level [Taylor,88]. Detection of such flaws using traditional techniques can require a field of view of 3cm square or less, resulting in large scanning times and a great deal of data to be processed. Early experiments using Fourier analysis led to a more elegant solution [Taylor,88].

At each stage of construction there is potential for the introduction of faults. Unfortunately, the further the assembly progresses, the more difficult it becomes to differentiate between faults and intentional features of the garment. Having said this, inspection of the completed garment has been usefully applied. Methods of detecting holes of diameter greater than 2mm have been used for checking socks of a uniform colour and automated visual checking of the dimensions of completed underwear has been described [Norton-Wayne,90 & Abbasszadeh,89].

5.2. LINE SCAN INSPECTION

Line scan methods have been used when the fabric is removed from the roll using either coherent [Erwin Sick] or non-coherent [Zellweger] light. Where non-coherent light is used, processing is normally carried out in the time domain.

An alternative [Monkman,90] is to scan the fabric panel with coherent light, such as a laser, and observe only those parts of the resulting diffraction pattern image which pertain to fabric flaws. These exist almost exclusively as harmonics in one or both spatial dimensions. Figure 8 shows such a system employing a rotating polygonal mirror and discrete sensor.

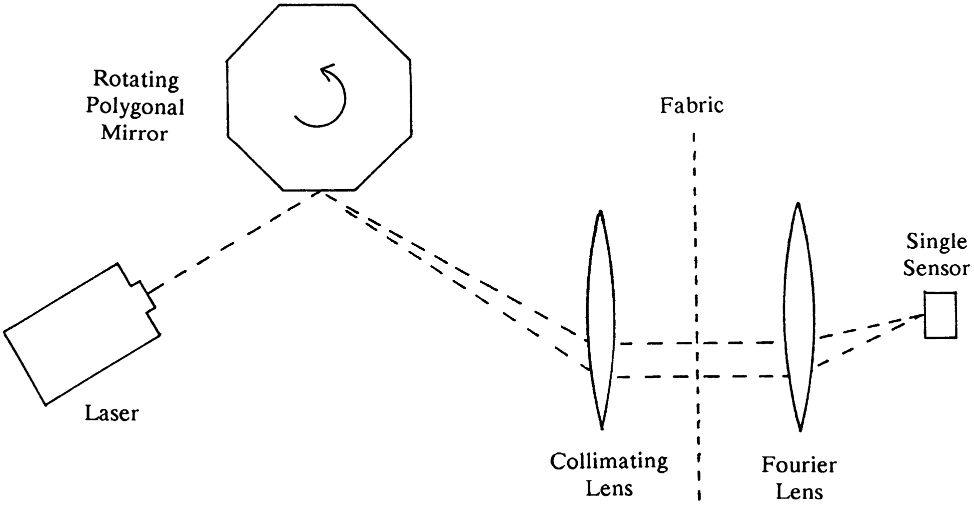

Figure 8. Rotating mirror and sensor configuration

The choice of discrete sensor is important, particularly with regard to operating bandwidth. As an example, consider a system capable of scanning an area of approximatley 100mm by 100mm each second. Given a fabric weave of 3 threads per millimetre over a scan width of 100 mm, a typical scanner would be an 8 surface mirror rotating at a speed of 18,000 rpm.

$$\text{scan rate} = \frac{18000 \times 8}{60} = 2400 \text{ scans/second}$$

$$\begin{aligned}\text{thread pulse rate} &= 2400 \times 3 \times 100 \\ &= 720{,}000 \text{ threads/second}\end{aligned}$$

Taking into account the Nyquist criterion, this gives an overall bandwidth requirement of at least 1.44 MHz. Add to this the fact that the scan must overlap the panel at the edges, then this figure is a bare minimum. The sensor chosen for this task was an IPL 10040 [IPL] which has a bandwidth in excess of 10MHz [Monkman,90].

6. Conclusions

From the preceding discussions it will be apparent that, although a very wide range of sensing schemes have been successfully applied, the situations in which a particular device may be employed are often very limited. The sensors which are most widely applicable appear to be the simpler ones whereas more elaborate systems find fewer areas of application (although these may be equally important).

It is inherent in the mechatronic approach to design that the mechanical handling and sensing requirements are considered in parallel. This may be thought of in two respects. Firstly, the point in a process at which sensing can most effectively be applied must be considered carefully since appropriately placed sensing may simplify both the sensor requirements and the mechanical handling requirements. It is not generally necessary to employ sensors at all stages of an assembly system but, if a cell is to operate without sensors, the process which feeds the cell must be designed so as to maintain known position and orientations. Secondly, if it is decided that a handling stage requires sensing then this must be considered from the outset of the design and will often affect the range of handling techniques which can be considered.

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