Management of Undergraduate Projects with Specific Reference to Redesign of a Jacquard Loom Card-punch System

J. K. RAINE, K. WHYBREW, G. R. DUNLOP, C. W. VAN RIJ & D. K. WARD

SUMMARY *This paper examines the management challenges encountered in running undergraduate projects in collaboration with industrial partners. A cooperative project between the University of Canterbury, Christchurch, New Zealand and Feltex Woven Carpets Ltd to design an automated machine to punch coding cards for Jacquard looms is used as an example. The design work described includes the mechanical system, control electronics, and communications hardware and software. The new machine is now in full-time service and performing very reliably.*

1. Introduction

In March 1992, the University of Canterbury and Feltex Woven Carpets Ltd entered an agreement for three final-year mechanical engineering students to redesign an unreliable automated machine used to punch Jacquard loom coding cards for patterned broadloom carpet production. Feltex relies on outside companies or consultants to provide engineering design services for mechanical plant, control systems and software. The university was approached for assistance after cooperation on an earlier project. The project ran through to early 1995 with formal management procedures introduced as the project gathered momentum.

A typical card, punched from 1.1 mm thick fibreboard, is shown in Fig. 1. The pattern is encoded in a matrix of up to 882 × 4 mm holes. Each card also has 4 × 10 mm location holes and 12 × 5.5 mm stitch holes. Simple patterned carpets require several hundred cards but complex non-repeating patterns may have up to 2000 cards. Both the original and the new punch machine produce the required hole pattern by pulling the card in the direction of its long axis under a programmable punch head. The punch head has four punches for the stitch holes, two for the location holes and two rows of seven punches for the pattern holes. The punches are all fixed in position and the pattern is produced by accurately positioning the card on its longitudinal axis and activating selected punches.

This paper first gives an overview of the project's history and project management, and potential problems which may be encountered in managing industry-based undergraduate student projects are discussed. Details of the mechanical and control system redesign are then described.

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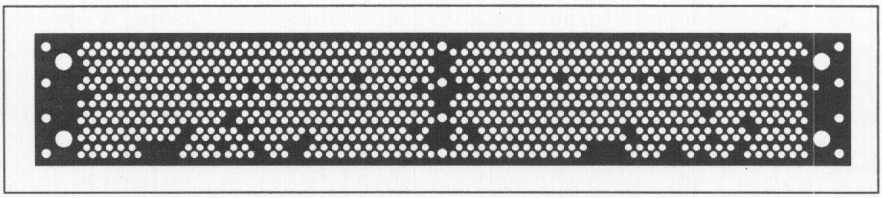

FIG. 1. Sample of punched card 457 mm long × 75 mm wide × 1.1 mm thick.

2. Project Management Overview

2.1 Project History

The project was initiated in January 1992 when a former student working at Feltex as a quality assurance engineer identified a serious problem with the existing card-punching machine. The machine, imported from England, had a bad history of breakdowns and, as a result of poor support from the supplier, was difficult to maintain. The continuous availability of the machine was crucial to Feltex's ability to respond to short lead-time orders for custom-designed carpet. Moreover, there was no reason to believe that purchasing a new machine from the previous supplier would solve the problem.

Because of his recent association with the university, the engineer recognized that this was a suitable subject for a student project. Feltex had no design staff within the company and redesign of the punch machine as an engineering student project was an attractive low-cost option, although it was clear from the start that this approach would yield results less quickly than if the design were placed with a private consultant or specialist machinery company.

The Mechanical Engineering BE degree at Canterbury has a heavy design content. Final-year students all complete a project-based course in design and also a final-year honours project. The honours project may be research based or a design and build task [1, 2]. Design of the complete machine and the associated control and programming system was clearly too much for a single student or a single project. However, the design was easily divided into clearly defined modules or subsystems which could be completed individually by members of a team of students. These subsystems are listed in Section 4. Aspects of the design were identified that could be assessed as project work in the design course while the remaining work formed the honours project. Defining the machine as an assembly of modules had clear advantages for project management as well as facilitating student assessment.

Of the three students assigned to the project in the 1992 academic year, two worked on the mechanical design while a third concentrated on the control system. This first project produced a good conceptual design for the control system and for a new punch head but had not progressed to the detail design phase. Design of the other subsystems was mediocre. A student from the Rheinische-Westfaelische Technische Hochschule, Aachen, was employed during the 1992/93 vacation to complete the detail design of a new prototype punch head which was then manufactured in the university's workshops. This punch head was retrofitted to the existing machine and in February 1996 had completed about 150 000 control cards without failure or serious wear.

In the 1993 academic year, one of the 1992 students, Ward, who had been responsible for the control system design, was awarded a postgraduate scholarship by Feltex and continued work part time on the control and programming system. Also in

1993, two students on a second honours project took the machine to an almost complete mechanical embodiment design of high quality. Encouraged by the success of the prototype redesigned punch head and completed work on the control system and software, Feltex contracted Ward and one of the 1993 students, van Rij, to complete the detail design and commission the new machine.

By March 1994, the bulk of the detail mechanical design and control software design was complete. The card transport subsystem was built. This together with the new control system was retrofitted to the existing machine for testing with the previously installed punch head module. These tests coincided with some changes in Feltex management and the departure of the company's project champions. The tests proved so successful that the management considered that its problems had effectively been solved and the project languished for the remainder of 1994. Early in 1995, a combination of encouragement from the university supervisors and an increased demand for control cards caused the project to be resurrected. The new machine was built and commissioned mid-1995, with final documentation and instruction manuals. It is now in full-time service and provides Feltex with an extremely reliable system that has approximately 50% higher output than the old machine, which remains available on stand-by. By February 1997, apart from minor adjustment, the new system had run for 18 months without breakdown.

2.2 *Project Management*

Management of the design technical content and programme was handled by the University staff Dunlop, Raine and Whybrew, who drew on their own industrial experience in control systems, mechanical design and manufacturing, respectively. The students were also made aware of roles and processes in management of design [3–5]. Progress was reviewed each week in group tutorials.

The project described here began informally with no written contract. This is typical of undergraduate projects which usually involve minimal cashflow for the university. A Feltex representative attended project meetings only at the early stages of project definition but the students maintained regular contact with Feltex personnel. As the project progressed and the students were employed on contract, the set-up became more formal, with minuted project review meetings, and management of the project passing from the university staff to a consulting engineer early in 1994. The university manufactured the new punch heads and other parts on a commercial basis. Other parts were subcontracted to jobbing machine-shops.

Beginning in 1993, project scheduling was done using Gantt charts and critical path using the CA Superproject package on a 486 PC. All mechanical design work was done using the Bentley Systems MicroStation 3D CAD system, which facilitated the modular approach to design and provided continuity between successive project teams. Much of the design and software work had to take place during each academic year (March–October).

Project management was complicated by the frequent changes to personnel. In the addition to the three supervising university staff and the student participants noted in Section 2.1, the Feltex team involved variously over the three years: two general managers (1992–1994, 1994–), a technical manager (1992–1993), a services manager (1993–1994), a weaving and finishing manager (1993–), two engineering workshop managers (1992–1994, 1994–), a quality assurance engineer (1992–1993), a punch machine operator (1992–) and a contract project manager (consultant) (1994–).

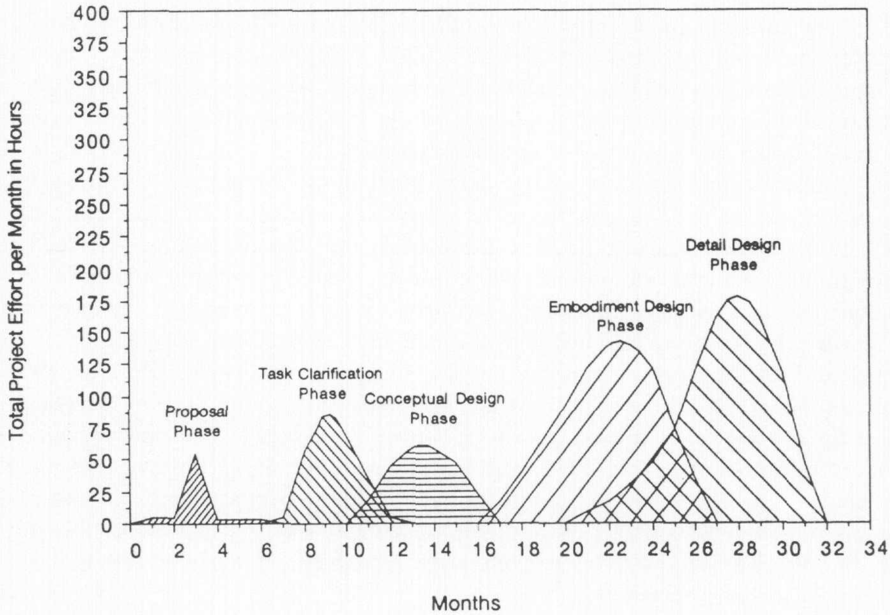

FIG. 2. Target phase diagram for typical design project (reproduced by courtesy of Hales [5]).

2.3 Phase Diagram

Students are encouraged to use a systematic approach to design along the lines described by Pahl and Beitz [4] and Hales [5]. Using this approach, the phases of design are considered to be: project proposal, task clarification, conceptual design, embodiment design and detail design. Hales [5] recommends the use of 'phase diagrams' as a management tool to record the progress of design projects. In these diagrams, effort for each phase of the project is plotted against a horizontal time-scale. A 'target' phase diagram for a typical design project reproduced from Hales [5] is shown in Fig. 2. Figure 3 is a phase diagram for the Feltex project. We have extended the diagram to include the extent of interest in the project by Feltex staff. This is shown in the area at the top of the diagram. The perceived degree of support for the project is indicated by the line weight. A dashed line indicates that that person has an interest but is not actively involved in the project. Short vertical lines indicate start and finish of employment by the company. The area at the bottom of the diagram has been used to record the various student projects and contracts. In this diagram, the mechanical design and the control system and software design have been recorded separately.

3. Special Characteristics of University–Industry Cooperative Projects

Cooperative design and development projects between university engineering departments and industry are now common [1, 2, 6]. Wray [7] has particularly emphasized the importance of collaborative projects in research in engineering design. Monniot [6] discusses the teaching company scheme, widely used in British universities, which has been successful in generating university–industry partnerships and technology transfer. These joint undertakings are, however, vulnerable to poor project management. There

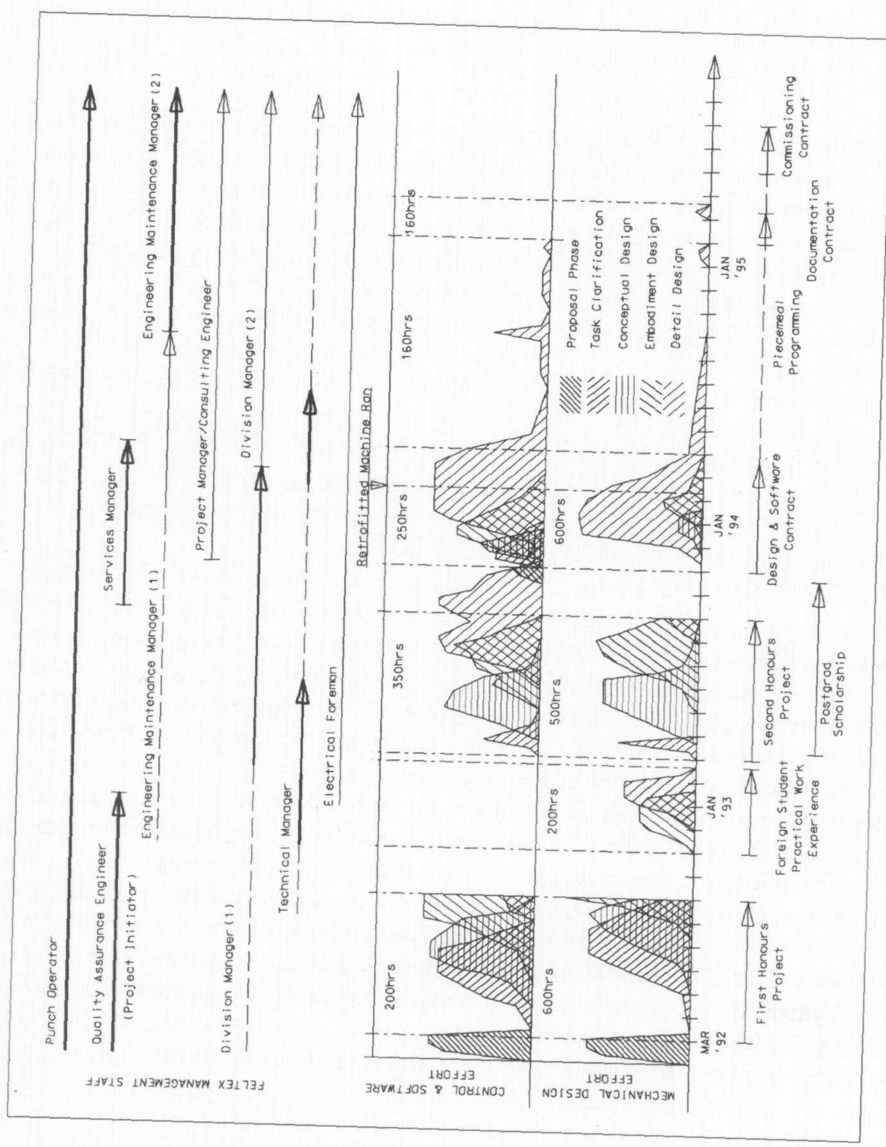

FIG. 3. Phase diagram for Feltex project.

are intrinsic differences between industrial and university-based projects. If these are not recognized, technical, cost and programme targets will not be met. Projects involving undergraduates are particularly susceptible to problems caused by failure to allow for these differences. Their effects are clearly seen by comparing the phase diagram for the Feltex project (Fig. 3) and the 'target' phase diagram (Fig. 2) which is for a project that has gone exactly according to plan. The five design phases are characterized by five overlapping bell-shaped curves. Apart from influences from purely technical aspects of the design process, the following factors contribute to differences between the actual and ideal diagrams:

- *Conflict of objectives*: Academic staff have objectives related to teaching, assignment assessment and research publication, whereas the industrial partner is focused on plant productivity and profit. Students usually have a more personal objective of maximizing the assessment return for their efforts. These differing objectives can bias the effort expended on the different phases of design.
- *Conflict of deadlines*: Undergraduate students have many conflicting demands on their time. It is unlikely that they will be able to reconcile these with commercial deadlines and will not respond to pressure to complete design tasks as quickly as a professional designer. Students have well-defined completion dates for projects. This is characterized on the phase diagram by vertical lines indicating that all work on a particular phase has reached a peak and then suddenly terminated when the project has been handed in for assessment, regardless of whether the design is complete. This is in contrast to the bell shape of the target phase diagram which indicates an orderly completion of the work.
- *Uncertain quality of students*: While, ideally, the best students are assigned to projects with industrial partners, poor performance by students may cause substantial delays through the need for repeated design work. For example, in year 1 (1992) of this project, excellent progress was made on respecifying computer hardware and rewriting control software, but some of the mechanical design work was mediocre, and complete reworking of this area was needed in 1993. This is characterized by repetition of the phases in the diagram.
- *Differing perspectives of the project scope*: Because of differences in objectives, the project partners may also have different views of the scope of the project. In the Feltex project, the academic partner viewed the scope of the project to be design and construction of a new machine but the industrial partner considered the project had reached a satisfactory conclusion when the new subsystems were retrofitted to the original machine and gave acceptable performance. This is characterized on the phase diagram by a sudden drop in detail design effort and a long tail on the curve.
- *Continuity of management*: Projects need a champion of sufficient seniority to ensure adequate allocation of resources and support to ensure completion. If management changes occur during the course of the project, there is a risk that support may be withdrawn or reduced. This will show on the phase diagram as a drop in effort.
- *Change of commercial priority*: Sudden changes in the market during the course of a project may cause the commercial partner to withdraw support. This can be disastrous for the morale of students who are part way through a project and will be reflected in a decrease in effort. (This did not occur in the Feltex project.)

- *Project ownership and responsibility*: Confusion over project ownership can lead to confusion over responsibility for progress, management and intellectual property rights.
- *Lack of a contractual agreement*: Most of the problems already listed are a result of the absence of a clear contractual agreement defining the responsibilities of each of the project partners. Undergraduate projects are usually started as a low-cost study with a clear understanding that the success of the outcome cannot be guaranteed. The time and cost of preparing a legal contract is usually not considered appropriate. However, many of the problems could be avoided by a simple letter of agreement defining the limits of management responsibility, scope of the project, financial support, and ownership of materials and intellectual property rights. (The situation is different for postgraduate research where a legal contract is the norm for industrially supported projects.)

4. System Design Overview

Although some of the Feltex Jacquard gripper looms have been converted to direct computer control of their solenoid yarn-selection mechanisms, most of the control is still by means of punched cards. Feltex is therefore very dependent on the integrity of the card-punch machine. The existing machine, which received its pattern instructions from a slow and obsolete BBC computer, was itself unreliable and frequently out of commission. Redesign for reliability therefore became a key issue.

At the start of the project a detailed appraisal was made of the existing punch machine, with analysis of the unreliable components or systems. To facilitate this process, the complete system was broken down into a three-dimensional matrix of subsystems which were analyzed in terms of their performance, reliability and operational sequence. Required geometric, kinematic, dynamic and information transfer compatibilities or actions at the subsystem interfaces were also identified.

The subsystems were:

- machine main frame;
- card infeed hopper and infeed transfer system;
- punch motor drive, clutch and crank system;
- card-punch head;
- card outfeed transfer system and outfeed hopper;
- card tractor and motor drive system;
- system feedback sensors and card identification device;
- electrical/electronic and pneumatic power and control devices;
- computer hardware and punch machine interfaces;
- computer software.

As this system was a one-off design, optimization of manufacturing processes was not generally required, although the redesign of the punch head using hardened steel anvils on the pneumatic cylinders was influenced by the availability of wire-cut electrical discharge machining. Concurrent engineering took place in the parallel design of mechanical subsystems and computer/electronic hardware/software. Good communication between all the design team members and Feltex operational staff was therefore essential. The software, for example, was influenced by the form of mechanical drive and transfer systems. A general arrangement of the new punch machine is shown in Fig. 4 as a rendered CAD view. Figure 5 shows the finished machine installed at Feltex Ltd.

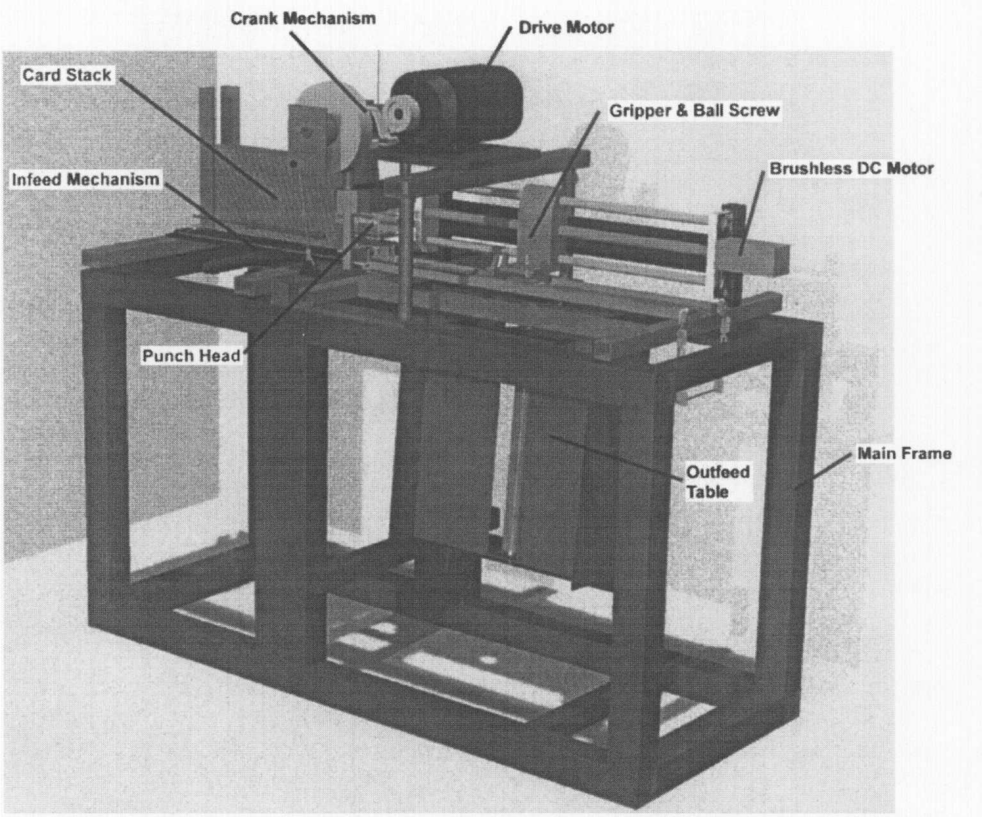

FIG. 4. CAD rendered view of new machine.

5. Features of the Mechanical Redesign

The machine shown in Fig. 5 performs three main processes:

- feeding individual blank cards from an infeed hopper to the punch mechanism;
- punching of the hole patterns received from the computer and correctly sequencing the spacing of columns of holes on the card;
- ejecting the punched cards and placing them in order on an outfeed stack.

Areas of unsatisfactory mechanical performance in the original machine were:

- card throughput rate too low and too reliant on operator supervision;
- infeed mechanism feeding more than one card to the punch head, causing jamming;
- repeated fatigue failure of the main cross head above the punch head;
- jamming of punch pins through wear of the pneumatic actuator cylinders;
- loss of synchronization in the card tractor mechanism.

5.1 Machine Speed

The existing machine was capable of a punching rate of 4.5 Hz and a throughput rate of 2 cards per minute. To speed up card throughput, the new system was designed for

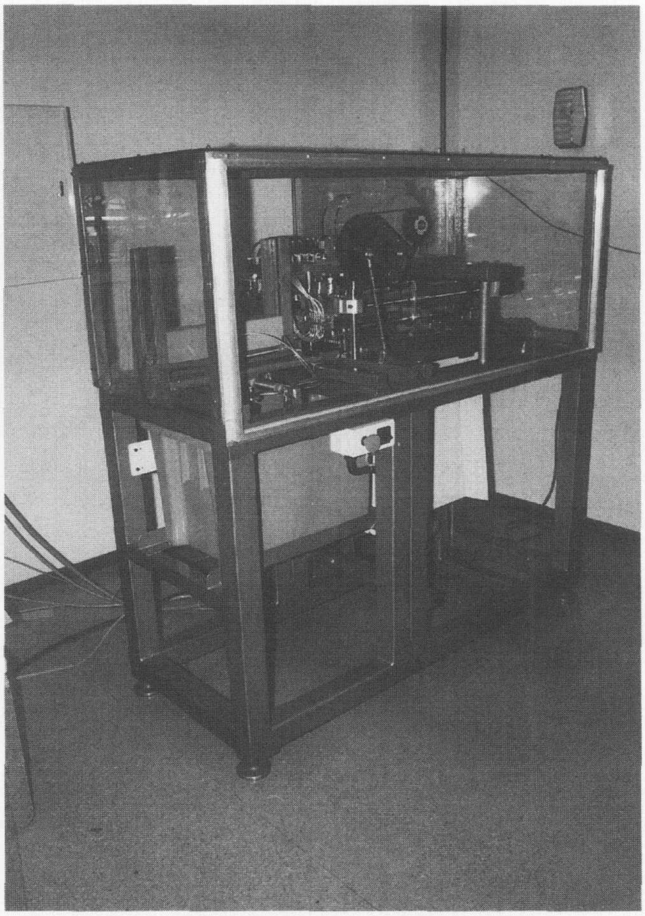

FIG. 5. New punch machine installed.

a 6–8 Hz punching frequency. In addition, by retiming other operations, the card throughput rate was increased to a maximum of 4 cards per minute. To avoid occasional punching errors related to the hole pattern, and consequent demands on the pneumatic circuitry to the miniature punch rams, a throughput of 3–3.5 cards per minute is normally used on the new machine.

The speed increase was achieved by optimizing the control sequences, increasing the number of concurrent activities and increasing the capability of the motor driving the ball screw used for moving the cards.

5.2 Infeed Mechanism

The previous machine used a stack indexed upwards on lead screws. Cards were lifted from the top of the stack using two suction cups, then placed on rails and transported beneath the punch head for the punching operation. Faults with the system included cards failing to separate, the indexing motor having enough power to lift only 200–300 cards of a nominal 500-card capacity, and excessive control complexity.

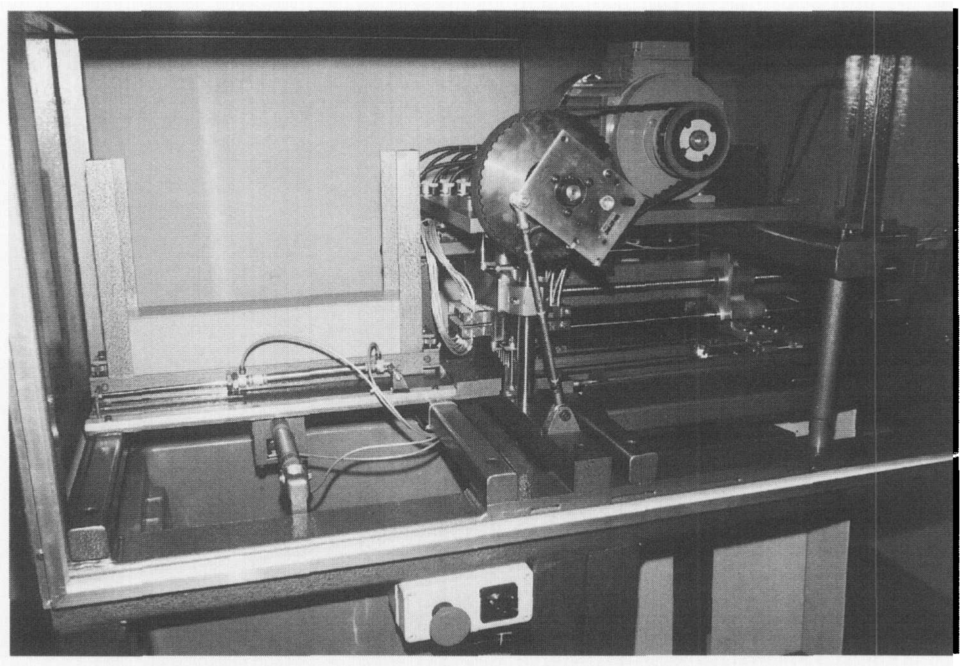

FIG. 6. Card infeed system—seen to left of punch assembly.

The new design uses a bottom-feed system, consisting of a gravity feed hopper of up to 300 cards. The bottom card is pushed out sideways, through a slot of depth equal to the thickness of the card, by a pneumatic-powered displacer. Another cylinder then pushes the card longitudinally under the punch head for the start of the punching operation. This is illustrated in Fig. 6. This system is much simpler, more easily adjusted and controlled, and allows queuing of a card while the previous one finishes a punching cycle, thus removing infeed time as a factor in the total throughput time.

An advantage of the earlier infeed mechanism was that it was adjustable for two of five possible card types (the remaining three being punched manually). In the interests of simplicity, it was decided to limit the new machine to the most complicated and numerous card type (gripper loom cards). It was decided that the existing machine should be upgraded and retained for the smaller batches of the other card types.

5.3 Crank Mechanism

The crank mechanism, on both existing and new machines, consists of a slider crank assembly driven by a single-phase induction motor through a belt drive and wrap spring clutch. The clutch allows rapid stopping and starting, and is used to stop the punch head at the end of a cycle to load the next blank card. The punch head is mounted to a cross head that slides on linear bearings, as shown for the new machine in Fig. 7. The new cross head is driven by a connecting rod made in the form of a turnbuckle which allows simple adjustment of the punch head height.

Major improvements made in the new machine include elimination of a gearbox on the drive motor, addition of a flywheel to smooth the motor load over the whole cycle, an inductive sensor at the end of the crankshaft to detect crank position on its 20-mm stroke, and improvement of the load path through the cross head. The new cross head

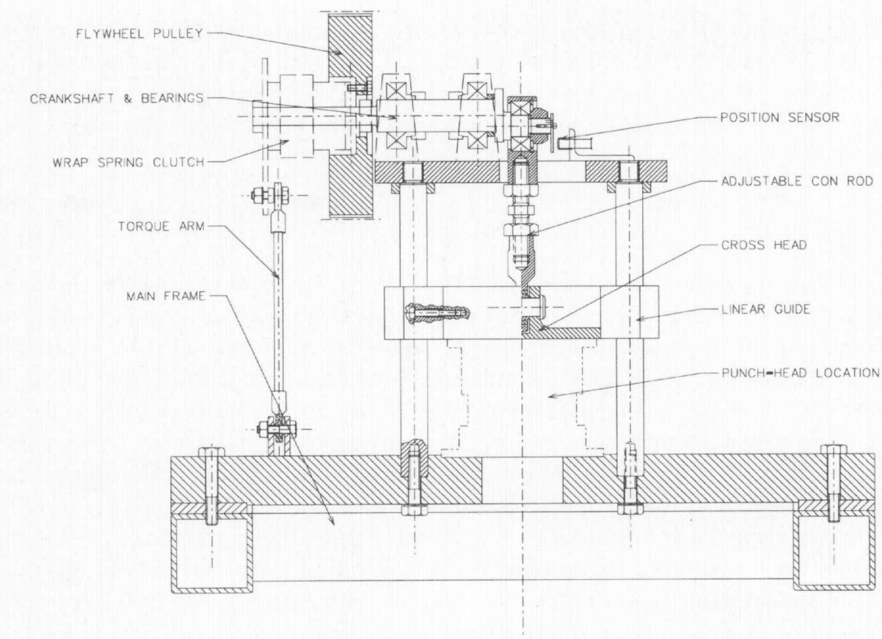

FIG. 7. Sectional arrangement of punch mechanism assembly.

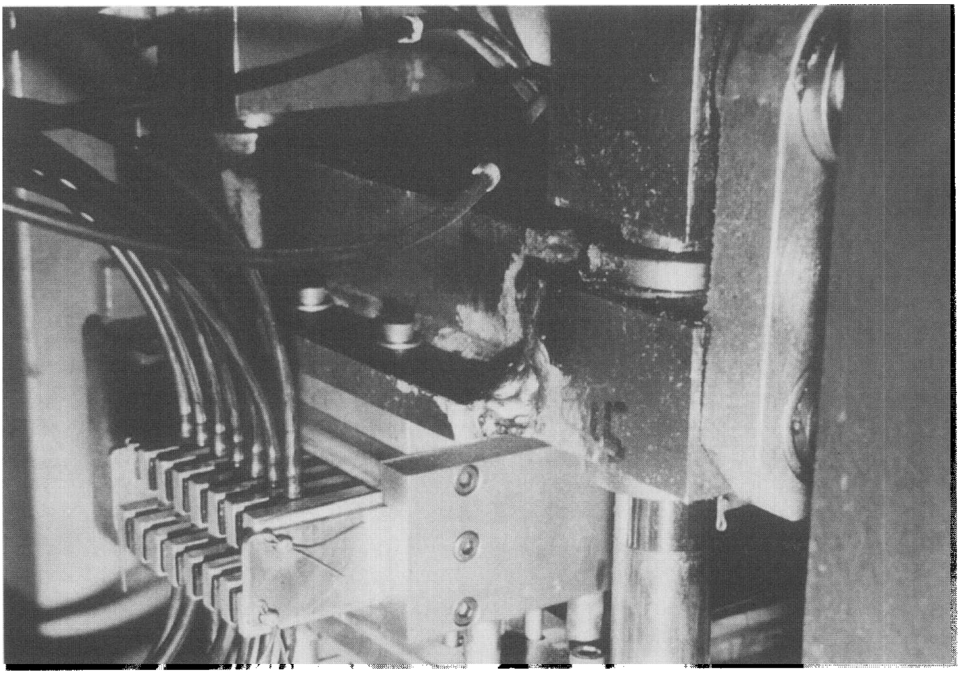

FIG. 8. Fracture in cross head on earlier machine. Fracture can be seen close to linear bearing at right-hand side; air lines to cylinder at left.

has a single connecting rod force applied directly above the punch head. The earlier design had connecting rod forces transmitted to each end of the cross head and the punch force applied at the centre. This cross head was very vulnerable to repeated fatigue failure at the welded connections to the linear bearings at each end. This is illustrated in Fig. 8.

5.4 *Punch Head*

A view of the new punch head is shown in Fig. 9. As the cross head drives the punch head downwards, the 20-tool steel punch pins slide freely into the punch head unless they are required to punch. Punch selection is by means of 20 miniature rectangular pneumatic cylinders. The rod of an actuated cylinder moves horizontally to bridge the gap between a punch pin and the downward-moving punch body, forcing the pin through the card. In the previous design, the relatively soft cylinder rods of the cylinder acted directly on the ends of the punch pins. This burred the ends of the rods and after a very short time they would fail to retract properly, causing the punch to remain active. The characteristic result of this was a line of holes down the length of the card and an incorrectly coded pattern. This problem was overcome by capping the rod ends with hardened tool steel anvils, as shown in Fig. 10. The principle was successfully tested on the existing machine and is still operating after more than three years with no noticeable wear of the caps.

The other major improvement to the punch head was to design the sandwiched head plate assembly such that punch loads were taken through the assembly in compression rather than through connecting bolts in shear.

5.5 *Outfeed*

The outfeed systems on the old and new machines are very similar. The outfeed, shown for the new machine in Fig. 11, consists of a ball screw with two linear guides driven by a Digiplan brushless DC motor with position encoder, whereas the earlier design had a stepper motor which was slower and less accurate. The new motor is able to accelerate the gripper much faster and operate at a higher speed, resulting in shorter move times, especially on the return stroke. After replacing the control system on the existing machine, a marked increase in throughput speed and reliability were observed, with operator supervision actions reduced simply to card hopper loading and unloading.

Attached to the cross head of the ball screw is a two-fingered pneumatic gripper which has a sensor in its mouth to detect the presence of a card. Two retractable rails run the length of the outfeed mechanism on to which the finished card is pulled. When the card is completely clear of the punch head, the rails retract and the card falls on to a carriage in the outfeed table. This carriage is mounted on a lead screw so the card does not fall very far. A small electric motor keeps the carriage at the required height.

5.6 *Main Frame and Sub-assemblies*

An advantage of the new design over the existing one is the use of modular sub-assemblies. Each major part, infeed, punch head, crank mechanism, outfeed and outfeed table, are separate sub-assemblies and can be easily removed from the fabricated steel main frame. The main frame is designed with machined datum surfaces on to which all modules are fixed to give accurate positioning of the modules with respect

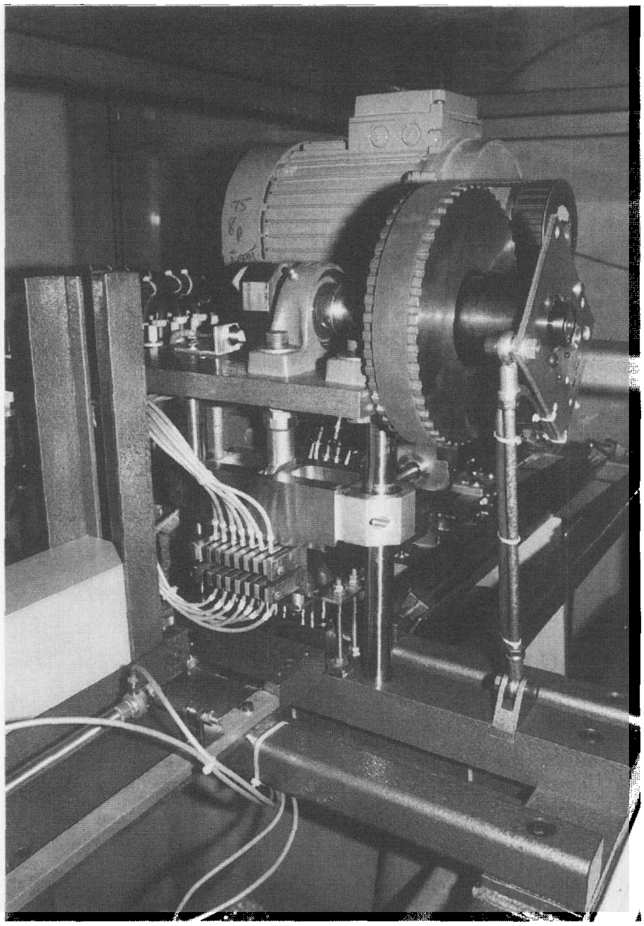

FIG. 9. View of new punch head with drive system above.

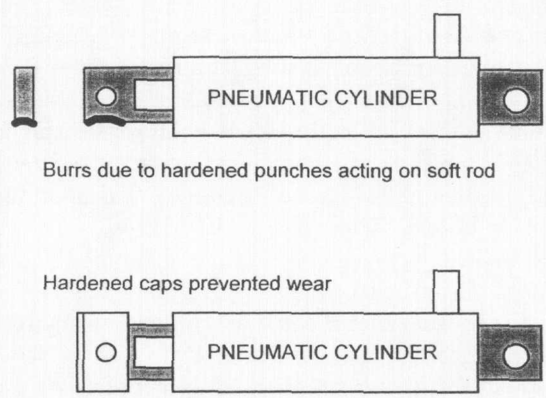

FIG. 10. Pneumatic cylinders modified for durability.

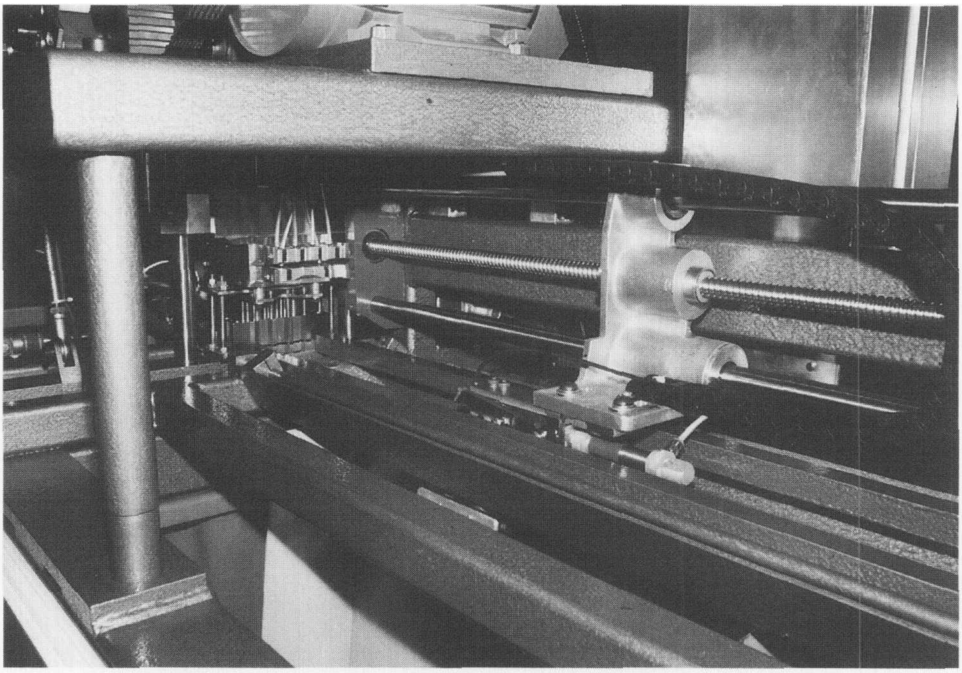

FIG. 11. Card outfeed system.

to each other. The only exception to this is the outfeed table but this does not have any tight positional tolerances.

6. Details of Control System Redesign

The redesign of the control system for the card-punching machine involved identifying deficiencies in the existing system, decoding of the CAD file format used by Feltex for carpet patterns, generation of new software for reading CAD files, selection of new control hardware, and development of software for the computer and microcontrollers used. As the original control system was becoming increasingly unreliable, the new control system was installed and run on the existing machine from January 1994, allowing complete debugging of the system before installation on the new punch machine.

There were several deficiencies in the original control system:

- An unreliable controller (BBC Home Computer) was used. This was difficult to service and already obsolete when it was installed.
- Incompatibility existed between the existing computer hardware and planned local-area network (LAN) extensions.
- The computer/motor drive interface and other components were custom built and difficult to maintain.
- The stepper-motor card-tractor system was run in open loop and on a time rather than a step basis. The motor was very small, tending to overheat and lose synchronization when friction variations occurred.

TABLE I. Key features changed in the control system

Feature	Difference made/advantage
Control hardware	Industrial controller (Fisher & Paykel Programmable State Controller): • designed to operate in harsh factory environment; • produced locally and widely used—support readily available; • supplied with application programming software and complete set of manuals; • standard controller/machine interface modules; • RS232C standard serial ports for downloading carpet-pattern data and communicating with servo-motor controller; • manufacturer debug support via modem; • LAN capability. IBM Personal Computer (IBM-compatible 486 DX40): • located near the card production area, this provides a user-friendly interface to the industrial controller; • enables pattern files to be retrieved across the extended LAN. Switches and sensors: • non-contact proximity sensors used wherever possible to increase reliability.
Control software	Fully documented source code has been supplied for all the software and a copy of all the necessary programming tools have been purchased by Feltex.
Card positioning	Brushless DC servo-motor drive/controller (Compumotor/Digiplan BLX30): • more powerful motor to achieve faster card movement without the overheating problems of the old motor—ideal for high-inertia loads; • closed loop control of motor position, ensuring correct card-hole spacing is always maintained; • datum set and limits of travel defined by inductive proximity sensors; • RS232C communication link with PSC and for programming via PC.

- There was a lack of documentation and local expertise for maintenance which was also very expensive. The control system software could not be modified and unreliable electronics-grade (rather than industrial-grade) switches and sensors had been used.

The changes made to the control system are listed in Table I. In principle, all of the control system except for the pneumatic solenoids has been replaced.

6.1 Computer Control Hardware and Machine Interfaces

The control system is designed to use an industrial-grade computer and programmable state controller (PSC), standard componentry rather than custom-made items, and as much local content as possible to enhance software and hardware support. The three major control system hardware components are as listed in Table I. These are modular, unpluggable units, which assist with fault finding. The servo-motor controller can be unplugged from the PSC and connected to a PC for function tests.

The control system block diagram is shown in Fig. 12. The PC uploads pattern files from the network or disk and transmits the relevant pattern information to the PSC. The PSC in turn sequences the movement of the cards through the machine, setting the pattern punches and sending the appropriate move requests to the servo-motor controller. The PSC has a high-level programming language with Pascal-like structures and objects. This reduced the software development time markedly.

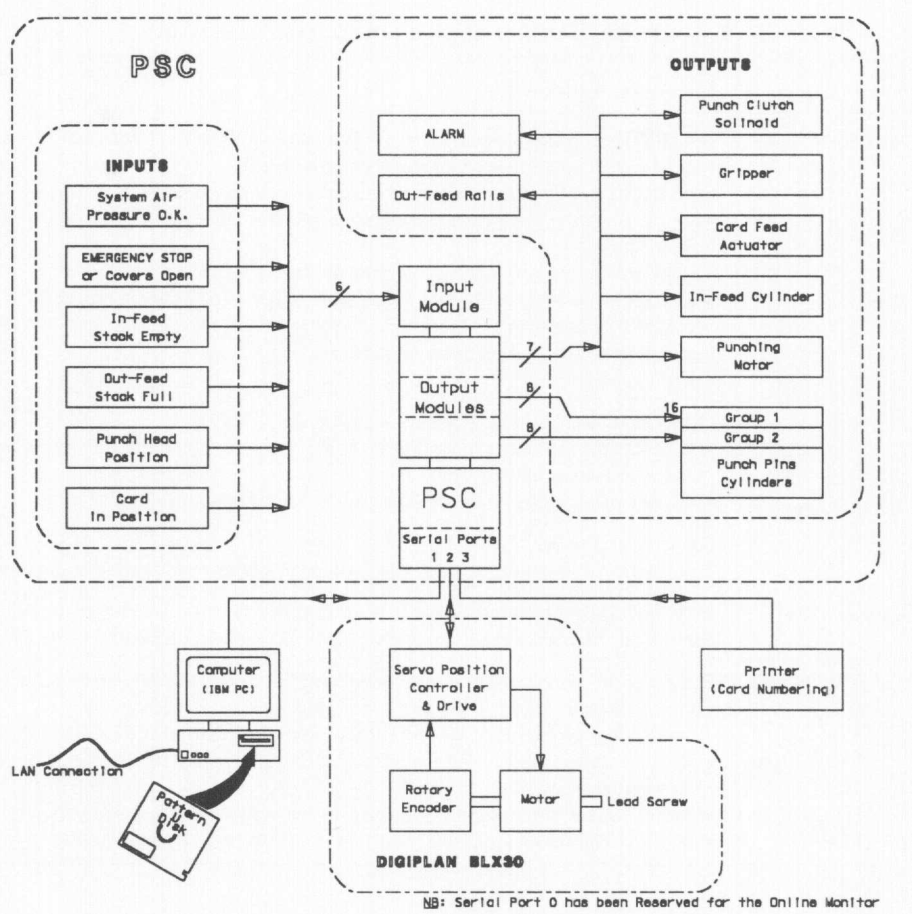

FIG. 12. Block diagram of the new control system.

Standard RS232C serial links connect the PC (which is on the Feltex LAN) to the PSC industrial controller and the PSC to the servo-motor controller. The output modules of the PSC directly drive the pneumatic solenoid valves, the solenoid-operated clutch and the motor relays, all at 24 V DC. The input module on PSC receives 24 V DC switched signals from the machine sensors.

6.2 Software Design and Implementation

A systematic approach was taken when writing the control software: top-down design with bottom-up implementation. Full documentation has also been provided for the software to allow modification in the future if the control system requirements change. Turbo Pascal for Windows version 1.5 was used to develop the PC software, proprietary state programming language compiler and programming environment for the PSC, and a proprietary communications package for downloading X-Code commands to the servo-motor controller (although any ASCII terminal program could be used).

A modular approach was taken with the programming, e.g. for the computer—CAD file retrieval, CAD file interpretation, controller communications, carpet-pattern display and card-pattern display. This modular approach was reinforced by the use of an object-oriented programming language for the PC (Turbo Pascal for Windows version 1.5) and the state control methodology of the PSC. Each module was tested and debugged before being incorporated into the whole. Enhancement of the control software was carried out after implementation on the original punching machine. This included addition of capability to interface with the LAN, to cut a second type of card and to recognize a new CAD system file format.

Planned future developments are:

- modification of PSC software to run other tasks in the new punch machine;
- addition of card-pattern verification hardware to the machine—this is required because the first sign of wear in the pneumatic solenoids is that they begin to stick intermittently, resulting in incorrectly punched cards which are difficult to detect;
- addition of a labelling system to number and name each card.

7. Conclusions

This cooperative university–industry development project has been valuable to the industrial partners Feltex Woven Carpets Ltd in delivering a reliable machine using state-of-the-art control technology at modest overall cost. The system was commissioned in July 1995 and after initial tuning has operated fault-free and is in full-time production. The students involved in the project declared it an excellent learning experience, albeit one whose time demands went beyond the requirements of their degree course. Undergraduate student work for industrial clients is usually most safely confined to low-priority experimental prototyping. Despite the risks relating to drawn-out time-scale and technical performance targets when undergraduate students work on a production design task, good results have been achieved in the present project, with greatly enhanced machine reliability.

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