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7/25/68

AUTOMATIC PATTERN CONTROL IN CARPET TUFTING

A THESIS

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The Faculty of the Division of Graduate Studies and Research

by

Germán Diego Schaefer

In Partial Fulfillment

of the Requirements for the Degree

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AUTOMATIC PATTERN CONTROL IN

CARPET TUFTING

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SUMMARY

The purpose of this research was to investigate the potential of computers in the field of automatic pattern control in carpet tufting. Patterning in tufted carpets is achieved primarily by varying the tension of the pile yarn, giving a patterned combination of high and low loops.

In the present investigation, a series of solenoids were used to vary the tension of the pile yarns, causing the yarns to be deflected into a U-shaped channel for greater tension, or passing them undeflected under low tension. An increased tension in the yarn feed causes a back-robbing effect, by which the tufter needles draw part of their yarn supply from the previously inserted loop, thus reducing its height.

The methods developed in this work attempt to overcome several limitations encountered in the systems in present use, including those described as follows:

(a) Patterns produced by commercial tufters are generally found to repeat at intervals too short to permit complicated designs. Also, mechanical restrictions limit the basic pattern to several repeats across the width of the carpet. Most attempts to eliminate these problems by modifying systems presently available lead to complicated mechanical arrangements, which increase costs and reduce operating speeds.

(b) The change from one pattern to another usually requires a considerable amount of time during which the machine stands idle.

(c) The storing of frequently used patterns usually is space-consuming and thus uneconomical.

The conclusions drawn from this work were:

(a) The use of programmable calculators as a means of controlling yarn tensions in tufting demonstrates the versatility of computer-based systems controlling a patterning device.

(b) Patterns encoded on punched tape, as used in this research, provide an easy way for pattern changeover and permit the storage of a large number of patterns in an easily accessible and compact filing system.

(c) The pile yarn tension control deflecting the yarns into a U-shaped channel provides sufficient sensitivity to produce a satisfactory index of pile height definition, compared to commercial patterned carpet.

CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

Automation and modern manufacturing techniques, while many times providing us with cheaper and more durable goods, often involve a very definite drawback as well: there is a certain ever-present uniformity about these goods, a feature not encountered in less automated production processes. This lessens the decorative value of the product, if such an effect should be desired.

In the carpet industry, and more specifically in tufted carpets, this is a common problem. A tufted carpet is produced by stitching a series of loops through a backing fabric, and tufting machine designers are constantly striving to eliminate the styling limitations imposed on them by their machinery. The parallel lines made by the paths of the tufting needles may be easily discerned on virtually all tufted carpets, no matter how clever the styling (1). Also, the basic design pattern repeats itself at intervals which often prove to be too short to achieve certain more complicated decorative effects.

The patterning problem of tufting is very closely resembled by that encountered in weaving: Simple patterns can easily be achieved by a conventional loom which uses a number of harnesses, each controlling simultaneously a large number of ends. If the number of harnesses is increased in order to achieve more intricate patterns and longer repeats, the machinery soon becomes uneconomical to operate, being too complicated and not performing satisfactorily beyond a certain number of harnesses. To overcome these limitations, a completely different system of controlling the ends or length-wise threads in a fabric was devised; the Jacquard loom, in which each thread is controlled individually, such that any end can appear on the face or the back of the fabric at any one time, independent of the positions (face or back) of all other ends.

Most patterning devices in use in the tufted carpet industry at the present time concentrate on ways of controlling the height of the loops of tufted carpets by means which in many respects may be likened to the harness system of controlling designs on a loom.* While in weaving many ends are controlled simultaneously by one harness, so in tufting most systems control simultaneously the feed to many needles. Also, similar to the restrictions on a harness-type loom, mechanical complications, operating speed, accuracy, manufacturing costs, along with other factors, will not allow the length of a repeat to be extended beyond a certain number of stitches.

A possible route toward the elimination of most of these patterning limitations seems to be the introduction of a system in which only a few yarns are controlled simultaneously, or each controlled individually as an extreme case, such that during any stitching cycle various combinations of high and low loops are achieved. In short, a "Jacquard system for tufted carpets" is desired. If in addition to the possibility of controlling the pile height at will across the carpet, means can be

* Section 1.4.2 of this thesis

devised to considerably extend the length of the pattern, then most of the limitations which caused objectionable uniformity in patterned tufted carpets will have been eliminated.

1.2 Historical Background

1.2.1 Woven Floor Coverings

In its highest form the carpet or rug is a work of art seldom equalled in other crafts. Thousands of years ago the Egyptians produced carpets composed of linen. Egypt is supposed to have influenced the Middle East countries and then Mongolia and China. In Europe the craft is said to have been well developed around 900 A. D. The Moorish conquests in the ninth century carried the knowledge of rug weaving into Spain. From there it spread into Northern Europe. The first carpet power loom was invented in England in 1854. The Spool Axminster loom invented in America was an important step in the mechanization of carpet manufacture (2). In the United States, production of woven carpets on a large scale dates back to 1780 (3).

1.2.2 Tufted Carpets

Tufting in the United States began as a cottage craft. The hand-tufting of candlewick bedspreads was established in Georgia in 1895. The so-called hooked rug may well be considered a forerunner of the tufted carpet, since the basic principle of manufacturing is very similar to the tufting process (4): a backing of burlap, canvas, etc., is stretched over a frame. A suitable hook is thrust through the backing, and a narrow strip of cloth, thick cotton or jute twine or candle wicking is pulled through the backing to form a loop of the desired height. Hooked rugs of this type are believed to have commonly been made in England and Scotland some 200 years ago. Others claim that this method was known well over 400 years ago (5).

The first machine that could tuft the full width of a cloth at one time was invented in 1940 by Joe Cobble (6). Tufted rugs started becoming more popular around 1950, and in a rapid process of evolution tufted carpets came into being. The tufted carpet industry immediately became a serious competitor to the well-established woven carpet manufacturers, being able to produce floor covering at less cost. Production costs for tufted carpets are about 25 per cent or more below costs for conventional woven carpets. Higher machine productivity creates a much better return on capital investment. In addition, the tufting process makes better use of the yarn: less pile yarn is used up in interlacing, and it is possible to use less expensive material for the backing fabric, which serves only to hold the tufts in place and is not visible in the final product.

The research efforts of tufting machinery manufacturers began to center around these three goals: (a) Increased output, through increased speed and wider machinery; (b) finer gauges, i.e. less distance between adjacent needles and between adjacent stitches of the same needle and (c) patterning equipment to provide relief and multi-color designs on bedspreads and carpets. The relative importance given to these goals brought about different trends in the development of the carpet industry in the United States, Britain and the rest of Europe.

In the United States, the tufted carpet output represented 92 per cent of the total broadloom shipments in 1969, as compared to 90.8

per cent in 1968 and 67 per cent in 1960. The price of tufted carpets as compared to their woven counterparts in 1969 was as follows (Average mill value per square yard): Woven, $6.44; tufted, $3.53 (7). In the United Kingdom and Continental Europe, tufting continues to encroach on the traditional woven carpet markets, but Axminster and Wilton woven carpets retain three times the market portion they have managed in the United States (8). At the present time, tufting accounts for one half the British carpet output and for one third of that in Continental Europe.

New applications for carpets are found as time goes on: it has been long since the use of carpet was restricted to the bedroom and parlor: carpets in dining rooms and kitchens have been a common feature for quite some time. Sales more recently have included outdoor carpet for the patio and swimming pool. Other locations for carpet application are constantly being developed, including automobiles, airplanes, miniature golf courses, tennis courts, elevators, hospitals, etc. Noise control achieved by carpeting can be an important and very desirable feature. H. E. Rodman and C. J. Kunz, Jr. (9) report that carpets in corridors of a high school caused a reduction of noise from an average of 94 db to an average of 75 db, a 94 per cent decrease in sound pressure level. The sound-reducing properties of carpets have prompted architects to install them on walls and even on ceilings.

As a wider variety of uses is found, it is obvious that the need for new design patterns, in color as well as in relief, increases in similar proportion.

1.3 Purpose of the Research

The purpose of the present research is to investigate the possibilities of controlling the tension of the yarns fed to the needles in a carpet tufter by means of plungers controlled by solenoids which are activated according to a predetermined pattern design. The desired pattern is to be encoded onto a series of punched or marked cards or a punched tape. A computer will selectively activate the different solenoids, thus restricting or not restricting the feed of pile yarn to the tufting needles. If a yarn feed is restricted, the needle carrying the yarn will draw back (backrob) some of the yarn inserted in the previous stitch, thus shortening this loop.* Through the use of computer programs to control the yarn feed, the patterning system will permit considerably longer pattern cycles at less cost than some of the systems now available, plus attaining a more intricate loop height control across the width of the carpet. The desirability of these goals was discussed in Section 1.1. It is also expected that the method to be explored will make it possible to change from one pattern to another with much less delay than that currently experienced in the tufting industry.

1.4 Review of the Literature

1.4.1 Basic Theory Underlying the Backrobbing Process

Most of the patterning devices in use at this time make use of the so-called backrobbing method, briefly mentioned in Section 1.3. A diagram explaining the tensions involved in the backrobbing process is

* For further discussions on this topic see Sections 2.3 and 3.4

given below. The needle, shown here in its lowest position, i.e. the position of maximum penetration into the backing fabric, has a fixed-stroke up-and-down motion, and will reach this lowest position every time a stitch is inserted. Thus loop (b) in Figure 1 is of a fixed length. The critical tensions which need to be compared to analyze the

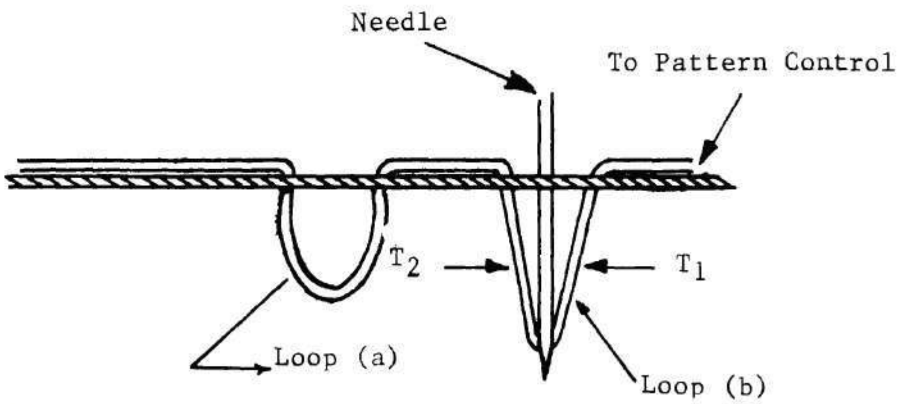

Figure 1. The Backrobbing Process

backrobbing process, are T_1 and T_2. If the difference between T_1 and T_2 reaches critical values, the yarn used to introduce the stitch will either come primarily from the pile yarn supply (T_2 greater than T_1) or primarily from the previous loop, marked as loop (a) in Figure 1 (T_2 smaller than T_1). By varying T_1, T_2 being fixed by such parameters as density and material of the backing cloth, type of yarn, etc., the amount of yarn provided by the supply and by the previous loop can be controlled, thus determining the height of loop (a). A thorough study of yarn tensions in carpet tufting was made by J. I. Dunlop (10). His experiments, carried out on a Venor 3/16 gauge sample tufter and using a wool yarn (R500 tex/2) tufted into a 13 oz./yd.^{2} satin weave hessian backing fabric, revealed a maximum yarn tension of 180 grams at the needle eye during tuft insertion. The maximum yarn tension just above the needle eye occurred at top dead center, when backrobbing was taking place due to the action of the reciprocating yarn-guide or jerker bar. A relationship between yarn tensions at the needle and the amount of yarn backrobbed was established. The maximum tension measured in these experiments occurred when the loop length was reduced to about 30 per cent of the nominal looper-setting value. In this instance, a tension of 500 grams was recorded.

1.4.2 Pattern Control Mechanisms in Use at the Present Time

The most relevant mechanisms devised to achieve pattern control have been patented, and the following is a summary review of mechanisms found in patent literature.

M. B. Penman (11) introduced a mechanism which firmly grips certain pile yarns selectively, to cause the corresponding needles to take part of their supply from the previous loop, thus causing backrobbing. This mechanism is shown in Figure 2. The cross-hatched center portion

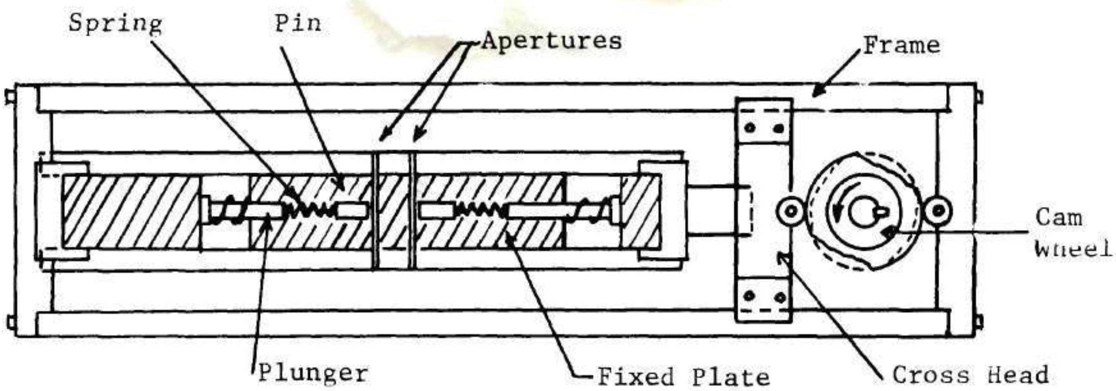

Figure 2. Pile Yarn Controlling Mechanism

contains two plungers which slide in horizontal bores. Reciprocating motion occurs through the cam drive which rotates with the main drive of the tufter. When the yarn supply is to be restricted, the cam will move the outer frame to the right and the crosshead to the left. Thus the pins will trap the yarn which is threaded through the vertically cut apertures.

Penman (12) suggested the use of solenoids to control the motion of the device presented above, instead of using the cam shown in Figure 2. The solenoids are energized selectively by a rotating drum made of

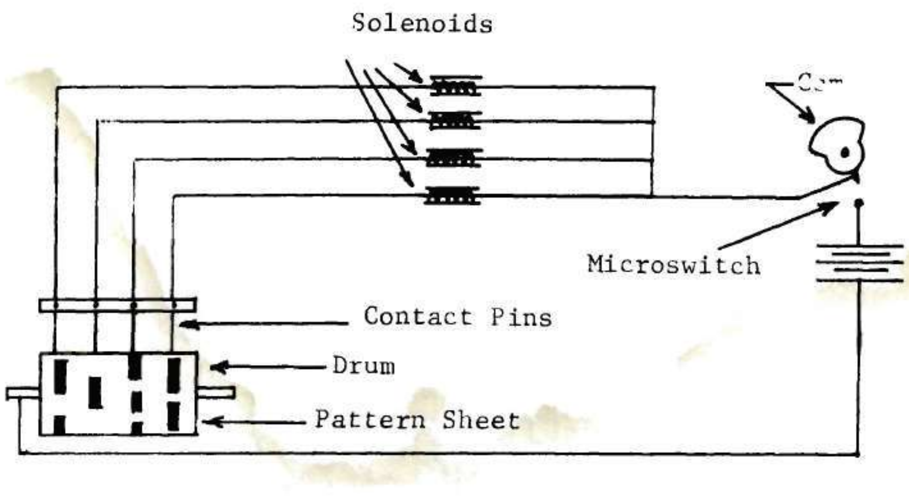

Figure 3. Pattern Drum and Circuit

conducting material and partially covered with a non-conducting pattern sheet (Figure 3). A number of contact pins are mounted perpendicularly to this drum, and each of these actuates one solenoid. As the drum rotates, the circuits to the solenoids will be closed and opened according to the pattern, thus either restricting the feeding of the pile yarn or allowing it to pass freely. The microswitch, also shown in Figure 3, closes the circuit as the needles begin their downward motion. Those needles which carry yarns that are being held by the patterning mechanism are supplied mostly with yarn from the previous stitch.

W. W. Hammel (13) presented a photocell unit which can replace the pattern drum used by Penman (12). Figure 4 shows this device covered with a patterned plastic sheet partially blocking the light inside the

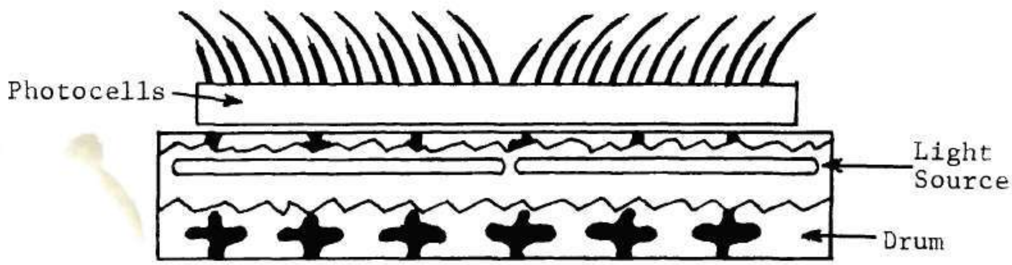

Figure 4. Photocell Unit

drum. Each photocell controls two magnetic clutches, seen in Figure 5. These clutches connect the yarn feed rolls either to a fast drive or a slow drive, thus producing high or low loops, respectively.

R. E. H. Hamilton and C. A. Bryant (14) described a mechanism, shown in Figure 6, which provides a way of pulling back yarns from the currently formed loop, before the needle starts upward to complete the loop. A solenoid presses the yarns into contact with a slow or fast feed roll. A yarn guide is actuated by another solenoid which receives the same impulses as the first solenoid. This loop shortener has a backrobbing effect if the yarn guide is in the high position. Otherwise, it will not interfere with the tufting process.

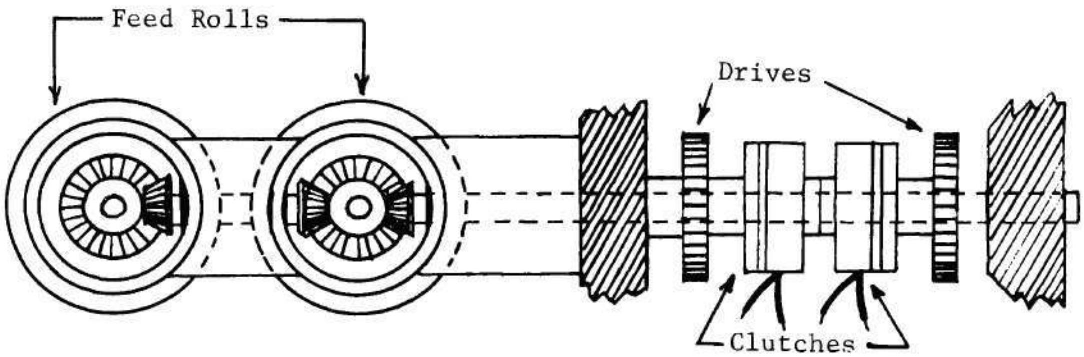

Figure 5. Two-speed Feed Roll Drive

R. E. Oberholtzer, et al. (15) suggested a mechanism shown in Figure 7. If the presser and feed rolls are engaged, the operator, controlled by the pattern chain, will form a loop using yarn from the supply. The pattern chain can be made to produce different loop lengths. During the stitching process, feed and presser rolls are disengaged, yarn is furnished by the supply through the action of the operator, while clamping plate and clamping roller are engaged.

G. D. Dedmon (16) developed the mechanism shown in Figure 8. Each yarn is fed through a tensioning device and a unidirectional feed. The arm pivots about its shaft, as the cams rotate. When the feed moves upward, it slides along the yarn. As it moves downward, it grips the yarn and feeds it to the needles. The amount of yarn fed can be modified

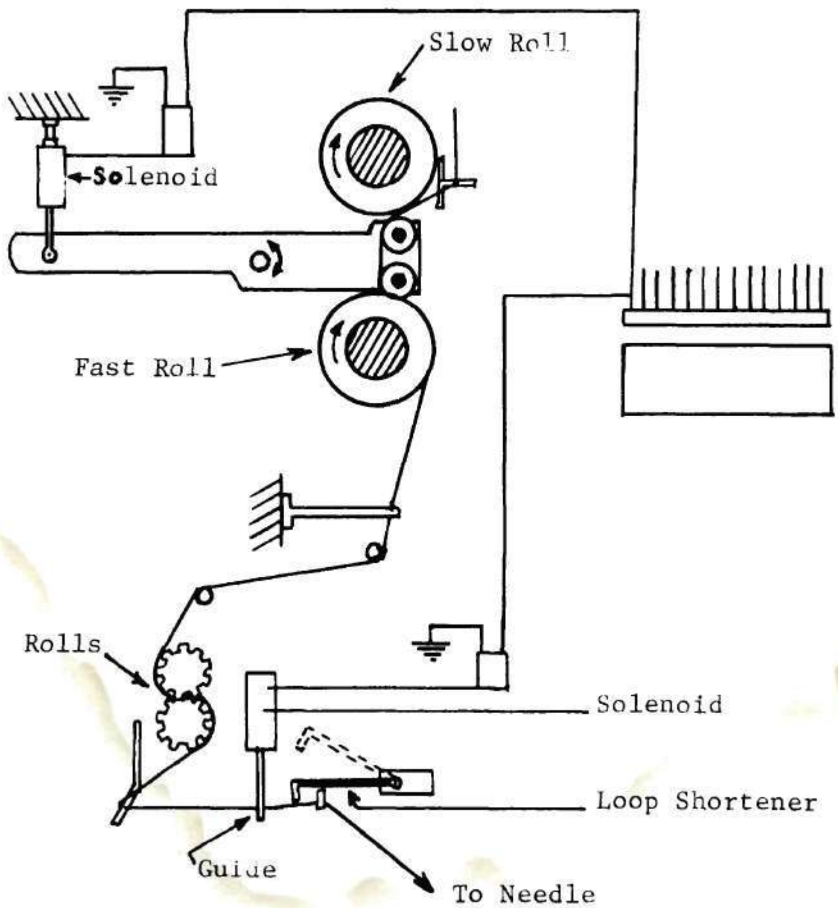

Figure 6. Loop-shortening Mechanism

by changing the angle through which the arm rotates.

H. F. Nowicki (17) suggested a pattern device using a series of profiled pattern bars shown in Figure 9, which intermesh with straight-

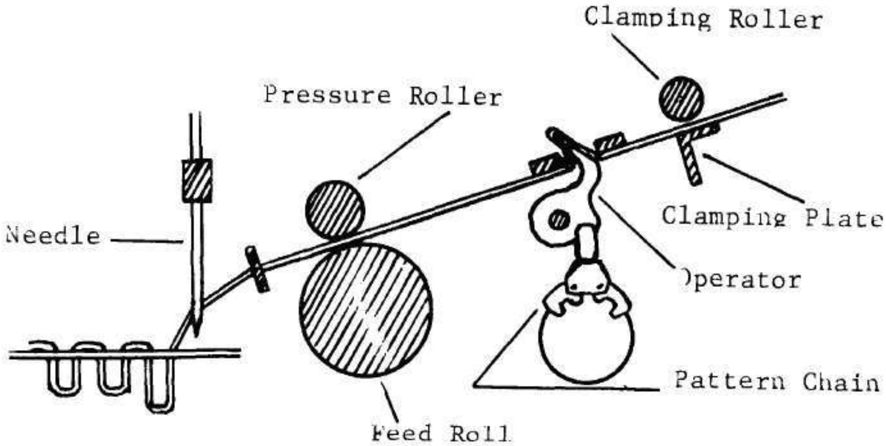

Figure 7. Variable Loop-length Mechanism

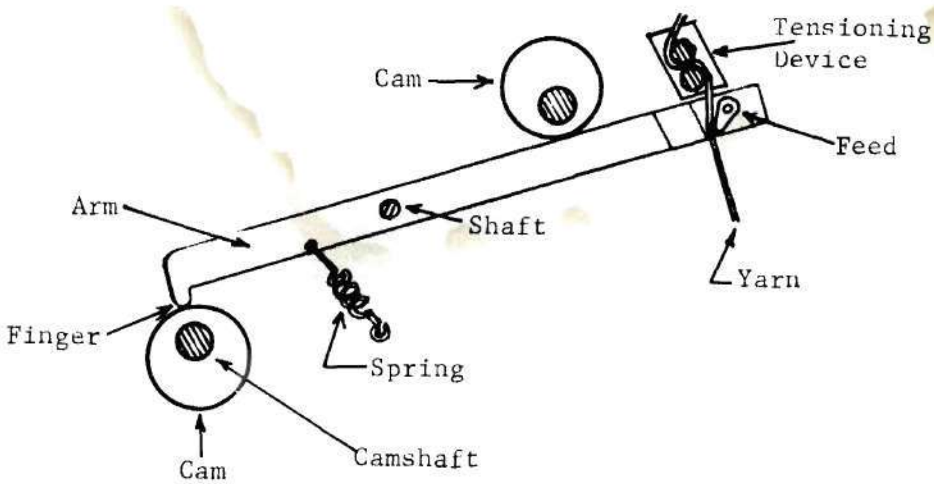

Figure 8. Unidirectional Yarn Feed Mechanism

edged bars. When high portions of these bars slightly deflect certain yarns, more yarn is fed than when low portions of the bars deflect the yarn through 45 degrees or more of bending. Figure 9 also shows an enlarged section of a pattern bar.

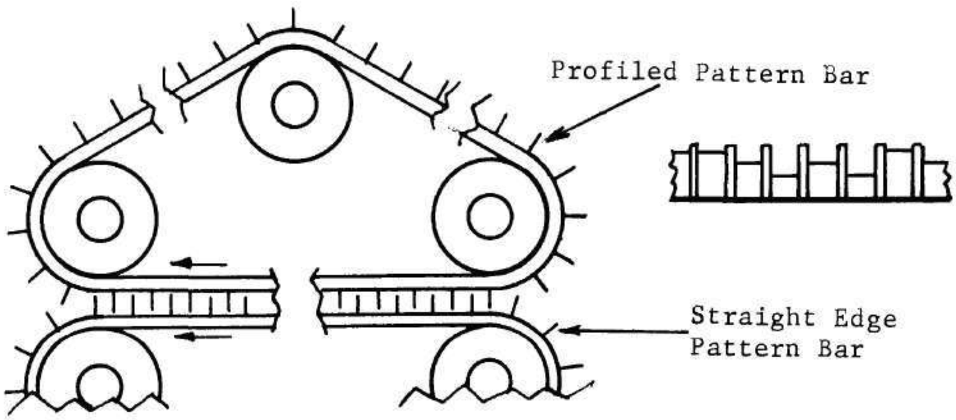

Figure 9. Profiled Pattern Bar Mechanism

W. C. Boteler, et al. (18) presented a yarn delivery system using a number of pulse responsive motors. Depending on the number of electrical impulses to each motor, a determined amount of yarn will be delivered to the needles. By selectively controlling the number and timing of the electrical impulses, a wide variety of predetermined loop heights can be produced.

The system which monitors the electrical impulses consists of a digital computer which is programmed to prepare a pattern program tape. This tape contains the information which will cause a precisely measured amount of yarn to be delivered to the needles.

C. W. Watkins (19) developed the pattern control system shown in Figure 10. It is intended to be an improvement over previous yarn feed control mechanisms in that it is composed of drives which are in motion at all times, a feature introduced to reduce the amount of wear of the machine. A solenoid valve controls the fluid actuator cylinder which controls the position of the linkage bar. Depending on the angular

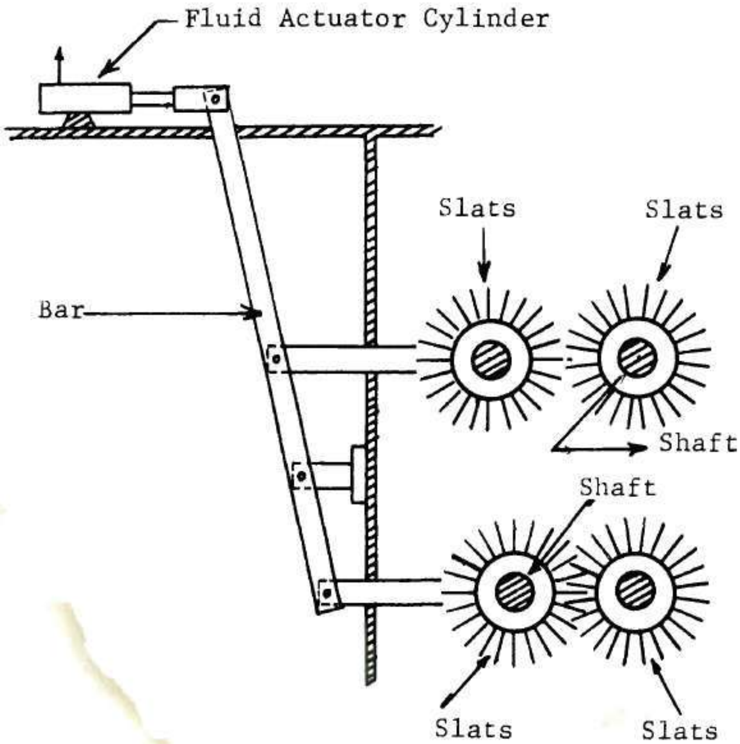

Figure 10. Two-Speed Yarn Feed System

position of the linkage bar, one or the other of the two feed rolls will be in control of yarn flow to the tufting needles.

Of the preceding inventions, the most commonly used in the United States are the profiled-bar mechanism invented by Nowicki (17) (p.12), and the two-speed magnetic clutch arrangement presented in connection with the photocell by Hammel (13) (p.10). The most common devices to control the above pattern mechanisms are the photocell and plastic scroll arrangement (Figure 4) and the pattern drum mentioned on page 9 and shown in Figure 3.

CHAPTER II

INSTRUMENTATION AND EQUIPMENT

2.1 The Tufter

The tufter was built by Cobble Bros. Machinery Co., Inc., Chattanooga, Tennessee (20). It was set up to produce loop pile carpet using a staggered, double-row needle bar, with 6.4 needles per inch, which is a 5/32 gauge. The number of stitches per inch in the direction of the carpet take-up was 5.25 stitches per inch. In order to insure sufficient time for actuation and release of the pattern control mechanism in its experimental stages, the motion of the tufter was slowed down by a 16:1 speed reducer and a pulley arrangement to approximately 22 stitches per minute.

The tufter used was originally equipped with a patterning device using a rotating pattern drum, referenced previously in Chapter I, and a magnetic clutch arrangement, also referenced in Chapter I. For the present work these mechanisms were disconnected, since a new patterning system was the object of this research.

A sample width of 12 inches was tufted, using 77 needles.

2.2 The Patterning Device

2.2.1 Yarn Tension Control

The tension of the pile yarn was controlled by modifying its path by means of a T-shaped bar, mounted on the end of the plunger of a solenoid, and a U-shaped channel. The whole arrangement is shown in Figure 11.

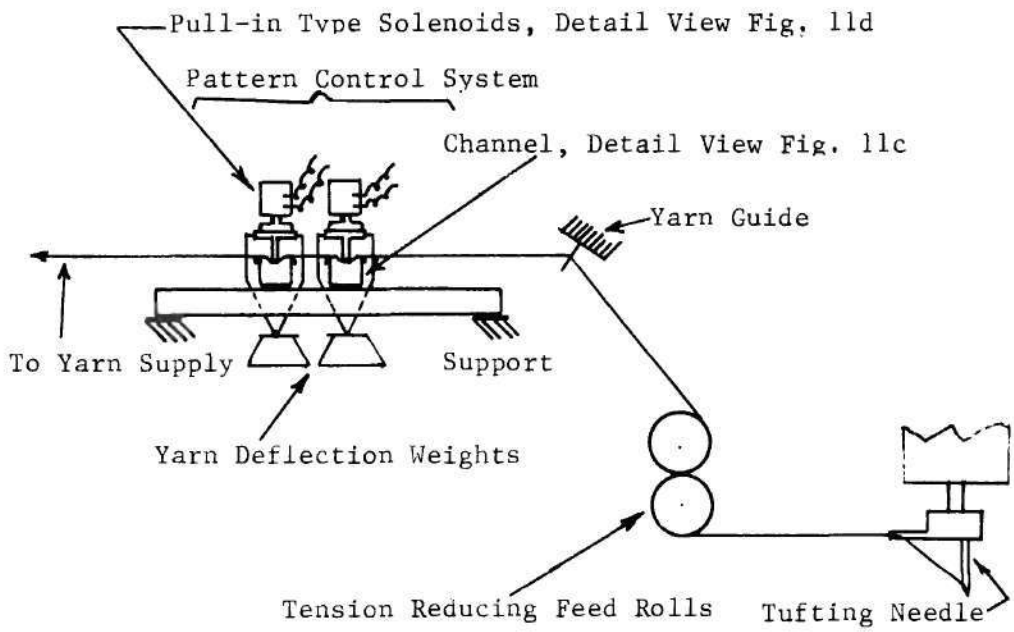

Figure 11a. Side View of Tension Control Device

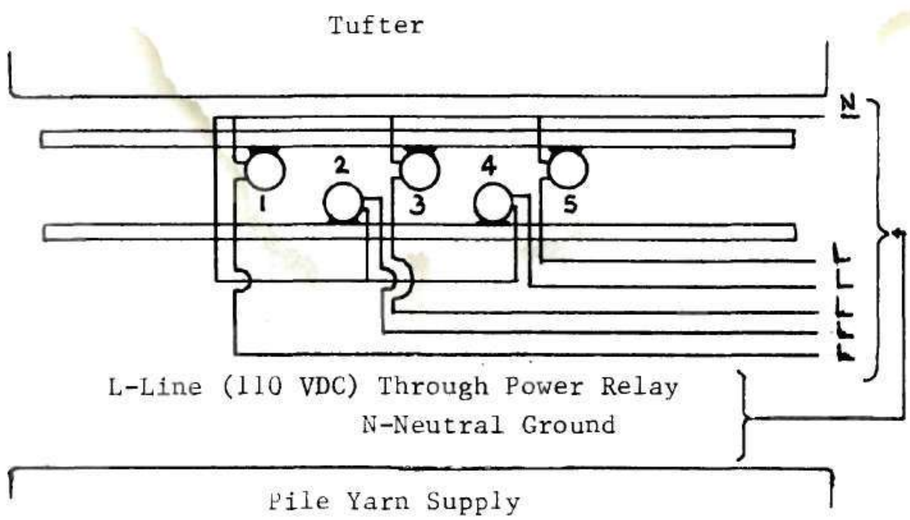

Figure 11b. Top View of Tension Control Device: Five Solenoids with Wiring Diagram

A weight was suspended from each T-shaped bar, in order to deflect the yarn into the channel. Deflecting five yarns per bar and considering the solenoid power rating specified below, a weight of 16 ounces was selected.

The solenoids had specifications of 110 volts AC supply continuous duty pull-type, a maximum allowable stroke of one inch and a maximum rating of 40 ounces at full stroke*.

In this experiment, each solenoid was made to control five pile yarns. Using five solenoids, a total of 25 yarns were controlled. Five additional yarns on either side of the above 25 were permanently deflected into the U-shaped channel, thus producing two uniform low-pile strips which offset the main pattern from the high pile sections along either edge.

A more thorough discussion of the effect of a modified path on yarn tension is found in Section 4.2.

2.2.2 The Control Circuit

Since the programmable calculator and peripheral equipment processing the input data in this experiment were not designed to control the 110 volt AC current required by the solenoids, the circuit shown in Figure 12 was devised to remotely switch the solenoids.

The 110 volt AC current was stepped down to approximately 12 VAC through a transformer. A full wave bridge rectifier converted the transformer output into direct current, while two 500 μf capacitors filtered the AC ripple to less than 10 per cent. Direct current with very low ripple was a requirement for operation of the calculator controlled

* Guardian Solenoids, Manufacturer's Type 18 (continuous)

relays. A 10 ohm, 10 watt resistor was included to increase filtering efficiency and limit current to the power relay coils. Thus, depending on the total amount of current drawn, i.e., the number of power relays switched on at any one time, the voltage ranged from 12 to 20 V.

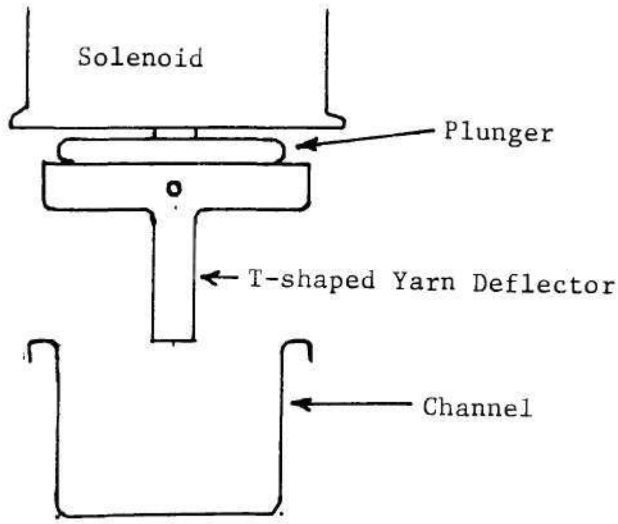

Figure 11c. Tension Control System: Details

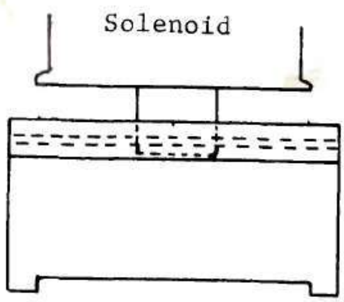

Figure 11d. Side View of T-shaped Yarn Deflector

Five relay coils* controlled by this low voltage power supply were used to switch the AC line power to the solenoids. The reverse biased diodes wired in parallel with each relay coil were included to prevent voltage spikes which occur in the power relay coil when the computer's relay contacts open. The calculator relay control circuit could be damaged through inductive coupling of high voltage transients. The 0.005 μf capacitors wired in parallel with each power solenoid were included as protection against high voltage transients at this source.

An additional circuit was required to synchronize the timing of the tufter with the calculator prepared pattern steps. This circuit is shown in Figure 12c. The DC power supply that operated the relay coils was used to operate this circuit. The microswitch was wired to be normally open, and was attached so that the tufter needle bar closed the circuit for a short period of time at the bottom dead center of each tufter stitching cycle. The resistor in this circuit was chosen according to the following reasoning, based on the fundamental relation Voltage = current (amps) x resistance (ohms), Ohm's Law. The current rating for commonly found resistors is 0.25 watt, equivalent to 0.01 amp at 25 volts. Thus,

$$R = \frac{V}{I} = \frac{25}{0.01} = 2,500 \text{ ohms}$$

which is the minimum resistance within the 0.25 watt rating. Thus the 10,000 ohm resistor will operate at one quarter of the maximum dissipa-

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* Potter & Brumfield General-Purpose Relay, Manufacturer's Type KRP5D, 12 VDC, single pole double throw.

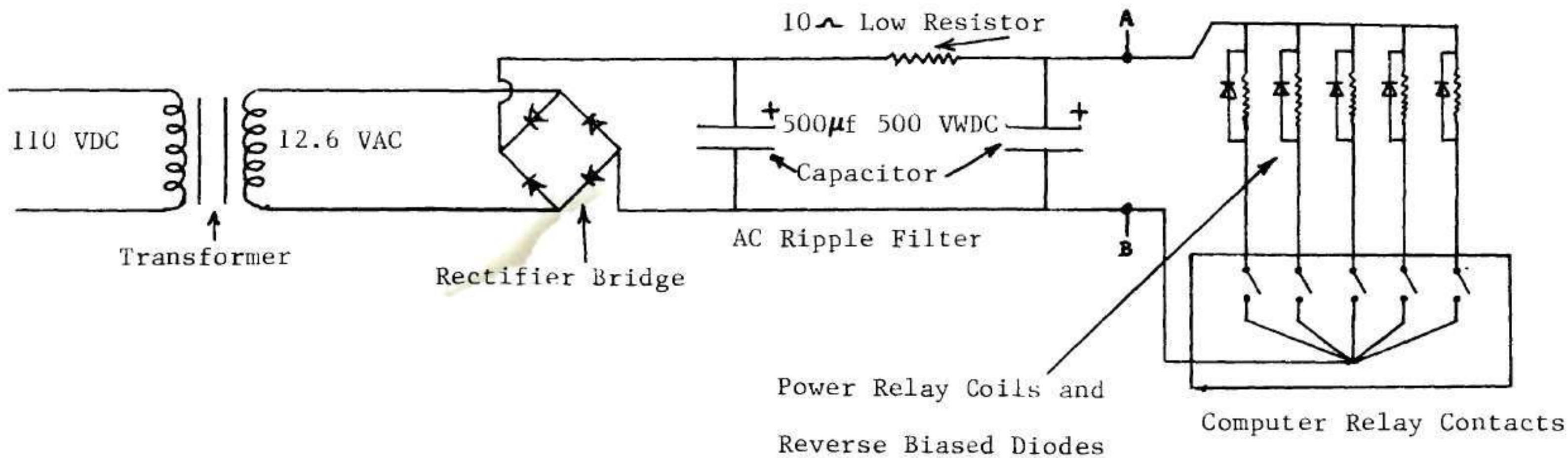


Figure 12a. Control Circuit Schematic Diagram

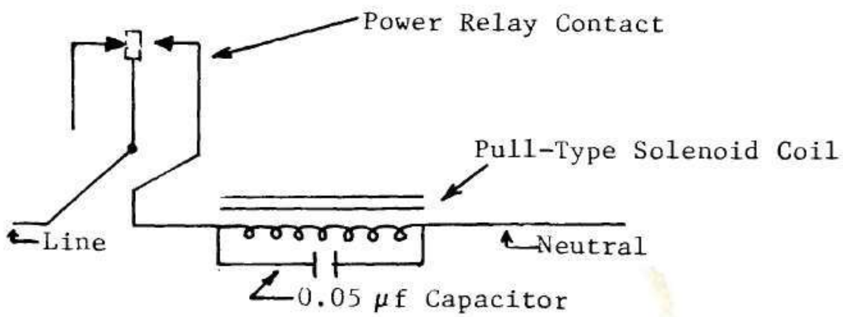


Figure 12b. Solenoid/Relay Power Schematic Diagram

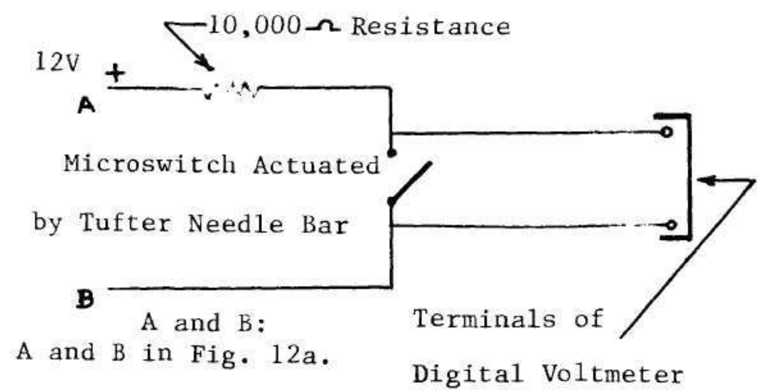


Figure 12c. Synchronization Circuit Schematic Diagram

tion rating.

The digital voltmeter will read zero volts each time the microswitch is closed, i.e., when the needles have fully penetrated the carpet backing. At all other times it will read between 12 and 20 volts.

2.2.3 The Programmable Desk Calculator and Peripheral Equipment

Figure 13 shows the major components of the system and directions of information flow. The calculator was a Hewlett-Packard Model 9100A, with an extended memory Model 9101A, coupler/controller Model 2570A and digital voltmeter Model 3480B. The teletype Model 2752A was a modified ASR-33.

2.3 Experiments on Backrobbing Tensions

In order to establish the magnitude of the tension differential for effective backrobbing, a series of experiments were carried out in the physical testing laboratory of the A. French Textile School.

The tests were conducted on the Instron Universal Instrument, Table Model 1130. The load cell had a maximum load rating of 500 grams. Each major division of the graph paper therefore represented 50 grams. Figure 14 shows the equipment used.

2.4 Tensions Developed by Deflecting a Yarn

A second series of tests attempted to establish a relationship between the angle of deflection and the tensions developed when a yarn is forced into a U-shaped channel.

The same Instron tester and load cell setting specified in Section 2.3 were used in this experiment. The equipment produced different deflections of the yarn and resembled as closely as possible the

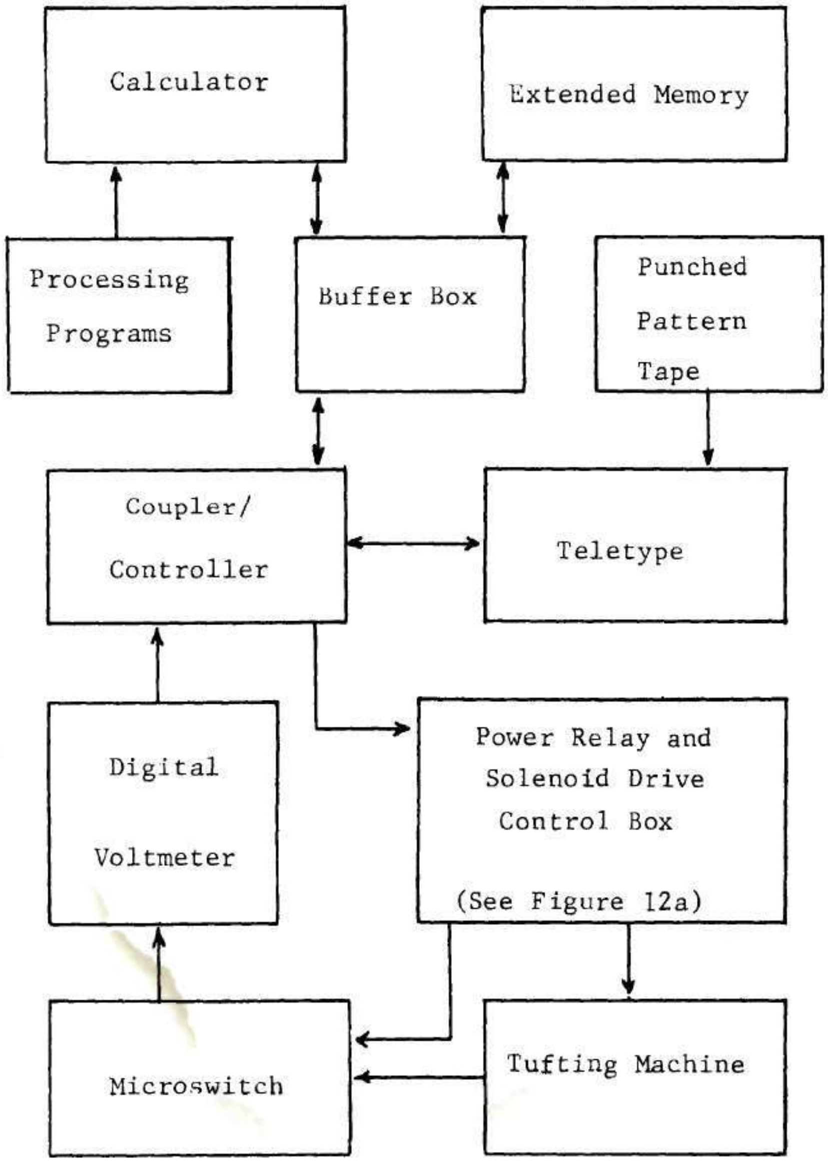


Figure 13. Elements of the Pattern Control System

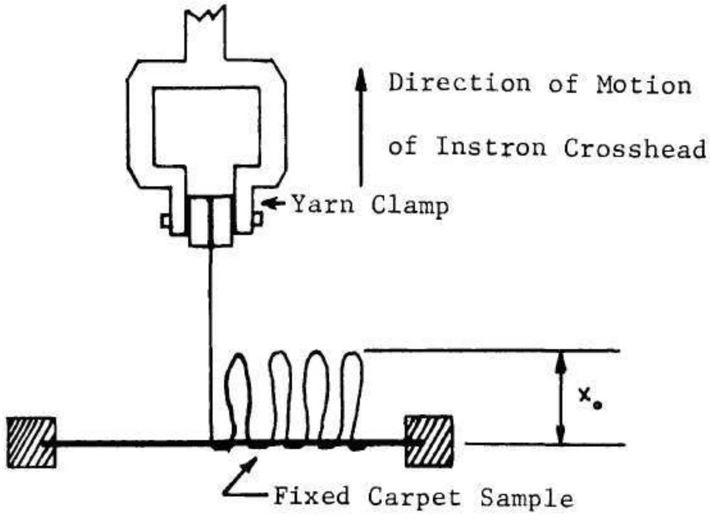


Figure 14. Instron Tester: Backrobbing Tension Tests

tension control device on the tufter, referred to in Section 2.2.1 and Figure 11b. Two steel rods were fixed perpendicular to a board A, while a third rod was fixed perpendicular to a second board B (Figure 15a). Both boards were clamped together such that distances C and C' were equal. By sliding the boards in the direction of the arrow D-D, the deflection E and the angle α were made to vary as shown in Figure 15b.

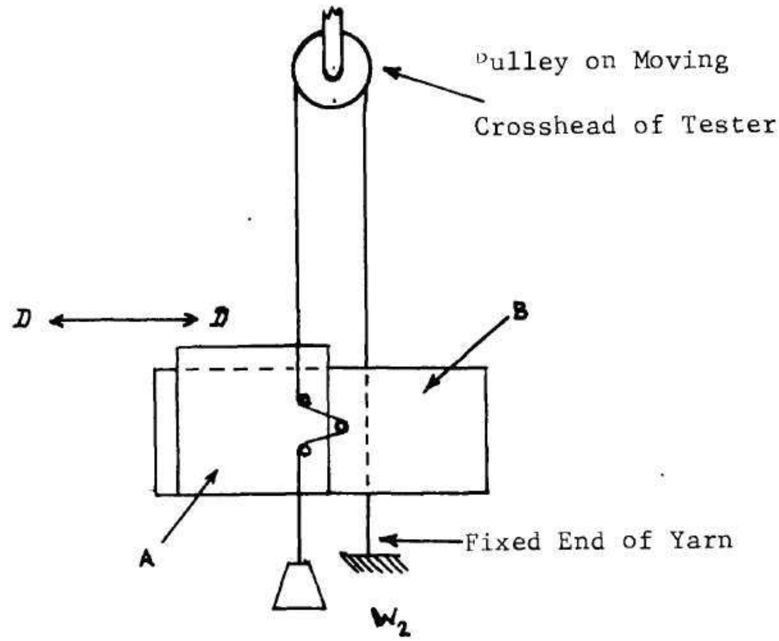


Figure 15a. Instron Tester: Measuring the Tensions Developed by Deflecting a Yarn

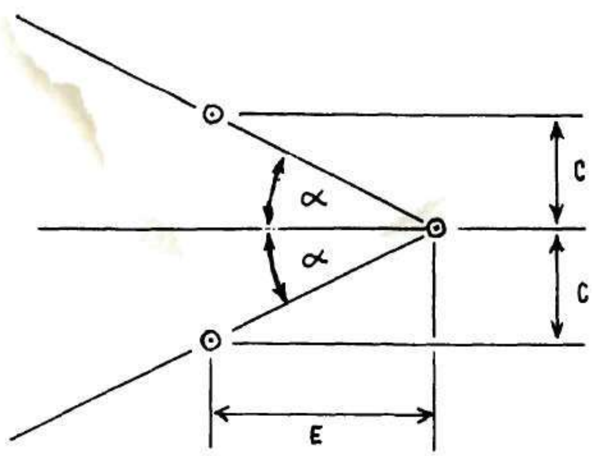


Figure 15b. Yarn Deflecting Device: Variables Involved

CHAPTER III

PROCEDURE

The process of setting up the equipment for production of a high-low loop pattern carpet can be divided into three phases:

1. Design of the pattern.
2. Transfer of the pattern prepared in the previous step onto a punched tape.
3. Introduction of the program steps and the data from the tape into the computer's memory.

3.1 Design of the Pattern

A simple layout on graph paper divided in squares was used to translate the desired design into a sequence of groups of stitches. For the arrangement of five solenoids with five yarns each in this experimental work, there are only five equal sections across the width of the carpet which can be controlled independently. However, this restriction is unnecessary in that the addition of more solenoids or the use of more or less yarns with each solenoid makes possible a wide variety of different designs.

The specifications in Section 2.1 show that five pile yarns across the carpet will occupy roughly the same space as five stitches along the direction of the carpet take-up. Thus, in order to obtain a square design of any sort, the layout should call for an equal number of consecutive stitches and pile yarns side by side.

3.2 Preparation of the Tape

Each combination of high and low loop sections is encoded by a series of zeros and ones, the zeros indicating that the corresponding solenoids will not be activated, thus producing a low loop, while the ones denote the solenoids to be activated, thus producing a high loop. Consequently, with the system described above, five zeros and ones, in any combination, will furnish a complete set of instructions for any given stitch. A figure proceding this group of digits, and separated from it by a decimal point, was programmed to store the number of consecutive stitches to be produced with the same combination of high and low loop sections. Further features of the calculator program are that each complete pattern is concluded by the code number 999. If the figure preceding this terminal code is a 99, the solenoids will all be turned off after going through the sequence of steps once. A number 88 in place of 99 provides a repetition of the pattern, after which the solenoids are turned off. Appendix A shows the method for changing the significance of this number 88 to make it call for any number of repetitions. If no additional figure separates the last combination of zeros and ones from the 999, the pattern will repeat indefinitely.

With the wiring and programs used in this system, the first zero (or one) punched in each group of five solenoids was made to control solenoid number five, the next one number four, etc. For the convention of numbering the solenoids, see Figure 11b.

3.3 Starting-up Procedure

A specific switching-on order of the calculator and peripheral equipment was followed, according to recommendations from Hewlett-Packard. A detailed description of the steps involved is given in Appendix A.

3.4 Backrobbing Tensions: Testing Procedures

Testing of backrobbing tensions with the Instron Universal Instrument was carried out on samples of loop-pile carpet produced on the Cobble tufter described in Chapter II. Pile yarn was fed to the needles without any additional tension placed on them, to achieve a high pile. Regular jute backing and a 50-50 blend, nylon and polyester, pile yarn were used.

The carpet sample was fixed horizontally directly under the moving crosshead of the Instron tester as shown in Figure 14. Each test consisted of backrobbing the previous loop until the loop height X_0 was reduced to zero.

3.5 Tensions Developed by Deflecting a Yarn

In order to establish the average tension on each pile yarn in the area of the pile height control device, the following method was used: A weight, W_1, of 20 grams was suspended from one pile yarn while the tufter was in operation, as shown in Figure 16a, with 3 cm between the points of support of the yarn. A deflection of 0.5 cm was observed. Then the same experiment was reproduced as shown in Figure 16b, and different weights were suspended at $W_2 = X$. It was found that a value of $X = 20$ grams would cause the same deflection of 0.5 cm. In the experiments carried out, the values used for W_2 were 10, 20 and 25 grams. Figure 16c describes schematically the tensions involved in the testing

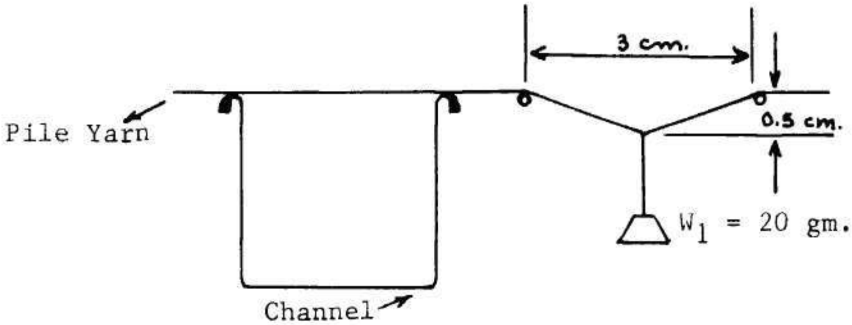


Figure 16a. Measurement of Tension of Pile Yarn on Tufter

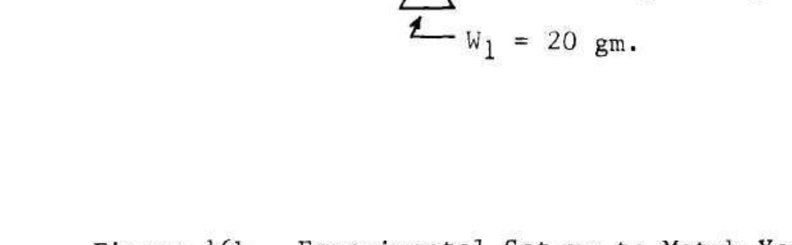


Figure 16b. Experimental Set-up to Match Yarn Tension on Tufter

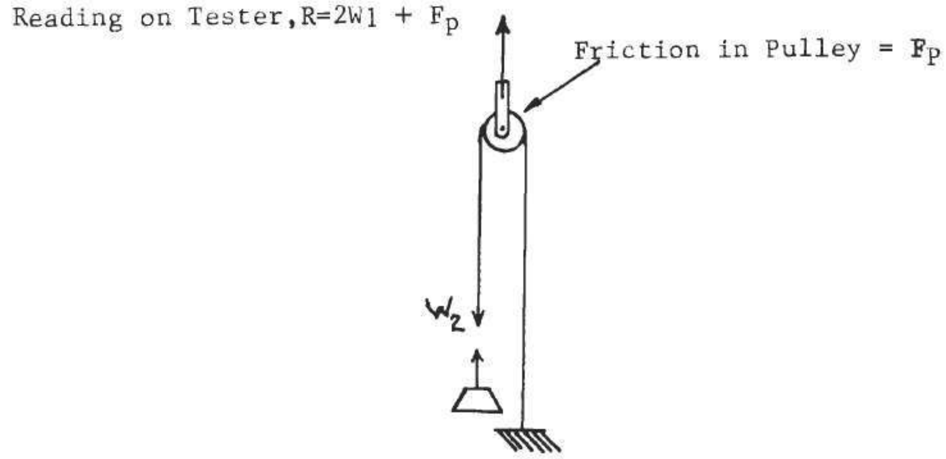


Figure 16c. Forces Involved in Tension Tests

process, with the equipment arranged as shown in Figure 15a. See Appendix C for a more thorough explanation of the measurements performed.

CHAPTER IV

DISCUSSION OF RESULTS

4.1 Results as Answers to the Problems Stated in Section 1.1

The main goal of the present research was to investigate ways of finding a solution to a common problem which arises when automation replaces hand-crafted products: the uniformity and repetitiveness of designs.

By proving the feasibility of the use of computer-controlled solenoids in pile-height control, it is felt that a means to overcome the limitations discussed previously has been found. The possibility of setting up an extensive and yet compact file of different patterns in the form of tapes or cards is seen as a definite advantage. Maintenance of the present system should be less time-consuming and wear is estimated to be at a minimum, especially compared to systems like the one described by W. W. Hammel (13), using magnetic clutches and drives of different speeds to vary the amount of pile yarn fed to the needles.

One of the most serious limitations of the previous pattern control systems has been the length of the repeat of the pattern, usually determined by the practical dimensions of the diameter of the pattern drum, as in the systems invented by M. B. Penman (12) and W. W. Hammel (13). In the present system, the length of a pattern is limited only by the capability of the computer's memory to store data taken off a tape or a series of cards, which is many times more versatile than a pattern drum.

The width of the pattern drum described in the patents mentioned above poses another obvious limitation, restricting the number of pile yarns or groups of yarns that can be controlled individually. Intricate patterns which do not repeat across the full width of a carpet present therefore a serious problem when such pattern control systems are used. Again the present method furnishes more possibilities, since the yarn tension controlling solenoids can be staggered or even arranged in multi-level fashion between the creel holding the yarn supply and the tufter, thus permitting the installation of many independent solenoids.

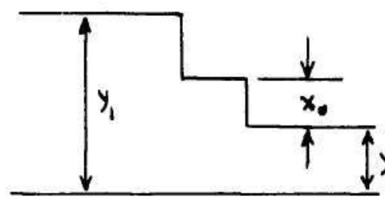
4.2 Pile Height Definition

A good indication of the precision with which a pile height control system works is the promptness with which the pile changes from a high to a low loop or vice versa, as consecutive stitches are introduced. A criterion chosen here to express this degree of precision is the index of pile height definition, and is composed of the following terms:

a) Pile height ratio: Y_1/Y_o, where Y_1 corresponds to the high pile level and Y_o corresponds to the low pile level.

b) X_o, the distance by which the first stitch after a high (or low) loop fails to achieve the new low (or high) pile now called for.

The index of pile height definition is defined as (Y_1/Y_o) (X_o/Y_o). The variables are illustrated in Figure 17.



High-to-low Pile Height

Figure 17. Pile Height Definition

Measurements have yielded the following results: The average for the height of the high pile level was found to be 1.69 cm. The average value for the low pile level was 1.00 cm. These are the values of Y_1 and Y_0 respectively, as used in the relation which defines the pile height definition.

It was found that approximately 30 per cent of the stitches in the first row of low (or high) stitches failed to achieve the new height called for. The average value by which the new row failed to adjust to the new requirements was $X_0 = 0.30$ cm.

See Appendix D for the tables on these measurements.

The index of pile height definition was thus found to be:

$$(X_0/Y_0)\ (Y_1/Y_0) = (0.30/1.00)\ (1.69/1.00) = 0.51$$

In order to establish a comparison between the values of pile height definition of the samples produced in this research and carpets produced on a commercial scale by tufters which use other means of pattern control, a series of measurements was made on samples obtained from the physical testing laboratory of the A. French Textile School. The same methods of measurement, as described in Appendix D were used, and the following results were obtained:

Y_1 (high pile) = 1.5 cm

Y_o (low pile) = 0.5 cm

X_o = 0.5 cm

Thus the pile height definition was found to be

$$(X_o/Y_o)\ (Y_1/Y_o) = (0.5/0.5)\ (1.5/0.5) = 3.0$$

It was found that approximately 35 per cent of the stitches in the first row after a change in pile height was called for failed to adjust to the new pile height requirement.

4.3 Results of Backrobbing Tension Experiments

The average value of backrobbing tension obtained was 58.65 grams, based on the backrobbing of 35 high loops. The standard deviation was found to be 16.2. This rather large value, indicating a considerable spread of values for backrobbing tensions, is due to the fact that when a tuft is introduced in a fabric backing, the needle may penetrate between two threads of the backing, or it may pierce a backing thread. In the latter case, the backrobbing tension would be considerably greater. Refer to Appendix B for a complete list of values obtained and statistical methods applied to the data.

4.4 Results of Experiments on Tensions Developed by Deflecting a Yarn

A summary statement of results is given below in Table 1, showing the different values of the angle α as specified in Figure 15b. All values for ΔT given here were obtained by using a 20 gram weight for the tensioning of the yarn, i.e., W_2 = 20 grams. This weight was shown to approximate adequately the tension actually existing in the pattern control area of the tufter (See Section 3.5). For a complete listing of values obtained, See Appendix C.

Table 1. Tension Differentials by Bending the Yarn

α Degrees	ΔT Grams
22	79.8
30	74.5
40	52.0
50	47.0
60	39.4

4.5 Comparison of Backrobbing Tensions and Results of the Yarn Deflection Tests

The average value from the backrobbing tension experiments was 58.65 grams (See Appendix B). This is the force which should be equalled or exceeded by means of the pattern control device if an effective backrobbing effect is to take place.

Taking the value corresponding to a yarn tension of 20 grams, which was determined on the tufter, a minimum deflection angle, α , of 30 degrees, as defined in Figure 15c, is required for the backrobbing effect. The angle α = 22 degrees represents the maximum deflection which the yarn tension control arrangement as described in Section 2.2.1 can produce.

The maximum load rating of 40 ounces of the solenoids was found to be adequate for suspension of enough weights from the solenoid plungers to cause this minimum required deflection.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The feasibility of using a programmable calculator to monitor a high-low loop pattern on a tufted carpet was proven.

The versatility of such a computerized system, regarding the changeover from one pattern to another by merely introducing another pattern tape was shown to be an important time-saving feature.

The possibility of storing a large number of pattern tapes in a very compact filing system represents a definite advantage over the system of pattern drums commonly used at the present time.

Tension control by deflection of the path of the pile yarn with a solenoid plunger was effective and mechanically simple.

5.2 Recommendations

5.2.1 Further Work on the Tufting Pattern Control System Described in this Thesis

a) The tufter was operated at a speed of approximately 22 stitches per minute during the experimental work. Further study and experiments are suggested directed to increasing speed of the present system, to full production rates.

b) In this research work the yarn tension was selectively controlled by modifying the path of the yarn by means of a T-shaped bar which forced the yarn into a channel, thus bending the yarn at three points. If the T-shaped bar (See Figure 11d) were given a flat lower edge instead of the inverted-U profile used at present, this edge could trap the yarn against the bottom of the channel, which would be covered with some rubber-like material to insure a sufficient and uniform tension differential. The tension differential could be obtained with less bending and, thus, less force on the solenoid plungers. This may prolong the life of the solenoids and cause them to respond more smoothly and promptly to the electric impulses furnished by the control circuit.

5.2.2 Application of the Findings of the Present Work to Dobby and Jacquard Looms

The feasibility of applying the present pattern control system to dobby and Jacquard looms seems quite evident. In the dobby systems, it could advantageously replace the pattern chains which control the harness motion, extending the length of the pattern repeat while simplifying the machine mechanically. In the Jacquard systems, the present apparatus may have the capability of replacing the pattern cards commonly used to control the individual warp ends. Here, more than in the high-low pile patterning of carpets, the changeover from one pattern to another would be tremendously simplified.

APPENDIX A

HEWLETT-PACKARD COMPUTER PROGRAMS

PROGRAM 0

Step No.	Key	Code	Step No.	Key	Code
0-0	CLEAR	20	1-b	FMT	42
0-1	·	21	1-c	y→()	40
0-2	0	00	1-d	4	04
0-3	2	02	2-0	ENT EXP	26
0-4	↑	27	2-1	4	04
0-5	3	03	2-2	CHG SGN	32
0-6	1	01	2-3	↑	27
0-7	FMT	42	2-4	3	03
0-8	y→()	40	2-5	4	04
0-9	·	21	2-6	FMT	42
0-a	0	00	2-7	y→()	40
0-b	0	00	2-8	2	02
0-c	4	04	2-9	ENT EXP	26
0-d	↑	27	2-a	4	04
1-0	3	03	2-b	CHG SGN	32
1-1	2	02	2-c	↑	27
1-2	FMT	42	2-d	3	03
1-3	y→()	40	3-0	5	05
1-4	·	21	3-1	FMT	42
1-5	0	00	3-2	y→()	40
1-6	0	00	3-3	1	01
1-7	2	02	3-4	FMT	42
1-8	↑	27	3-5	GO TO	44
1-9	3	03	3-6	3	03
1-a	3	03	3-7	FMT	42
			3-8	GO TO	44
				END	

PROGRAM 1

Step No.	Key	Code
0-0	CLEAR	20
0-1	ST FLAG	54
0-2	3	03
0-3	9	11
0-4	↑	27
0-5	2	02
0-6	4	04
0-7	0	00
0-8	FMT	42
0-9	y→()	40
0-a	IF FLAG	43
0-b	1	01
0-c	6	06
0-d	↑	27
1-0	2	02
1-1	3	03
1-2	9	11
1-3	IF X=Y	50
1-4	5	05
1-5	2	02
1-6	FMT	42
1-7	f	15
1-8	↑	27
1-9	9	11
1-a	9	11
1-b	9	11
1-c	IF X=Y	50
1-d	5	05
2-0	3	03
2-1	↓	25
2-2	↑	27
2-3	INT X	64
2-4	x→()	23
2-5	a	13
2-6	-	34
2-7	3	03
2-8	1	01
2-9	x→()	23
2-a	b	14
2-b	↓	27
2-c	↑	25
2-d	2	02
3-0	FMT	42
3-1	GO TO	44
3-2	y⇄()	24
3-3	b	14

Step No.	Key	Code
3-4	1	01
3-5	+	33
3-6	y→()	40
3-7	b	14
3-8	3	03
3-9	6	06
3-a	IF X Y	53
3-b	2	02
3-c	c	16
3-d	2	02
4-0	4	04
4-1	0	00
4-2	FMT	42
4-3	π	56
4-4	↑	27
4-5	1	01
4-6	+	33
4-7	2	02
4-8	4	04
4-9	0	00
4-a	FMT	42
4-b	y→()	40
4-c	a	13
4-d	x⇄y	30
5-0	GO TO	44
5-1	0	00
5-2	8	10
5-3	2	02
5-4	4	04
5-5	0	00
5-6	FMT	42
5-7	π	56
5-8	↑	27
5-9	2	02
5-a	4	04
5-b	1	01
5-c	FMT	42
5-d	y→()	40
6-0	4	04
6-1	0	00
6-2	↑	27
6-3	2	02
6-4	4	04
6-5	0	00
6-6	FMT	42
6-7	y→()	40
6-8	FMT	42
	END	

PROGRAM 2

Step No.	Key	Code
0-0	1	01
0-1	0	00
0-2	x	36
0-3	↓	25
0-4	↑	27
0-5	INT X	64
0-6	−	34
0-7	↑	27
0-8	b	14
0-9	FMT	42
0-a	π	56
0-b	x	36
0-c	a	13
0-d	+	33
1-0	ENT EXP	26
1-1	5	05
1-2	CHG SGN	32
1-3	+	33
1-4	y →()	40
1-5	a	13
1-6	FMT	42
	END	

PROGRAM 3

Step No.	Key	Code
0-0	2	02
0-1	4	04
0-2	0	00
0-3	FMT	42
0-4	π	56
0-5	FMT	42
0-6	π	56
0-7	↑	27
0-8	INT X	64
0-9	−	34
0-a	x→()	23
0-b	a	13
0-c	↑	27
0-d	9	11
1-0	9	11
1-1	IF X=Y	50
1-2	7	07
1-3	d	17
1-4	8	10
1-5	8	10
1-6	IF X=Y	50
1-7	5	07
1-8	7	05
1-9	CLEAR X	37
1-a	x→()	23
1-b	b	14
1-c	FMT	42
1-d	1	01
2-0	x⇄y	30
2-1	6	06
2-2	CONT	47
2-3	CONT	47
2-4	CONT	47
2-5	IF X<Y	52
2-6	1	01
2-7	c	16
2-8	ROLL ↑	22
2-9	FMT	42
2-a	2	02
2-b	PAUSE	57
2-c	PAUSE	57
2-b	PAUSE	57
3-0		57
3-1		57
3-2		57
3-3		57
3-4		57
3-5		57
3-6		57
3-7		57
3-8		57
3-9		57
3-a		57
3-b		57
3-c		57
3-d	PAUSE	57
4-0	↑	27
4-1	b	14
4-2	↑	27
4-3	1	01
4-4	+	33
4-5	y→()	40
4-6	b	14
4-7	a	13
4-8	IF X>Y	53
4-9	1	01
4-a	c	16
4-b	2	02
4-c	4	04
4-d	0	00
5-0	FMT	42
5-1	π	56
5-2	↑	27
5-3	1	01
5-4	+	33
5-5	2	02
5-6	4	04
5-7	0	00
5-8	FMT	42
5-9	y→()	40
5-a	2	02
5-b	4	04
5-c	1	01

PROGRAM 3 (Continued)

Step No.	Key	Code
5-d	FMT	42
6-0	π	56
6-1	↑	27
6-2	1	01
6-3	+	33
6-4	↓	25
6-5	IF X>Y	53
6-6	0	00
6-7	0	00
6-8	4	04
6-9	0	00
6-a	↑	27
6-b	2	02
6-c	4	04
6-d	0	00
7-0	FMT	42
7-1	y→()	40
7-2	GO TO	44
7-3	0	00
7-4	0	00
7-5	1	01
7-6	ACC +	60
7-7	RCL	61
7-8	↑	27
7-9	2	(*) 02
7-a	IF X>Y	53
7-b	6	06
7-c	8	10
7-d	·	21
8-0	0	00
8-1	0	00
8-2	0	00
8-3	0	00
8-4	FMT	42
8-5	2	02
8-6	PAUSE	57
8-7	↓	57
8-8	↓	57
8-9	PAUSE	57
8-a	FMT	42
	END	

(*) This figure determines how many repeats of the pattern will be produced when the final 999 on the pattern tape is preceded by 88.

APPENDIX A

STARTING-UP PROCEDURE OF THE EQUIPMENT

The switching-on order of the equipment is as follows:

1. Desk Calculator
2. Extended Memory
3. Coupler/controller
4. Digital Voltmeter
5. Teletype

The reverse sequence should be used when switching the equipment off.

3.3.1 Desk Calculator

Set display mode on FIXED POINT. Enter programs zero to three. These programs are given on the preceding pages.

If the programs are entered from the keyboard, set the mode of operation of the calculator on RUN; press: GO TO () ()
0
0

Set mode on PROGRAM: press: keys in program sequence.

If the programs are to be entered from magnetic program cards, set the mode of calculator operation on RUN, insert appropriate card, beginning with program zero.

Press: ENTER
Press: The number corresponding to the program (0, 1, 2 or 3
Press: FMT
FMT

3.3.2 Extended Memory

Line switch: ON; file protect switch: OFF as long as programs are entered. After that: file protect switch: ON.

3.3.3 Coupler

Line switch: ON; computer plug with connections to relays on pattern control panel: plug in SLOT I/02.

3.3.4 Digital Voltmeter

Connect red line from microswitch to input marked HI (coded red), and black line from microswitch to input marked LO (coded black). Set: Range unit: 1,000 V; Sample rate: HOLD; Filler: OUT; Terminal: FRONT; line: ON.

3.3.5 Teletype

Main switch: LINE; Tape reader: START; Tape punch: OFF. Insert tape in starting position.

On the calculator press: Zero
FMT
GO TO () ()
FMT
ZERO

At this point the teletype will read the pattern tape. When this process is finished, press: END (Also, press RESET button on coupler)
CONTINUE

The system is now ready for the tufter to be started. As soon as the microswitch is closed for the first time, the first pattern combination specified on the pattern tape is set up by the solenoids.

APPENDIX B

BACKROBBING TENSIONS

Methods of Recording the Values Obtained from the Instron Tester Graphs

Ten values were taken at equal intervals along the x-axis on each graph corresponding to the backrobbing of one loop. It was found that when nine additional values were recorded, each of these being taken from the graph at the midpoint of the above intervals, the average values obtained disagreed only by approximately 1.5 per cent. The ten readings per loop backrobbed were therefore considered adequate.

In order to determine the possible error in the process of establishing the true average value for backrobbing tensions by using a relatively small number of samples, i.e., by backrobbing a small number of loops, the following relation was used, which has been developed to determine the number of samples or readings which should be taken in order to have a possible error of E or less per cent.

$$n = \frac{V^2 \ T^2}{E^2}$$

where

$$V^2 = \frac{\sigma 2}{\overline{X}^2}, \quad \sigma -$$

representing the standard deviation, defined as

$$\sigma = \sqrt{\frac{\Sigma(\overline{X} - X_i)^2}{n}}$$

t = this value is called "Student's t", and is a quantity given by S. S. Wilks (21) for varying degrees of freedom and different confidence limits

E = Percentage error permitted

Applying the above relation to the first six values obtained, the following results were reached (the values are given in Table 2 below):

X_5 = 55.2 grams

σ = 16.19

$$V = \frac{16.19 \times 100}{55.2} = 29.33$$

t = 2.015 for v = n-1 = 5, i.e., degrees of freedom = 5, and 10% error

Thus,

$$n = \frac{V^2\ T^2}{E^2} = \frac{(29.33)^2\ (2.015)^2}{10^2} \cong 35$$

Consequently, a total of 35 values were considered adequate.

Table 2. Backrobbing Tensions in Grams

59.3	53.7	40.1	54.6	67.4	44.8	74.4
55.6	56.1	50.5	40.1	66.7	50.5	74.3
44.4	62.2	109.7	84.1	50.4	56.2	44.4
47.8	42.2	37.7	78.6	54.5	91.7	38.9
53.5	44.6	46.5	55.1	75.7	76.6	67.9

The new average value was found to be X_{35} = 58.65 grams, and the standard deviation was again 16.19.

APPENDIX C

TESTS ON TENSIONS DEVELOPED BY DEFLECTING A YARN

Figures 15a and 16c in the text show the equipment used and the tensions involved in the tests.

In performing the tests, first the value of the friction developed by the pulley for the different weights W_2 was determined. This was done by taking readings without the use of the device designed to deflect the yarn. The results obtained are given in Table 3, where R represents the readings on the Instron charts, W_2 the tensioning weight and F_p the friction in the pulley arrangement.

Table 3. Instron Tester: Readings Without the Yarn Deflecting Device

W_2	$R = 2W + F_p$
10 gm	32.5 gm
20 gm	60 gm
30 gm	75 gm

All the readings on the charts were evaluated as described on p. 48 of this appendix in the section dealing with backrobbing tensions. The results obtained for values of W_2 of 10, 20 and 25 grams and for angles of 22, 30, 40, 50 and 60 degrees are given in Table 3.

The additional tension introduced by the deflecting device, called ΔT, was calculated by the following expression, were R_1 is now the respective reading with the deflection device and R is the reading without the device:

$$\Delta T = \frac{R_1 - R}{2}$$

First the individual values obtained from the Instron graphs are given, followed by their average. Each individual value listed in Table 4 is the average of ten readings taken off the graph at regular intervals. Each group of the readings corresponds to one yarn sample. An average of 12 samples was used with each weight W_2 and angle α . This number was considered adequate since the relation $n = t^2 V^2/E^2$, explained on p. 47 of this appendix and applied to the readings corresponding to $\alpha = 22$ degrees and $W_2 = 20$ grams, indicated that only four samples are required for a 5 per cent or less error.

$X_{14} = 221.5$ grams

$\sigma = 10.11$

$t = 2.16$ for $v = n-1 = 13$ and 5 per cent error

$$V = \frac{\sigma \times 100}{\overline{X}} = 4.56$$

$$n = \frac{(4.56)^2 \, (2.16)^2}{5^2} = 3.9$$

Table 4. Tensions Achieved by Bending a Yarn

W_2 Grams	α Degrees	R_1 Grams	$\overline{R}_1$ Grams	R Grams	$\frac{R_1 - R}{2} = T$
10	22	150, 145, 140, 150, 152, 152, 175, 140, 145, 175, 140, 215	156.6		62.2
10	30	150, 160, 150, 145, 135, 132, 125, 130, 127, 138, 140, 135	138.9		53.2
10	40	107, 130, 130, 122, 124, 115, 105, 106, 110, 112, 107, 105	114.4	32.5	41.0
10	50	118, 115, 100, 110, 110, 105 112, 107, 105, 108, 97, 96	106.9		37.2
10	60	72, 75, 80, 80, 92, 75, 90, 86, 86, 85, 90, 95	83.8		25.7

Table 4. Tensions Achieved by Bending a Yarn (Continued)

W_2 Grams	α Degrees	R_1 Grams	$\overline{R_1}$ Grams	R Grams	$\frac{R_1 - R}{2} = T$
20	22	235, 215, 212, 207, 213, 220, 220, 215, 220, 216, 226, 235	219.5		79.8
20	30	198, 217, 212, 236, 205, 212, 210, 217, 200, 188, 209, 204	209,0		74.5
20	40	170, 165, 160, 160, 160, 171, 166, 174, 170, 154, 157, 160	163.9	60.0	52.0
20	50	168, 161, 163, 152, 155, 150, 147, 155, 150, 147, 155, 145	154.0		47.0
20	60	145, 145, 147, 135, 134, 132, 140, 147, 135, 135, 140, 130	138.8		39.4

Table 4. Tensions Achieved by Bending a Yarn (Continued)

W_2 Grams	α Degrees	R_1 Grams	$\overline{R_1}$ Grams	R Grams	$\frac{\overline{R_1} - R}{2} = T$
25	22	255, 260, 274, 260, 273, 274, 275, 281, 273, 300, 271, 252	270.7		97.9
25	30	236, 230, 227, 210, 214, 226, 231, 221, 234, 235, 255, 252	233.2		79.1
25	40	202, 201, 193, 194, 200, 196, 195, 201, 195, 206, 201, 207	199.3	75.0	62.2
25	50	174, 173, 168, 185, 184, 180, 183, 182, 173, 182, 180, 177	178.4		51.7
25	60	162, 157, 155, 148, 145, 146, 148, 150, 154, 152, 149, 145	150.9		38.0

APPENDIX D

PILE HEIGHT DEFINITION: MEASUREMENTS AND CALCULATIONS

In order to accurately measure the length of individual loops of a tufted carpet, the set-up shown in Figure 18 was used. The loop was stretched to its full height by means of a hook or similar instrument, designated as 1, taking precautions so as to prevent backrobbing from either of the adjacent loops. A scale divided into millimeters was then placed next to the loop to be measured, and the loop height, here shown as Y_1, read.

The measurements on the samples produced in the present work were as shown in Table 5 below, which gives individual values, averages and standard deviations for Y_o, Y_1, Y_1-X_o and $Y_o + X_o$. For an interpretation of these values, refer to Figure 17 in the text.

Table 5. Measurements on Pile Height Definition Samples Produced in the Present Research

	Values Measured	Averages	σ	n
Y_o	1.0, 1.1, 1.0, 1.0, 1.2, 0.9, 1.0, 1.0, 1.1, 0.9, 1.0, 1.1	1.0	0.09	12
Y_1	1.6, 1.8, 1.8, 1.8, 1.7, 1.7, 1.6, 1.5, 1.8, 1.5, 1.9, 1.6	1.7	0.13	12
$Y_o + X_o$	1.2, 1.2, 1.3, 1.4, 1.3, 1.5, 1.3 1.4, 1.5, 1.4, 1.3, 1.2, 1.1, 1.1, 1.4	1.3	0.12	15

From the values of Table 5, the magnitudes of X_o were calculated. For the case of high-to-low loop change:

$$Y_o + X_o - Y_o = 1.3 - 1.0 - 0.3 \text{ cm} = X_o$$

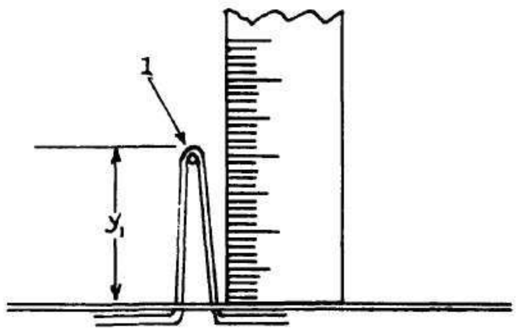


Figure 18. Pile Height Measurements

In order to determine the percentage of loops which failed to achieve the new pile height required, 50 random loops were measured, all of them taken from the first row of stitches after a pile height change. All loops which failed to reach the new required pile height by less than 0.1 cm were considered as having properly adjusted to the new pile height. Fifty samples were taken from the high-to-low pile height change and 50 for the low-to-high pile height change. Both series of measurements showed that approximately 30 per cent of the loops failed to achieve the new pile height in the first stitch after a pile height change is called for.

The measurements on the commercially produced carpet samples yielded the values given in Table 6. On these samples the measurements for the X_o values from high-to-low pile height change and low-to-high pile height change were taken together, since it was not possible to distinguish between these two types of pile height change.

Table 6. Measurements on Pile Height Definition Commercial Sample

	Values Measured (cm)	Averages (cm)	σ	n
Y_1	1.3, 1.4, 1.6, 1.6, 1.5, 1.3, 1.6, 1.7, 1.4, 1.5, 1.7, 1.5	1.5	0.13	12
Y_o	0.4, 0.4, 0.6, 0.5, 0.5, 0.6, 0.5, 0.3, 0.5, 0.7, 0.6, 0.4	0.5	0.11	12
$Y_o + X_o$	1.1, 1.2, 1.0, 0.9, 1.1, 1.0, 1.2, 1.3, 0.9, 1.0, 1.1, 1.0, 1.1, 1.3, 0.8	1.0	0.14	15

To determine the percentage of loops which failed to achieve the required new pile height by 0.1 cm or more, 50 samples were taken. It was found that approximately 35 per cent failed to adjust to the new pile height requirements during the first stitch.

From the values of Table 6, the magnitude of X_o was calculated.

$$Y_o + X_o - Y_o = 1.0 - 0.5 = 0.5 \text{ cm} = X_o$$

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