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Computer Numerical Control of Woodworking Machines in Secondary Manufacture

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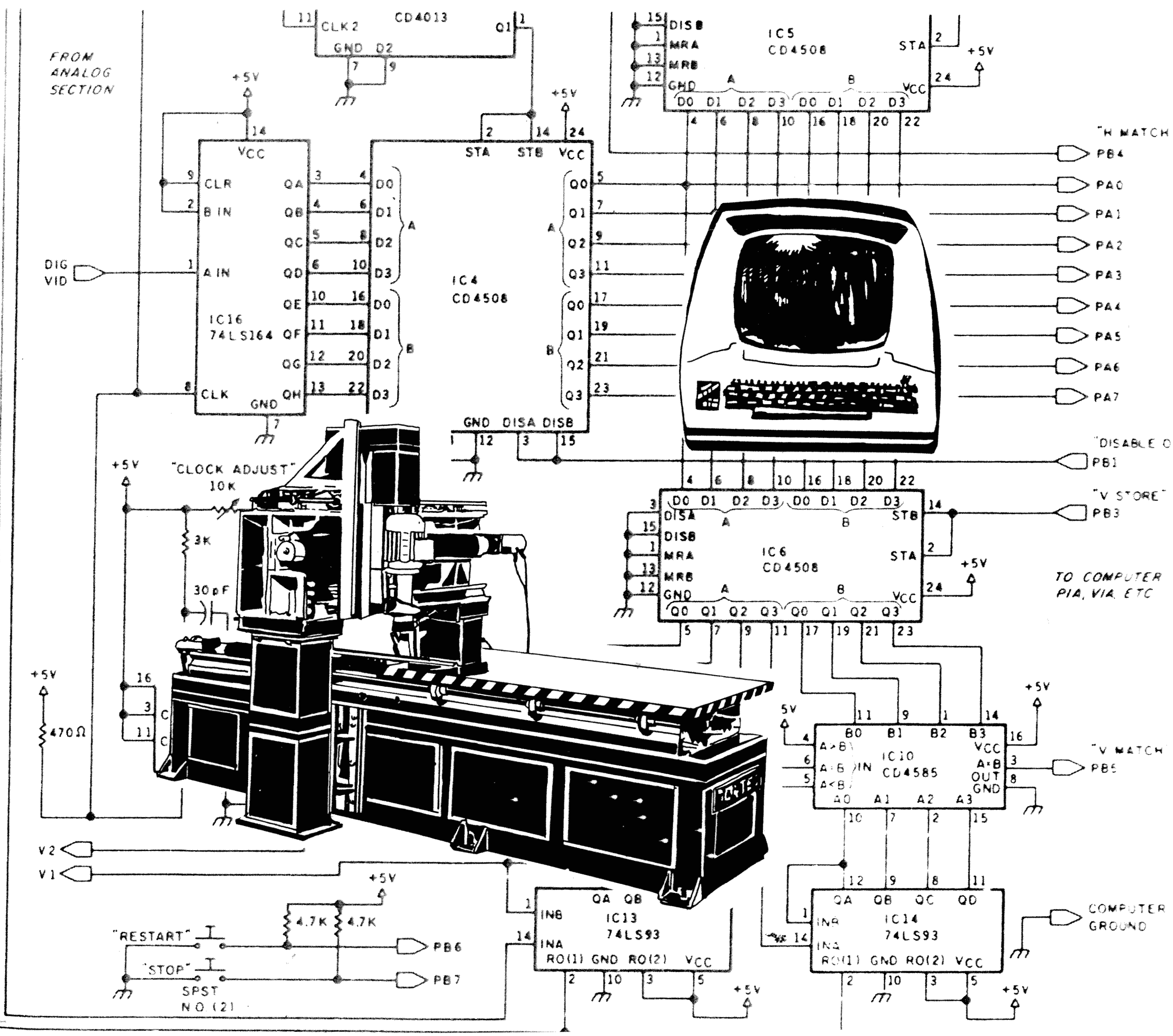

SUMMARY

The function and operation of computer numerical controllers is summarized and a number of computer controlled machines used in secondary manufacture are described and illustrated. Included are machines for routing, boring, carving, laser profiling, panel sizing, injection bonding, and upholstery and foam contour cutting. Additionally, a discussion is given on a proposed computer-aided manufacturing system for laser cutting furniture parts under control of defect scanners.

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INTRODUCTION

The manufacture of wood commodities in everyday use — furniture, decorative molding, cabinetry, recreational items, etc. — requires a variety of woodworking machines to surface, drill, and shape wood into complex parts. In the past, parts were assembled largely by hand by a single skilled workman who carefully checked for dimensional accuracy at each stage until final assembly. By the mid-19th century, sufficiently accurate woodworking machinery was developed, thus eliminating the need to machine and assemble single parts by hand. Workers instead produced hundreds of identical parts which were later joined by others in a final assembly operation. This was the beginning of mass production, a precursor of automation.

Innovative automatic machines developed rapidly and by the turn of the century, woodworking machines could turn out thousands of identical parts with little human interaction. Productivity improved but the machines were limited in that they could only perform a series of sequential operations.

The "program" was created by a series of cams and ratchets that actuated tools needed to manufacture the part and little change could be made in the variety of sequences. The cost of creating new "hardware" programs was high.

More versatile machines were clearly needed. Especially desired was one that could be guided by a set of written instructions and on command carry out the operations — positioning the workpiece, routing grooves, drilling holes in specified locations — with no human intervention. Refinements on the concept of feedback, and the modern digital computer made development of such machines possible.

A numerically controlled routing and shaping machine was introduced into the wood industry in 1966. The machine could mill, drill, and bore at any angle, using a punched-paper-tape program read by an electronic controller. The program also positioned the tool and dictated its depth and rate of cut. To alter the shape or create an entirely different part it was only necessary to amend the old punched tape or create a new one.

Because the computer controllers were expensive, the industry was slow to respond. The cost of microprocessor-based controllers no larger than desktop calculators has, however, decreased dramatically within the past 10 years, and magnetic media and solid state bubble memory are replacing punched paper tape. Microprocessor controllers thus now add relatively little to the cost of numerically controlled machines.

Aside from reduced machine cost, other factors favor increased introduction of computer-numerically-controlled equipment for secondary wood conversion. Costs associated with labor have reached the point where the investment return on programmable machinery is attractive. But perhaps more important is the potential for improved productivity. Computer numerical control of machines can often reduce rejects and waste, minimize handling, and improve dimensional accuracy.

The objective of this paper is to summarize the functions and operation of computer numerical controllers and describe a number of computer controlled woodworking and other machines used in secondary manufacture.

COMPUTER NUMERICAL CONTROLLERS

At the heart of the computerized numerical control (CNC) is a low cost, small microprocessor that is the central arithmetic and logic unit of the system. Miniaturized to fit on a single silicon chip such microprocessors frequently hold thousands of transistors, resistors, and related circuit elements

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(fig. 1). By adding additional chips to provide timing, program memory interfaces for input/output signals, random-access memory, and other ancillary functions, it is possible to assemble a numerical controller on boards no larger than standard 8- by 10-inch sheets of paper.

It is the function of the microprocessor to accept data in the form of binary digits (0's and 1's), to store the data, and to perform arithmetic and logic operations in accordance with a previously programed set of instructions. After processing, the microprocessor delivers the results to a user output mechanism. Typically, a microprocessor would contain the following components: a decode and code control unit to interpret instructions from programs, an arithmetic and logic unit, registers for manipulating data, an accumulation register, address buffers to provide access to sequential instructions, and input-output buffers to read instructions or data into the micro-processor or to send them out.

Figure 2 shows a computer numerical controller consisting of an operator control panel, part program data reader, and peripheral device connecter panel. Typically, the components are also available for individual mounting according to the machine tool builder's requirements. Such free-standing cabinet configurations measure about 30 × 30 × 70 inches high, weigh about 250 pounds and are air cooled during operation.

Not shown in figure 2 is the controller's power supply located within the dust proof cabinet. Power supplies usually operate at 60 HZ, 120 volts A.C., and are normally provided with over and under voltage protection as well as overtemperature detection display circuitry and automatic shutdown in case of excessive internal temperatures. Some power supplies feature battery backup to maintain part program data storage during power failures, as well as diagnostic indicators and external voltage test points.

The operator's control panel usually consists of a CRT video display, various push buttons, indicators, and selector switches used to initiate, monitor and govern control operations. Typical operations include on/off control, manual axis jog, machine home, and part program load/execute functions. A serial communication link is normally provided between the operator control panel and the controller circuit boards, enabling the control panel to be on or near the machine tool while the controller and power supply are placed in a more desirable location.

CRT displays range in size from 5 to 12 inches measured diagonally. Some are capable of displaying up to 15 lines with 32 alphanumeric characters per line. Most feature a selectable character size to assist reading position coordinates

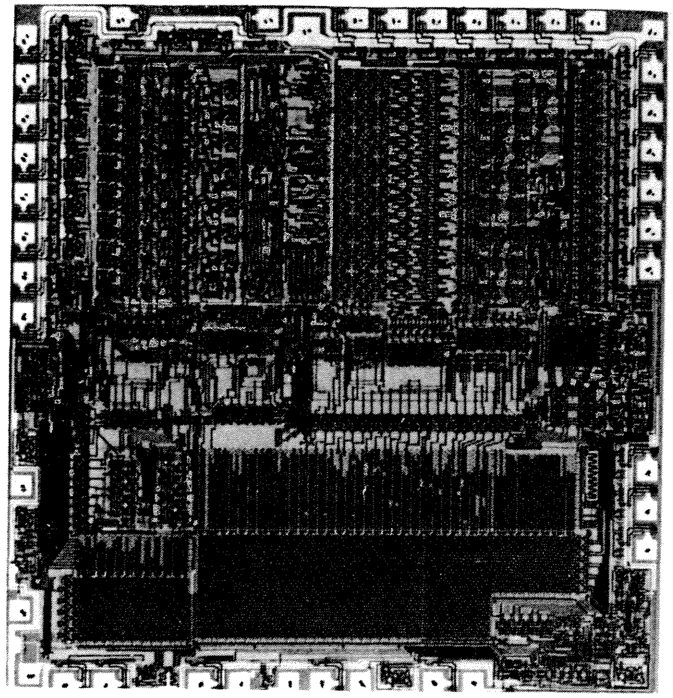

Figure 1.—*Photograph of a microprocessor chip measuring 6 × 6-mm containing over 7,000 transistors.* (Photo courtesy Bell Laboratories).

and other data at a distance. Typical readouts include stored part program, current position coordinates, distance to go, command blocks, cutter compensation and diagnostic data messages from the programmable controller interface, alarm messages, and total and part machining operation time.

A typewriter-like alphanumeric keyboard enables the operator to manually enter part program data and tool offsets, as well as edit programs and initiate various control operations. Some control panels contain space for additional hardware used in specialized applications; they may also provide for emergency termination of machine operations and interlocks to prevent unauthorized modification of stored part programs.

The electronic circuitry needed to implement machine operations are sometimes contained on individual printed circuit modules assigned to specific slots within the controller chassis. In other controllers, the functions of individual digital logic boards are combined and incorporated on a single board using very large scale integrated (VLSI) circuitry. Each module or operational circuit performs specific control functions, such as data processing or input/output/servo control.

The main processor module containing the system microprocessor executes the control program and provides supervisory control over system operations. Additionally, it performs CNC functions, including part program data decoding and distribution, arithmetic and logic, and interpolation.

A programmable interface supplies the necessary circuitry to interface the CNC with machines and allows the user to define and store in program form his own sequential machine tool logic. A microprocessor on the module executes the programmable interface program and coordinates functions with the main processor module.

Random access storage for part program data is provided by one- or several-part memory circuits. Such data are read from either punched paper tape or magnetic media, such as tape or disks. In some controllers, part program data are permanently stored in recently developed magnetic readers.

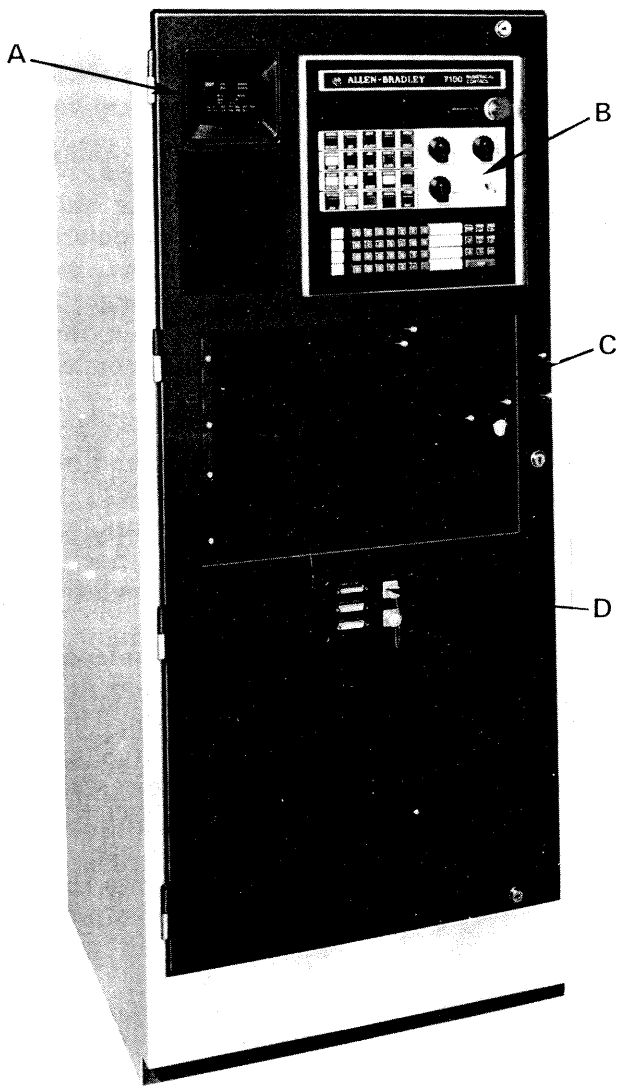

Figure 2.—*Typical free-standing computer numerical control. A. CRT video display. B. Operator's console. C. Tape reader. D. Peripheral device connector. (Photo courtesy Allen Bradley Corp.).*

Lastly, the input/output/servo circuitry facilitates the electronic interface between the CNC and the external machine tool. The input/output modules which vary in number depending on user needs actuate such devices as relays, limit, and proximity switches. One or more servo modules provide the electronic interface with position feedback devices and servo drives.

The concept of feedback is a characteristic common to most computer controlled machines. Feedback involves the interaction of machine servo-mechanisms and the controller. As an example, figure 3 shows a schematic diagram of a feedback loop that determines the positions of a movable work table. The controller is told what position is desired by the part program data storage device. The drive motor and lead screw then move the table until the position transducer reports to the controller via a comparison unit that the correct position has been reached. Various types of feedback transducers are used, such as encoders, tachometers, Selsyn motors, variable resistors or, in highly accurate machines, optical interferometers. Depending on the sophistication of the feedback system, computer controlled machines are routinely accurate to within 0.001-inch or less.

PROGRAMMING

Computer numerical control programs may be either written manually or prepared by ancillary computer systems. The method used depends mainly on the type of machining operation and the complexity of the part.

The first step in manual programming is to determine the operations and the order in which they are to be performed. Working from blueprints, the programmer next establishes position coordinates that define the shape of the part or tool path. The coordinates may be in absolute or incremental units. In absolute units all points are in reference to the origin of the coordinate axes (machine zero) with quadrant defined by sign. In the incremental mode, movement is in a step or increment from the present position to the new position. The sign associated with the coordinate indicates if the position is to move in forward or reverse.

The program is then written, using a series of statement blocks preceded by a line number. Each statement block contains instructions for the

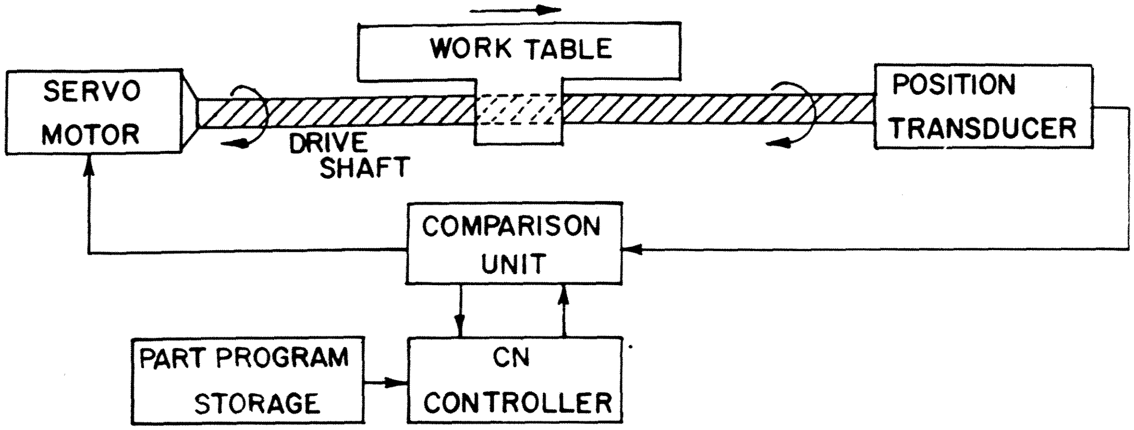

Figure 3.—*Feedback loop to control worktable position.*

machine to perform a movement and/or function. Typically, these include preparatory functions, words to place the control in various mode of operation (i.e., linear interpolation mode, circular interpolation mode), axis movement instructions, feed rate and spindle speed data, and tool offset number.

A typical 2-axis program to move the tool in a path as in figure 4 is given below with an explanation of each line.[1] The program assumes the controller is in the inch, absolute coordinate, and inch per minute feedrate modes.

n100	g01	x2500		f30000	EOB[2]	(P0 to P1)
n105		x17500	y15000		EOB	(P1 to P2)
n110		x22500			EOB	(P2 to P3)
n115			y2500		EOB	(P3 to P4)
n120		x32500	y7500		EOB	(P4 to P5)
n125		x45000	y5000		EOB	(P5 to P6)

In block n100, a single axis movement of 0.75 inches in the +x direction from P0 to P1 occurs at 30 IPM.

In block n105, a 2-axis linearly interpolated movement of 1.5 inches in the +y direction and 0.5 inches in the +x direction (from P1 to P2) occurs at 30 IPM.

In block n110, a single axis movement of 0.5 inches in the +x direction from P2 to P3 occurs at 30 IPM.

In block n115, a single axis movement of 1.25 inches in the -y direction from P3 to P4 occurs at 30 IPM.

In block n120, a 2-axis linearly interpolated movement of 0.5 inches in the +y direction and 1.0 inches in the +x direction (from P4 to P5) occurs at 30 IPM.

In block n125, a 2-axis linearly interpolated movement of 0.25 inches in the -y direction and 1.25 inches in the +x direction (from P5 to P6) occurs at 30 IPM.

[1]Anonymous. 1980. System 7320 Programming Manual. Allen-Bradley, Cleveland, Ohio.

[2]An end-of-block (EOB) flag is required at end of each statement block.

After debugging, the program is reproduced on punched tape or other storage media, and verified by a dry run.

Because each coordinate point need not be calculated, programs written with the aid of a computer are greatly simplified. Computer-aided part programming does, however, require knowledge of a programming language. While many different languages are available, the best known and most widely used is APT (Automatically Programmed Tools).

The APT programmer used English-like words to define operations involving geometry and motion. Geometry statements include POINT, LINE, PLANE, CIRCLE. Motion statements include GOTO, GOON, GOPAST, and others. Such input commands produce the necessary calculations to define the tool path.

While the APT processor is machine independent, it operates with a machine dependent post-processor specific to individual needs. The post-processor formats numerical data in a manner understood by the controller and processes such commands as DELAY, CYCLE AUXFUN, AND REWIND. These commands are oriented to the numerical controller system and always result in execution of the same process. Post-processor machine segment commands, which typically include SPINDL (spindle on/off), COOLNT (coolant on/off), and GOHOME, differ between machines. This section of the post-processor also defines maximum travel and velocity of each axis and its acceleration limits.

The programmer first assigns alpha-numeric names to variables or geometric surfaces (figure 5). This both simplifies geometry definition and allows easier detection of variables when checking the program against a blueprint. The variable names in figure 5 are assigned as HL1 (horizontal line 1), C1 (circle 1), and VL1 (vertical line 1). Statements frequently contain a major word preceding a slash

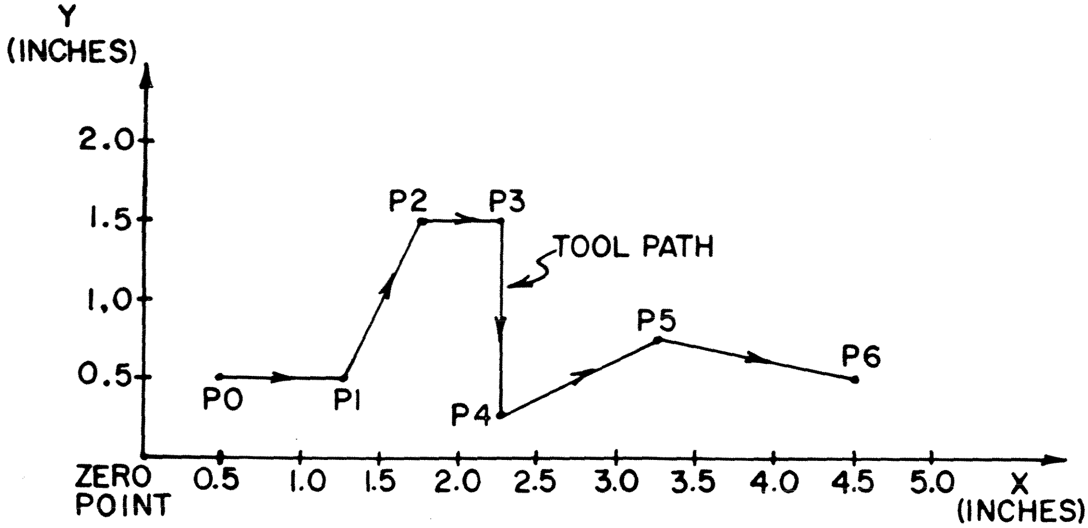

Figure 4.—*Tool path movement by linear interpolation. (Drawing courtesy Allen Bradley Corp.).*

(/) followed by minor information. The program statements to move the tool along the path shown are:

1 GOLFT/HL1, TANTO, C1

2 GOFWD/C1, TANTO, VL1

Line 1 means that, based on the previous move, go left along HL1, and stop where HL1 is tangent to C1. Line 2 instructs the controller to continue in a forward direction along C1 and stop where C1 is tangent to VL1. As with manual programming, the completed program is stored on punched tape or magnetic media.

Through use of a digitizing graphics tablet (fig. 6), part program data can also be input to the controller. The shape of the desired part is first drawn on paper and attached to the table. The outline of the part is traced with a hand-held sensor equipped with a cross-hair cursor. Microprocessors in the interface circuitry automatically digitize the x-y coordinates for subsequent processing to machine ready tape. Operation command insertion, editing, program review, curve smoothing, and cutter diameter compensation are activated with appropriate codes at a CRT/keyboard module.

Many manufacturers of CNC woodworking machines provide in-house programming facilities for users preferring to contract some or all of their programming needs.

COMPUTER CONTROLLED MACHINES

Routers

Routers, the most widely used computer numerically controlled machines in woodworking, are available in a range of configurations from a number of manufacturers. Some CNC routers are termed "machining centers," being capable of such additional woodworking operations as shaping, boring, drilling, carving, engraving, and dadoing. By using specialized heads that can be positioned and actuated automatically, it is also possible to drive screws, insert dowels, paint, stamp, saw, and broach.

A wide variety of parts can be made with CNC routers or "machining centers". Included are gunstock checkering (the cross hatched shallow groove pattern on butts and forearms), kitchen cabinet and furniture parts, guitar blanks, picture frames, and tool cases. Figure 7 illustrates some typical parts and attests to the complexity of pattern attainable with computer numerical control.

CNC routers are most frequently controlled in 2 or 3 axes (fig. 8). Axes 1 and 2 define the relative position of the tool to the work in the horizontal x-y plane, while axis 3 establishes the up and down movement of the tool in the z plane. In some machines, additional control axes are provided to

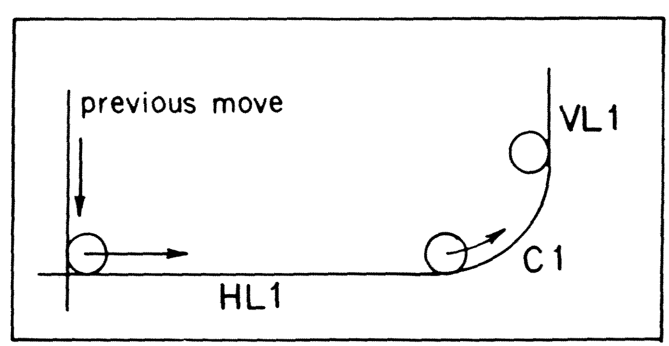

Figure 5.—*Simple motion with variables labeled for programming by APT. (Drawing courtesy Allen Bradley Corp.).*

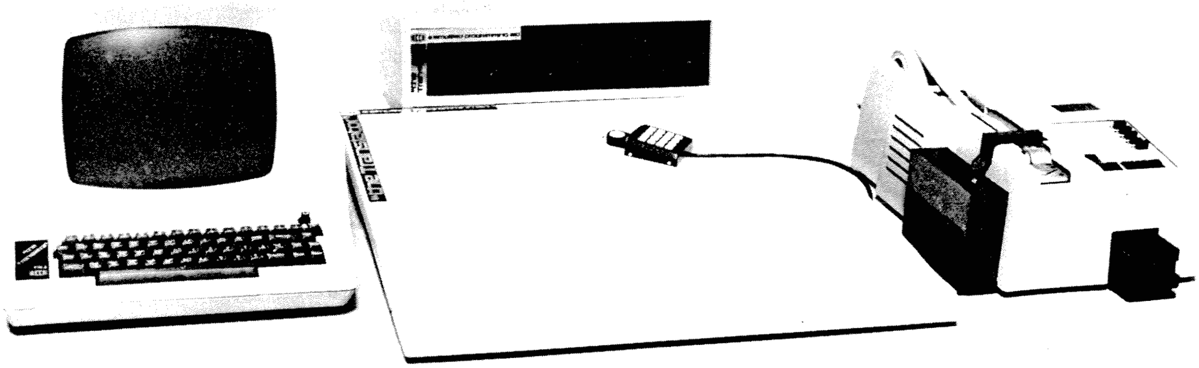

Figure 6.—*Undimensioned shapes are traced on a digitizing tablet to automatically produce machine ready part program tape. Center front — Table and cursor. Center rear — Microprocessor interface. Left — Terminal computer. Right — Tape reader/punch. (Photo courtesy Ekstrom, Carlson & Co.).*

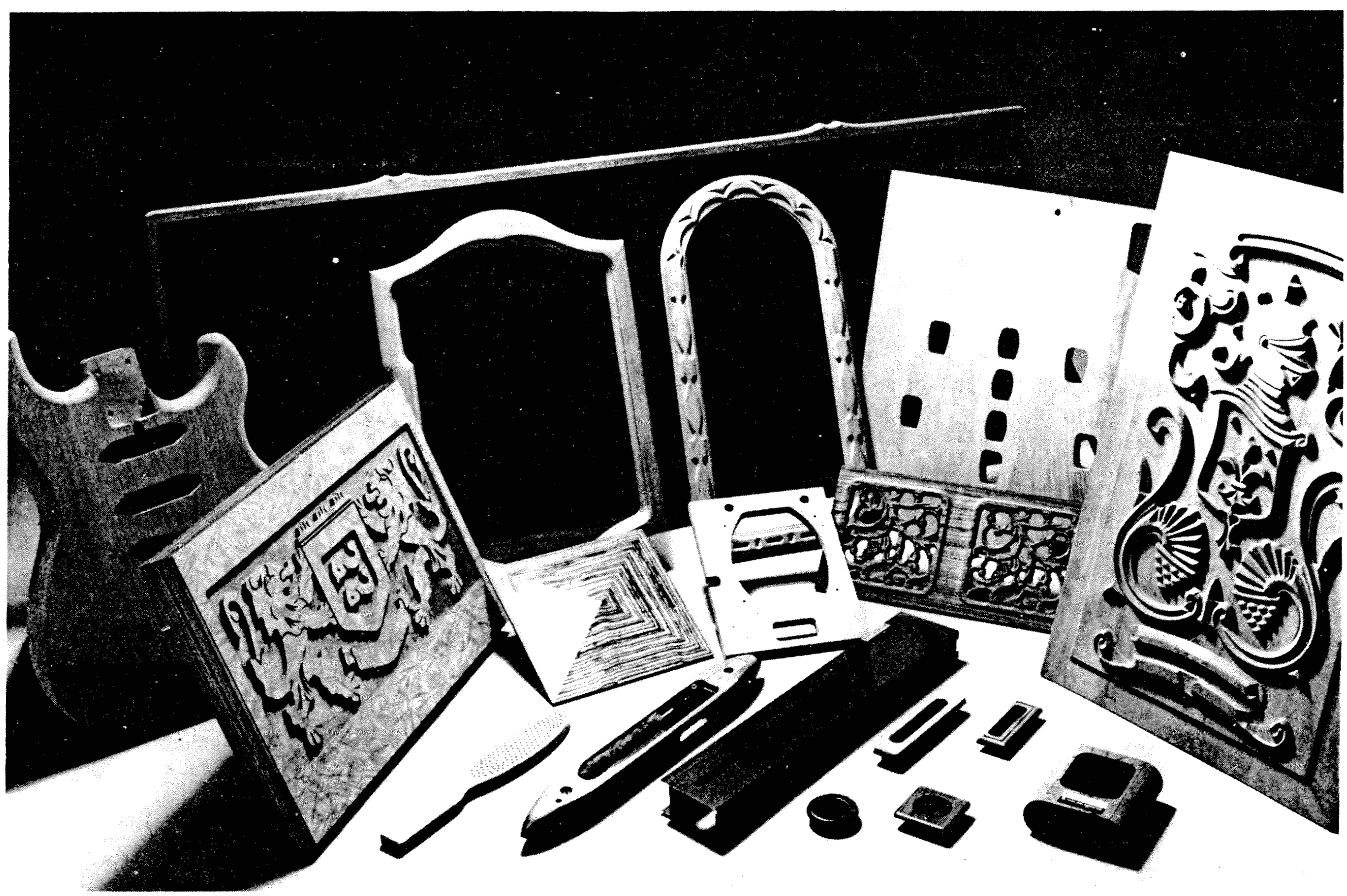

Figure 7.—*Typical parts manufactured with a CNC router.*

rotate the tool holder about the vertical x-axis and to tilt the tool in the vertical plane.

The method of obtaining relative motion between the tool and the work differs between machines and manufacturers. In some machines, the worktable moves unidirectionally in the x-y plane beneath a stationary spindle. In others, the table moves along the x-axis and the spindle along the y-axis; still others move the cutterhead in the x-y plane over a stationary table. Although some tables have T-slots, the flat workpiece table may be drilled to mount positioning fixtures and clamps. A programmable vacuum chuck is also frequently attached to the table. Such chucks hold thin workpieces flat, with clamping forces distributed over the entire work surface.

Machines are available with a single or multiple spindle cutting heads. Multiple spindle machines allow simultaneous production of more than one part and numerous types of machining operations with a single setup. Depending on user requirements, auxiliary tools are sometimes added to individual spindles. Included are programmable high speed air operated drills and additional air operated routers with or without floating heads. Some manufacrturers equip large routers with single or multiple turret heads each containing up to six spindles.

Because manufacturers usually offer a wide range of options designed to meet specific user needs, it is difficult to describe the machines in depth. The following discussion is instead intended to provide the reader with summary information on a few of the many types of currently available CNC routers.

A 2-axis x-y moving table router with the numerical control (left) housed in a free standing cabinet is shown in figure 9. The 24 × 36-inch usable stroke table is driven by a D.C. Servo system at rates from 0 to 400 inches per minute. In such two-axes machines, the spindle is usually positioned against adjustable stops to establish depth of cut. Optional equipment allows the operator to select and program several depth stops through tape command functions.

A continuous path, 2-axis, single spindle router with a fixed table and movable ram is illustrated in figure 10. The fixed table/moving ram design is claimed to improve productivity as parts can be machined on one end of the table while completed parts are unloaded and new blanks loaded on the other. Measuring 24 inches wide by 72 inches long the table may be hand lowered 14 inches below the spindle. The computer controlled moving ram can position the cutting tool at any location over the entire table surface. Feed speeds of the moving ram are computer controlled through pulse width modulated DC servo motors and can be varied from 0 to 600 inches per minute in 0.001-inch increments. The feed rate of the computer activated spindle is manually set. The spindle is belt driven by a 15 hp motor at 11,500 or 23,000 rpm and electrical dynamic braking is provided.

Figure 11 illustrates a typical 3-axes continuous path, single spindle CNC router with moving x-y table designed for high speed routing and light shaping. The table which rides on case hardened ball shafts and bushings, is driven by high performance, closed loop, DC servo motors coupled to double lead, lead screws. The mist-lubricated spindle is belt driven by a 5 hp, 1800/3600 rpm motor with switch selectable spindle speeds of 10,000 and 20,000 rpm. The 1-3/4-inch thick, T-slotted aluminum table measures 25-inch by 41-inch and has a usable movement of 22 inches in the y-axis and 38 inches in the x-axis. Feed speeds are programmable from 0 to 600 inches per minute with a rapid traverse rate of 800 inches per minute. A chip exhaust system surrounds the cutting tool.

A 3-axis, continuous path CNC router of bridge type construction with moving carriage and single router head traveling in the y-axis and the router

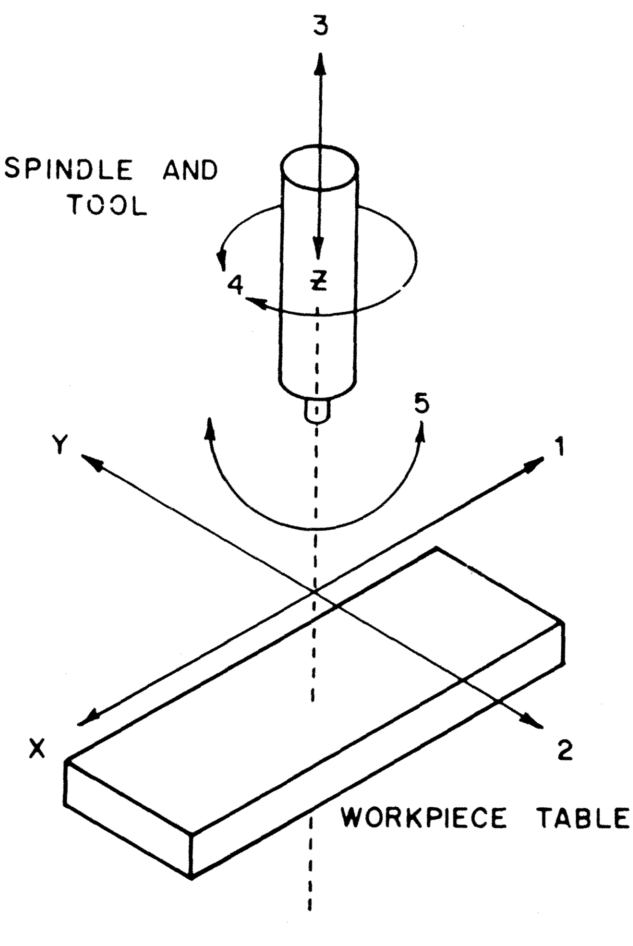

Figure 8.—*Motion of control axes relative to the tool for CNC routers.*

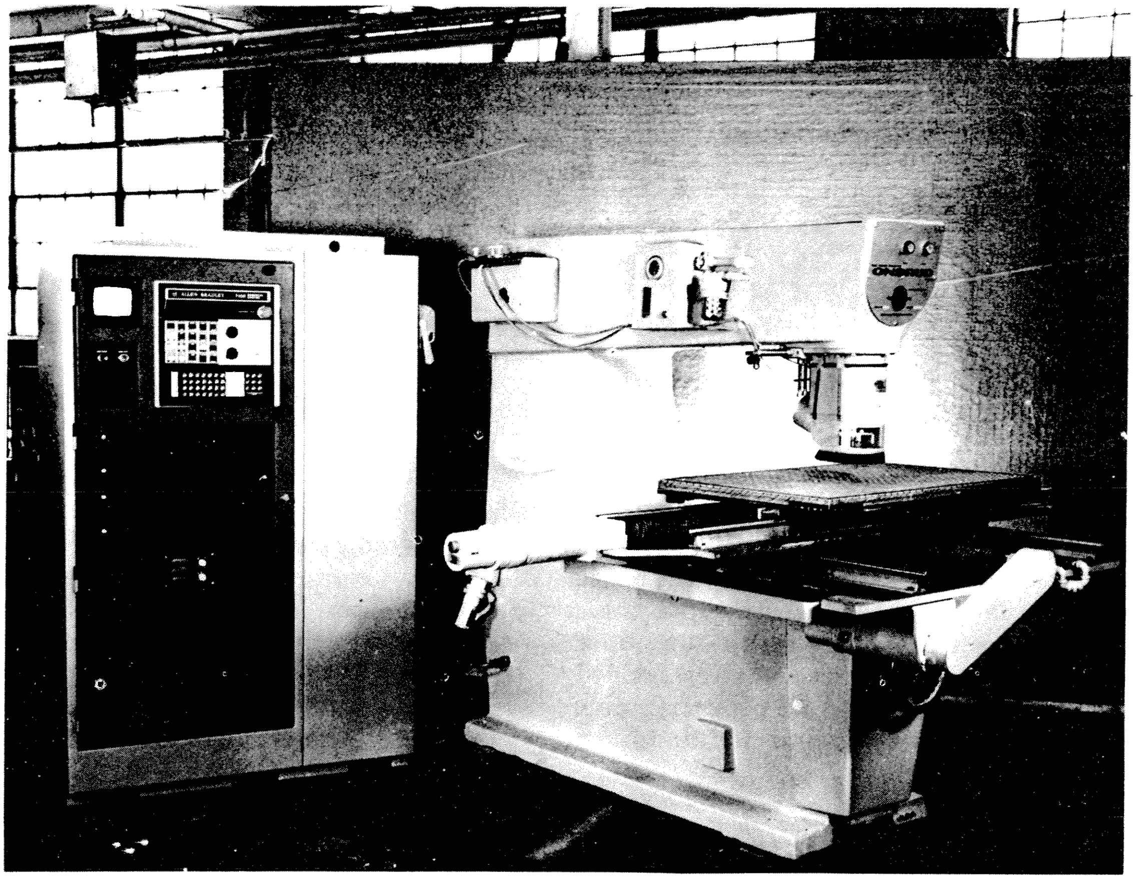

Figure 9.—*A 2-axis, moving table NC router with electrically selectable spindle speeds of 10,000 and 20,000 rpm. Part program storage is available to 360 feet of tape which can be read at 200 characters per second. (Photo courtesy Danly Machine Corporation-Onsrud Division).*

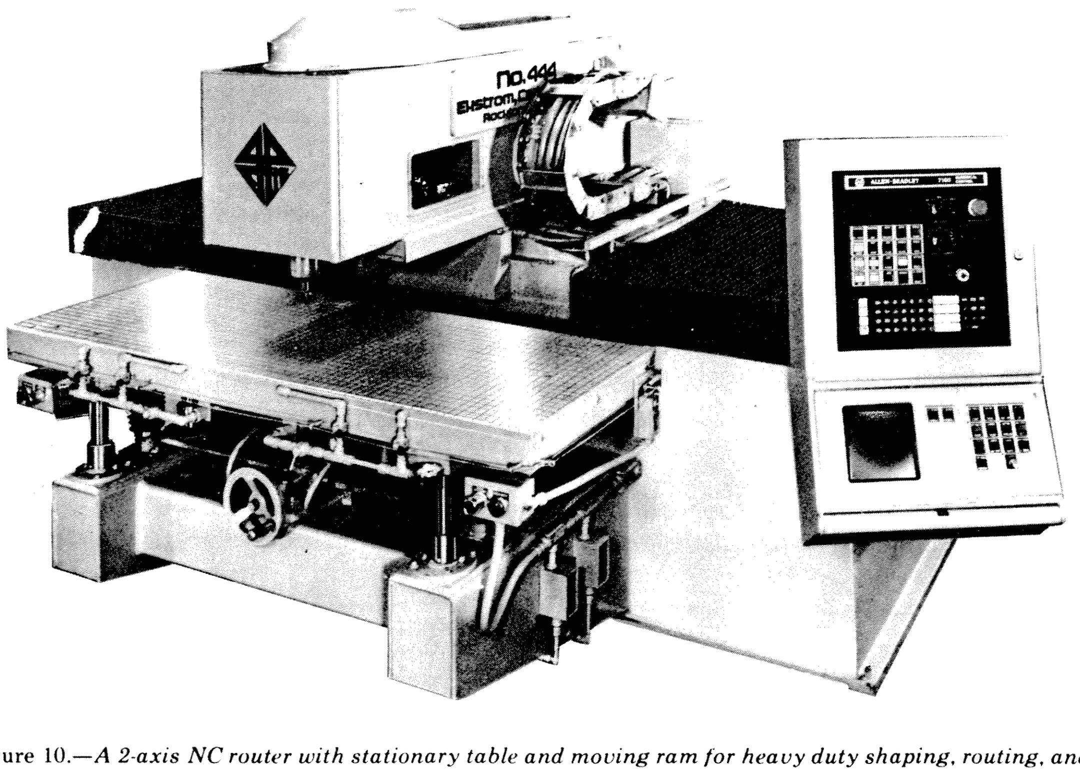

Figure 10.—*A 2-axis NC router with stationary table and moving ram for heavy duty shaping, routing, and contouring. The numerical control with operator's console and CRT display are machine mounted. (Photo courtesy Ekstrom, Carlson & Co.).*

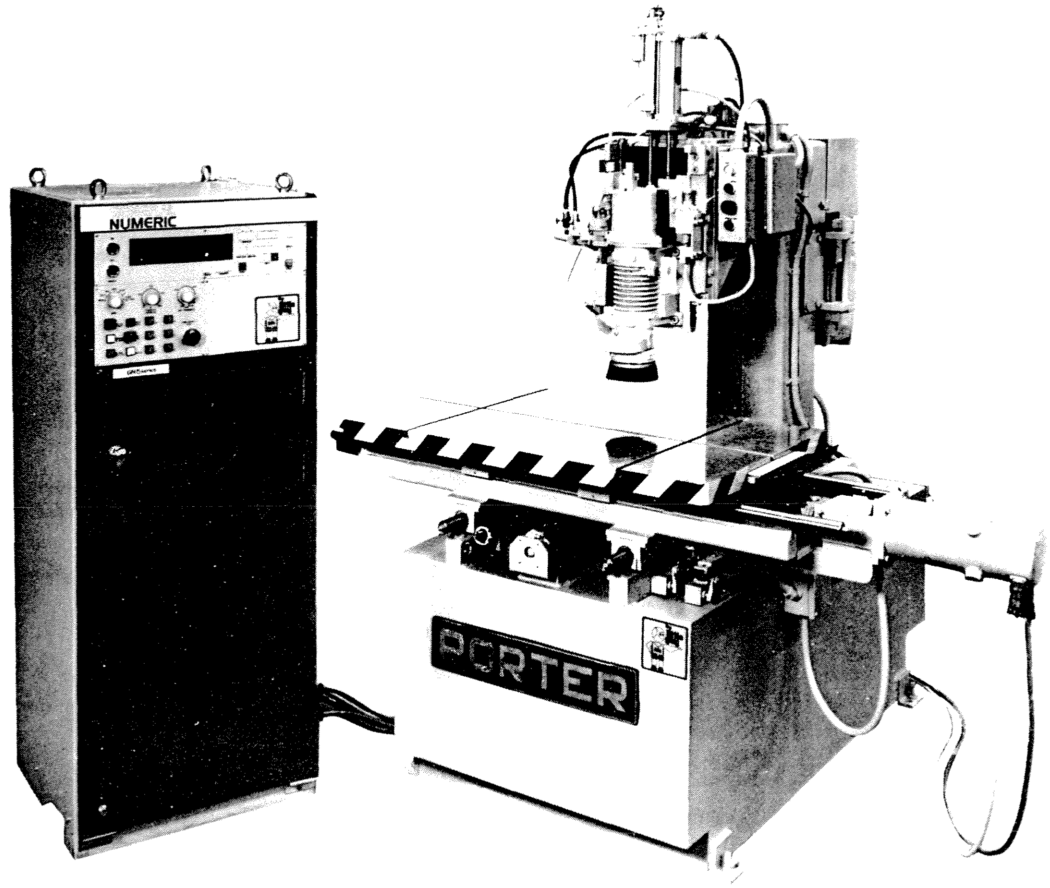

Figure 11.—*A 3-axis, single spindle, movable table CNC contouring router. (Photo courtesy C. O. Porter Machinery Co.).*

table traveling in the x-axis is shown in figure 12. Machines of bridge-type design are useful for routing large panels; with some capable of accepting material as large as 5 by 10 feet. In the router shown, the spindle is directly driven by a 6.5 hp motor at spindle speeds of 10,000 or 18,000 rpm. Up and down z-axis spindle feed is computer controlled between 0 and 200 inches per minute. X and y table feed speed in both linear and circular interpolation is controlled between 0 and 600 inches per minute. Both router head and table are powered by DC closed loop Servo motors and driven by rolling ball screws and preloaded ball nuts.

Figure 13 shows another 3-axes bridge type router with a stationary table. In this design, two independently programmable tool carriages, each having two directly driven routing heads and two air powered boring spindles, traverse the bridge in the x-axis. The entire bridge in turn traverses the work in the y-axis direction. The router shown uses a simplified, self-contained, solid-state controller with editing capability. No external tape readers are used.

A 6-spindle-turret type CNC router especially designed for machining gunstocks is shown in figure 14. The turret rotates about its axis, moving vertically in the z-direction. Gunstocks in jigs are attached to the movable table which traverses the x-y axes.

Illustrated in figure 15 is a computer numerically controlled machining center. The machine is equipped with a 4-spindle turret type routing head, two horizontal circular saws for crosscutting and ripping, two horizontal boring spindles, and a vertical boring spindle.

Boring

Figure 16 shows a computer numerically controlled machine for boring, drilling, and routing holes in the face of flat panels. The unit replaces several specialized machines as cutters of different types and diameters can be chucked in multiple spindles, properly positioned, and individually activated.

The machine frame is of welded construction and incorporates a vibration damping system. Two parallel circular guideways with serrated tops are fixed to the frame and transfer thrust forces from cutters to machine body. The tool unit assembly

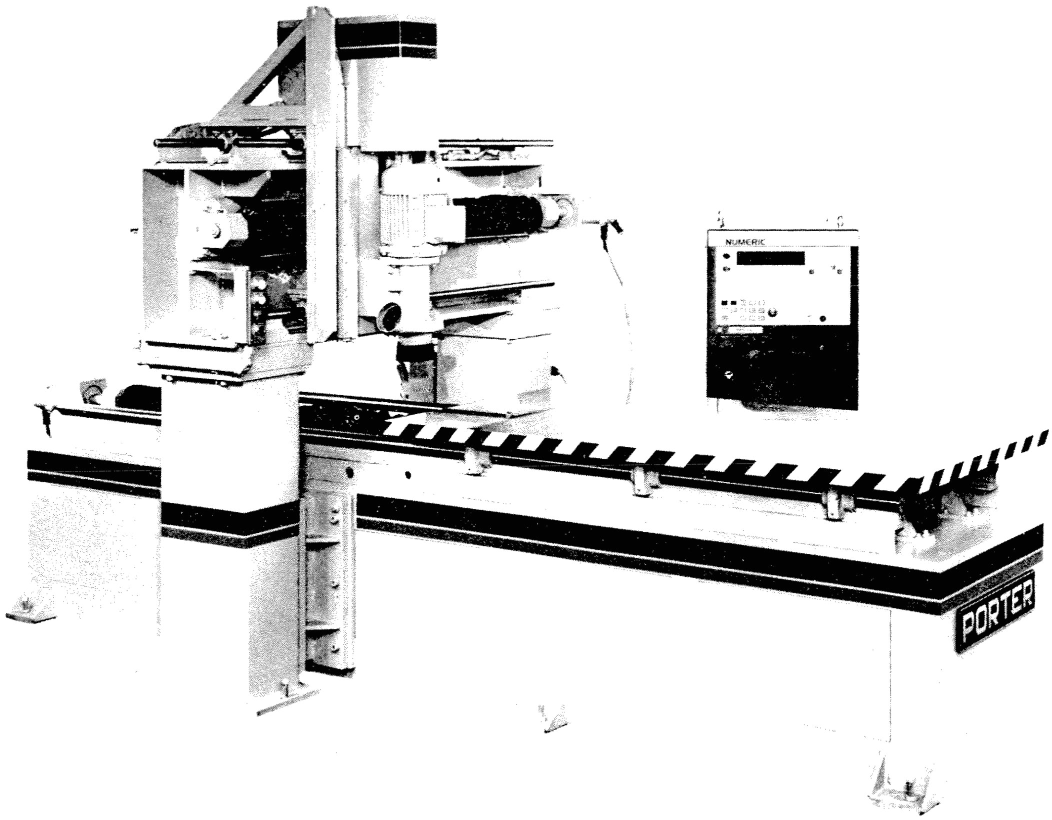

Figure 12.—*A 3-axis numerically controlled bridge type router with moving table and moving head. (Photo courtesy C. O. Porter Machinery Co.).*

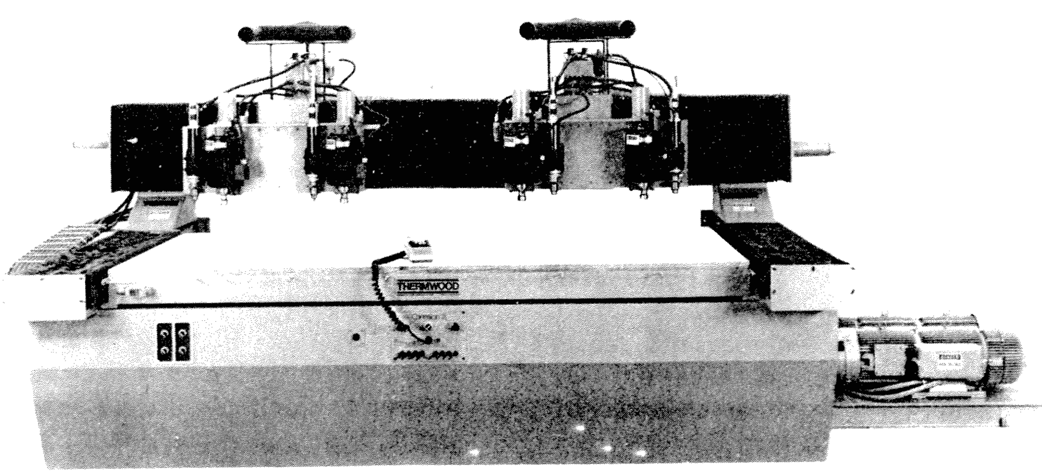

Figure 13.—*A bridge-type NC router with stationary table. A hand-held calculator type module (center of machine) is used to program machine operation. (Photo courtesy Thermwood Machinery Mfg. Co., Inc.).*

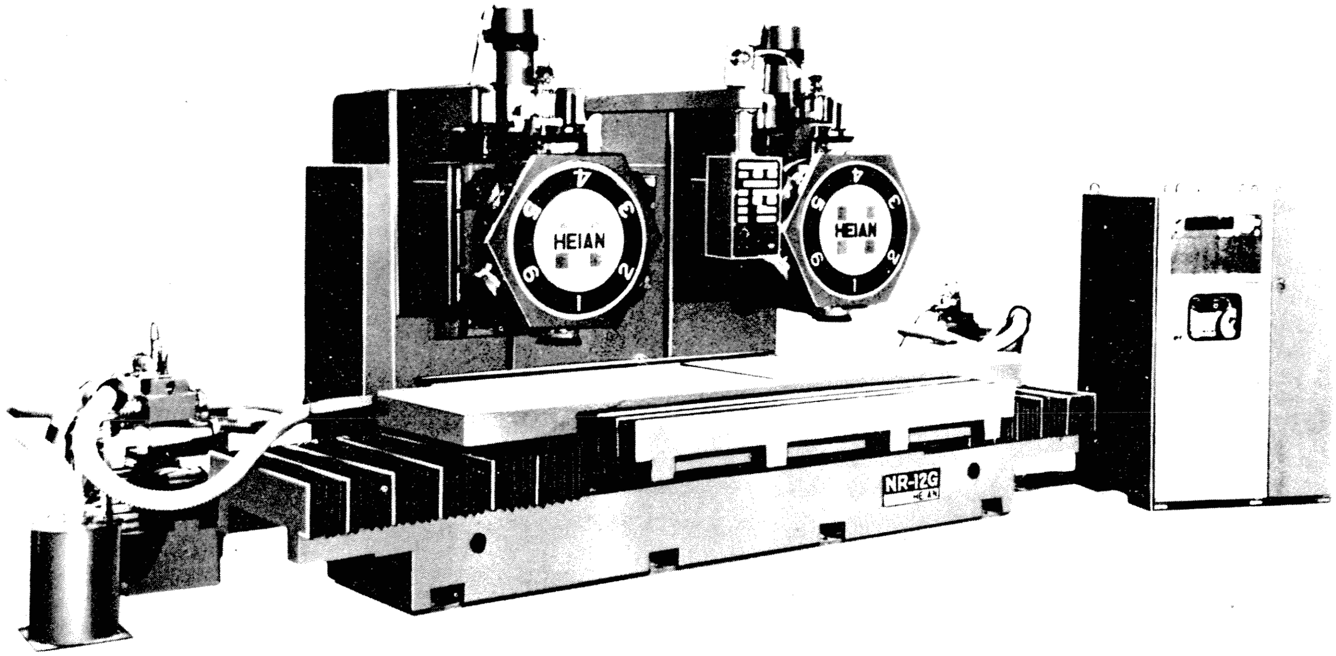

Figure 14.—*Heavy duty moving table router with 6 spindle turret head. (Photo courtesy Heian Iron Works, Ltd.).*

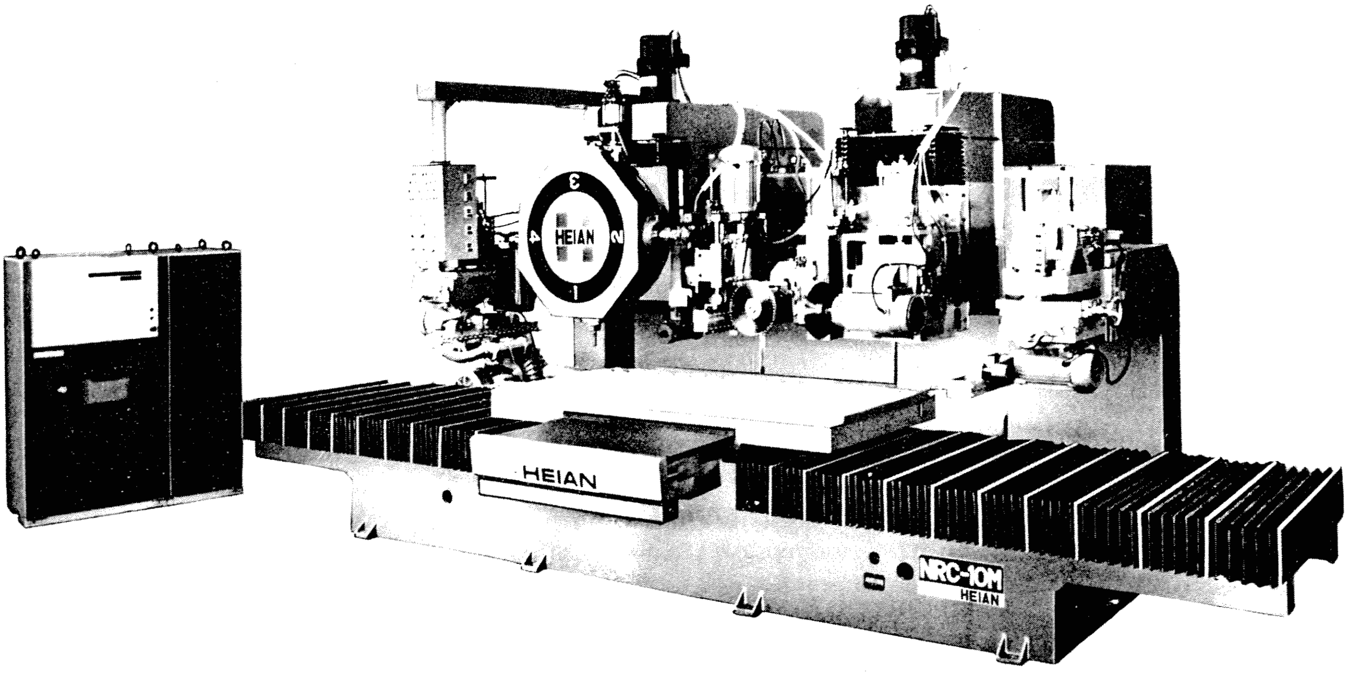

Figure 15.—*Complex moving table machining center replaces 6 separate woodworking machines. (Photo courtesy Heian Iron Works, Ltd.).*

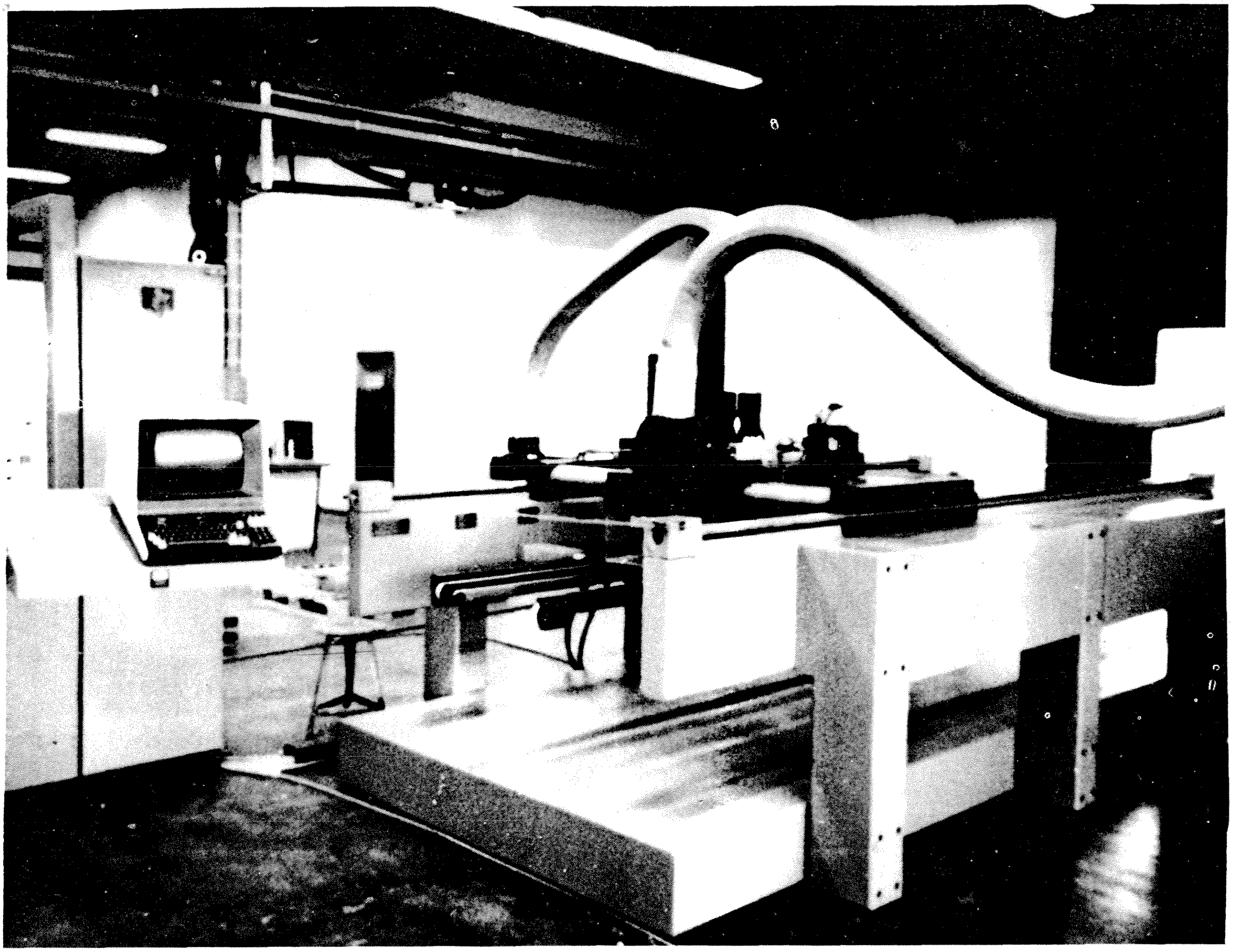

Figure 16.—*Computer numerically controlled machining center for boring, drilling and routing holes in furniture panels of varying size. (Photo courtesy INCOR INCORPORATED).*

consists of a pilot carriage for x-axis longitudinal motion, tool carrier for y-axis transverse motion, and tool holder. Both pilot carriage and tool carrier are independently powered by hydraulic motors. Positioning speed is variable from 0 to 500 mm/sec (0-20 in/sec) and with an accuracy of ± 0.1 mm (± 0.004 inch).

The pilot carriage is supported by eight pretensioned castors (four on each side) aligned radially to the longitudinal axis of the guideway. Power is transmitted to the guideway by a shaft within a protective tube connecting the two sections of the tool carriage. The tube also serves as a guideway for the tool carrier, which is moved by a rotating ball spindle shaft. Unidirectional movement of pilot carriage and tool carrier properly position the bits over the work.

The tool carrier (fig. 17) is equipped with eight gear-driven ball bearing spindles powered by a single hydraulic motor (spindle speeds are variable from 800 to 6,000 rpm). Each spindle operates independently, with tool stroke, return rate, and spindle speed determined for each cycle and workpiece position by data commands from the CNC unit. The spindles have quick-change collet chucks for rapid (less than 6 seconds) replacement of cutters.

An adjustable, hydraulically powered workpiece transport and clamping system is located in the center of the machine frame. The mechanism can accommodate panels 200 to 800 mm (7.9 to 31.5 inches) wide and 14-20 mm (0.55-0.79 in) thick. Clamping gibs along the length of the transport chain assure positive holddown during boring. Once the holes are bored, the stop is retracted and the work ejected by advancing the transport chain. All operations of the transport system are under computer control.

Carving

Carvings for furniture and other uses are conventionally produced in quantity on multiple-spindle carving machines. The process requires a skilled, highly paid, and increasingly difficult to obtain operator to move a blunt follower over the entire surface of a master pattern, thus causing a gang of motor-driven cutterheads to duplicate the contours of the master on multiple workpieces. A 4-axis computer controlled carving machine that duplicates the human skills needed for this craft is available (fig. 18). It is designed to carve either flat two dimensional (base relief or intaglio) objects or fully sculptured three dimensional structures.

A heavy base provides a rigid foundation for the workpiece table and upper bridge. A left to right horizontal table motion (x-axis) moves the workpiece incrementally at the completion of the front to rear table movement (y-axis). Traverse speed along the y-axis is variable from 0 to 2 meters/min (0 to 6.6 ft/min). Z-axis motion which is independent of the table, moves the upper bridge with attached cutterheads vertically. The z-axis position is determined by an electromechanical stylus (fig. 19) in contact with a master pattern that translates the contours in its path along the y-axis into movement along the z-axis. Z-axis displacement together with y-axis movement produces a two-dimensional profile the width of the cutter. A fourth axis (r-axis) rotates at the end of a y-axis movement and is used to carve round three-dimensional objects. All axes are driven by DC-servo motors.

When carving, the direction of y-axis motion is reversed according to geometry of the workpiece. There may be areas where y-axis movement is the exact length of the part and reversal occurs at the

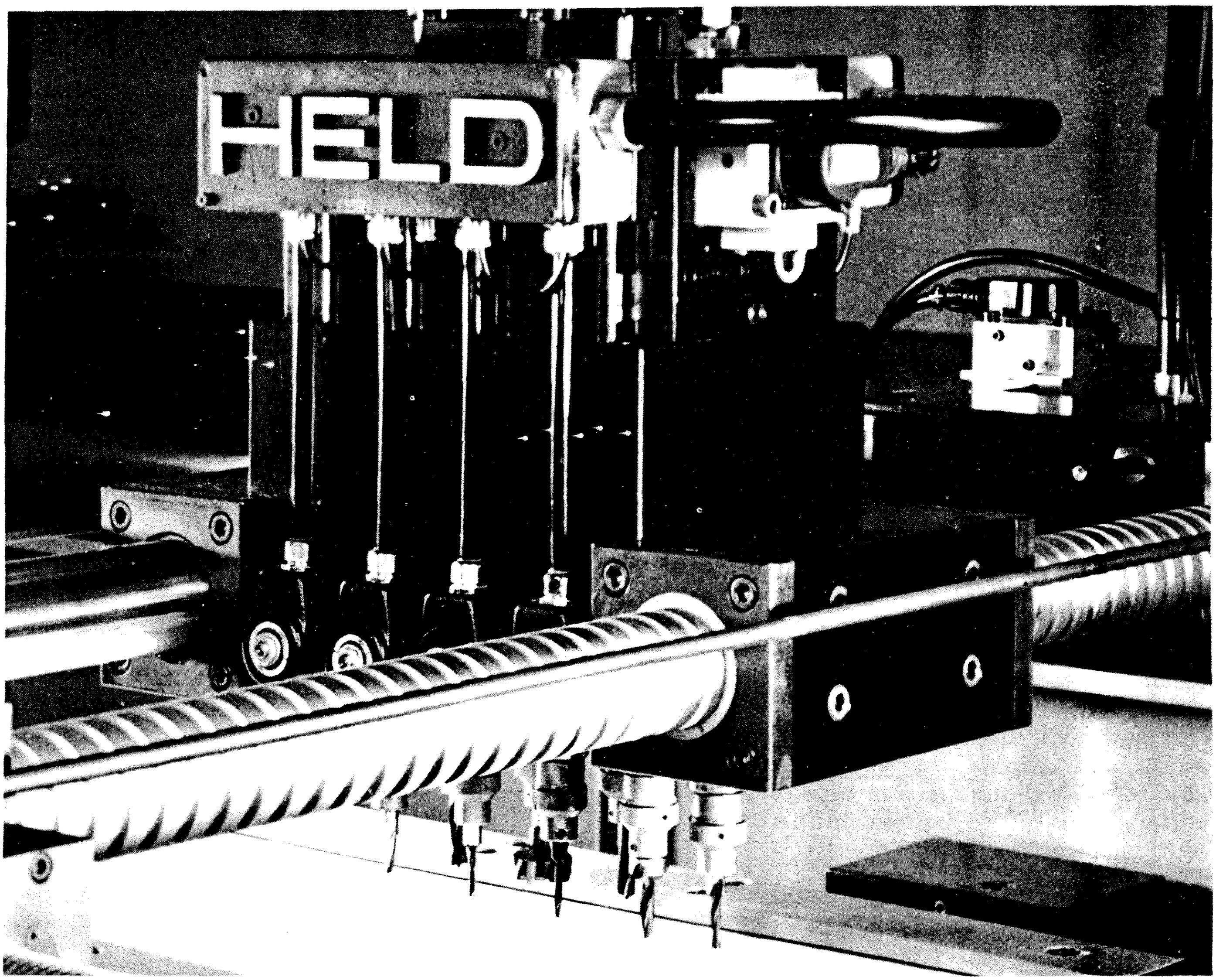

Figure 17.—*Multiple spindles can chuck a variety of cutting tools, each under computer control. (Photo courtesy INCOR INCORPORATED).*

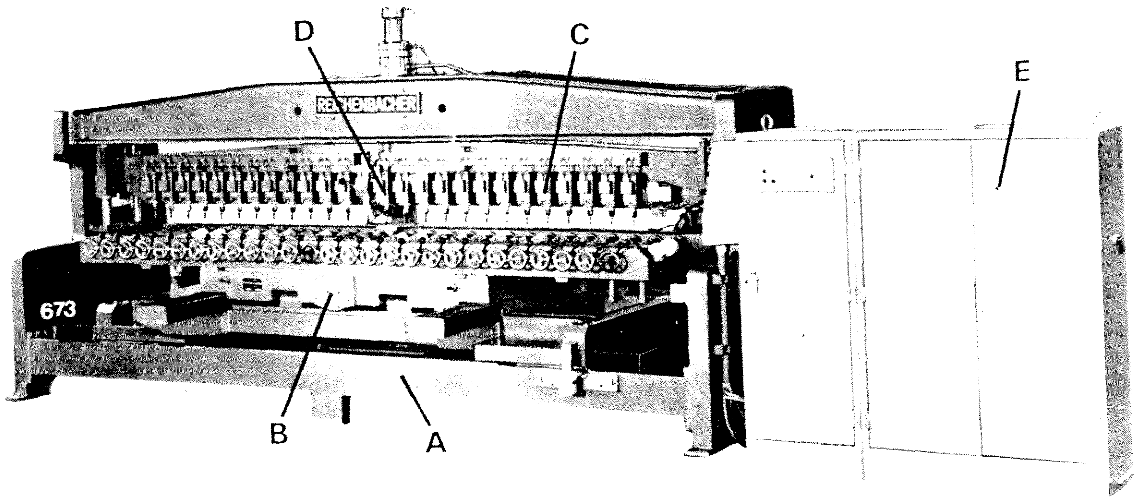

Figure 18.—*CNC carving machine produces up to 36 carvings simultaneously. A. Machine base. B. Feedbed. C. Cutterhead and motor drive. D. Tracer control. E. Controller and power supply for DC servo-drives. (Photo courtesy H. Reichenbacher GMBH).*

extreme ends. However, reversal may also take place in a small area for special operations or where no carving is required. Coordinates needed to designate up to 400 such areas are stored in a programmable controller. The controller also initiates incremental movement in either the x-axis or r-axis whenever y-axis motion changes direction and sets the feed speed in the y-axis. All data may be stored on magnetic tape for future use.

Fine detail can be obtained in a "pencil" mode whereby the machine operates as a servo-assisted hand carver. The operator grips the x-axis stylus and by maintaining contact with the model, causes the machine to move along a selected path.

A computer controlled, 4-axis attachment that converts existing multiple spindle carving machines to automatic operation is a recent development. Coordinate data are stored on magnetic tape by hand tracing the master pattern. When the data are subsequently output, the machines axes automatically position to reproduce the pattern. The operator need only load parts and change cutters; the control detects malfunctions, stops, and signals the operator. An editing capability permits mirror imaging (reverse carving), axis offsets (pattern shift), and repetitive pattern operation.

Laser Profiling

Numerically controlled laser profilers have recently been developed to cut intricate profiles and complex patterns in wood and veneer for furniture parts. Inlay and marquetry, for example, can be laser cut from stacks of mixed species veneers. Special machine compensation results in mating parts that fit together with zero tolerance. Cabinet door tracery can also be produced by lasers at less cost than any other method. Die cutting such parts leaves rough edges which require sanding and routers cannot produce the required corners. Computer controlled laser profilers are also extensively used to prepare steel-rule die blocks for cutting and/or creasing paper, gaskets, and cloth (fig. 20).

In these machines the conventional cutting tool is replaced by a coherent beam of radiation from a carbon dioxide laser. Focused to a small diameter spot (0.004 to 0.020-inch), the beam's power density at the focal point is sufficient to rapidly vaporize wood with little thermal distortion (fig. 21).

Laser profilers create no sawdust and cut with a small kerf (about 0.015-inch). No reaction forces are exerted on the work and hold-down systems are frequently not needed. Cut surfaces are smooth but moderately charred. The upper edge of the cut part may be somewhat darkened, but the natural color of the wood can be restored by bleaching or sanding. In many applications, the darkened edge is left as part of the finishing appearance. There is no tool wear in the conventional sense, and noise is minimal.

Custom designed to user specification, laser profiles vary greatly in degree of sophistication, operating characteristics, and cost. One such configuration is shown in figure 22. The large console to the right of the laser service console (fig. 22-G) contains the numerical control equipment (fig. 22-H). The workpiece table (fig. 22-C) is

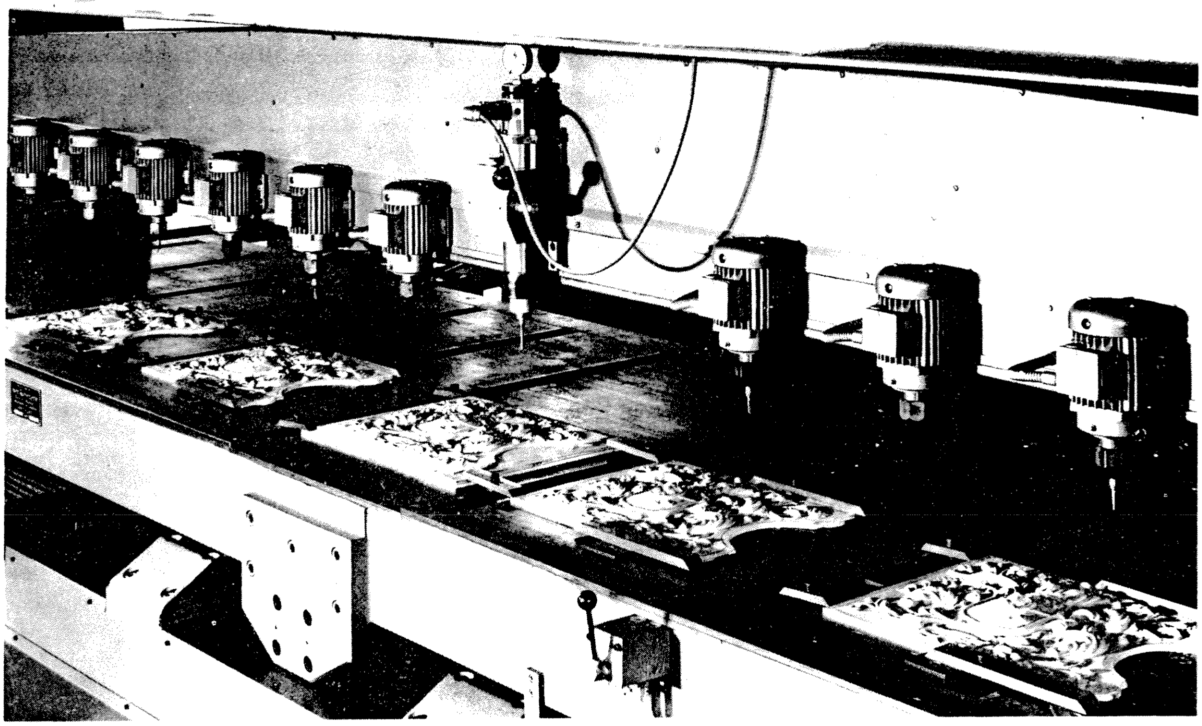

Figure 19.—*Tracer for servo-control of Z-axis contour is located in center of photograph over master pattern. Carving heads on either side are directly driven at 12,000 or 18,000 rpm by 1-hp motors. (Photo courtesy H. Reichenbacher GMBH).*

electrically driven in the x-y plane by orthogonally opposed lead screws (fig. 22-E) on precision ways. The workpiece (fig. 22-F) is supported by a series of square steel rods which also protect the undersurface from reflected laser radiation. Smoke and other by-products of the cutting process are vented through an exhaust system (fig. 22-D).

A single mirror deflects the beam from the optical resonator (fig. 22-A) downward through the focusing lense and gas-jet assembly (fig. 22-B) in the configuration of a router. Different cutting heads and focusing optics which yield different kerf width are attainable. A protective metal hood normally shields the cutting area from stray laser radiation.

The program tape is loaded into the reader at the front of the numerical control. Information is automatically read and translated into electrical signals which drive the table in the x-y plane along the preprogrammed path to cut the desired part. All cutting operations are controlled directly from the tape including attenuation of the laser for those times when no cutting is required. With some laser profilers, the workpiece is held stationary and the laser moved in the x-y plane; in others, both the table and the laser move unidirectionally.

Most profilers operating in the United States are equipped with lasers of 250-500 watts output power. Energy costs amount to about $1.00 per hour of operating time including gases consumed by the laser. Cutting speeds vary from a few inches per minute to as high as 14 feet per minute, depending on laser output power, the type and thickness of material being cut, and other factors.

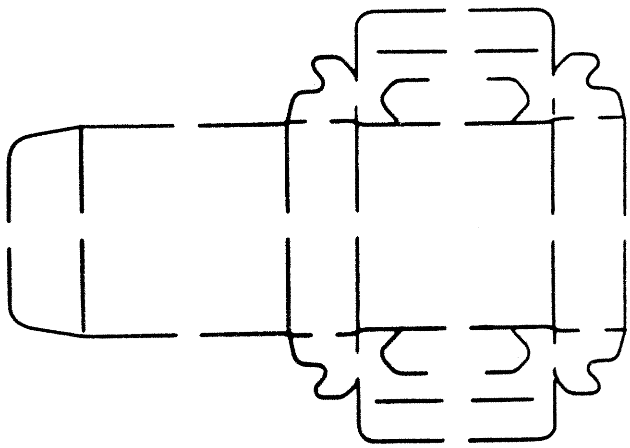

Figure 20.—*Pattern of laser-cut kerf slots in steel-rule die block of 3/4-inch birch plywood. With steel rules inserted in the kerf slots, the die is used to cut and crease stock for a cardboard box. (Photo courtesy British Oxygen Co.).*

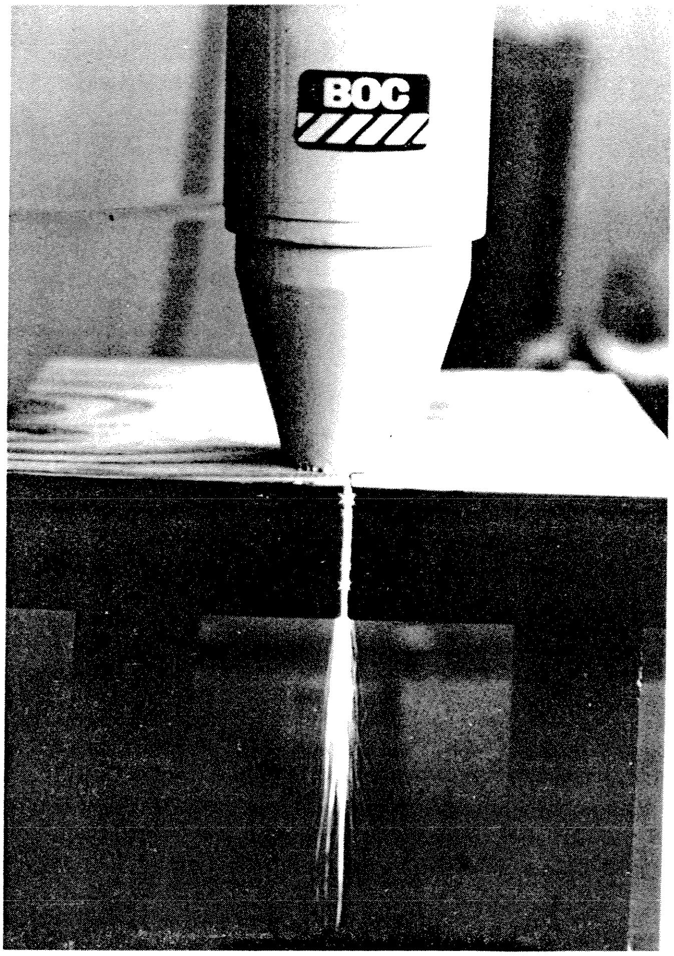

Figure 21.—*Cross-cutting a one-inch thick southern pine board with a 200 watt laser. A coaxial jet of compressed air within the cutting head removes vapors and debris from the cut region. (Photo courtesy British Oxygen Co.).*

Panel Sizing

Panel sizing machines are used to produce variable-sized panels for furniture and cabinet components from plywood, particleboard or fiberboard sheets in a single pass. Such machines are most frequently used in operations that cut more than 20,000 square feet of full sheets per day into a wide range of sizes and where cutting patterns change more than five to 10 times a shift. Computer control permits storage and recall of pattern information, cutting dimensions and machine logic functions, thus substantially reducing setup time. Typically, conventional equipment requires 30 to 50 percent of production time to setup; numerically controlled machines require less than 5 percent.

Figure 23 shows one type of computer controlled panel sizing machine. A schematic drawing of the major machine components and the material flow pattern is given in figure 24. In this machine, full size stacked panels (4 × 8 ft. to 5 × 16 ft.) are brought to the infeed rolls (fig. 24-A) by fork truck. Each panel is vacuum lifted and loaded into an accumulator area (fig. 24-B) to build a book of material up to three inches thick. The book is then squared, advanced, and positioned for a traveling rip saw to cut all boards lengthwise (fig. 23-B and fig. 24-C). The lengthwise rip operation may be repeated several times to produce stacks of panels of varying width.

The cut strip (fig. 24-D) then advances on an infeed chain (fig. 23-A), passing through up to nine numerically controlled crosscut saws (fig. 23-C and fig. 24-E). All saws may be rapidly positioned on a crossbeam to yield panels of varying dimension. The cutting pattern may be repeated on the next strip or it may be changed. Some examples of possible cutting patterns are shown in figure 24-F.

Parts are then conveyed from the crosscut saws and routed to appropriate conveyors for automatic stacking.

Injection Bonding

Figure 25 illustrates a machine designed to join the four sides and back panel of a cabinet by using molten polyamide plastic instead of conventional dowels and glue. In this relatively new process, the five panels are firmly held in the proper position while plastic is injected under high pressure into pre-cut hollow corner joints. The molten plastic fills the cavities, penetrating the porous wood surface and setting rapidly to form a strong joint. The production cycle time, from introduction of parts to finished cabinet, is about 45 seconds as compared to several minutes using the conventional method.

Corner units, which move along a serrated tie-rod system, form a variable dimension jig for clamping cabinet panels of any size. Hydraulic motors attached to the tie-rods are used between set-ups to rapidly vary the dimension between corner units in three planes as follows:

Horizontal length	200-2200 mm (8-87 inches)
Horizontal width	325-750 mm (13-30 inches)
Vertical height	290-1200mm (11-47 inches)

Movement occurs simultaneously in each axis at a rate of 2 inches per second.

The four corner units contain suction pads which are used during clamping to accurately hold parts in line with corner guides and stops. Each of four leadscrew injection heads meter plastic granules to melting tubes. The molten material is then extruded through an orifice into the panel corner joint, with each injection unit supplying a quantity of plastic proportional to the length of the joint. Once the molten plastic has set, clamping forces are released, stops are retraced, and a chain operated removal

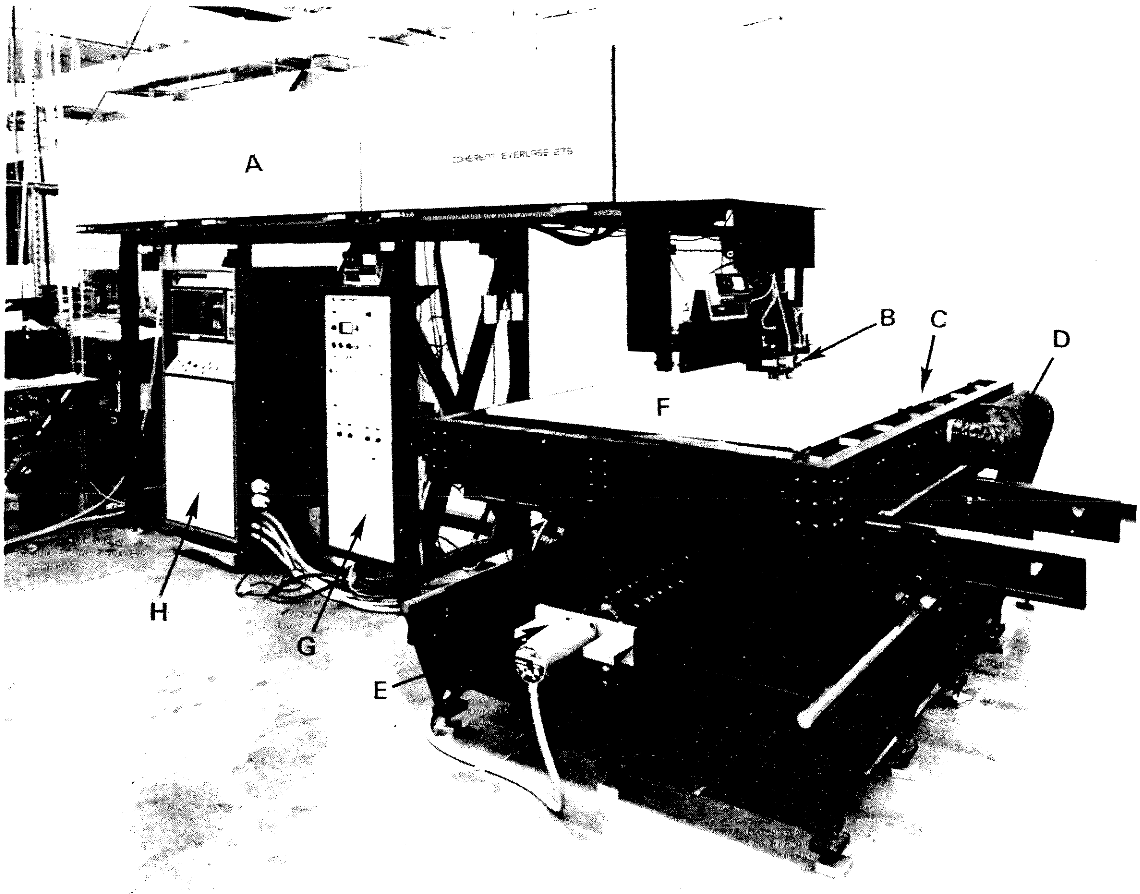

Figure 22.—*Laser profiler cuts steel rule dies and furniture parts. A. Laser resonator. B. Optics and gas jet. C. Workpiece table. D. Exhaust duct. E. Servo-motor and drive screw. F. Workpiece. G. Laser control panel. H. Computer numerical control. (Photo courtesy Coherent, Laser Division).*

system withdraws the assembled cabinet from the jig work area onto a conveyor.

A control unit and operator's console contain electronic equipment to automatically initiate operational sequences and dimension distances between corner units. Jig dimensions cannot be operator programmed in this machine. Rather, the controller uses a hardwired program specified by the user. Special keys on the operator's console are used to select combinations of standard dimensions. The program normally provides for 20 different dimensions in horizontal length, 12 in horizontal width, and six in vertical height. The program can be subsequently modified to accept other dimensional set-ups.

Upholstery Cutting

Upholstery fabric for furniture accounts for 25 to 35 percent of the manufacturer's selling price. Computer controlled fabric cutters achieve substantial material savings through efficient placement of patterns on the fabric lay and the use of common edge cuts. Two systems using different cutting tools are in current use.

Impingement jet type cutters use a high velocity, narrow diameter jet of water to sever the fabric. Such jets require an especially designed fluid intensifier that generates continuous water pressures of about 50,000 psig. A typical unit (fig. 26), consists of a reversible-flow low pressure hydraulic pump coupled to a double-acting piston and cylinder. Two smaller diameter high pressure plungers are axially attached to the low pressure piston to generate the working water pressure in the small cylinder. A high pressure accumlator located between the intensifier and the jet minimizes pressure fluctuations during piston reversal. The jet consumes about 60 gallons of water per operating hour. Because layers of fabric are usually stacked for cutting, it is essential that the jet remain coherent over distances up to five inches. While addition of low molecular weight polymers to the jet have proven useful, chemicals may stain fabrics and nozzle design is critical. Typically, nozzles are made from synthetic sapphire mounted in brass.

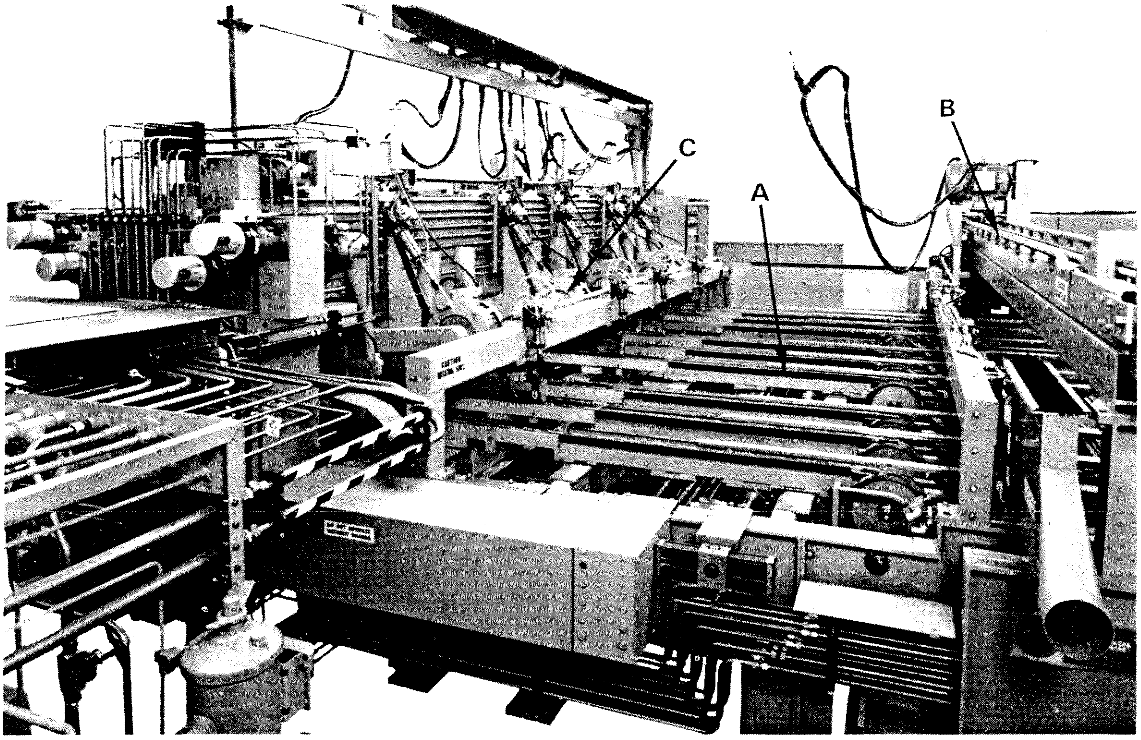

Figure 23.—*Numerically controlled chain feed cut-to-size machine showing (right to left) traveling rip saw, infeed chain beam assemblies and numerically controlled hydraulically adjustable cross cut saws. (Photo courtesy Mereen-Johnson Machine Company).*

Orifice diameters range from 50 to 350 μm and have a conical entry point to a cylindrical throat.The operating life of such nozzles ranges from 250 to 500 hours.

While water jet cutters can be controlled through a variety of input methods, a typical system consists of a minicomputer, pattern digitizer, operator's terminal/printer, and graphics display console.

Irregularly shaped parts are described to the computer using a large digitizing table. It is only necessary to trace half if parts are symmetrical, as software programs can automatically create the remaining portion of the outline. For square or rectangular pieces, dimensional data can be input at the operator's console without digitizing the outline. Other operational parameters, such as starting point position and jet activation sequencing, are programmed with special keys or commands.

Patterns are next displayed on a graphics terminal, (fig. 27), where the operator can rotate, move and position parts to obtain common cutting edges. Error trapping software prevents overlapping. The operator can also alter dimensions or retrieve standard patterns from an inventory of stored pattern data.

Digitized data are stored on magnetic disks which can contain pattern information for as many as 1,000 different upholstered units. Using ancillary software programs, the operator can retrieve such information as lineal inches of pattern cut or lineal yards of fabric needed. Costs can thus be evaluated while initial patterns are being cut.

Figure 28 shows a water jet pattern cutting machine. Operator controls are positioned at the front of the machine; the computer and terminal/printer are located to the right. Uncut fabric is stored on large rolls to the rear of the machine. On command, material is fed from the rolls onto a fabric cutting bed located in the center of the machine. The jet nozzle is attached to a crossbeam with flexible high pressure hose and moves along the beam; the crossbeam moves in a direction perpendicular to that of the jet. Extending the width of the machine and parallel to the crossbeam is a trough embedded between rollers in a fabric bed. It follows the movement of the crossbeam and collects water ejected from the underside of the fabric lay.

When activated by the operator, the jet is positioned at the starting point and energized. The crossbeam and jet then move unidirectionally in the x-y plane under computer control to yield the preprogrammed patterns. Cutting speed is computer controlled and varies, depending on the material being processed. Cutting forces are directed downward, so there is little fabric slippage

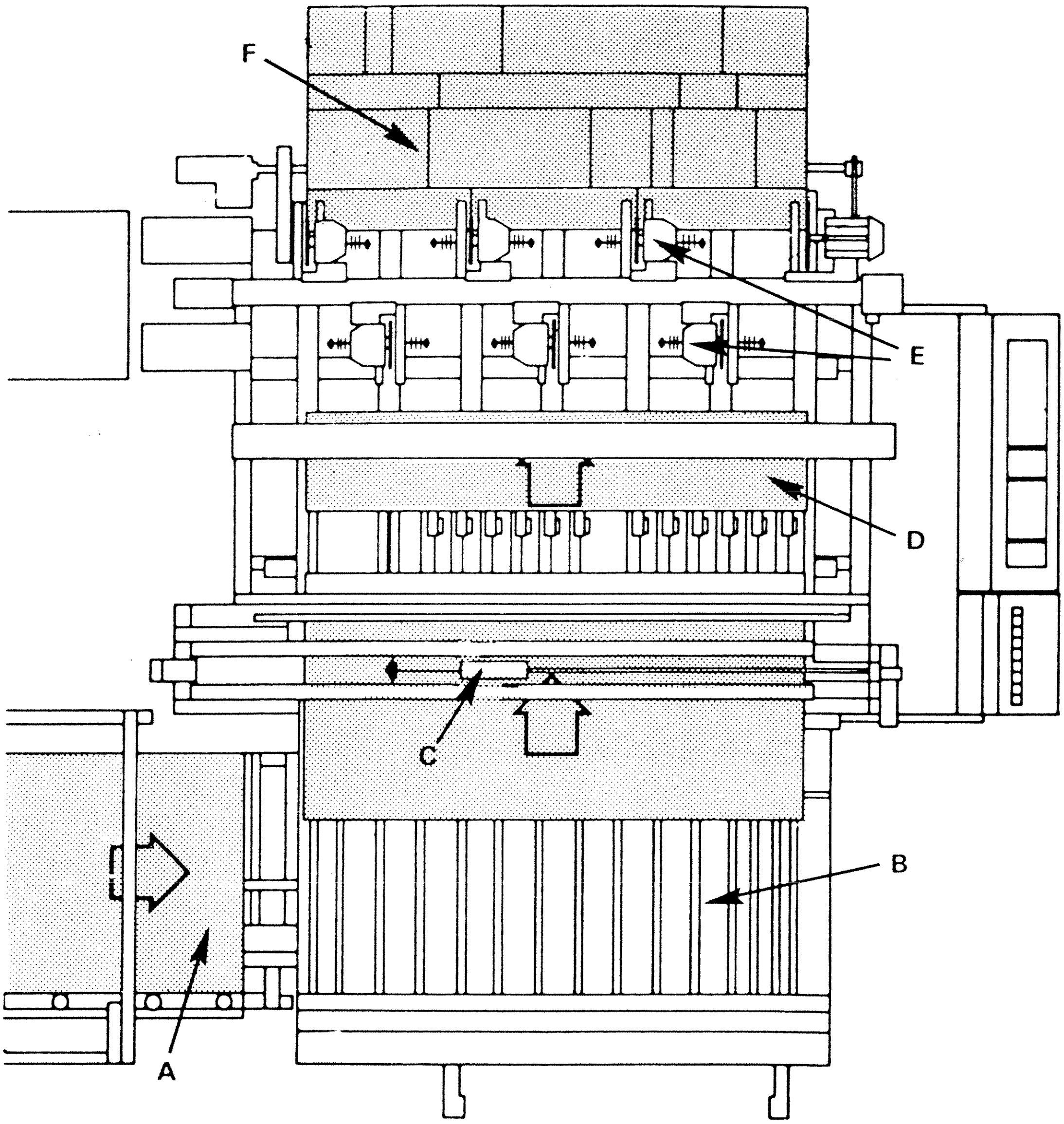

Figure 24.—*Schematic drawing of a panel sizing machine. A. Panel material and infeed rolls. B. Accumulator area. C. Traveling rip saw assembly. D. Panel material after ripping. E. Numerically controlled cross-cut saw assemblies. F. Ripped and cross-cut panel parts. (Drawing courtesy Mereen-Johnson Machine Company).*

and dimensional accuracy is maintained. Because the jet is of small diameter, very sharp or curved corners can be generated with equal ease.

While primarily designed to cut apparel fabrics, water jets can also cut other types of materials, such as paperboard, veneer, and medium density fiberboard. It seems likely that they will find use in the furniture industry for certain types of specialty cuts.

The second type of upholstery cutter employs a reciprocating knife to cut the fabric (fig. 29). The blade has a tungsten carbide tip while the shank and edge are of high speed steel. Such blades, which cost about $150, can be sharpened about 35 times before discarding.

As with water jets, full scale pattern outlines are digitized on a large graphics table via a cross-hair cursor. Special keys on the cursor provide for ancillary instructions, such as start-stop, speed up, slow down, etc. The resulting data and instructions are then encoded on punched tape or magnetic disks which drive the cutter control.

Figure 30 shows a cutting machine with a lay of partially cut fabric. The layup table measures 60 feet long by 72 inches wide and contains hinged sections of closely packed plastic bristles fused in a rubber base to create a continuous conveyor. The bristles form a rigid surface to support the fabric and permit the knife to penetrate about 3/8-inch through the lay. A vacuum applied through the

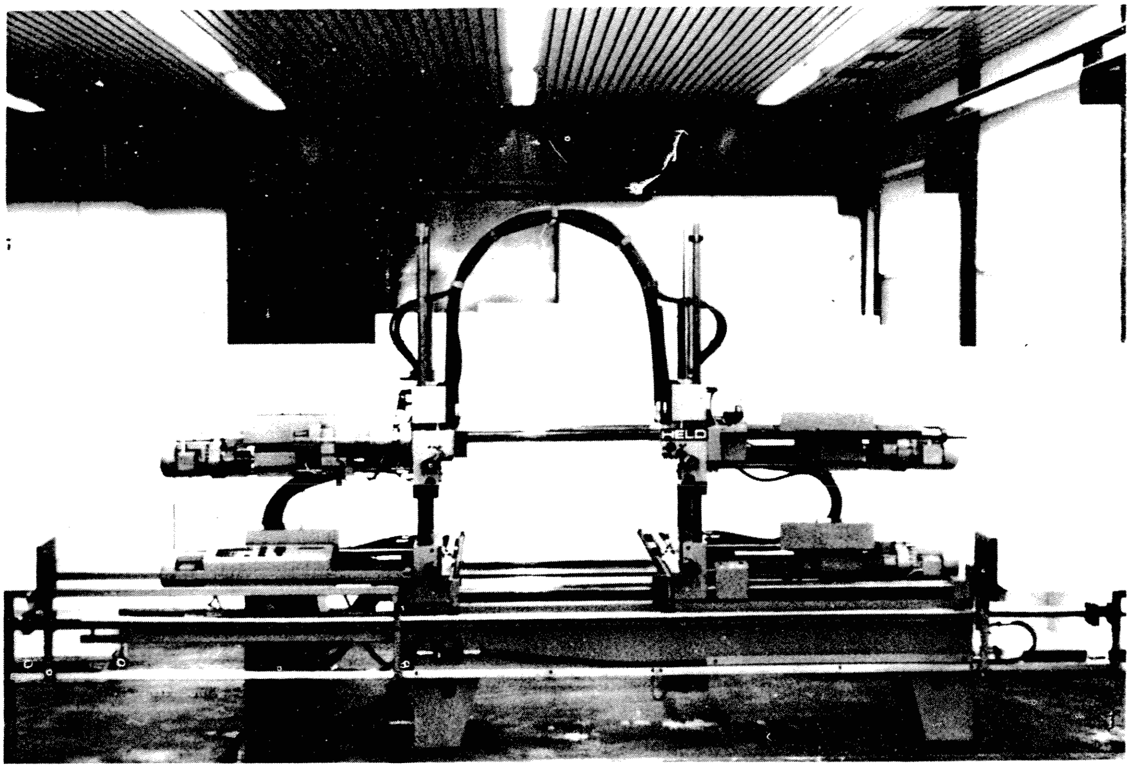

Figure 25.—*Injection bonding machine automatically produces 5-sided cabinets of varying dimensions using a plastic joint. (Photo courtesy INCOR INCORPORATED).*

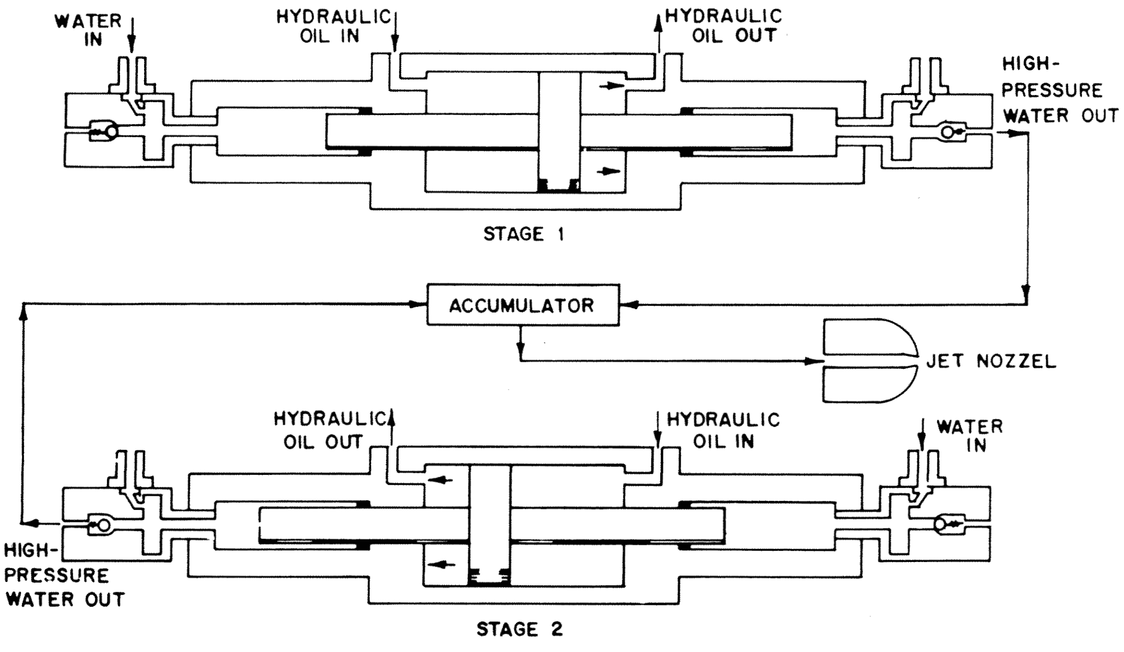

Figure 26.—*Typical design of a two-stage hydraulic intensifier used in water jet cutting.*

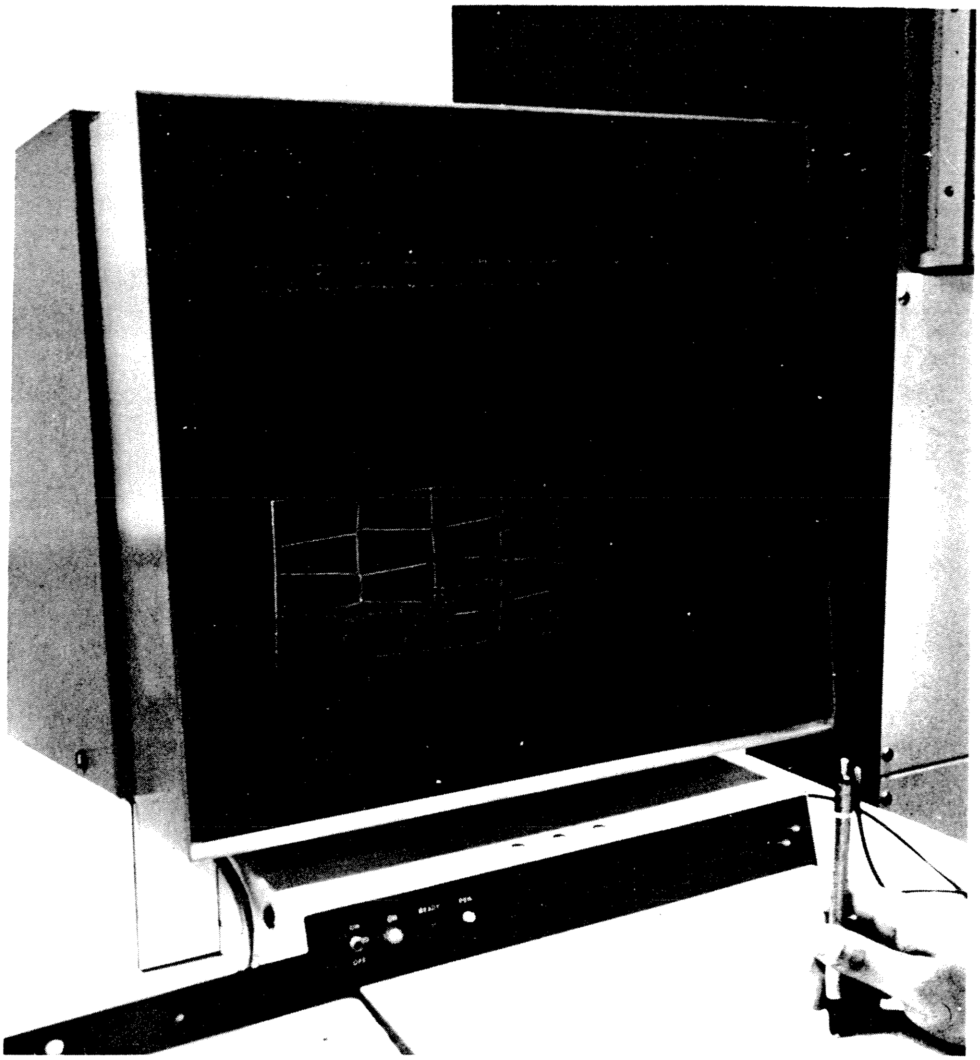

Figure 27.—*Pattern pieces are displayed on a graphics terminal where they are computer positioned for optimum materials utilization. (Photo courtesy CAMSCO).*

bristles compresses and holds the fabric in place. Special suction gates in the area of the cut apply an additional holding pressure. To attain full holding efficiency, a disposable one-mil polyethylene sheet is sometimes placed over the fabric lay.

The reciprocating knife and special devices for hole drilling and notching are affixed to a crossarm extending the width of the layup bed (center structure in fig. 30). The cutting assembly is computer driven across the beam while the beam itself traverses the length of the table.

Fabrics are conveyed to the cutting table from large storage rolls to the left of the cutter. The lay may be of mixed fabric types up to 4-1/4-inches thick. Cutting occurs on command in a sequence of operations. First, holes are drilled for button tufting. The cutting head assembly then returns to the starting point and cutting is performed as preprogrammed. At assigned positions, a notching fixture automatically descends and cuts through the lay. For sharp corners, the knife is programmed to lift out of the lay, turn to a new direction, re-enter the lay and continue cutting. After all patterns have been cut, the bristle bed conveyor is again activated to remove pattern pieces and waste, while simultaneously feeding a new lay for cutting.

Foam Contour Cutting

A numerically controlled contour cutting machine used to shape flexible polyurethane foam components for furniture padding is shown in figure 31. The machine cuts with a narrow diameter endless wire driven by four pulleys at a velocity of 90 m/sec (295 ft/sec). The pulleys, located within the top and bottom of the upright columns, tension the wire which does not require guides over its working width. The work table and vacuum chuck move on ways to provide x-axis displacement, while the wire and pulleys move up and down for y-axis control. Cutting speeds of 1 to 5 m/sec (3.3 to 16.4 ft/sec) can be achieved depending on material and shape.

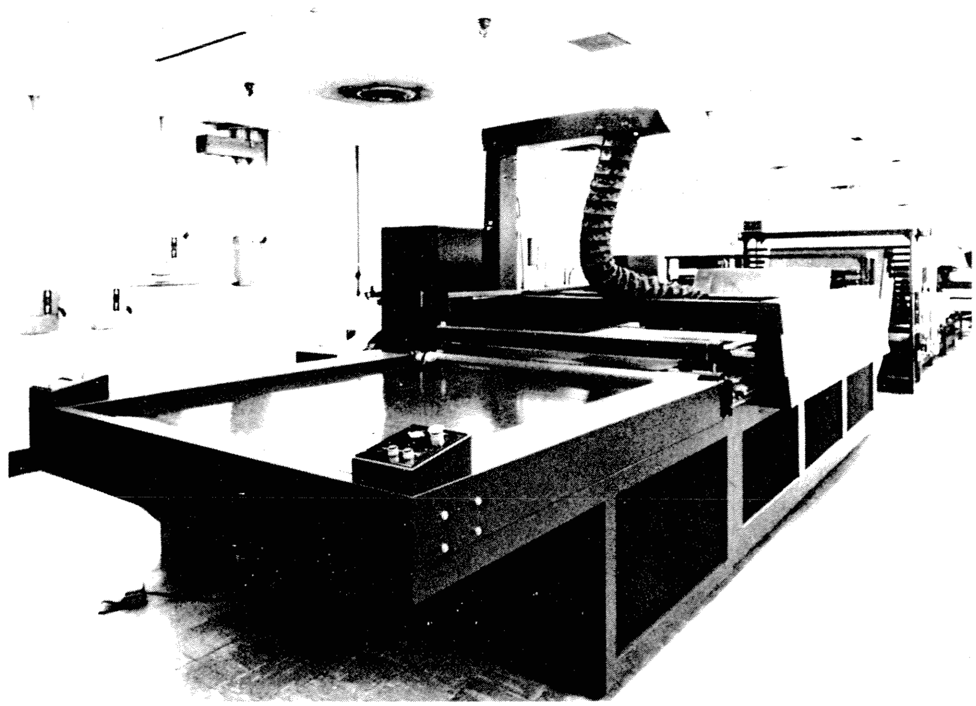

Figure 28.—*A computer controlled water jet fabric cutting machine. The cutting bed is located in the center area with fabric feed rolls at rear. (Photo courtesy CAMSCO).*

The operating system is equipped with a digitizer for producing part programs on magnetic tape. The digitizer accepts components up to 840 mm square (33.1 inches square) at a magnification ratio of 1 : 1; larger components can be digitized at a ratio 1 : 2.5. The system automatically compensates for magnification to yield parts of the correct size.

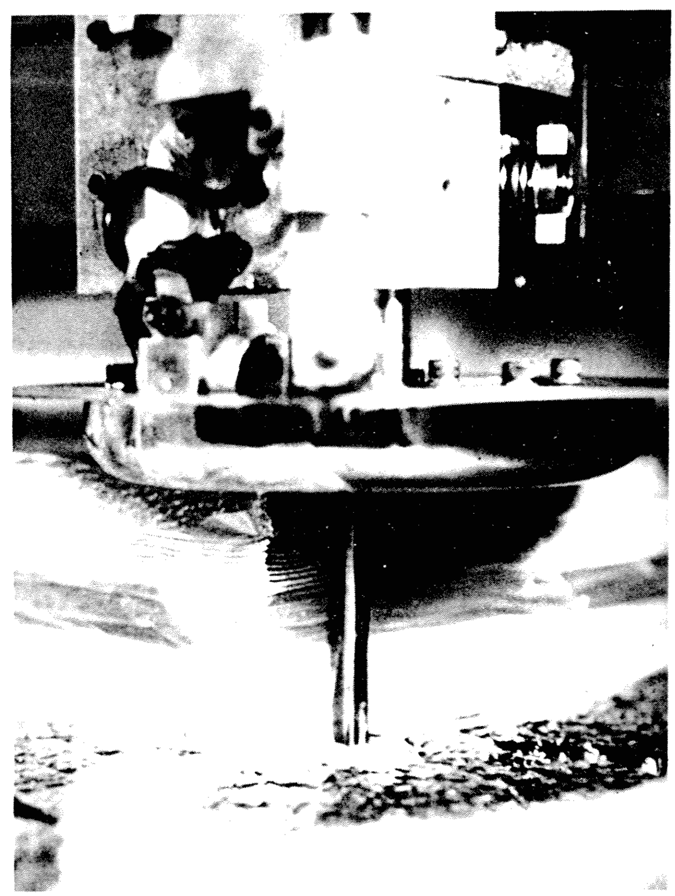

Figure 29.—*Cutting knife is mounted in an electro-mechanical reciprocating holder and guided through fabric by computer control. (Photo courtesy Gerber Garment Technology).*

DISCUSSION

Tasks performed by computers are complex and varied. They serve as automated economists, accountants, and consultants by storing, retrieving, and processing staggering amounts of information. They can recognize and synthesize human speech, provide malfunction diagnostics, and undertake automatic repair. Computer perception by visual, tactile, audible, thermal, and chemical means is rapidly expanding. The concept of computer-aided-manufacturing (CAM) is a major innovation. Such computer systems facilitate the design, production, and inspection of products in a single automated process.

When producing parts for furniture in the conventional way, hardwood logs are first sawn into different lumber grades with defects randomly located throughout the board. The defective lumber is then remanufactured into smaller parts and the defects removed by ripping and cross cutting. The process is labor intensive, and saw kerf losses alone waste substantial volumes of valuable lumber.

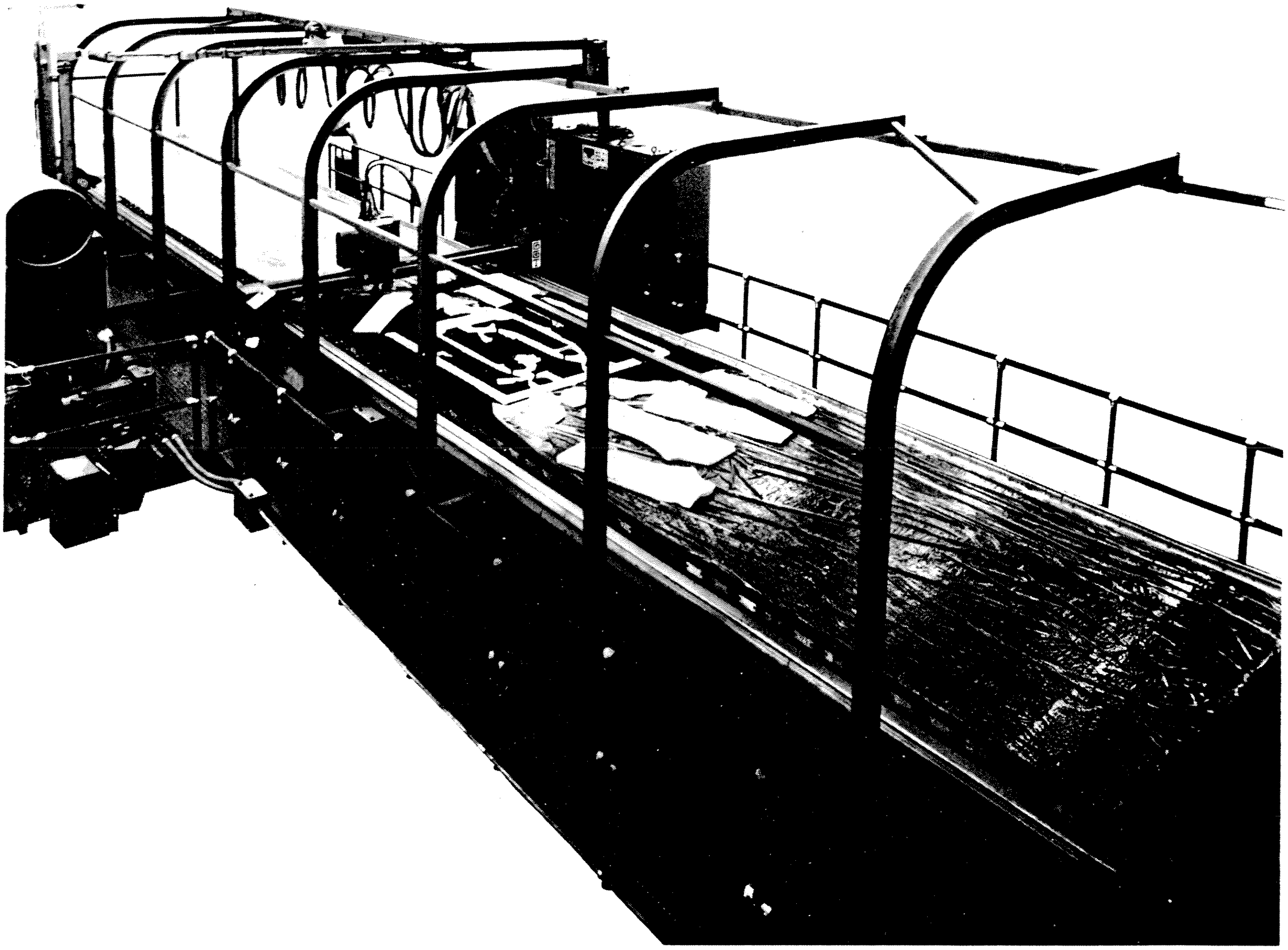

Figure 30.—*Computer controlled reciprocating knife type fabric cutter showing a lay of material with pattern pieces and residue displayed. (Photo courtesy Gerber Garment Technology).*

Consider now an automated lumber processing system (ALPS) producing the same parts. Hardwood logs enter the process stream and are scanned by computerized axial tomography (CAT) to nondestructively locate internal knots and establish log geometry. Figure 32 shows a tomograph of the interior of a southern pine log; no crosscut was made. Clearly visible in the tomograph is a knot located at the lower left periphery and two areas of annual ring deviation near knots. A series of such tomographs results in a three-dimensional image of the entire log.

Using information developed by the log defect detection algorithm, a second computer program determines the log positions needed to maximize grade or value yield. The program automatically positions and turns the log as needed, activates the log dogs and carriage stroke, and sets feed speeds. Many boards, however, will still contain defects (i.e., knots, wane, stain, worm holes, checks), which must be removed.

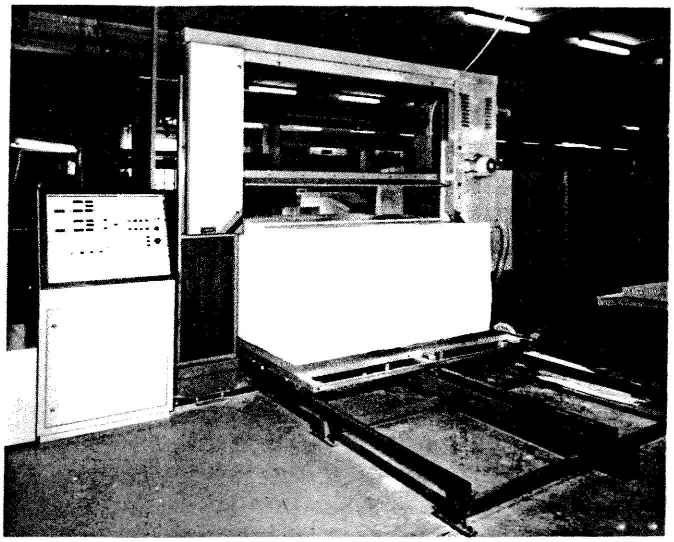

Figure 31.—*Polyurethane foam is cut for furniture padding with an endless wire. (Photo courtesy Baumer of American Inc.).*

Figure 32.—*Tomograph of the interior of a log. In the contemplated process, no visual image would be needed as defect data for successive slices along the log axis would be stored and manipulated in numerical arrays by the computer.*

After drying and light surfacing, defective boards are scanned on both surfaces by optical image analysis methods. Complex textural and pattern recognition programs permit the computer to identify defects and provide coordinate data on their location; the data, specific to each board, is stored in numerical arrays. The envisioned system uses the image-derived defect data to compute an optimum cutting pattern for each board, thus yielding the maximum number of parts based on a given furniture cutting bill.

Parts are cut from the board using a numerically controlled high-power laser directed by the computer derived optimum cutting pattern. Advantages of laser cutting are numerous. Most important to this process is the small kerf (approximately 0.015-inch) and the ability to start and stop cutting at any location.

Lastly, parts are optically scanned for quality and sorted by size by a computer controlled manipulator. Residue material is chipped and used as fuel.

Tomography and optical scanning techniques are emerging as practical industrial inspection methods but new approaches need to be developed and tested for a material as variable as wood. Computer programs for determining optimum yield of specified size pieces from variable size boards having randomly located defects have been written and used for yield data. These programs need to be modified and rewritten specifically for this process so as to give guidance to numerically controlled cutting equipment. High power lasers that cut one-inch thick wood in excess of 50 feet per minute are already available, but the equipment must be creatively coupled to the system.

While additional research and development is clearly indicated, the key elements seem available for integration into the proposed system. Such an automated mill is a radical departure from current practice, but the future competitive nature of the wood furniture industry may depend on innovations such as this.

McMillin, C.W. Computer numerical control of woodworking machines in secondary manufacture. Gen. Tech. Rep. SO-42. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station; 1983. 24 p.

The function and operation of computer numerical controllers is summarized and a number of computer controlled machines used in secondary manufacture are described and illustrated.

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