

ANALYSIS AND DESIGN OF A SIMULATED  
NUMERICALLY CONTROLLED MACHINE TOOL

by

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## INTRODUCTION

Numerical control of machine tools is simply the control of machine tools by numbers. It is essentially an efficient means of reading blueprints and translating the data into a series of machine positions. Numerical control is often described as a form of flexible automation. For the first time, true three dimensional metallic mathematical shapes can be obtained by applying numerical control. The concept has also been employed in petroleum and chemical processing, preparation of food, and for non metal-removal operations like panel wiring, type setting and telephone call routing (20). Numerical control is likely to be used in many items of equipment now controlled by an operator.

Though there are wide differences among the various numerical control systems, they all have the same basic elements. The parts programmer first fills out the programming process sheet with the specifications from the engineering drawing. These numerical data are punched on a tape and fed into the system. The tape is then read by a translating unit and the data converted to a suitable electrical form that the machine tool can use. The data are stored in a memory system until they are required. The data are converted into machine movements by servo units. In closed loop systems, information is fed back from a measuring device to compare response with command so that the machine tool may be stopped or corrected when necessary. Punched cards can be used instead of punched or magnetic tape.

Numerical control systems can be classified into two types (?):

1. Point-to-point or positioning.
2. Continuous path or contouring.

In the simpler point-to-point system, the cutting tool is controlled only with respect to its final position. It is used for operations like simple boring or drilling that require positioning in just one plane. The punched tape is directly put on the machine control unit. In some systems, the operator merely turns dials to control the machine tool. A computer is not necessary for this type of numerical control.

In the continuous path system, the entire path of the tool must be continuously controlled, as in milling or turning. This type of numerical control is used for machining objects like dies, cams and gears. For continuous path programming, a computer is necessary to prepare instructions for the machine tool control unit. The computer calculates the coordinates of sufficient points on the desired path to the required accuracy. Even for simple contours, manual calculation of the path of the tool would consume a great deal of time. In addition, the synchronization of the instructions fixing the coordinates of each point is done by the computed instructions as well as the control unit.

Numerical control equipment can also be classified as:

1. Two-axis controls, used for two-dimensional machining.
2. Three-and-more-axis controls, used for three-dimensional machining.

The information conveyed by the tape is converted into either analog or digital signals which transmit the information (7). An analog signal is continuous and analogous to the variable it controls. An analog quantity is always an approximation. A digital signal consists of discrete pulses. Digital systems are costlier and more complicated than analog systems.

The Massachusetts Institute of Technology demonstrated for the first time, in 1952, a three-axis, manually programmed, numerically controlled machine tool (3). In 1954, MIT used a computer and successfully applied the

technique of automatic programming. This prototype forms the basis of many present day numerical control programming systems. The APT (Automatic Programming of Tools) program, developed by the Aircraft Industries Association, was commercially available in 1959. Some of the automatic programming systems in use today are AUTOPROMT (Automatic Programming of Machine Tools), AUTOSPOT (Automatic System for Positioning Tools), AUTOPROPS (Automatic Programming for Positioning Systems), AUTOMAP (Automatic Machining Program), SPLIT (Sundstrand Processing Language Internally Translated), and SNAP (Simplified Numerical Automatic Programmer). Today, more than two thousand numerically controlled machine tools are in operation.

The important advantages of numerical control are:

1. Numerical control brings about considerable savings in setup, machine, lead, inspection and finishing times.
2. The increased accuracy results in improved quality.
3. Numerical control requires less tooling and cost of tooling is decreased. Tool storage space will be smaller.
4. With numerical control, repeatability is accurate.
5. Numerical control results in less inventory and less floor space to stock it.
6. Scrap is virtually eliminated.
7. Human mistakes are avoided since machining operations are fully automatic.
8. There is an increase in machine tool utilization.
9. Process preparation can be done away from the manufacturing area.
10. The machine tool, not the operator, sets the production pace.

11. Numerical control instructions do not deteriorate with use, can be easily modified, are conveniently stored, and can be shipped anywhere with speed and economy.

12. Numerical control has versatility in production setup. It has the advantages of automation, without the disadvantages of its mass production inflexibility.

13. With the aid of numerical control, new business opportunities can be found in previously uneconomical work.

Numerical control is by no means a "cure-all" for manufacturing problems. Fixed program automatic machines are better suited for mass production. For some operations, conventional machining may be more economical than numerical control. Highly skilled personnel may be necessary for the maintenance of numerical control equipment. There is a probability of serious problems being caused by tool breakage.

#### OBJECTIVE

In a little more than a decade, numerical control has made startling advances and has found wide application in industry. It has become almost essential for manufacturing engineers to have a working knowledge of numerical control. Not much effort has been made to adapt this important development to the engineering curriculums of universities. The purpose of this project was to build a numerically controlled data plotter for instructional purposes. This equipment is intended for classroom demonstration and so, from the industrial point of view, is not very efficient.

## BASIC DESIGN

The system concept for this numerically controlled data plotter is shown in Fig. 1. First, the tape is prepared with the aid of a Friden Flexewriter. The tape advance feeds the tape to the tape reader. The instruction frame determines the axis selected or a stop code and also the direction on the selected axis. The instruction circuitry transmits this information to the digimotor drivers and initiates tape advance. The second tape frame determines the distance to be moved in terms of number of pulses. The dimension is set in the dimension counter with the toggle gate off. The toggle gate subsequently is turned on and the master clock enters the counter. The counter employs a backward count logic. The digimotors convert pulses into linear motion. The end point is reached when all counter stages are zero. This zero condition stops movement and counting, turns off the master clock, activates the "reset" circuitry, which resets the tape reader gates and instruction circuits, and initiates tape advance and a new cycle.

The basic numerical control system used here was designed at the Southern Methodist University, Dallas, Texas, under a National Science Foundation Grant (25). The equipment was designed to control a three-axis machine tool table for demonstration purposes. That design has been modified here to control a two-axis data plotter, the third axis being used to control the movement of a pen.

Four types of printed circuit boards are used in the construction of the electronic circuitry. In all, seventeen printed circuit boards have been used. Transistors and diodes are extensively used, as in the original design, for two reasons:

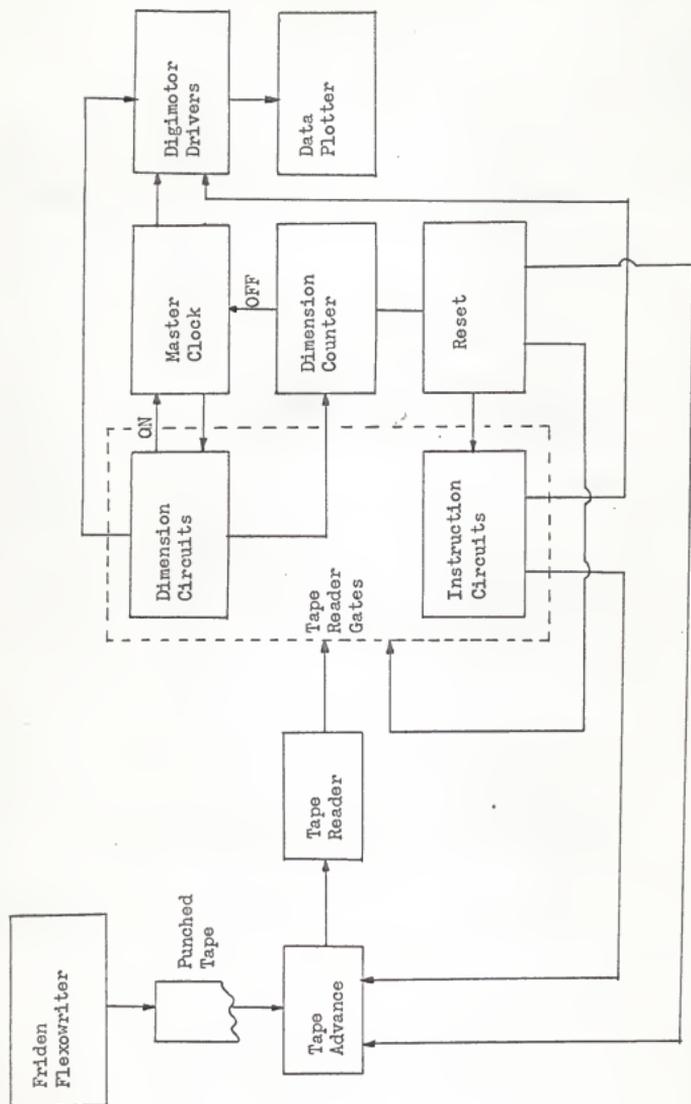


Fig. 1. Block diagram of the numerically controlled data plotter.

1. Low voltages are required with a reduction of shock hazard.
2. New equipment in industry is likely to be of this design.

Both synchronous and asynchronous circuits are used in the equipment. The synchronous circuits are synchronized by a master clock.

Dual regulated power supplies are employed to obtain the main power supply for the equipment. The main power supply and the circuitry for the special voltages are built on a single chassis. Standard transformers and chokes are used.

The three digimotor drivers, one for each axis, are built on another chassis. The digimotor drivers employ the special voltages mentioned above.

Two screws at right angles to each other provide motion in the two axes. A solenoid actuates the pen. Each screw rod is  $1/2$  inch in diameter, has 4 square threads per inch for a length of 18 inches, and is driven by a digimotor. The second digimotor is mounted on a collar riding on the first screw rod. The solenoid is mounted on a collar riding on the second screw rod. Motion is transmitted to the collars from the screw rods by means of set screws. The Ledex digimotors used are size 3, bi-directional, 28 volts D.C. nominal, with 12 positions per revolution. These digimotors have been found to be fairly reliable at a speed of 15 steps per second. The increment of motion is  $1/48$  inch. The data plotter is designed for intermittent use. Simultaneous motion by two axes has not been provided. As mentioned earlier, the data plotter is not very accurate, Cost was a limiting factor.

## PRINTED CIRCUIT BOARDS

## Preparation of Etched Circuit Boards

The boards are made with Kepro photosensitive copper clads. Each of these copper clad phenolic sheets has a light sensitive material coated on it. When a sheet is exposed to light through a properly prepared negative, the translucent areas admitting light to the plate cause the coating on the plate to become insoluble in a developer. This "resist" forms a protective barrier against the etching solution.

The process of preparing an etched circuit board consisted of the following five stages:

Making a Photographic Negative. A full size photographic negative was made from a drawing of the circuit board layout.

Exposing the Plate. Only semi-dark conditions were used in exposing since the plate sensitizing material was responsive to ultra-violet radiation. The negative was sandwiched between the copper side of the plate and a glass sheet, and the assembly was made secure by sliding the provided clips over the ends of the assembly. Care had to be taken to clean the negative and the glass sheet. The plate was exposed for 6 minutes, 10 inches from a No. 2 photoflood lamp.

Developing the Exposed Plate. The exposed plate was placed face up in a glass tray. The developer was gently poured into the tray. The tray was covered with a lid and rocked gently for one minute. The plate was then removed and dried for 30 seconds without shaking or blowing.

Etching. The dry plate was then placed face up in another glass tray. The etching solution was poured into the tray. The tray was covered with a lid and rocked gently until all undesired copper was removed. This took about 30 minutes. When etching was complete, the plate was removed and rinsed in running water for 5 minutes.

Removing Resist. The plate was dried and scoured with a cleaning pad before mechanical processing.

The plate was then drilled and cut to shape.

#### Details of Circuitry

As stated earlier, four types of printed circuit boards are used in this equipment. They are:

1. Flip flop board.
2. Common collector board.
3. Common emitter board.
4. Indicator board.

The details of the seventeen boards are shown in Table 1. The type of board is indicated by the number given above.

Table 1. Details of the printed circuit boards.

Board No.	Type of board	Circuitry
1	1	60 cycle and variable frequency pulse generators, and 1 type B flip flop.
2	1	4 type A flip flops.
3	1	Toggle gate and 1 type B flip flop.
4	1	4 type A flip flops.
5	1	Counter "and" gate, 2 emitter followers, and 1 inverter.
6	1	Reader dimension circuits.
7	1	Reader instruction circuits.
8	1	Instruction decode circuits, 1 emitter follower, and 3 inverters.
9	1	4 type B flip flops.
10	2	8 emitter followers.
11	1	4 type C flip flops.
12	3	8 inverters.
13	1	4 type C flip flops.
14	3	8 indicator inverters.
15	4	14 indicators.
16	4	14 indicators.
17	2	7 input gates.

Three types of flip flops--type A, type B and type C--are used in the circuitry. Types A and B are bistable multivibrators and are illustrated in Fig. 2. They differ only by one capacitor. The former is used for counting circuits and the latter for control logic circuits. They are stable

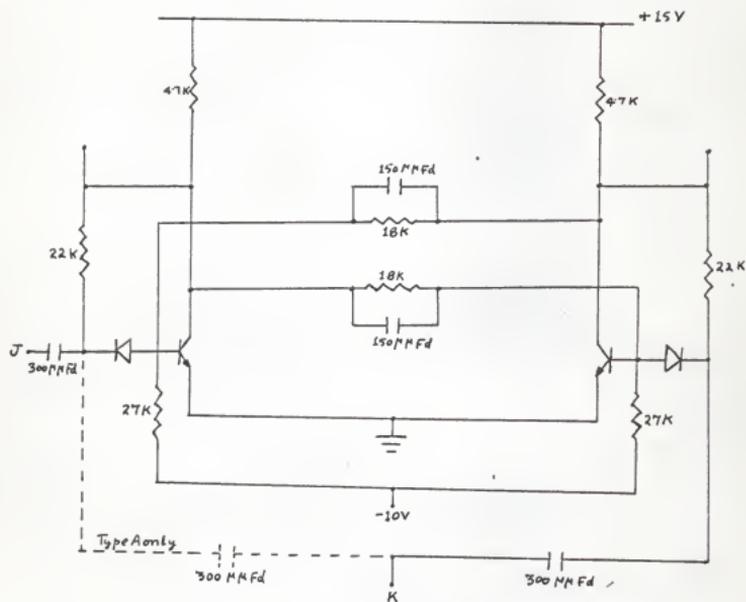


Fig. 2. Circuit diagram of type A and type B flip flops.

in both the positions  $Q$  and  $\bar{Q}$ . A signal shifts the multivibrator from position  $Q$  to position  $\bar{Q}$ . Another signal is necessary to shift it back to position  $Q$ .

Type C flip flop is a monostable multivibrator. It is illustrated in Fig. 3. It is used for time dependent logical circuits. It is stable in position  $Q$  only. A signal shifts this multivibrator from position  $Q$  to position  $\bar{Q}$ . After a certain length of time determined by the timing capacitor, it shifts back to position  $Q$ .

For the sake of simplicity, the notation shown in Table 2 has been used in all the layout and circuit diagrams in this thesis.

Table 2. Notation used in layout and circuit diagrams.

Symbol	Component
	Resistor
	Capacitor
	Electrolytic capacitor
	Logic diode 1N 461
	Transistor 2N 1302
	Transistor 2N 1303
f/f A	Type A flip flop
f/f B	Type B flip flop
f/f C	Type C flip flop

The values of resistors and capacitors are indicated on the diagrams. The symbol for diode 1N 461 is also used for other types of diodes, but the type is indicated. The same procedure is followed for transistors other than 2N 1302 and 2N 1303.

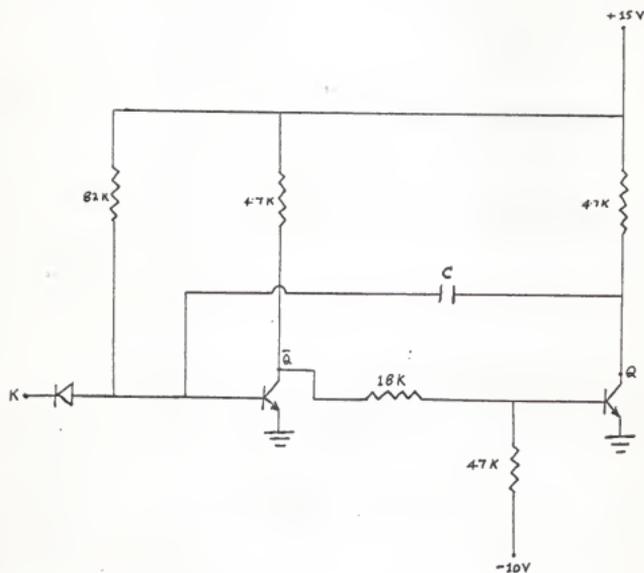


Fig. 3. Circuit diagram of type C flip flop.

In the layout diagrams, the terminals are indicated by numerals, and, capital and small letters. Terminals having the same numeral or letter are wired together in the final assembly. Any voltages applied to the terminals are indicated in the diagrams. Wherever it was necessary to isolate a portion of the wire on the printed circuit boards for special purposes, the standard wire has been cut. Isolated portions of a circuit are connected together by means of jumper wires or solder. After assembling the components on the boards, they were soldered using the minimum heat necessary. The excess lead wire was cut off with a pair of shears. Diagonal cutters were not used since the shock could have damaged the seals and the junctions. The layout diagrams show the component side of the boards and not the wire side.

The layout of components on board 1 is shown in Fig. 4. The variable frequency pulse generator is assembled on the lower half of the board. This is one source of master clock pulse. It has a steep leading edge to the pulse. The upper left part of the board layout shows the 60 cycle pulse generator. This is a square wave master clock pulse source. A type B flip flop is shown in the upper right part of Fig. 4. This flip flop is used in the counter gate circuitry.

Four type A flip flops are assembled on board 2, as shown in Fig. 5. The details of components are shown for one flip flop only. Board 4 also has four type A flip flops on it. The terminals in parentheses in Fig. 5 refer to board 4. The four flip flops on board 2 and two of the flip flops on board 4 are used for the reverse counter and toggle gates. The remaining two flip flops on board 4 are used in the clock rate and mode selection circuitry.





Figure 6 shows the layout on board 3. The type B flip flop shown in the lower right part of Fig. 6 is a part of the tape reader gates circuitry. The rest of the components on this board form the toggle gate. The dimension is set in the dimension counter with the toggle gate off. When the toggle gate is turned on, the master clock enters the counter.

The component layout on board 5 is shown in Fig. 7. The counter "and" gate is assembled on the top half of the board. When the condition of all counter stages zero is reached, the counter "and" gate is activated. The inverter shown in the bottom left part of the diagram is a part of the instruction decoding and pulse shaping circuitry. The two emitter followers adjacent to the inverter are part of the read count, toggle on, portion of the "housekeeping" circuitry.

The common layout diagram for boards 6 and 7 is shown in Fig. 8. The terminals in parentheses refer to board 7. Board 6 is the dimension board and board 7 is the instruction board. These two boards are part of the tape reader gates circuitry.

The layout on board 8 is shown in Fig. 9. The components on the top half of the board are part of the instruction decoding and pulse shaping circuitry. The three inverters and one emitter follower on the bottom half of this board, along with the type B flip flop on board 1, comprise the counter gate.

Board 9 has four type B flip flops assembled on it, as shown in Fig. 10. The flip flop on the lower left part of the board is a part of the control circuits for "On", "Off", "Automatic" machine operation and "Manual" step wise movement. The other three flip flops on this board, the type B flip flop on board 3, and boards 6 and 7, form the tape reader gates. Channel 7











is used for each instruction and initiates the logic sequence on a start signal. Channels 1, 2 and 3 set (or do not set) three type B flip flops. These comprise the instruction register. Two denote the axis selected or a stop code, and the other determines the direction on the selected axis.

Figure 11 shows the component layout on board 10. The four emitter followers on the bottom half of the board are part of the control circuits for "On", "Off", "Automatic" machine operation and "Manual" step wise movement. The emitter follower shown in the upper right part of Fig. 11 is a part of the instruction decoding and pulse shaping circuitry. To the right of this is shown another emitter follower used in the portion of the "housekeeping" circuitry that inhibits the reader, advances the tape and resets flip flops. The emitter follower assembled on the top left portion of the board is a part of the tape reader advance circuitry.

Four type C flip flops are assembled on board 11, as shown in Fig. 12. The flip flop on the top left portion of the board is a part of the circuitry for clock rate and mode selection. This flip flop, two of the type A flip flops on board 4, and a two pole, five throw switch, form the clock rate and mode selection circuitry. The output at the point M is the master clock pulse for the entire system. Only one source is required. The type C flip flop on the top right portion of board 11, the inverter on board 5, the top half of board 8, and one emitter follower on board 10, form the matrix for instruction decoding and pulse shaping which yields an X, Y or Z axis signal. Point bb is a programmed stop signal. The type C flip flop on the bottom right portion of board 11 is used in the reset, toggle off, read instruction, part of the "housekeeping" circuitry. The type C flip flop shown in the bottom left portion of Fig. 12 is a part of the control circuits for "On", "Off", "Automatic" machine and "Manual" stepwise movement.



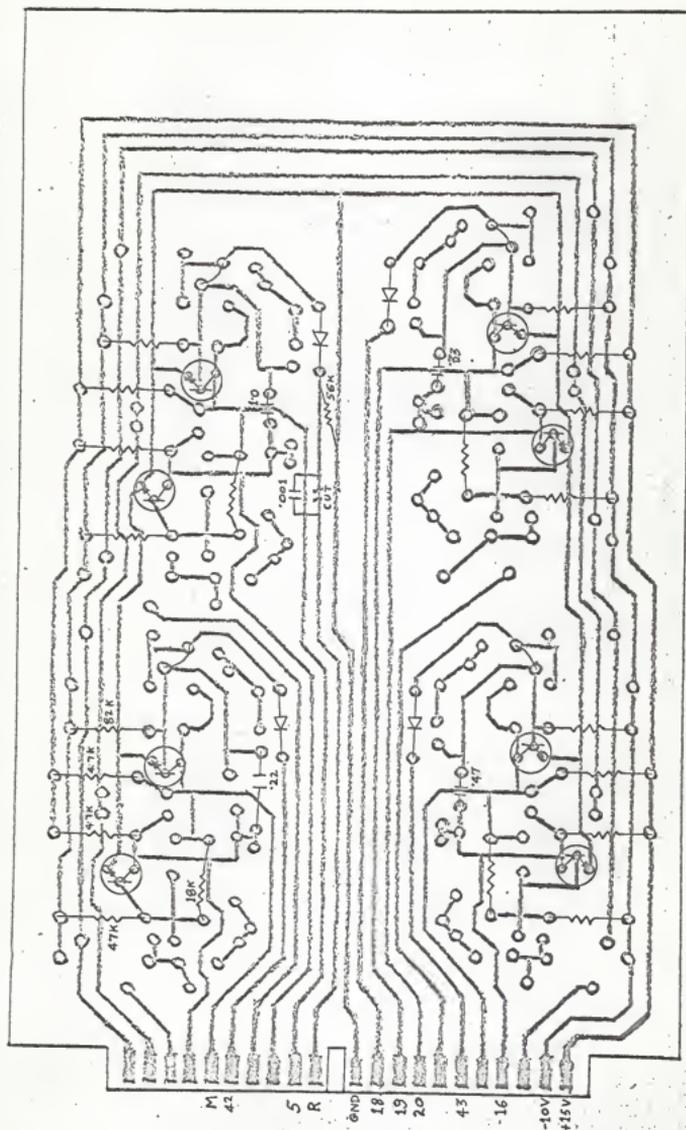


Fig. 12. Layout diagram of board 11.

Figure 13 shows the component layout on board 12. The two inverters assembled on the left half of the board and the inverter on the lower middle part of the board are employed in the portion of the "housekeeping" circuitry that inhibits the reader, advances the tape, and resets flip flops. The other three inverters on the upper half of this board are part of the reset, toggle off, read instruction, portion of the "housekeeping" circuitry. The two inverters shown on the lower right part of Fig. 13 are part of the control circuits for "On", "Off", "Automatic" machine operation and "Manual" stepwise movement.

Board 13 has four type C flip flops assembled on it, as shown in Fig. 14. The two flip flops on the upper half of the board are used in the portion of the "housekeeping" circuitry that inhibits the reader, advances the tape and resets flip flops. The two flip flops on the lower half of the board are part of the read count, toggle on, portion of the "housekeeping" circuitry.

Eight indicator inverters are assembled on board 14, as shown in Fig. 15. Only five of these inverters are used in the circuitry. The common layout for boards 15 and 16 is shown in Fig. 16. Each of these two boards has fourteen indicators assembled on it. An indicator light is used wherever it is necessary to indicate the state of a circuit. Depending on the polarity of the circuit point, the indicator is connected either directly or through an inverter to the point to be indicated.

Board 17 has seven input gates assembled on it, as shown in Fig. 17. The input gates make the output of the tape reader compatible with the input to the system.



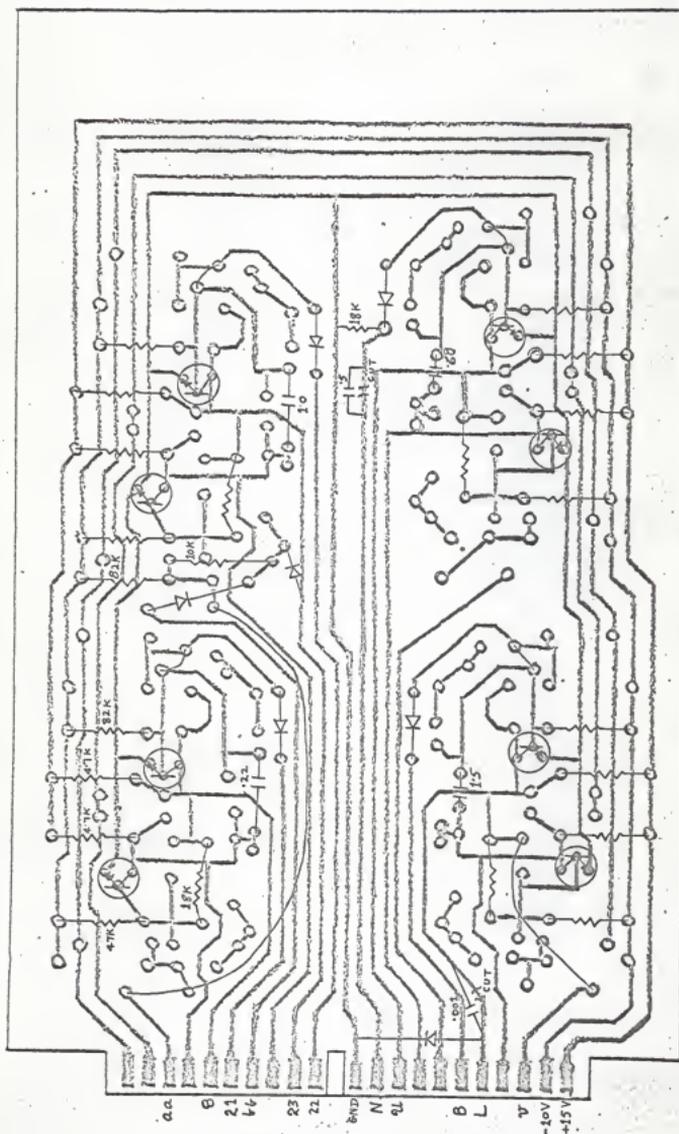


Fig. 14. Layout diagram of board 13.

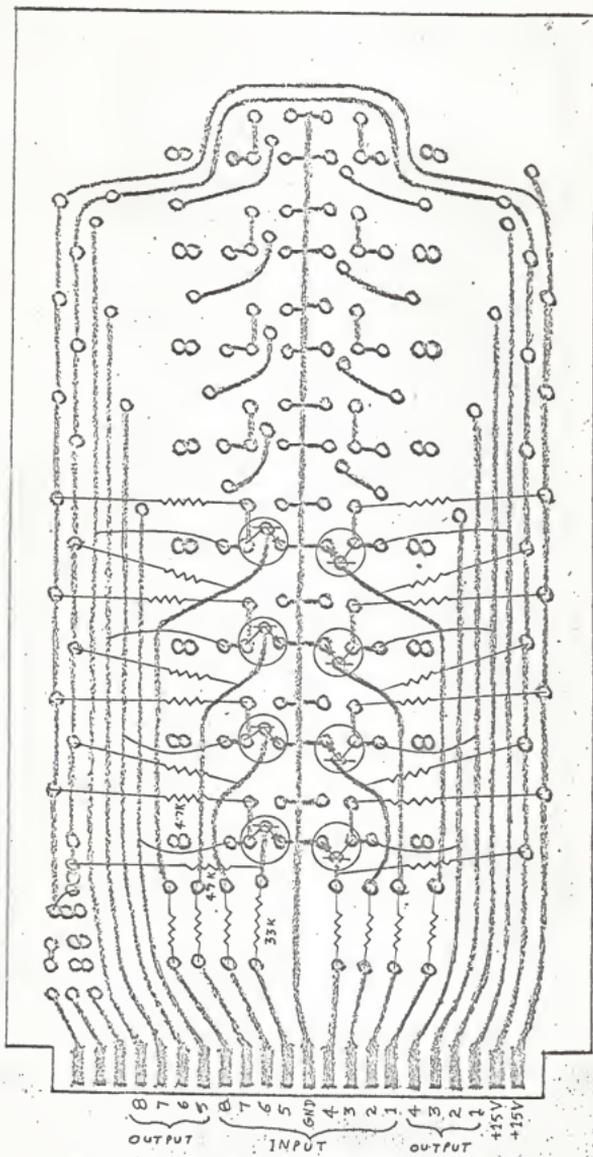


Fig. 15. Layout diagram of board 14.



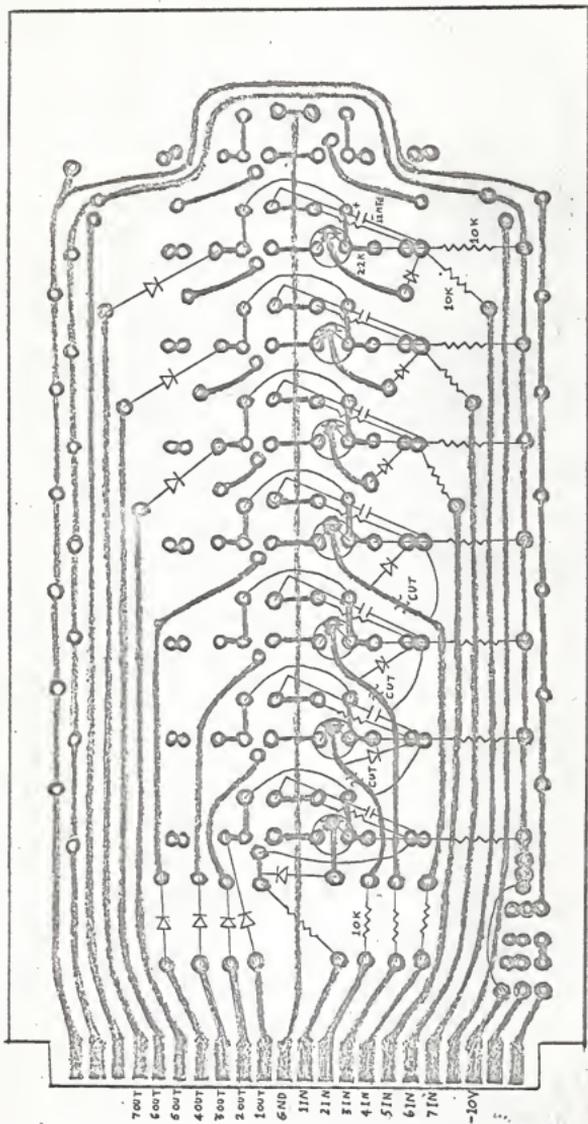


Fig. 17. Layout diagram of board 17.

The two emitter followers on board 5, one of the emitter followers on board 10, two of the type C flip flops on board 11, six of the inverters on board 12, and board 13, form the "housekeeping" circuitry. The type C flip flops effect the timed sequence of control pulses. The sequence can be demonstrated with the aid of an oscilloscope by means of the three test points u, v and w.

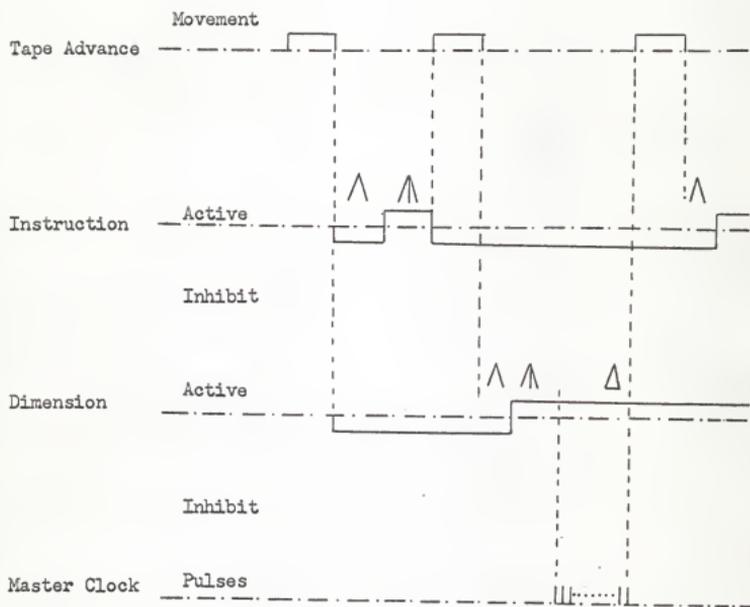
The individual boards were tested by applying the appropriate input voltages to the terminals and noting the reactions at the output terminals.

#### Circuit Operation

The circuit operation is easily understood by referring to the printed circuit board layout diagrams already shown. After the three bit axis code is in the instruction register, the master clock pulse appears at M. A signal on I sets the type A flip flop to  $\bar{Q}$  condition. A coincidence signal will then appear at q at each clock pulse time. Two sequences will be propagated.

One pulse sequence will pass R, coincide with the static decoded axis signal and activate the drive motor circuit pulse wise. This will cause the motor to step one unit of rotation for each pulse. Simultaneously, a second pulse sequence will pass p and then be counted by the reverse counter.

This will continue till the counter counts down to a condition of all stages zero in each of the six bits. This condition will be sensed by the "And" gate. The "And" gate will give a signal at q, turning off the master clock, and another at P, which initiates the sequence illustrated in the timing diagram shown in Fig. 18. The timing diagram has time along the horizontal axis and activities along the vertical axis.



^ Reset flip flops

^ Set flip flops

Δ Flip flops count down to zero

Fig. 18. Timing diagram.

The instruction and dimension circuitries have two states--active and inhibit. Referring to Fig. 18, the tape is first advanced, and then the instruction and dimension circuitries are inhibited. The flip flops in the instruction circuitry are reset and the circuitry is activated. Next, the flip flops of the instruction circuitry are set and the circuitry is inhibited. The tape is advanced, after which, the flip flops in the dimension circuitry are reset and the circuitry activated. These flip flops are then set and the master clock is turned on. When the flip flops of the dimension circuitry count down to zero, the tape is advanced. The flip flops of the instruction circuitry are reset and the circuitry is once again inhibited.

#### POWER SUPPLIES

The main power supply for the unit consists of twin regulated power supplies, as shown in Fig. 19. One power transformer with two isolated secondary windings is employed. The regulating circuits are isolated from a chassis ground. One of the power supplies is used for the positive supply with its negative terminal common with the positive terminal of the other power supply, which is used for the negative supply. One set of meters and a switching system are used.

The layout diagrams indicate the absolute maximum permissible voltages. The circuits have been found to operate reliably with the voltages 15% below the indicated values. Recommended values are 5% below the indicated values. The circuit diagrams for the special voltages, shown in Figs. 20 and 21, are exceptions to these remarks. The 48 volt negative supply may vary by 10%. The 15 volt positive supply, the 13 volt and 8 volt negative



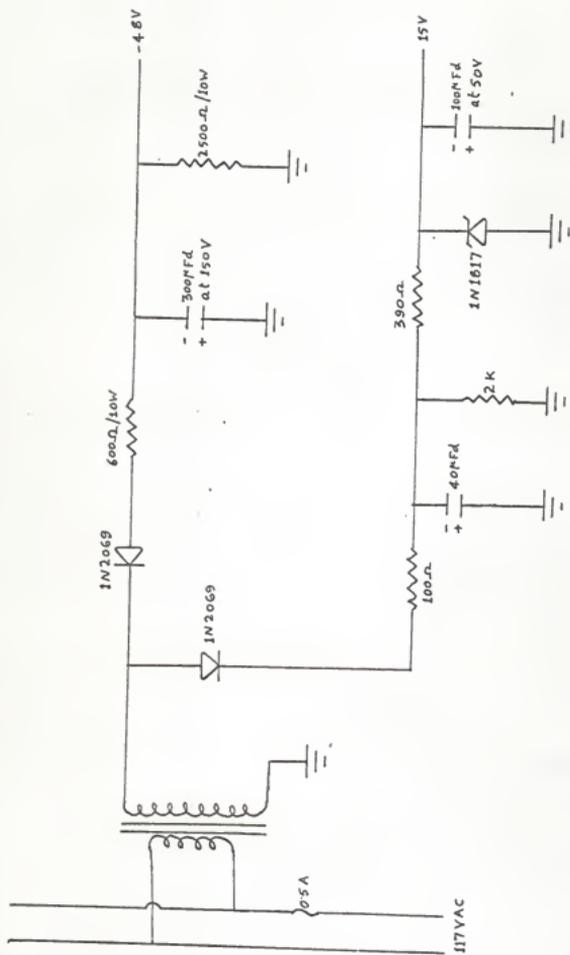


Fig. 20. Circuit diagram of -48 and +15 volts power supplies.

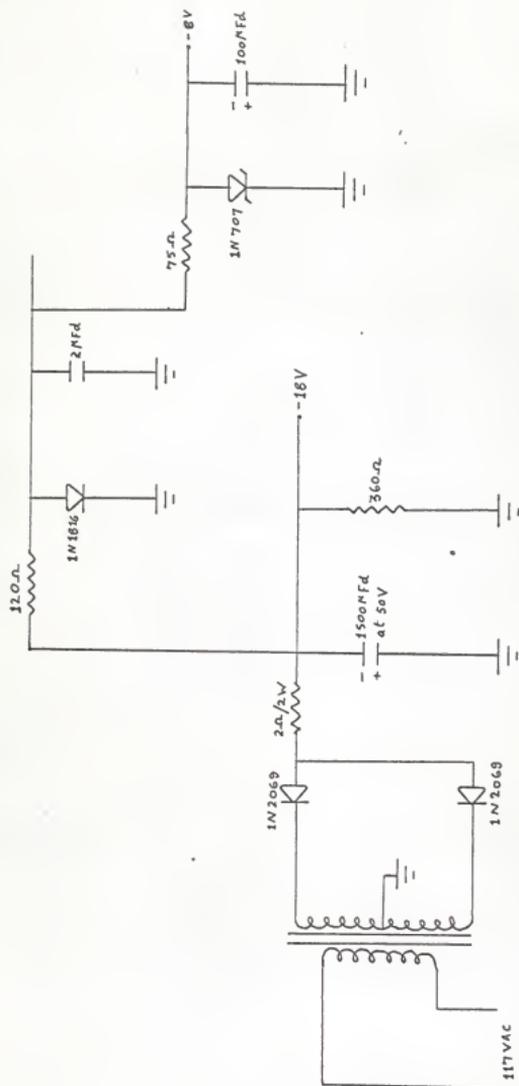


Fig. 21. Circuit diagram of -8, -13 and -18 volts power supplies.

supplies, are regulated by Zener diodes. The 18 volt negative supply is not regulated and deliberately swings as it is the energy source for the driving motor. These special voltages were found necessary to prevent common mode current disturbance in the logical circuitry. They serve the driver amplifier circuitry exclusively.

The indicator lights require an 80 volt negative supply. The circuit diagram for the 80 volt negative supply is shown in Fig. 22.

All the power supplies mentioned above are assembled on a single chassis, 17 inches long, 11 inches wide, and 3 inches deep. The 2N 1375 transistors are mounted on transistor sockets. Resistors, diodes and capacitors are assembled on terminal strips. Photographs of the chassis, as viewed from above and below, are shown in Figs. 23 and 24, respectively. The indicator light bulbs are sensitive and so, a voltage regulating switch for the 80 volt negative supply is provided at the rear of the chassis.

#### DIGIMOTOR DRIVERS

The power amplifier circuit for a digimotor is shown in Fig. 25. Three of these circuits, one for each axis, are built on a chassis 17 inches long, 11 inches wide and 3 inches deep. Photographs of this chassis, as viewed from above and below, are shown in Figs. 26 and 27, respectively. The transistors are mounted on transistor sockets. Resistors, diodes and capacitors are assembled on terminal strips. The special voltages shown in Figs. 23 and 24 are used exclusively for the power amplifier circuits.





Fig. 23. Photograph of the power supplies chassis, as viewed from above.

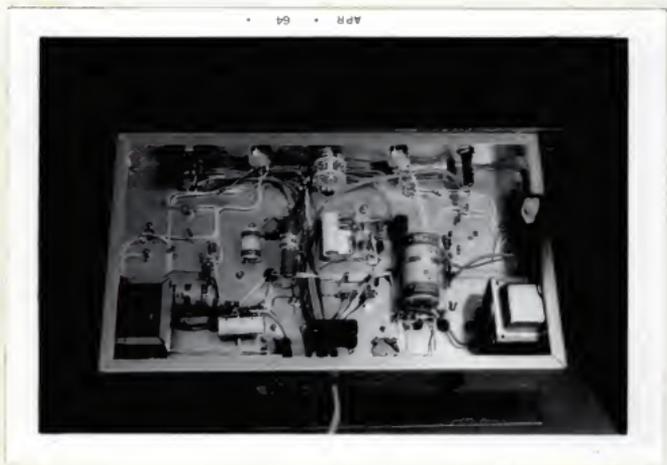


Fig. 24. Photograph of the power supplies chassis, as viewed from below.

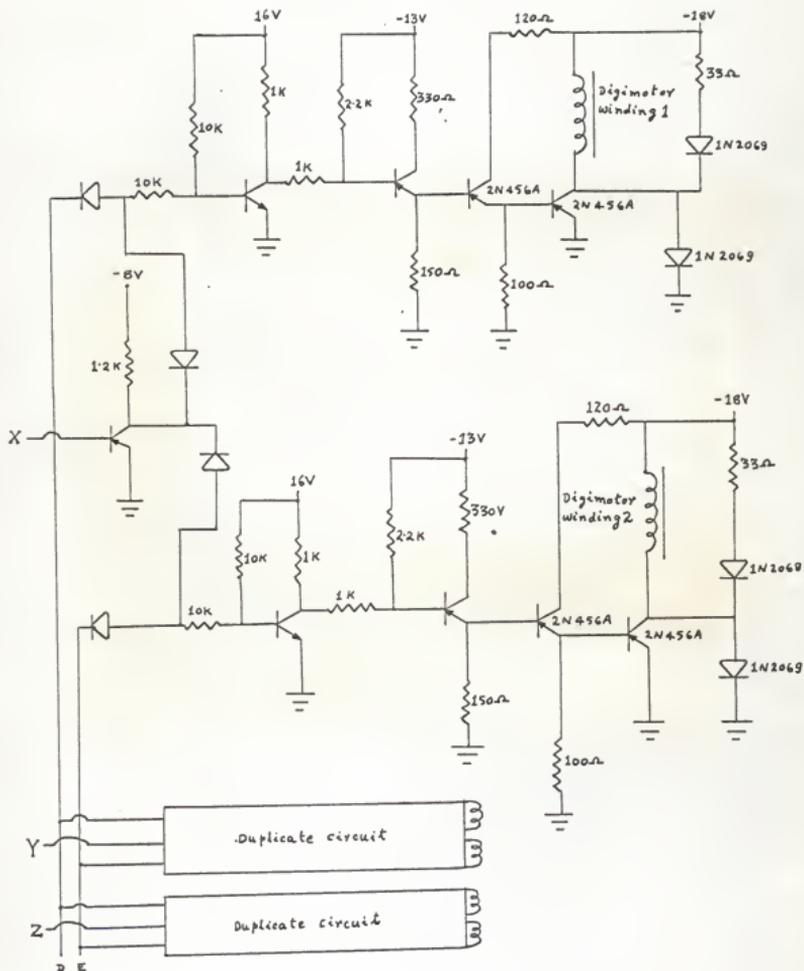


Fig. 25. Circuit diagram of the digimotor drivers.



Fig. 26. Photograph of the power amplifier chassis, as viewed from above.



Fig. 27. Photograph of the power amplifier chassis, as viewed from below.

## WIRING AND ASSEMBLY

The numerical control equipment is assembled in a single cabinet 36 inches high, 22 inches wide and 15 inches deep. Figures 28 and 29 show photographs of the data plotter and the entire numerical control equipment, as viewed from the front and the rear, respectively. For convenience, the front panel is divided into four parts.

The top portion of the front panel consists of a transparent plastic cover to facilitate viewing of the printed circuit boards. The terminal ends of the boards are inserted into sockets mounted on a rack, as in the photograph shown in Fig. 30. Insulated wires are soldered to pins projecting from the sockets. This method of mounting the boards was found to be very convenient. Wires going from pins to the same point are laced together.

The two indicator boards are mounted parallel to and behind the front panel, just below the rack of printed circuit boards. The indicator lights project out of the front panel through rubber gromets. Test points u and v are provided to the left of the indicator lights, and test point w and point X (+15 volts) are provided to the right of the indicator lights. The seven lights on the left half of the top row are for the dimension circuitry. The extreme left lights on the right half of the display indicate "Start" and "Stop". The other six lights on the right half of the top row are for the instruction circuitry. The extreme left light on the second row indicates zero count, the next light indicates "No connection", and the next five lights are for the counting circuitry. The second and third lights on the right half of the second row indicate "Clockwise" and "Anticlockwise" rotation, respectively. The fourth light indicates "Tape advance". The next three lights indicate "Read", "Dimension" and "Instruction" inhibits, respectively.



Fig. 28. Photograph of the numerical control equipment, as viewed from the front, with the data plotter placed on top of it.



Fig. 29. Photograph of the numerical control equipment, as viewed from the rear, with the data plotter placed on top of it.



Fig. 30. Photograph of the rack of printed circuit boards.

The digimotor driver amplifier chassis is attached to the portion of the front panel below the indicator lights. The top left part of this portion of the front panel has the seven tape reader contact switches. The circuit diagram for the tape reader contacts is shown in Fig. 31. The "On" and "Off" switches, the manual-auto switches for input, stepping and tape advance, the two pole, five throw, switch for the clock rate and mode selection, and the frequency regulating knob are mounted below the tape reader contact switches. The manual-auto input controls power to the input gates. The circuitry for the manual-auto switch of the tape reader advance is shown in Fig. 32.

The power supply chassis is attached to the bottom portion of the front panel. The meters and the knobs for voltage regulation are mounted on this portion of the front panel. The positive 15 volts, and the negative 10, 24 and 80 volt supplies can be regulated.

#### DATA PLOTTER

The two lead screws were the key elements in the design of the data plotter. They had to be fairly light in order to be operated by the digimotors. At the same time a fast lead was required. The method of transmitting motion from each screw rod to the collar was also an important factor. Multiple start threads were considered impractical because of construction problems. Bearing these factors in mind, it was decided to have a square thread, with a pitch of  $1/4"$ , on each rod, with a collar sliding on the rod, motion being transmitted to the collar by means of a set screw in the thread. Size 3, bidirectional, 28 volts D.C. (2140 ampere turns at  $20^{\circ}\text{C}$ ) Ledex digimotors, with twelve steps per revolution, are used. The pulse times will allow accurate operation on pure friction loads as long as the digimotor is operated within temperature limits specified and with a

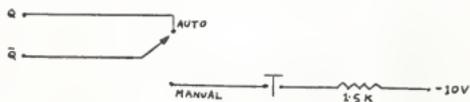


Fig. 31. Circuit diagram of the tape reader advance.

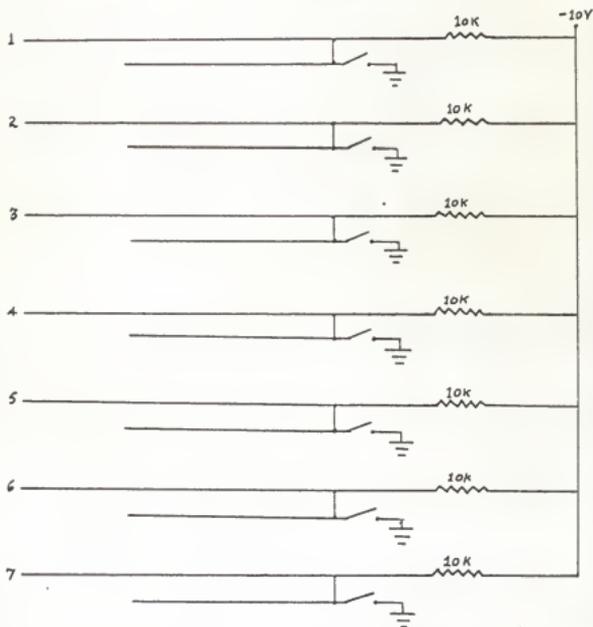


Fig. 32. Circuit diagram of the tape reader contacts.

detent setting of 5 to 6 oz.-in. The time limit for intermittent stepping is 2 to 3 minutes. Loads up to 10 oz.-in. can be detented if load is not pure friction and if detent setting is changed. The equipment has been found to operate with fair reliability at a speed of 15 steps per second or 75 rpm.

$$\begin{aligned} \text{The incremental motion per step} &= \frac{\text{Pitch}}{\text{Number of steps per revolution}} \\ &= \frac{1}{4} \times \frac{1}{12} \\ &= \frac{1}{48} \text{ inch} \end{aligned}$$

$$\text{Axial motion per second} = \frac{1}{48} \times 15 = \frac{5}{16} \text{ inch}$$

A photograph of the data plotter is shown in Fig. 33. Dimensional drawings of the various parts of the data plotter are shown in Figs. 34 to 42.

#### Design of Set Screw

It was decided to make the minimum diameter of each set screw equal to the width of the square groove,  $1/8"$ . The shear stress produced in the set screw by a torque of 10 oz.-in. or  $5/8$  lb.-in. =  $\frac{16 (\text{Torque})}{(\text{Least diameter})^3}$

$$= 16 \times \frac{5}{8} \times \frac{1}{(0.125)^3}$$

$$= 1630 \text{ psi}$$

The maximum shear stress developed in the set screw is well within allowable limits.

#### Design of Screw Rod

The diameter of each screw rod was chosen as  $1/2$  inch.

Mean diameter of the screw rod =  $3/8$  inch.



Fig. 33. Photograph of the data plotter.

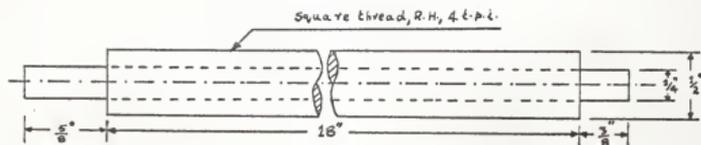


Fig. 34. Sketch of the first screw rod.

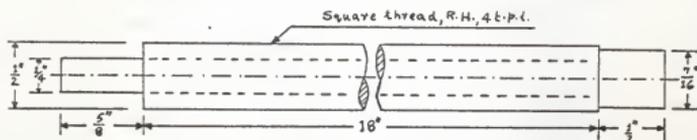


Fig. 35. Sketch of the second screw rod.

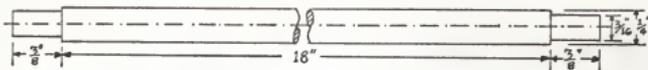


Fig. 36. Sketch of a guide rod.

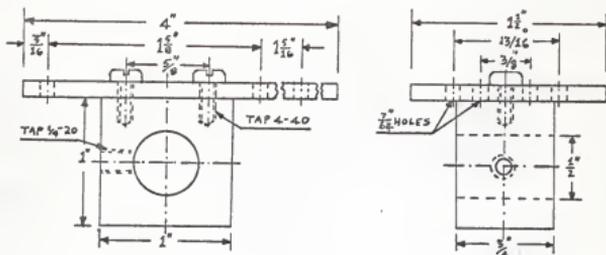


Fig. 37. Sketch of the first collar.

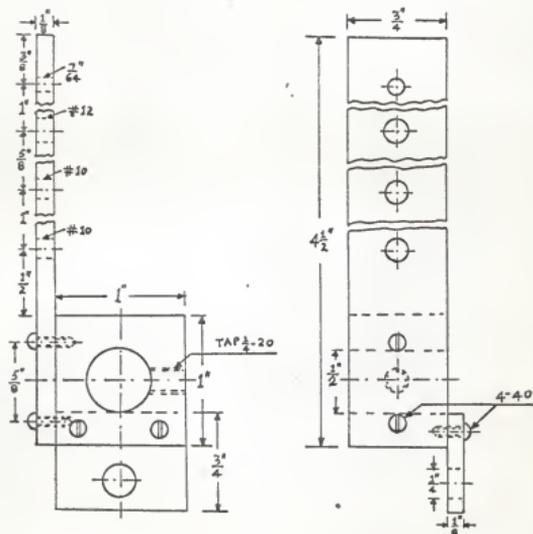
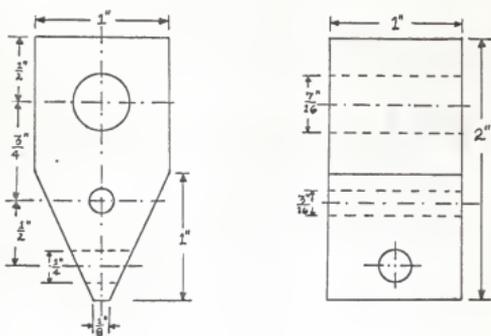


Fig. 38. Sketch of the second collar.



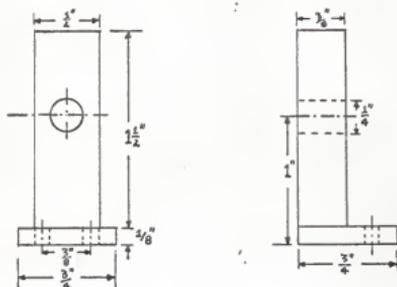


Fig. 40. Sketch of a bearing for the first screw rod.

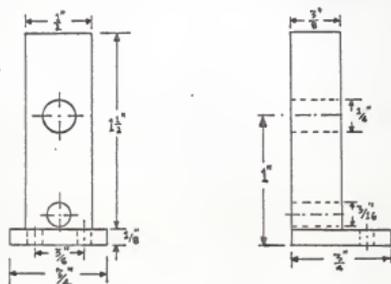


Fig. 41. Sketch of the bearing for the second screw rod.

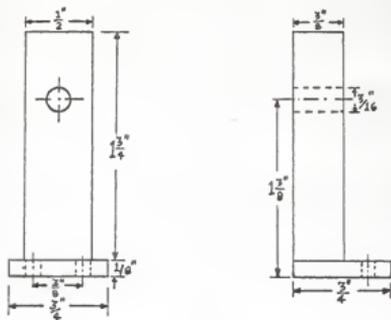


Fig. 42. Sketch of a bearing for the guide rod.

Root diameter of the screw rod =  $1/4$  inch.

$$\begin{aligned} \text{Weight of the first screw rod} &= \frac{\pi}{4} \left[ \left(\frac{3}{8}\right)^2(18) + \left(\frac{1}{4}\right)^2(1) \right] \quad (0.28) \\ &= 0.56 \text{ lb.} \end{aligned}$$

$$\begin{aligned} \text{Weight of the second screw rod} &= \frac{\pi}{4} \left[ \left(\frac{3}{8}\right)^2(18) + \left(\frac{1}{4}\right)^2\left(\frac{5}{8}\right) + \left(\frac{7}{16}\right)^2\left(\frac{1}{2}\right) \right] \quad (0.28) \\ &= 0.56 \text{ lb.} \end{aligned}$$

Weight of the bearing supporting the digimotor end of the second screw

$$\begin{aligned} \text{rod} &= \left[ 1 \times \frac{1}{2} \times \frac{3}{8} \times \frac{1}{2} + 1 \times \frac{3}{4} \times \frac{1}{8} - \frac{\pi}{4} \left(\frac{1}{4}\right)^2\left(\frac{3}{8}\right) - \frac{\pi}{4} \left(\frac{3}{16}\right)^2\left(\frac{3}{8}\right) \right] \quad (0.28) \\ &= 0.10 \text{ lb.} \end{aligned}$$

$$\begin{aligned} \text{Weight of each collar} &= \left[ 1 \times 1 \times \frac{3}{4} - \frac{\pi}{4} \left(\frac{1}{2}\right)^2\left(\frac{3}{4}\right) \right] \quad (0.28) \\ &= 0.60 \text{ lb.} \end{aligned}$$

$$\begin{aligned} \text{Weight of the guide rod for second collar} &= \frac{\pi}{4} \left[ \left(\frac{1}{4}\right)^2(18) + \left(\frac{3}{16}\right)^2(1) \right] \quad (0.28) \\ &= 0.22 \text{ lb.} \end{aligned}$$

Weight of each digimotor = 0.66 lb.

Weight of the solenoid = 0.28 lb.

$$\text{Frictional torque on square thread} = \frac{Wd}{2} \left( \frac{\pi \mu d + l}{\pi d - \mu l} \right)$$

where  $W$  = total weight acting on the thread

$d$  = mean diameter of screw rod

$\mu$  = coefficient of friction (assumed to be 0.15) and

and  $l$  = lead of screw.

$W$  is maximum when the collars are closest to the digimotors.

$$\begin{aligned} W &= 2(0.60) + 0.66 + 0.10 + \frac{1}{2}(0.56) + \frac{1}{2}(0.22) + 0.28 \\ &= 2.63 \text{ lb.} \end{aligned}$$

Frictional torque on the thread of the first screw rod

$$= 2.63 \times \frac{3}{8} \times \frac{1}{2} \left[ \frac{\pi (0.15) \left(\frac{3}{8}\right) + \frac{1}{4}}{\pi \left(\frac{3}{8}\right) - (0.15) \left(\frac{1}{4}\right)} \right]$$

$$= 0.19 \text{ lb.-in.}$$

$$\text{Frictional torque on bearings} = \mu W \frac{d}{2}$$

$$W = 0.56 + 0.56 + 2(0.60) + 0.66 + 0.10 + 0.22 + 0.28 = 3.58 \text{ lb.}$$

$$\text{Frictional torque on bearings} = 0.15 \times 3.58 \times \frac{1}{2} \times \frac{1}{4} = 0.07 \text{ lb.-in.}$$

$$\text{Torque due to inertia} = I\omega$$

where  $I$  = polar moment of inertia

and  $\omega$  = angular velocity of rotation.

$$I = \frac{\pi (2)^4}{32 \cdot 8}$$

$$= 0.002 \text{ in.}^4$$

$$= \frac{2\pi \times 100}{60}$$

= 10.5 radians per second, assuming a speed of 100 rpm. Torque due to inertia =  $0.002 \times 10.5$

$$= 0.02 \text{ lb.-in.}$$

Total maximum torque required =  $0.19 + 0.07 + 0.02 = 0.28 \text{ lb.-in.}$

The capacity of the digimotor with detent = 6 oz.-in.

$$= 0.375 \text{ lb.-in.}$$

Hence, the design is safe.

#### Construction

The square threads on the screw rods were cut on a thread milling machine. The data plotter is mounted on a wooden board 2 feet long, 2 feet wide and  $3/4$  inch thick. The first digimotor is mounted in a corner of the board. The first screw rod is supported by bearings mounted on the board. The second digimotor is mounted on an aluminum platform screwed to the collar riding on the first screw rod. The digimotor end of the second screw rod is supported by a bearing mounted on the same platform. The other end of this screw rod is

supported by a block that slides along a plain rod supported by bearings mounted on the board. All the bearings are braced to their bases. The solenoid is fixed to a strip of aluminum screwed to the second collar. The second collar is held in position by a mild steel strip sliding on a plain rod that moves with the second screw rod. The core of the solenoid is held up by a spring. When the solenoid is magnetized, the core is attracted down. The pen also comes down with the core and makes a mark on a sheet of paper affixed to the board.

#### APPLICATIONS

Application of this equipment offers a wide range of use. It is specially designed for purposes of demonstration. The equipment can be operated either manually or automatically. Optimum time methods are not employed in the design in order to create a better teaching device. As an example, the tape is advanced while the mechanical movement is stopped.

The data plotter simulates a machine tool positioning table. A hole punched in channel 3 of the tape will give the z-axis. A hole punched in channel 2 of the tape gives the y-axis. A hole punched in each of channels 2 and 3 gives the x-axis. A hole punched in channel 1 gives rotation in the counterclockwise direction. Rotation in the clockwise direction is obtained if no hole is punched in channel 1.

This numerical control equipment can be modified to control a three-axis machine tool table. Further, channels 4, 5 and 6 are not used in the present setup, and are available for auxiliary functions like operating a coolant pump. The equipment is designed as an open loop system. The open loop can be converted to a closed loop, if desired.

## FUTURE OF NUMERICAL CONTROL

In a little more than a decade, numerical control has become a widely applied production tool. More than two thousand numerically controlled machine tools are in operation now. This concept has revolutionized the practice of metalworking. Industry is doing considerable research in the field of numerical control.

Many of the developments in numerical control are the result of research projects undertaken by a number of companies. The Lucas Division of New Britain Machine Company, Cleveland, has developed a horizontal spindle, continuous path, universal contouring and boring machine that has five simultaneously controlled axes of motion and two alternatives, thus providing control of seven axes of motion (13). The Numerical Command System, developed by Space Ships Incorporated, achieves accuracy and reliability without costly memory devices (14). After the initial command tape is recorded on magnetic tape from a general purpose computer, solid state motor controls are electronically planned with high-audio tape. A numerical control system developed by BHI in England predicts a fault in data tape before data goes into machine control, by comparing the next information to be put in with the last supplied, and stops the machine if the path is not smooth (3). Tornetic, an electronic system having a torque sensing device that feeds cutting data to a computer which instantly sends speed-feed instructions to the tool, was developed by Norair Engineers and Dyna Systems Incorporated (6). This results in an optimum cutting torque at all times. The Fuji Communication Apparatus Manufacturing Company, Japan, has provided for automatic compensation for any cutter radius up to 80 mm. in a numerical control system (12). The same input

tape controls roughing and finishing cuts with different sized cutters. Also, the system can generate male and female workpieces from the same tape. Japanese numerical control systems use parametrons (16). A parametron is a device that replaces electronic tubes and transistors. It is almost unaffected by temperature. However, the response of electronic tubes and transistors is faster than that of parametrons. Tracer and numerical controls have been combined in a lathe developed in Japan.

A new concept, known as adaptive control, is being developed by the Bendix Corporation (1). Adaptive control is a system that can adapt feeds and speeds to changing process conditions in order to attain and maintain the best level of performance of a machine tool. Numerical control does not take into account the changes in machining conditions. The adaptive control system would supplement the dimensional numerical control feedback loop by an additional loop around the tool-work interface. Tool life, surface finish and accuracy can be improved.

The elements of an adaptive control system for a numerically controlled machine tool are shown in Fig. 43. The tape reader gives commands to the numerical control system. The servo drives position the machine axes to generate the required contour. Information on machine slide positions is fed back by transducers.

In the adaptive control part of the system, sensors coupled close to the cutting point measure the tool-tip temperature, spindle torque and tool vibration, and feed this information to the adaptive controller. The data-reduction subsystem converts this information into signals representative of actual performance factors. It is also fed speed and feed data from the numerical control system, and constants relating to constraint limits, width and depth

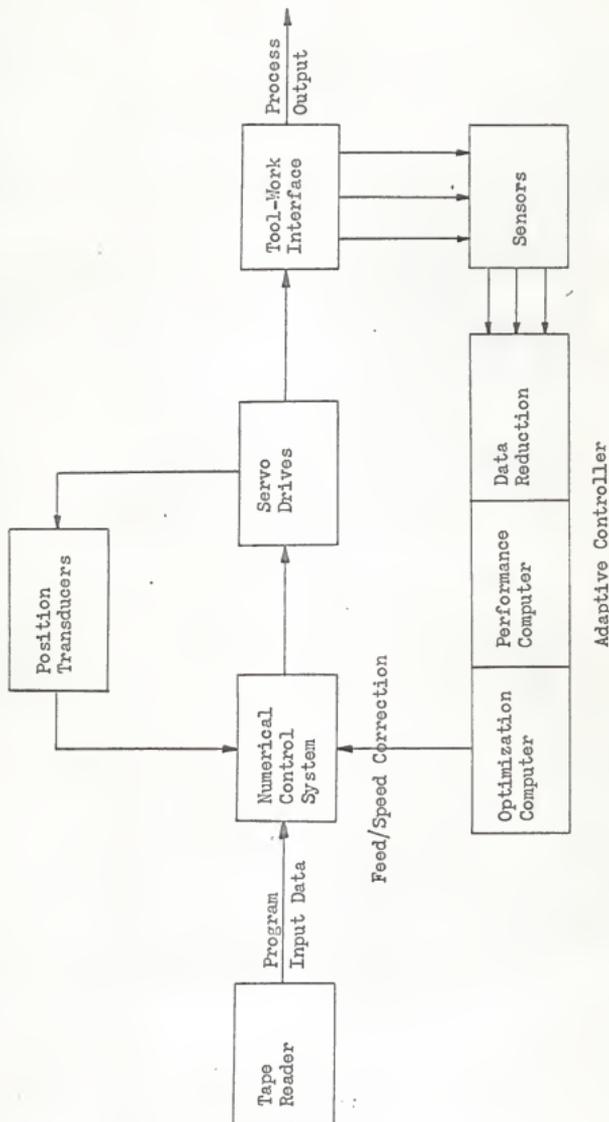


Fig. 43. Block diagram of the adaptive control system.

of cut, and tool wear. Two analog output signals corresponding to metal-removal and tool-wear rates, and a number of on/off signals to keep within predetermined limits various aspects of machine performance, are generated by this subsystem.

The performance computer then generates a quantity called the figure of merit, indicating overall machine performance. The figure of merit,  $H$ , in cu. in. per dollar or minute, is given by the equation

$$H = \frac{\text{MRR}}{K_1 + \left( \frac{K_1 T + K_2 B}{W} \right) (\text{TWR})}$$

where MRR = metal-removal rate in cu. in. per minute

$K_1$  = machine overhead in dollars per minute

$K_2$  = tool-change cost in dollars

$T$  = tool-change downtime in minutes

$W$  = maximum allowable wear land on tool in in.

TWR = tool-wear rate in in. per minute

and  $B$  = constant between 0 and 1.

If the value of  $B$  is 1, the criterion is machining cost and  $H$  is in cu. in. per dollar. If the value of  $B$  is 0, the criterion is production rate,  $K_1$  factors out, and  $H$  is in cu. in. per minute. Intermediate values of  $B$  result in a compromise between cost and production rate.

The optimization computer then adjusts the feed and speed values to obtain the best value of  $H$ . The computer makes small changes in feed and speed, notes the effects of the changes, then predicts the general direction in which better performance lies, and makes a greater change in feed and speed in this direction. This optimizing strategy is known as the method of

steepest ascent. The small and greater changes are repeated until no further improvement results.

Numerical control is finding newer and more applications with the passage of time. But there probably will be no major change in the numerical control system except for additional provisions for correction signals from the adaptive controller. The adaptive control system is still in its initial stages of development. Adaptive control may well be the next form of automation.

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ANALYSIS AND DESIGN OF A SIMULATED  
NUMERICALLY CONTROLLED MACHINE TOOL

by

BANGALORE P. LINGARAJ

B.E. (Mechanical), University of Mysore, India, 1961

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

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Department of Industrial Engineering

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Manhattan, Kansas

1964

Numerical control of machine tools is simply the control of machine tools by numbers. It is an efficient means of reading blueprints and translating the data into a series of machine positions. The object of this project was to build a numerically controlled data plotter for instructional purposes. The basic numerical control system used here was designed at the Southern Methodist University, Dallas, Texas, under a National Science Foundation Grant, to control a three-axis machine tool table. That design has been modified here to control a two-axis data plotter, the third axis being used to control the motion of a pen.

A punched tape, prepared with the aid of a Friden Flexowriter, is fed to a tape reader located on the Flexowriter. The instruction tape determines the axis selected and its direction. The instruction circuitry transmits the information to the digimotor drivers and initiates tape advance. The second tape frame, which is the dimension frame, determines the distance to be moved in terms of the number of pulses. The dimension is set in the dimension counter and subsequently the master clock enters the counter. The counter employs a backward count logic. The digimotors convert pulses into linear motion. The end point is reached when all counter stages are zero. This zero condition stops movement and counting, turns off the master clock, activates the "reset" circuitry, and initiates tape advance and a new cycle.

In all, seventeen printed circuit boards have been used in the construction of the electronic circuitry. The boards are made with Kepro photosensitive copper clads. Standard transistors, diodes, capacitors and resistors have been used in the circuitry. The terminal ends of the printed circuit boards are inserted into sockets mounted on a rack.

The main power supply for the equipment and the circuitry for the special voltages are built on a single chassis. The three digimotor drivers are built on another chassis.

The entire equipment is assembled in a single cabinet. The rack of printed circuit boards is mounted at the top of the cabinet. The indicator lights for the various parts of the circuitry are displayed on the front panel, just below the rack. The manual-auto switches for input, stepping and tape advance, the on and off switches, the frequency control knob, and the two pole, five throw, switch for clock rate and mode selection, are mounted on the front panel just below the indicator lights. The driver amplifier chassis is attached to the rear of this portion of the front panel. The meters and the knobs for voltage regulation are mounted on the bottom portion of the front panel. The power supply chassis is attached to the rear of this portion of the panel.

The data plotter consists of two screws at right angles to each other, each driven by a digimotor. The second digimotor is mounted on a collar riding on the first screw rod. A solenoid, mounted on a collar riding on the second screw rod, actuates a pen. Motion is transmitted to the collars from the screw rods by means of set screws.

Application of this equipment offers a wide range of use. It can be modified to control a three-axis machine tool table. Further, three of the seven channels are not used in the present setup, and are available for auxiliary functions. This equipment is intended for demonstrational purposes and so, from the industrial point of view, is not very efficient.