DIGITRON

FROM PRINTS...TO PARTS...THROUGH PUNCHED TAPE

This report presents to industry a new fundamental concept: that finished metal parts can be produced on machine tools which are controlled automatically by instructions prepared on punched tape directly from blueprint information . . . without manual operation . . . and without the use of templates, cams, models, fixtures, gages, or similar mechanical devices to position the cutting tools or guide their movements.

Only recently has the need arisen for such machines. It has come about largely in the aircraft industry, now confronted with the job of manufacturing or fabricating structures and components larger than ever before, or more complex in shape, or to closer limits of accuracy than practical on even the most versatile existing machine tools.

One of the most urgent problems today, which punched tape control system for machine tools should help to solve, is the production of so-called integrally-stiffened wings and other aircraft components—structures consisting of solid slabs or sheets of metal, machined or forged to shape, as contrasted with structures assembled or built up from "bits and pieces" welded, riveted, or bonded together. Many other manufacturing problems will occur to engineers and planners whose designs for parts go beyond the limits of existing equipment.

The term *"Digitron"* has been coined to describe this new system of machine tool control. It is derived from the words "digit" and "electronic." The paper tape is punched using a system of holes to furnish the control data to the machine. Electronic devices are used in converting the control data into mechanical movements of the machine tool, co-ordinating the direction and speed of travel in three planes.

The requirement for the *Digitron* control system to meet a specific need for extremely accurate templates in the manufacture of aircraft structures became apparent to Parsons Corporation in 1947. Because the basic idea held promise of application to other problems, it was submitted to Air Materiel Command, Wright Field, and a contract for development of the project was awarded Parsons Corporation in June of 1949. Continuation of this development is now in progress at the Servomechanisms Laboratory of the Massachusetts Institute of Technology.

The concept of tape-controlled machine tools is a challenging one, suggesting important possible contributions to the aircraft industry and other industries as well. It is too early to forecast accurately a list of *Digitron* applications for it is still in the laboratory stage. But to emerge from the laboratory, it will require evaluation by engineers and management in industry who are seeking ways of doing conventional jobs better or of doing jobs never done before.

Thus the purpose of this report is three-fold:

(1) To describe the system now being incorporated in a demonstration machine.

(2) To present a brief history of the development from its inception to the present time.

(3) To suggest possible applications and future courses of development.

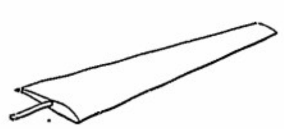
ORIGIN OF THE DIGITRON IDEA

Parsons Corporation, a major producer of helicopter rotor blades, has long been concerned with the problem of producing accurate templates for manufacturing and inspecting airfoil contours. Many rotor blades are tapered from root to tip, and are twisted as well. Thus dimensional inspection is required at many stations along the blade, and often 50 or more templates are required for a single blade. The contours to be checked sometimes are 24 inches long and so in laying out the templates it has been customary to establish approximately 20 co-ordinate points. To lay out these co-ordinates within the desired close limits of accuracy by means of conventional height gage and surface plate practice requires a large expenditure of time. Furthermore, even the most experienced template makers have difficulty in connecting the points with a smooth curved line and then hand filing to produce a faired contour which will have the desired final accuracy. Inspection of these templates is a time-consuming job and there is no way to inspect contours between co-ordinate (layout) points.

The increasing urgency of this problem in 1946 led Parsons Corporation to intensified efforts to find better, quicker ways to make templates. It appeared that the high degree of accuracy attainable on precision machine tools—jig boring mills, for example—might be used to relieve the laborious hand work of the conventional method. To make use of this accuracy, it was reasoned that templates could be made without any layout work by using a jig boring mill to drill a series of closely spaced holes whose edges would be tangent to the desired curve. It was realized that elimination of all manual layout would not only save labor but would result in template contours having jig boring mill accuracy.

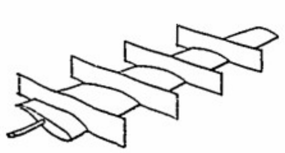
A means, of course, had to be found for determining the machine table settings for each hole in the series. Since a large number of holes might be required, determining the longitudinal and transverse table settings involved a large number of calculations.

Parsons Corporation had been confronted with similar computing problems previously—in design calculations for rotor blades—and had developed time-saving procedures for using standard IBM punched card machines such as had been used up to that time primarily for accounting and statistical work. It was, therefore, logical to apply these machines to this template work as well.

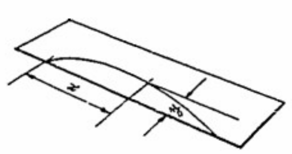


Manufacture and inspection of rotor blades . . .

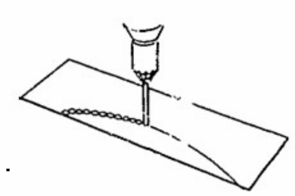
calls for templates at many "stations" along the blade.



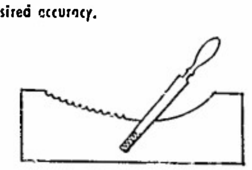
Ta reduce time-consuming hand layout work in making templates . . .



Parsons Corp. sought ta use drilling equipment ta produce a series af holes on a curve



which could be filed smooth by hand to desired accuracy.



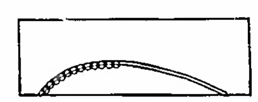
This was done, and it was found that a group of punch card machines could—from mathematical specifications of the curves for the airfoil sections involved—make all the calculations necessary for determining the boring mill table settings in less than ten minutes per template. This included the time required to print the table settings on a chart which served as the boring mill operator's information sheet.

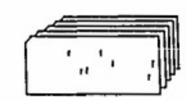
After drilling the holes the template maker had only to coat the edges of the holes—the contour line—with bluing and then file the scalloped edge down until the bluing was about to disappear. Time for hand filing was less than ten minutes per template and customary layout and gaging procedures were eliminated entirely. Spacing of the holes is controlled in the calculations so that the height of the scallops is pre-determined and uniform—generally to .002″. The result is that templates can be consistently produced without any layout work in tolerances of .001″ to .002″ at *any* point on the contour—using only standard machines—at lower cost than the old manual layout and filing method which cannot possibly yield the same accuracy.

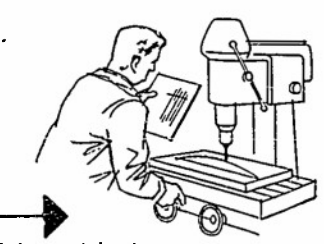
Since punched cards are used to "direct" or actuate the operation of tabulating and accounting machines, it appeared that devices could be developed to "read" punched cards and translate the instructions directly and automatically into precise mechanical movements of a machine tool table—manual operation and chance of human error being completely eliminated.

Early in 1947, Parsons Corporation took the next basic step: the conception of a machine control device which would receive its instructions from the punched card itself, thus eliminating the "translation" of punched card data back into written tabulations or instructions for the boring mill operator.

And so the idea for *"Digitron"* was born.







Ta speed up calculations af table settings, standard punch card computing techniques were used . . .

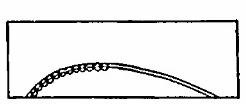
to convert the curve specifications into sets af co-ordinates far the hole centers, which were then tabulated by machine . . .

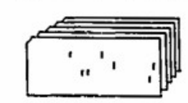
and the printed tabulations used by the machine operator far manual positioning af the work table.

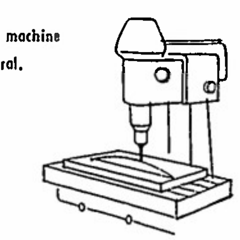
This procedure led to the final concept af deriving hole center co-ordinates fram the original specifed curve . . .

and using the punch cards themselves . . .

to direct or actuate a sequence af machine tool movements without manual control.







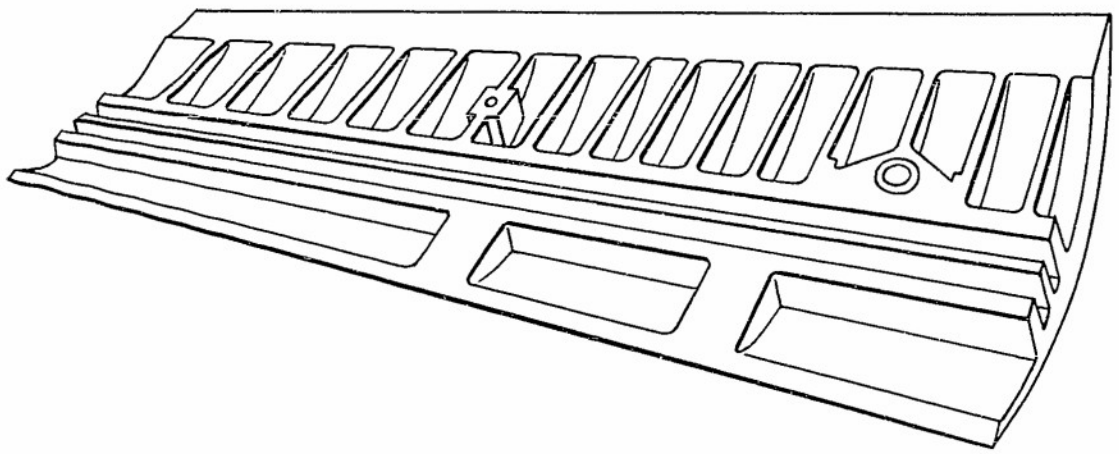
THE WING PANEL PROBLEM

Concurrently with the Parsons template problem, another more complicated problem was giving concern to aircraft designers and builders: the integrally-stiffened wing, which designers wanted to "carve from the solid" instead of building up from individual ribs, spars, stiffeners, sheet metal skins and rivets. The problem of machining such structures was complicated by three factors:

(1) They often tapered both in plan and thickness.

(2) They were often too large to be accommodated by existing die making and duplicating machines.

(3) Accuracies closer than obtainable on existing machines were required.



An analysis of this vast problem led to the realization that while the machine tool industry had made great advances in building ruggedness and accuracy into a wide range of machine tools, this accuracy was often lost due to the human element involved in *transferring dimensions from blueprints or engineering specifications to the machines,* in which cases the built-in accuracy of the machine tool itself was wasted. It was realized that all machine tool control systems designed to follow a curved path were basically dependent on cams, templates, models, or other mechanical devices, the accuracy of which, in turn, completely depended on manual layout at some point in their creation.

It was then reasoned that if a method could be found to eliminate the manual layout operation completely—both in tooling and production—the built-in accuracy of machine tools could be used to the fullest extent, and the mating parts of large assemblies could be relied upon to fit accurately—even in the case of large wing panels composed of a hundred or more separate sections.

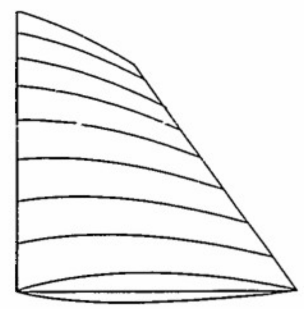
Furthermore, it appeared that the Parsons technique as originally conceived for two-dimensional control in making templates, could be applied as well to three-dimensional control which would be necessary for machining irregular surfaces.

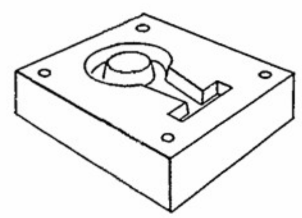
THE PROPOSAL

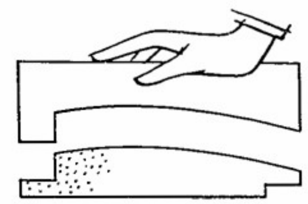
This basic idea was presented in April 1948, to personnel at Air Materiel Command, Wright Field, Dayton, Ohio. It was welcomed as providing a possible answer to an urgent problem; for it was clear at that time that the demand for increasingly large wing panels would soon exceed the capacity of equipment then in existence or even in the design stage.

A contract was awarded Parsons Corporation to study the design problems involved in making an experimental machine which would produce contoured surfaces from instructions prepared in the form of punched cards—and thus eliminate the time-consuming operations involved and the element of human error inherent in the making of models, templates, and other gaging devices, and would reduce the chance for error which is inherent in all visual gaging procedures.

Consideration was also given to the probability that very large forging presses would someday become available for volume production of large aircraft structures, at which time facilities for making large dies would be called for. Consequently the experimental machine was to be designed to produce forging dies as well as parts for aircraft prototypes.



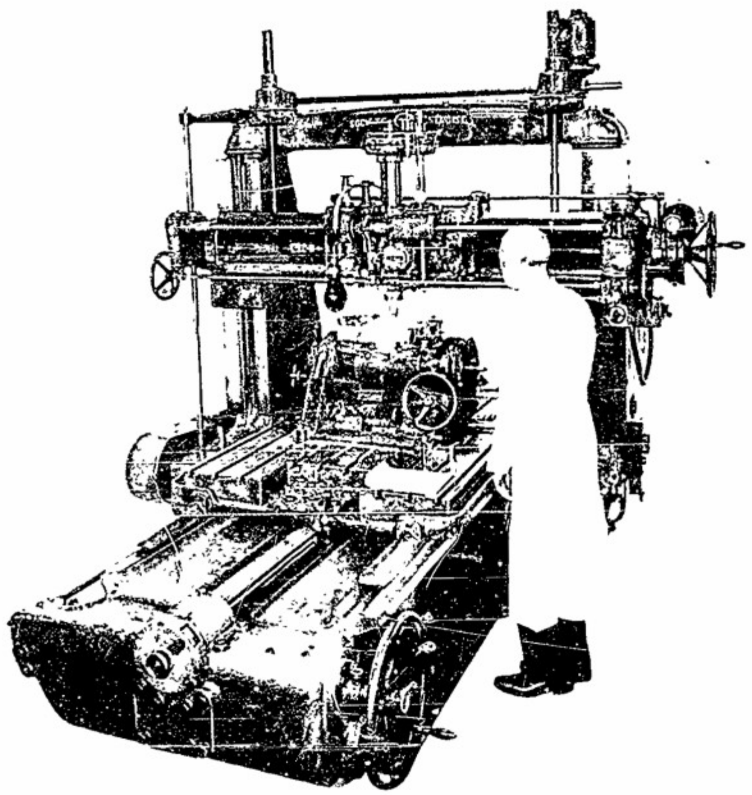




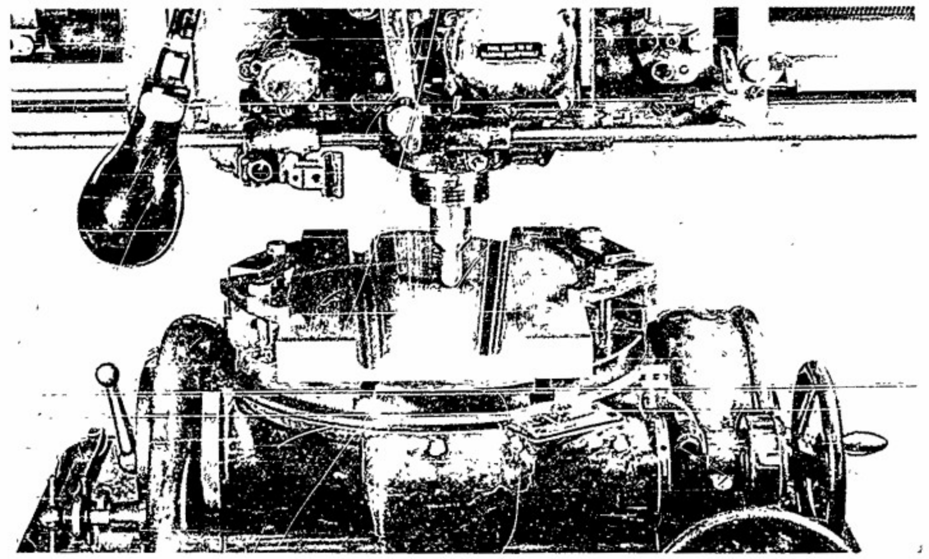
FIRST STEPS

It was first contemplated to design and build a machine similar to a bridge-type planer milling machine with a universal table (which could be moved both vertically and horizontally, and in addition tilted, to position the work piece) so that a series of straight line cuts could be made to produce airfoil or other "warped" surfaces. For each cut, or pass of the cutter, the work piece was to be automatically positioned by instructions contained in a single punched card. Further study of this plan revealed that punched tape would simplify some of the design problems, provide better insurance against loss or disarrangement of the cards, and at the same time provide a faster means of feeding instructions to the machine.

To demonstrate the possibility of machining wing panels by this method, a small scale wing, tapering both in plan form and airfoil section was machined on a standard Swiss boring mill equipped with a universal table. The operator was given a diagram showing the starting position for the machine, and also a punched card tabulation of machine settings for each of the series of cuts necessary to machine the complete part. Then, to demonstrate further the soundness and accuracy of the system, a template was produced on another boring mill while the wing panel was being machined. Template and wing panel matched within .0015″.



Operation of a Swiss boring mill with the use of tabulated co-ordinates



Study had revealed that if the machine were to follow the punched tape instructions faithfully, a means would have to be provided for actual table movements being reported back to the control system, to confirm the fact that the instructions had been properly carried out. Devices which perform this function—"reporting" back to the control source and confirming the completion of a specific instruction—are called servomechanisms, and are now widely used in automatic pilots, gun fire control, and a variety of other control systems.

Because the Servomechanisms Laboratory at the Massachusetts Institute of Technology had long been pioneering in the field of electrical, mechanical, and hydraulic control systems, a proposal to participate in the project was extended to M.I.T. in 1949, and was accepted. The work done at the Servomechanisms Laboratory under their subcontract with Parsons Corporation had the following objectives:

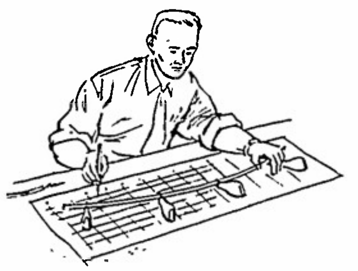
(1) Development of a method of "coding" punched tape to minimize the amount of tape required and to provide "checking" features to minimize errors in the event of equipment failure.

(2) Development and designing of electronic equipment to "read" the tape, convert the instructions to electronic signals and use these signals to control mechanical movements of table and/or cutter in longitudinal, crosswise and vertical travel simultaneously.

(3) Modification of an existing tracer-controlled milling machine (a Cincinnati Hydro-Tel Die Milling Machine from which the tracer control had been removed) for use with the experimental control system, to test the system, and to point the way for future development work.

(4) Demonstration that it will be technically feasible to build and use machine tools employing punched tape control.

CONVENTIONAL METHODS



Production of irregular shaped parts or forging dies by conventional methods calls for two- or three-dimensional models to be used on duplicating machines or for more laborious procedures of using templates and manually operated die sinkers. In making three-dimensional models, templates must be made at various sections of the model, the number of the sections or "template stations" depending on the complexity and accuracy requirements of the finished part. The templates of course must be laid out, cut, and filed manually. Their accuracy depends on the number of co-ordinate points established in the layout, and the skill of the template maker in fairing or connecting the points with smooth curves.

Even with extremely accurate templates to check the model, the areas which lie between the template stations must be carved by hand and checked visually—for no other means of inspection is possible.

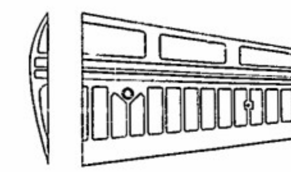
Once the model is made, conventional machines can reproduce the model within accuracies of approximately .001″. However, hand finishing of the part or die is generally required, and elaborate gaging procedures are frequently necessary to insure desired accuracy.

Where models of mating parts are involved, separate sets of templates (male and female) must be used, and the possible accumulation of errors during the procedure presents a serious problem.

Aside from the problems of accuracy in this procedure, size limitations are imposed by the fact that duplicating machines generally require full scale models. Thus the machine must have a table for the model as large as the table provided for the work piece. Increasing the size of the duplicating machine to accommodate large parts of course adds to the difficulties of maintaining desired accuracy.

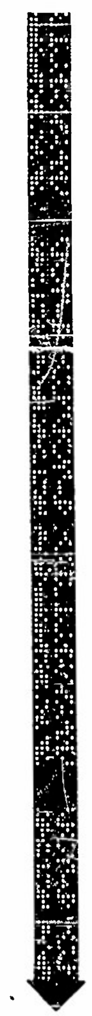
While important advances have been made in developing electronic and optical tracing devices to guide the movements of a duplicating machine cutter, these devices generally depend on guide lines laid out manually, and hence are subject to the same limitations of accuracy which exist for metal templates—the human element necessary to lay out and draw the guide lines.

WITH DIGITRON



No manual layout of templates or models is involved.

Conventional punch card calculating machines provide a rapid and reliable means of computing the paths the machine tool cutter must follow to produce the part. Computations are based on dimensions specified on the part drawing, or from mathematical formula which define the desired curves. The punch card computations are coded and transferred to a standard seven-channel punched paper tape ⅞ inch wide. The machine tool is equipped with a control system which "reads" the tape instructions and performs corresponding mechanical movements.



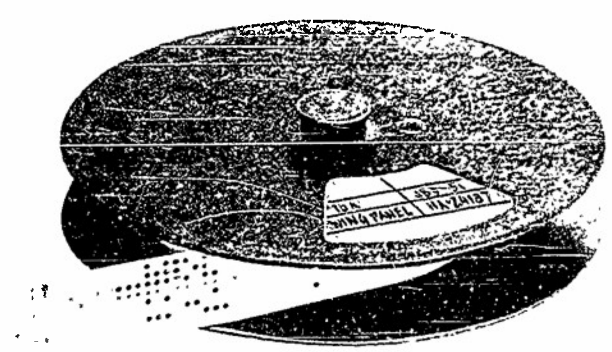
Variation in the paper tape due to temperature changes, etc., has no effect on the accuracy of the work. The tape can be moved or stored readily, and can even be duplicated in quantity if desired. Thus, the superiority of tape over cams or models as a source of machine control information is obvious.

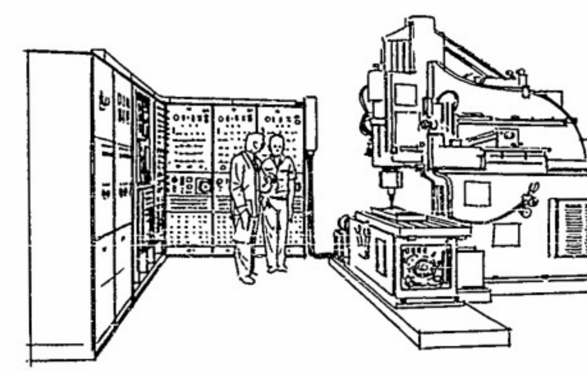
Limits of accuracy for the *Digitron* control system itself can be held within plus or minus .0005 inch. Final accuracy of the part will, of course, be subject to the limits of accuracy of the machine tool.

Size of the work presents no special problem for *Digitron* control. Since no physical model is involved, *Digitron* control can be applied as readily to a large machine as to a small one, although the control unit now being built would naturally have to be expanded if it were to be applied to a larger machine.

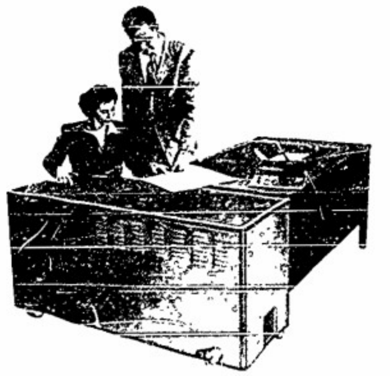
Consideration has been given—at the request of a prominent aircraft manufacturer—to the problem of machining a complete wing panel 60 feet long which had been assembled from detail components. The problems involved in machining work of this size with conventional duplicating machines are so great as to make the cost prohibitive. There is no forseeable limit to the size of work which can be produced with *Digitron* control.

At this writing, M. I. T. is continuing this development on a USAF prime contract. Below is shown an artist's conception of the milling machine as it will appear when finished at M. I. T.





COMPUTATION AND TAPE PREPARATION



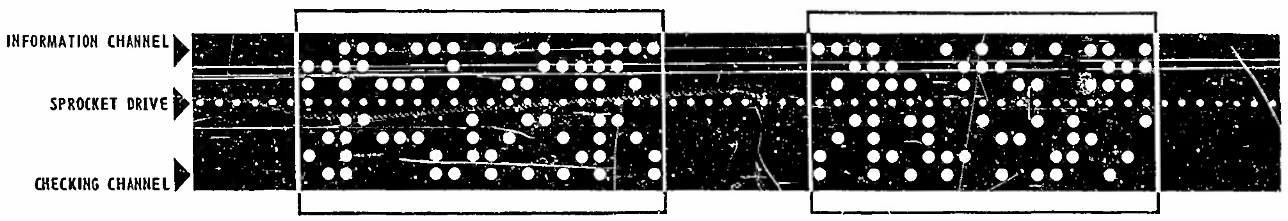
Digitron tape as now used in the demonstration machine is standard ⅞ inch wide paper tape used for automatic typewriters, with the exception that one additional row of holes is used. A section of tape is illustrated with two "blocks" of information. Each block specifies three "positions"—one position for each of the three axes of machine movements: longitudinal table movement, cross-wise travel of the cutter head, and vertical travel of the cutter head. Thus three "position channels" appear in each block. In addition, four rows of holes, punched automatically by the tape punch, are provided for checking purposes: to enable the tape reading equipment to detect and correct errors.

Each "block" defines a point on the surface to be generated; and any two "blocks" will direct the tool to move from one point to the next. Thus a section of tape only four inches long is sufficient for a single straight-line cut of any length within the capacity of the machine. Complex or warped surfaces would of course require more tape than simple ones.

The problem of converting blueprint data into tape instructions is basically a matter of geometry and mathematics. Since the axis of the cutting tool may assume positions different from the point or surface of cutter contact with the work, calculations must be made to "translate" co-ordinates of the surface to be machined into co-ordinates for the cutter axis. A variety of techniques on standard office-type punch card computers has been developed for these problems, which can now be programmed and solved readily. Many shapes may require only the use of a standard desk calculator.

Parsons Corporation has for four years used techniques for performing all the computations for a set of 45 templates for a helicopter rotor blade, in less than 10 minutes per template. In one demonstration, it was found that 26 lineal inches of punched tape were sufficient to program a series of 19 cuts.

The time required for computations varies considerably for different types of work. However, experience has shown that computation and tape preparation time requirements, even for large complex surfaces, are well within reason. Certainly they represent only a small fraction of the time which would be necessary for construction and inspection of models, assuming it were physically practical to make full-size models to do equivalent work.



A FEW DEFINITIONS

On the following pages, a description of the *Digitron* control as it exists in the demonstration model is presented. Since some of the system components are special-purpose devices, the reader may welcome at this point an explanation of terms as used in this description.

Punched card computers: calculating machines which receive their "problems" in the form of punched cards. The patterns of holes in the cards stand for numbers, which are read and processed according to a "program" of multiplication, division, etc. The answers may be provided in the form of punched cards which are later tabulated or translated back into written numbers by tabulating machines. Such machines are now commercially available through International Business Machines Corporation and others and are widely used in routine or special computation work.

Tape punch: a machine which punches tape in accordance with instructions inserted manually with a keyboard, or automatically from a punch card machine. Tape punching equipment of several kinds is now commercially available.

Data storage register: an electrical device which receives numerical data in the form of electrical impulses in groups of quantities specified in the punched tapes, and stores them in readiness for later use. Such devices are generally designed and built for individual applications.

Synchro: a type of motor. Where two synchro motors are connected, moving the shaft of one motor causes the other to move "in synchronism" with it.

Servo-mechanism: a control system which continuously compares its output (result) with input (instruction) and keeps the difference at all times within a small specified value. Servomechanisms make use of mechanical, electronic, pneumatic, hydraulic, and other components or combinations of components and are generally engineered for individual applications.

HOW DIGITRON WORKS

1 From drawings or dimensional specifications for a part or die . . .

2 Dimensions are tabulated and put on punched cards . . .

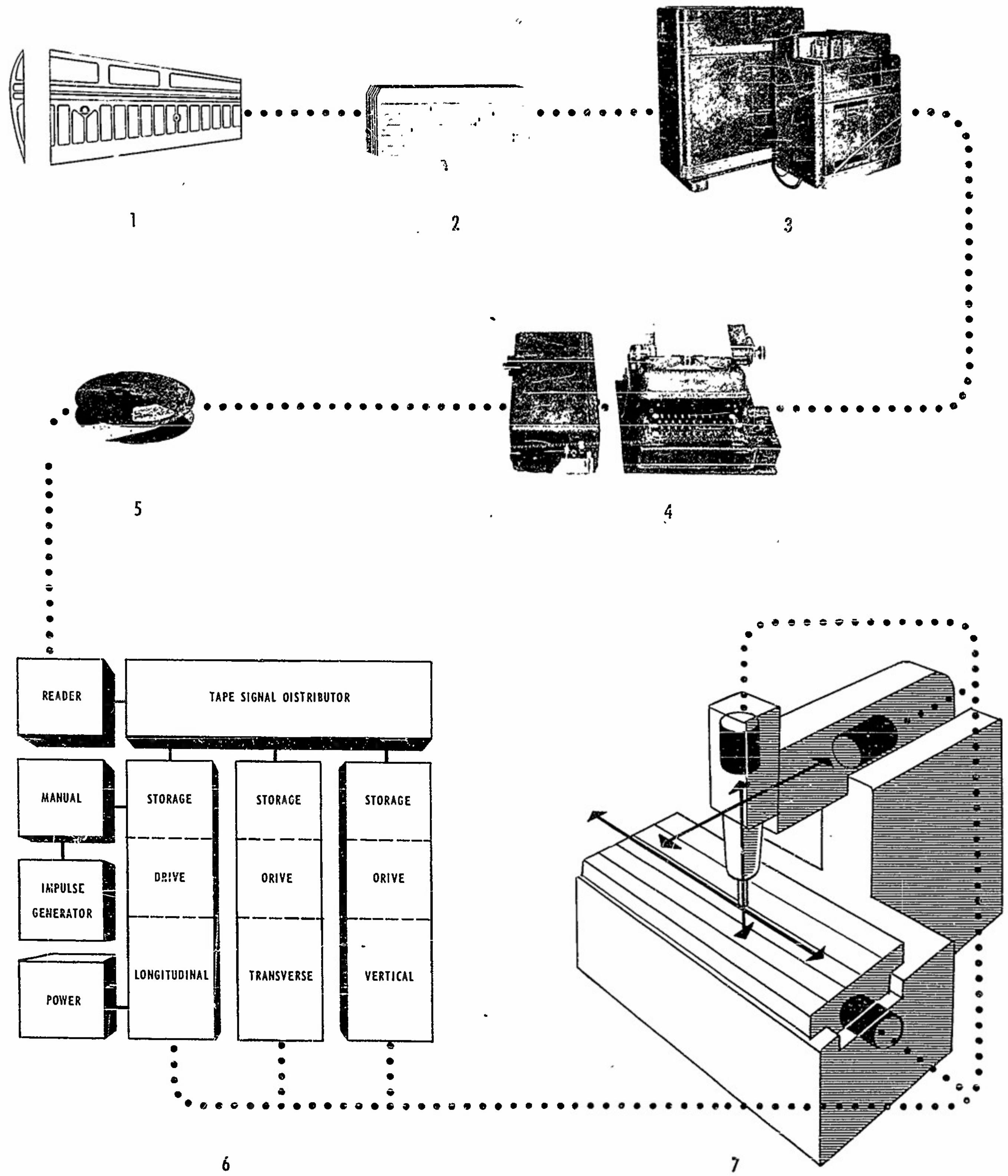
3 Which are processed on a standard business machine type computer to calculate the desired positions and movements of the machine tool to complete a prescribed sequence of machining operations.

4 The calculations are then transferred from punched cards to punched tape. In the development stage, this is a manual keyboard operation; however, existing equipment could be modified to perform this operation automatically.

5 The punched tape contains—in convenient, compact form—all the data necessary to direct the movements of the machine tool. The data in tape form is not subject to dimensional variations as are physical models or templates. It can be stored or moved readily for use at anytime on a *Digitron* controlled machine tool. Furthermore, duplicates of an "original" tape can be made accurately and quickly if it is desired to produce the same part on a number of *Digitron* controlled machines.

6 The tape is placed in the *Digitron* tape reader in the master control panel. Once the work piece has been mounted on the machine table and positioned for the first cut, the machining operation can begin and will progress automatically until the prescribed work has been completed.

7 Three axes (or directions) of movement of the machine can be controlled simultaneously and automatically with *Digitron*. In addition to responding to "position" instructions to make the cutter follow prescribed paths, *Digitron* can also control rates of feed automatically during a machining cycle—in response to "rate data" on the tape itself. In addition to controlling movements in three directions, angular movements of the cutter head or work table could also be provided with additional *Digitron* control systems.



FOR THE TECHNICIAN

As the *tape reader* scans the tape, the three "positions" are "read" simultaneously from one "block" or section of tape, and transmitted to *storage registers*. One storage register is provided for each axis of the machine. In the schematic on the following page the components for only the longitudinal (table feed) control system are shown.

The storage register retains a single "position" at all times in readiness for transmission to an array of relays which regulate, or meter, the flow of electrical impulses. A steady source of electrical impulses is provided by a special generator.

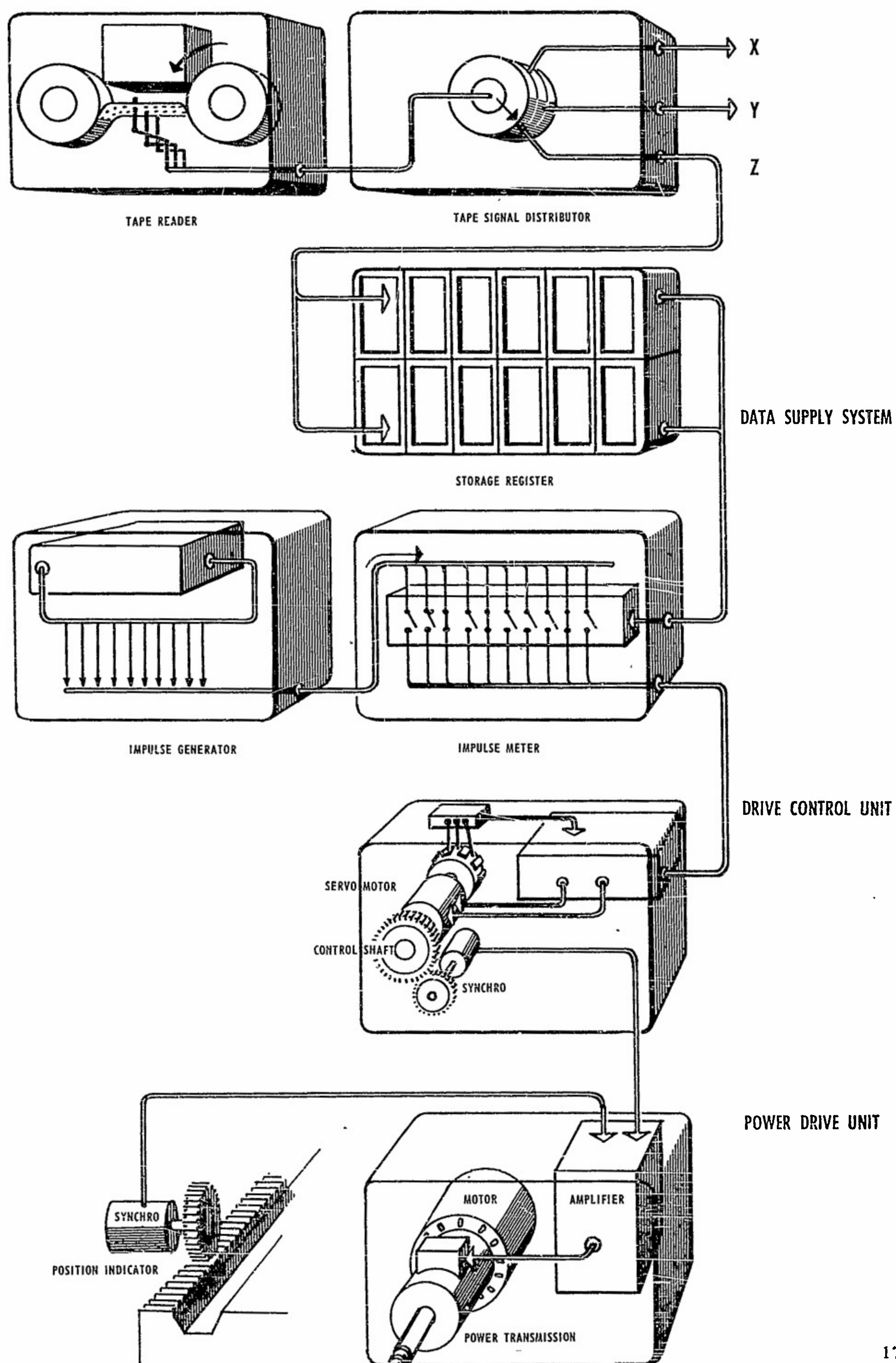
The system is arranged so that each impulse allowed to pass through the *"impulse meter"* will cause a table movement of .0005 inch. By providing for as many as 500 impulses to be transmitted per second, a movement of 500 times .0005 inches—or .250 inches per second is obtainable. This is equivalent to a feed rate of 15 inches per minute, which was selected as being best for this first unit. Feed rate can be doubled by doubling the allowable tolerance, or other units can be designed to provide for higher speeds.

We now have a "chain" of electrical impulses, their number being proportional to the desired movement. These are transmitted to the *drive control unit,* which responds by rotating a *control shaft* through an angle proportional to the number of impulses.

Rotation of the control shaft produces so-called "response" impulses. A special counting device called a summing register continually compares the number of response impulses with the command impulses, and thus insures correct rotation of the *control shaft.*

The machine power drive consists of a constant-speed motor connected through a variable speed transmission to the leadscrew. The control shaft in the drive control unit specifies the *desired position* to which the machine table is to move. A position indicator on the machine table indicates at all times the *actual position* of the table in relation to a definite reference point. All difference between *specified* and *actual* position is measured continuously, and this difference (measured as a voltage) is used to control a torque motor which in turn allows the variable speed transmission to turn the leadscrew and move the table.

The first demonstration model of the *Digitron* controlled milling machine is designed to follow tape instructions accurately within plus or minus .0005 inch. Because table movements are controlled by the difference between actual (measured) positions and specified positions, leadscrew errors do not affect accuracy of the part.



A LOOK TO THE FUTURE

While *Digitron* was originated to solve a two-dimensional template manufacturing problem, and is now being demonstrated on a conventional vertical milling machine, a number of other potential applications appear of equal or even greater promise. Let us consider a few of them.

Production milling machines for producing forging dies. A *Digitron* equipped machine would not remove any more pounds of metal per horsepower than any other machine. It would, however, remove metal continuously and rapidly, eliminating the need for interruptions to check progress with templates. Since work could be programmed to take the largest practical cuts (considering cutters, materials, and accuracy) it follows that time for machining forging dies with *Digitron* would be considerably less than customary. Furthermore far less bench work would be required before the dies were ready for the hammer or press.

High-speed planer-type milling machines for aircraft wing panels, spars, etc. Relatively high table feed rates in the longitudinal axis might be provided, with slower rates in the other axes. Control of angular movements of the table and/or tool have also been considered. In any event, the use of cams or models would be completely eliminated, thereby reducing set-up time and increasing net production per machine.

Drilling and boring machines might incorporate *Digitron* control of table or tool movements for performing a prescribed sequence of operations, possibly with provision for automatic interruptions of cycles to permit manual changing of tools. The demonstration machine is equipped with sets of selector switches which regulate table or cutter travel for specified distances. The operator sets a combination of switches calling for table movements equivalent to blueprint dimensions, then throws the starting switch, whereupon the work travels the desired distance, plus or minus .0005 inch.

Gaging devices or systems might employ the *Digitron* system working in reverse, so to speak, with the stylus traversing or scanning the work and translating the movements into printed tabulations of actual dimensions or deviations from specified dimensions.

Centralized Digitron control of several machines: a single *Digitron* control unit might direct a number of machine tools simultaneously or in sequence. Consideration has been given to *Digitron*-controlled and actuated tables as accessories for standard machines.

Digitron control of short, non-repetitive operations. Machine tools might be equipped with a keyboard and tape punch for the operator who might set up a machining "program" on tape, and do other work while the machine performs the operations without attention. Tape preparation, however, is apt to be the normal function of the engineering or tooling department, with the machine operator performing only those simple operations which can be controlled directly from switches.

Transmission of Digitron tape data. Since the punched tape is compact and easily portable, economies in computing and tape preparation might be effected by centralizing this function and having one organization process blueprints and provide punched tape for a number of different companies—in much the way that teletype news services now furnish coded punched tape which can be fed directly to typecasting machines. Telegraphic reproduction of the tape is also possible if desired.

Digitron control of manufacturing processes. Automatic control of processes in textile, chemical, and other industries might be developed employing continuous inspection of end results and coordination of many measurements which high-speed computers and tape-coded controls could facilitate.

Since the feasibility of actuating mechanical movements directly from blueprint dimensions—without models, guides, or human error—has now been demonstrated, we can look to the future with confidence that new applications for *Digitron* will be developed as rapidly as skills and imagination can make them both technically and economically practical.

DIGITRON

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