An Automatic Machine Tool

Feedback control has begun to advance in the working of metals. Presenting the first account of a milling machine that converts information on punched tape into the contours of a finished part

by William Pease

THE metal-cutting industry is one field in which automatic control has been late in arriving. The speed, judgment and especially the flexibility with which a skilled machinist controls his machine tool have not been easily duplicated by automatic machines. Only for mass-production operations such as the making of automobile parts has it been feasible to employ automatic machinery. New developments in feedback control and machine computation, however, are now opening the door to automatization of machine tools built to produce a variety of parts in relatively small quantities.

The problem will be clearer if we first review briefly the history of machine tools and their relationship to manufacturing processes. The story begins in the last quarter of the 18th century. Prior to that time the tools of the millwright, as the machinist of that day was called, consisted chiefly of the hammer, chisel and file. His measurements were made with a wooden rule and crude calipers. His materials were prepared either by hand-forging or by rudimentary foundry casting. Crude, hand-powered lathes were already in existence, but they were used only for wood-turning or occasionally for making clock parts.

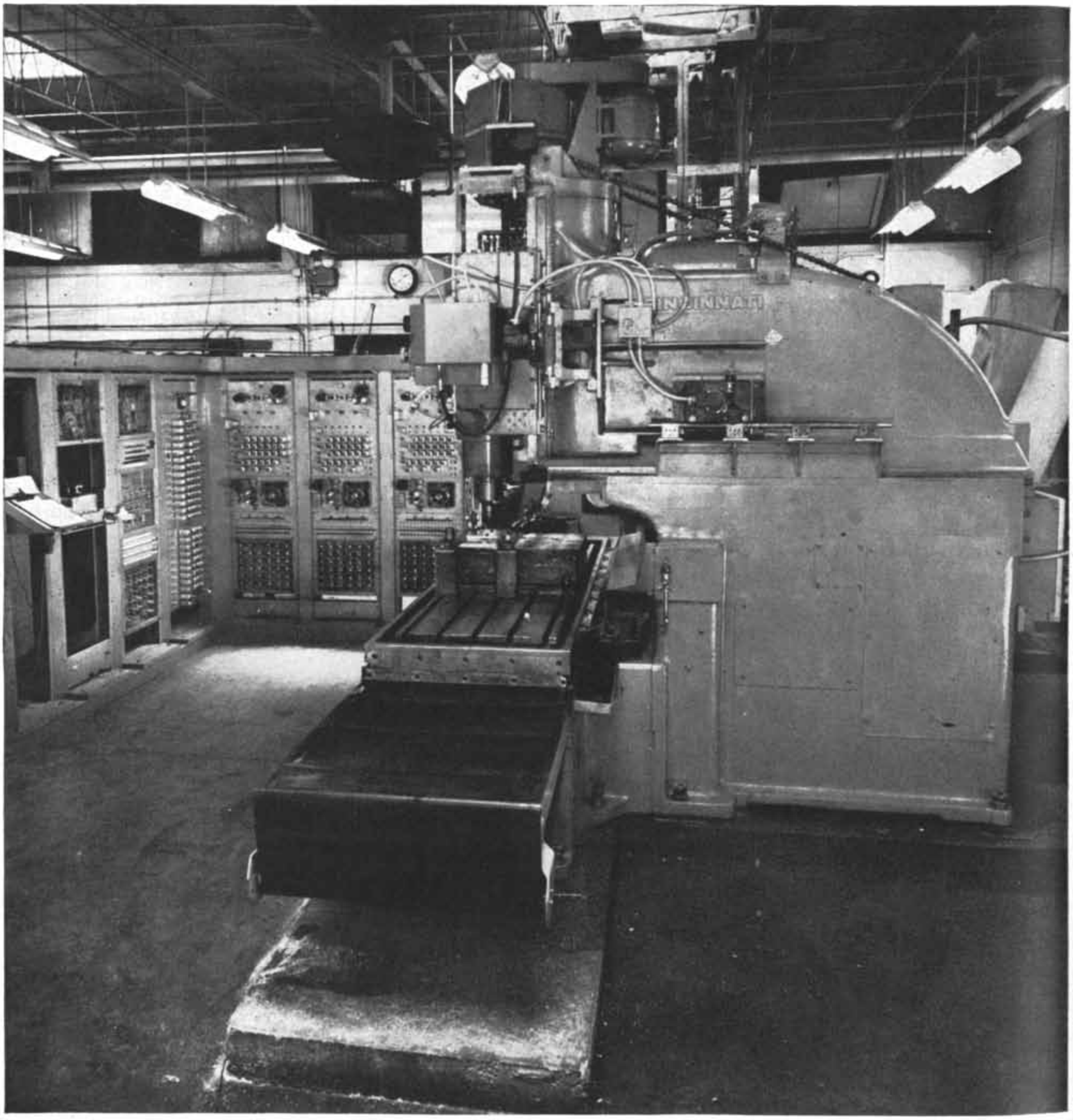
The first machine tool in the modern sense of the word was a cylinder-boring device invented in 1774 by John Wilkinson. Wilkinson is by no means as well-remembered as James Watt, but it was his invention that enabled Watt to build a full-scale steam engine. For 10 years Watt had been struggling vainly to turn out a cylinder true enough for

SAMPLE PRODUCT of the automatic machine tool described in this article is the cam shown at right. The instructions which direct the cutting of the cam from a square blank are encoded on paper tape.

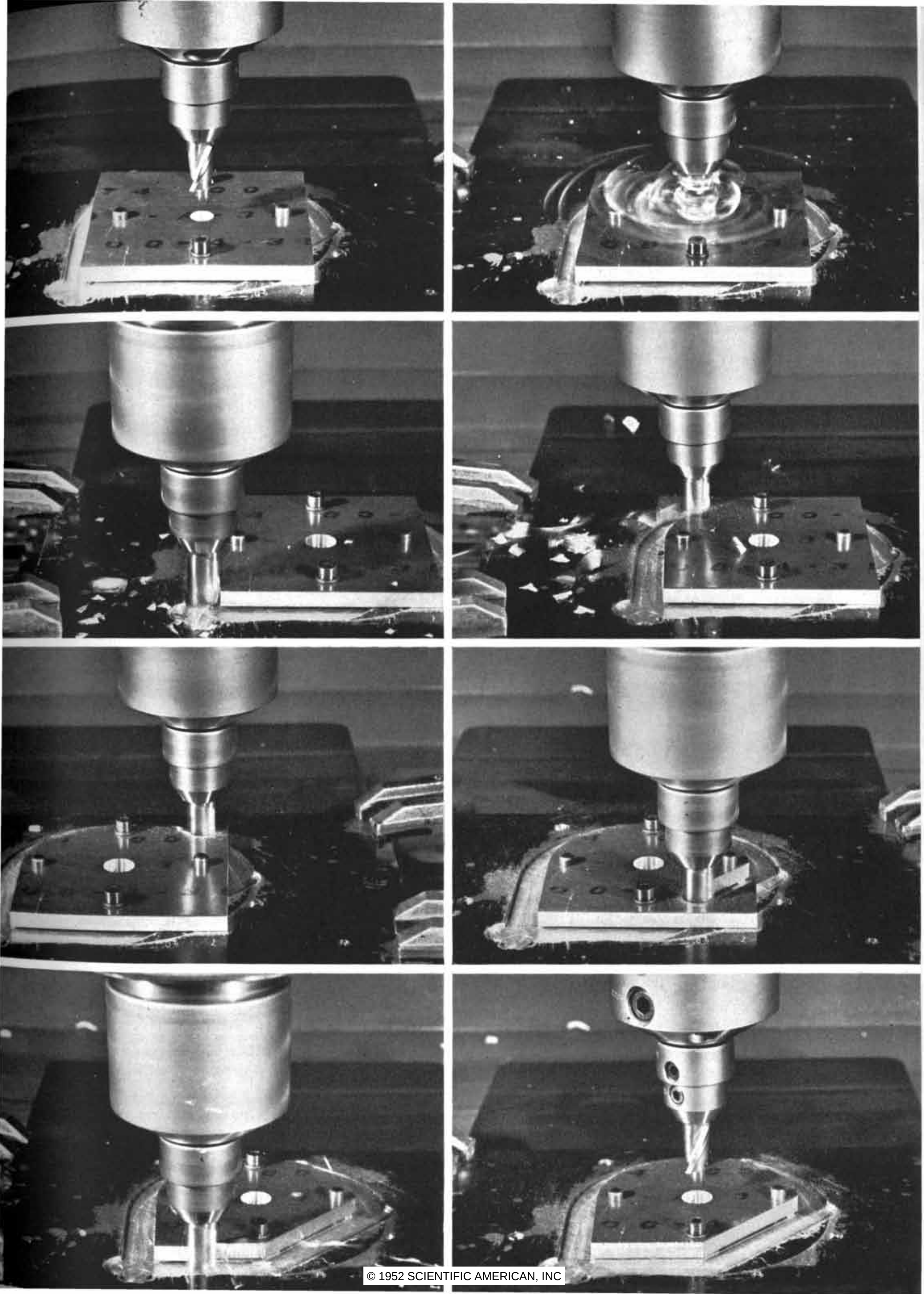
the job. After one effort he reported in discouragement that in his cylinder of 18-inch diameter "at the worst place the long diameter exceeded the short by three-eighths of an inch." But in 1776 Watt's partner, Matthew Boulton, was able to write: "Mr. Wilkinson has bored us several cylinders almost without error; that of 50 inches diameter, which we have put up at Tipton, does not err the thickness of an old shilling in any part." The importance of Wilkinson's boring machine cannot be overestimated. It made the steam engine a commercial success, and it was the forerunner of all the large, accurate metal-working tools of modern industry.

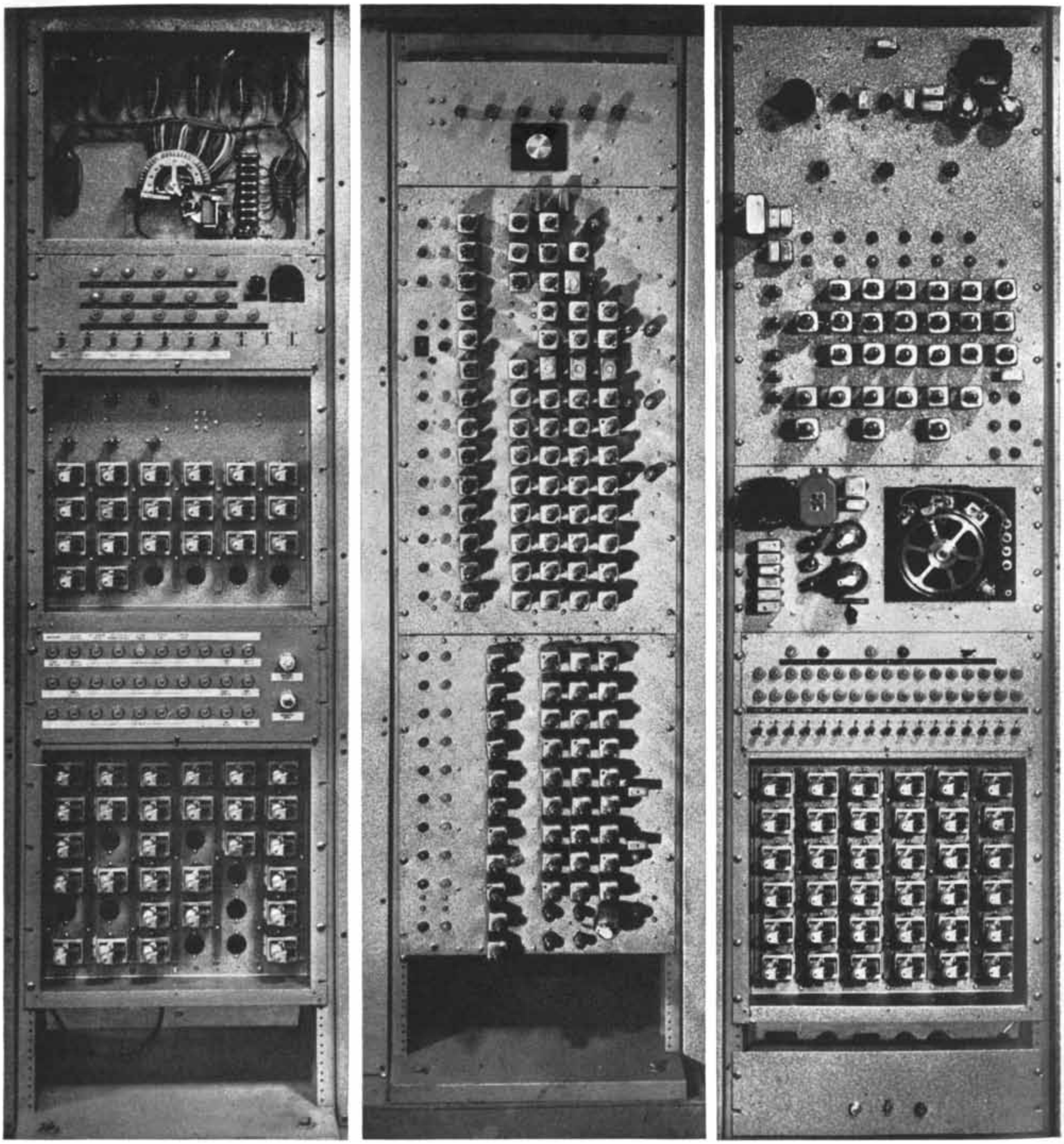
Another productive Englishman of the same period was Joseph Bramah. His inventions included one of the most successful locks ever devised, the hydraulic press, various woodworking machines, the four-way valve, a beer pump and the water closet. To manufacture his inventions he and an associate, Henry Maudslay, created several metal-cutting machines. The most significant of these was a screw-cutting lathe with a slide rest and change gears remarkably like our modern lathes.

THE NEXT great step forward in machine technology was pioneered by Eli Whitney. Although he is remembered mainly as the inventor of the cotton gin, his greatest contribution was an innovation of much more general import: interchangeability of manufactured parts. In 1798 Whitney, hav-



MACHINE AND CONTROL are shown here in entirety. For details of the control panels (*left*) see pages 104 and 105. The machine has universal motion: the "head," holding the cutting tool, moves vertically; the "cross slide" moves the head back and forth across table; the table moves from side to side under tool. The control system coordinates all three motions simultaneously to perform the operations shown on the opposite page.



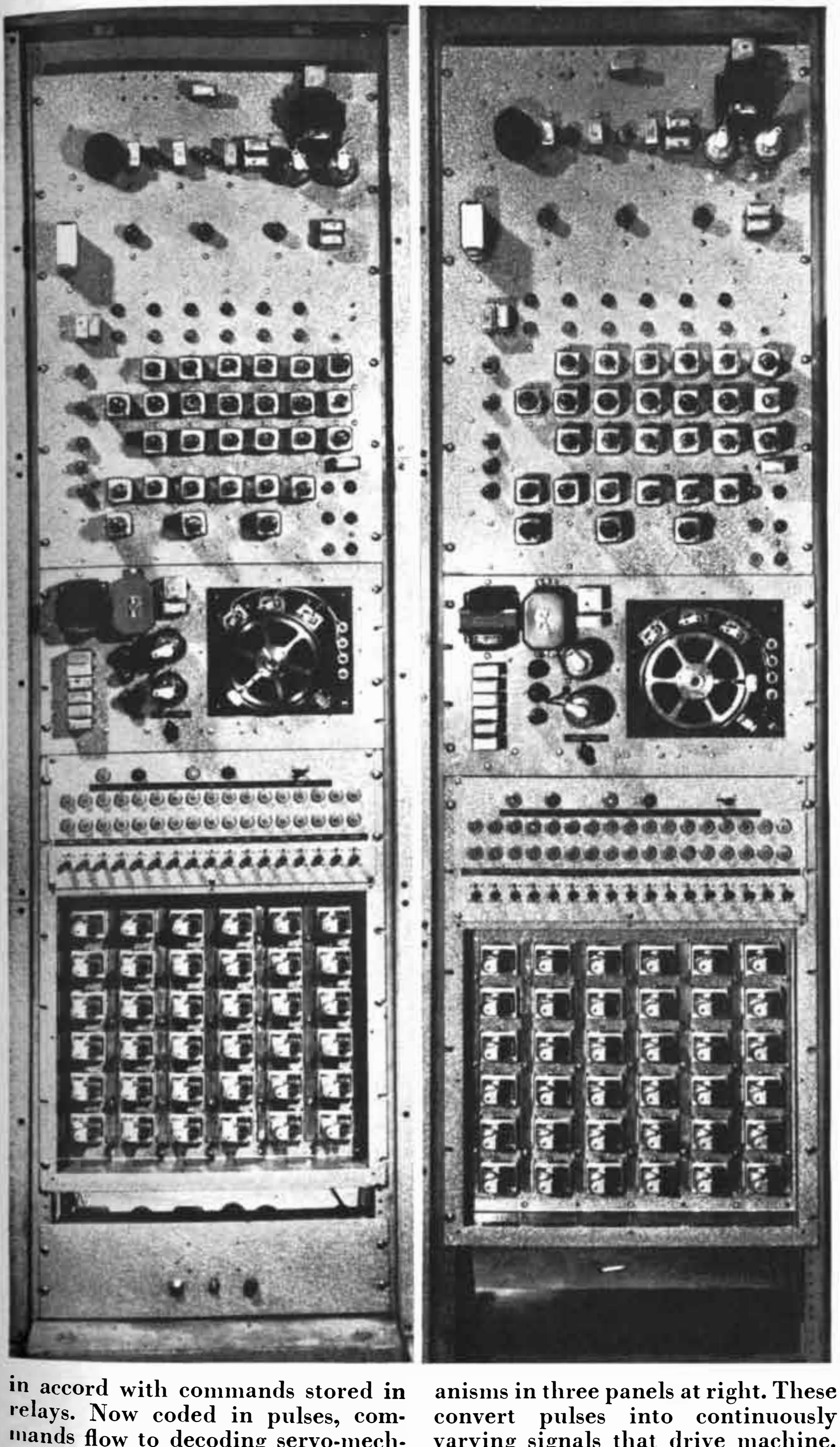


CONTROL-SYSTEM panel at left distributes commands to banks of relays in three panels at right, one for each motion of the machine. An electronic oscillator "clock" at top of second panel generates steady flow of pulses. These are blocked or passed on by flip-flop switches in data-interpreting system below clock,

ing made little money from the cotton gin, set up in New Haven as a manufacturer of muskets for the U. S. Government. He employed on this contract the interchangeable system of manufacture which was at that time still considered impractical by most experts. In fact, two years later it was necessary for Whitney to go to Washington to reassure the Secretary of War and officers of the Army that his idea was sound. Displaying 10 muskets, all tooled as nearly alike as he could make them, he showed that the gun parts could be interchanged among all 10 without affecting the guns' operability. He went on to prove in his New Haven shop that precision machinery operated by relatively unskilled labor could make parts accurately enough for interchangeability, so that expensive handwork was no longer required.

Whitney's idea was received with skepticism, but it eventually won out. Interchangeable manufacture is a fundamental principle of all quantity production as we know it today. Automobiles and washing machines, typewriters and egg beaters—every common machine we use is manufactured with interchangeable parts.

The two primary tools of interchangeable manufacture are the lathe and the milling machine. The modern lathe owes its form mainly to Maudslay, but about 1854 the addition of the tool-changing turret equipped the lathe and its cousin, the automatic screw-cutting machine, for interchangeable manu-

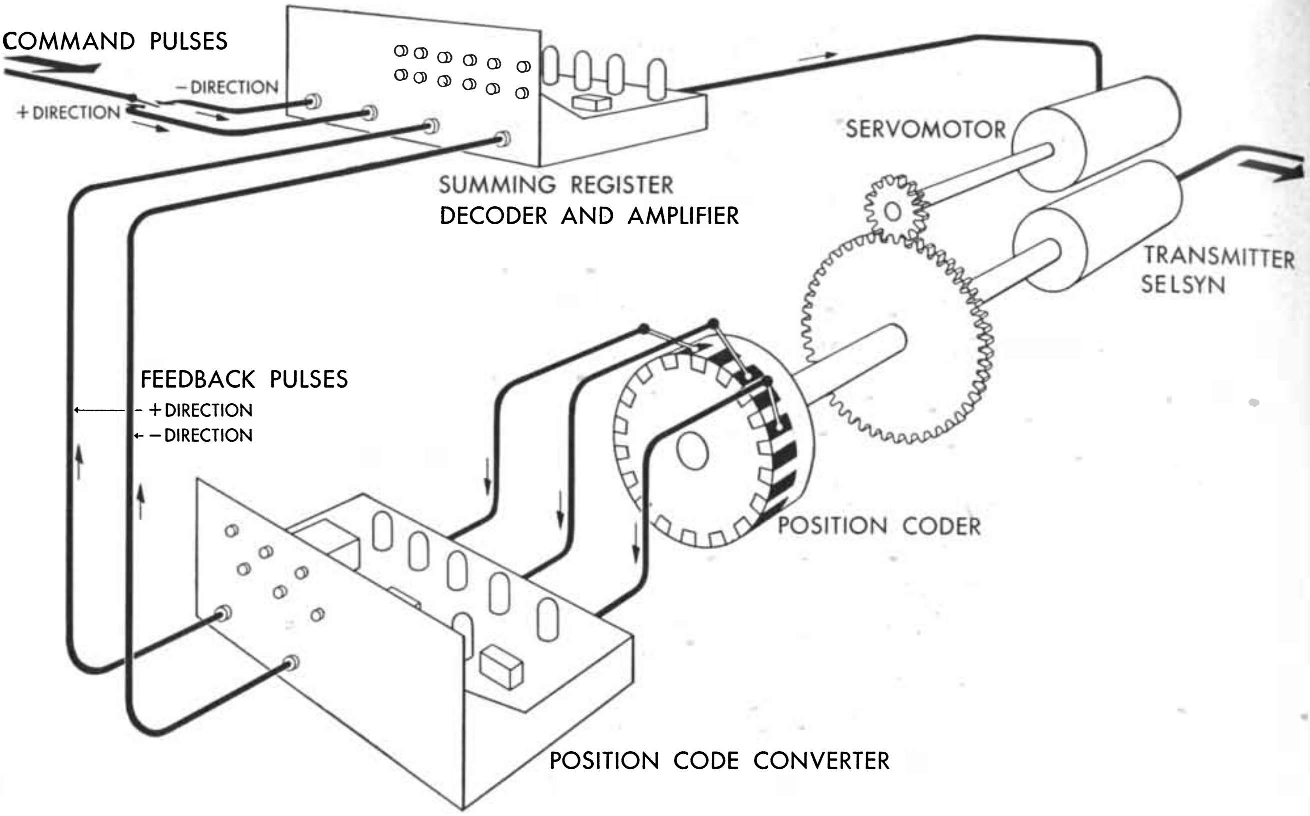


in accord with commands stored in relays. Now coded in pulses, commands flow to decoding servo-mechanisms in three panels at right. These convert pulses into continuously varying signals that drive machine.

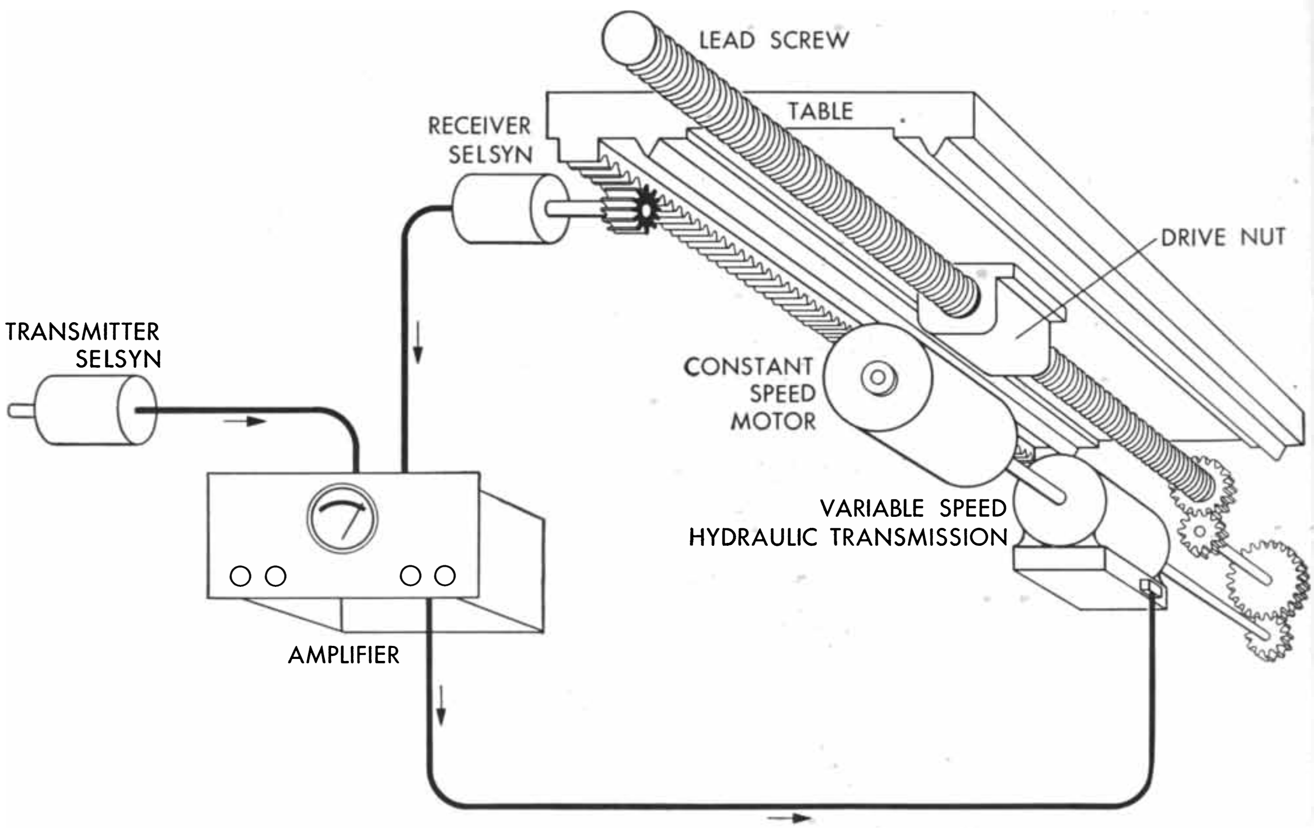
facture. The first milling machine suitable for interchangeable manufacture was built by Whitney. In 1862 the Providence inventor Joseph R. Brown developed the universal milling machine, the type in common use today. To these basic tools the 19th century added machines for drilling, punching, sawing and shaping metal.

In a sense the guides, tracks and other devices built into machinery to raise its precision level are a kind of automatic control. This type of automatism is no new concept in the metal-cutting industry. From the beginning machine tools were created to reduce the amount of human skill required in manufacture. These automatic aids to proficiency, always adhering to the double principle of accuracy for interchangeability and speed for economy, have increased through the years.

FLEXIBLE MACHINES, capable of manufacturing a wide assortment of parts, are an essential part of modern



DECODING SERVO-MECHANISM ensures that commands are correctly translated from pulse form into the analogue form of a varying shaft angle. Pulses from amplifier cause servomotor to rotate the transmitter shaft one degree per pulse. Rotation is sensed by brushes on position coder, which feed back one pulse to amplifier for each degree of rotation. Transmitter selsyn converts shaft motion into varying electrical signal.



MACHINE-DRIVE SERVO-MECHANISM ensures that commands in the form of a varying electrical signal from decoding servo-mechanism transmitter are correctly reproduced by the motions of the milling machine. Receiver selsyn under table at right feeds back to amplifier a signal corresponding to the motion of the table. This signal is compared with the transmitter signal and a corrected signal is sent to the table drive.

manufacturing technique. The reason why they have thus far been untouched by automatic control can be given in terms of the concepts of information flow and feedback control.

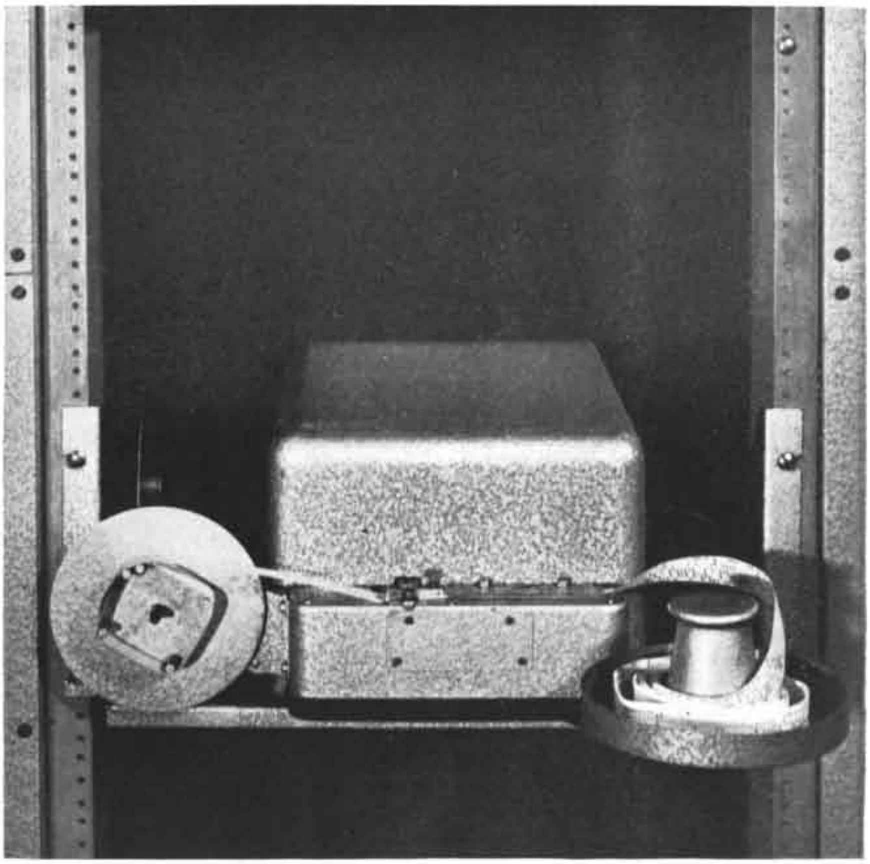
A rough measure of the cost of automatic control is the amount and nature of the information the automatic machine must handle. To perform a complicated operation such as manufacturing a metal part, we must build into the machine a great deal of information-handling capacity, for it has to carry out a whole complex of instructions. This initial equipment is expensive. If the machine is to manufacture only a single product, say an automobile crankshaft, in large quantities, the investment is spread over many items and the cost of each crankshaft is small. In such a case the automatic machine is worth its cost.

But suppose we want an automatic machine which will make not one particular product, or part, but a number of different kinds of products, and only a few of each—as the versatile machine tool must do. Now the machine must handle a different set of instructions for each product, instead of the single set of instructions for the crankshaft. In other words, it must be able to deal with more information. And the cost of the information-handling capacity needed for each product is spread over only a few items instead of many. This is the essential problem in automatizing machine tools.

Obviously one way to attack the problem is to economize in the information requirements of the machine for the various operations. What are these requirements? To begin with, the machine tool must orient itself continuously toward the material on which it is working; if it is to drill a hole in a piece of metal, it must drill the hole in the right place and to the right depth.

Early in their history machine tools began to acquire automatic feed mechanisms. Maudslay's screw-cutting lathe, which controlled precisely the distance that the cutting tool was advanced for each revolution of the work piece, was an expression of this principle. Another step toward automatization was Thomas Blanchard's invention in 1818 of the "copying" lathe for turning gunstocks—the first of a class of tools now known as "cam-following" machines. This type of tool is automatically oriented to machine irregular shapes. The information required to specify the irregular shape is stored in a cam built to represent that shape. An important weakness of these machines is that all the force required to position the cutting tool is furnished by the cam itself. It is costly to build a mechanism strong and accurate enough to transfer motion from the cam to the work piece, and the cam wears out.

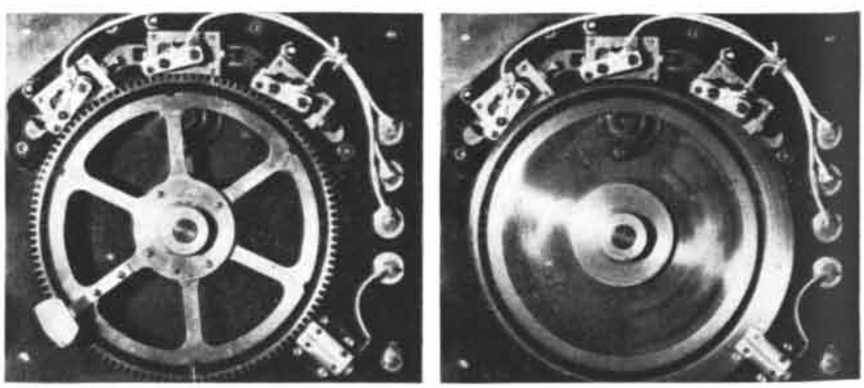
Feedback control made its first sig-



TAPE READER transfers commands from paper tape to relays in control system. Each punch hole closes a relay. Paper tape is not subject to dimensional instability which afflicts cams and other analogue controls.

nificant entrance into the machine-tool field in 1921, when John Shaw, working in the shop of Joseph Keller, invented the Keller duplicating system. In this system the information source is not a cam but a plaster-of-paris or wood model of the part to be machined. An electrical sensory device traces the model shape and transfers the information to the tool. By permitting the use of soft, easily fabricated models, the method reduces the cost of information storage. Modern versions of the duplicating system are embodied in the die-sinking machines of the Pratt & Whitney Division of the Niles-Bement-Pond Company. An hydraulic form of it was originated by Hans Ernst and Bernard Sassen at the Cincinnati Milling Machine Company in 1930. Since World War II a number of manufacturers have developed systems of this kind, employing a variety of electrical, mechanical and optical devices.

A further step in the reduction of the cost of information storage and



POSITION CODER translates the continuous rotation of the decoding servo-mechanism shaft back into pulse code. As the wheel spins, electrical contacts around its rim close circuits with brushes mounted above.

transfer is promised through the use of digital information processes. A number of applications of digital processes to machine-tool control are currently being made. Let us look in detail at one of the most ambitious of these completed this year at the Massachusetts Institute of Technology.

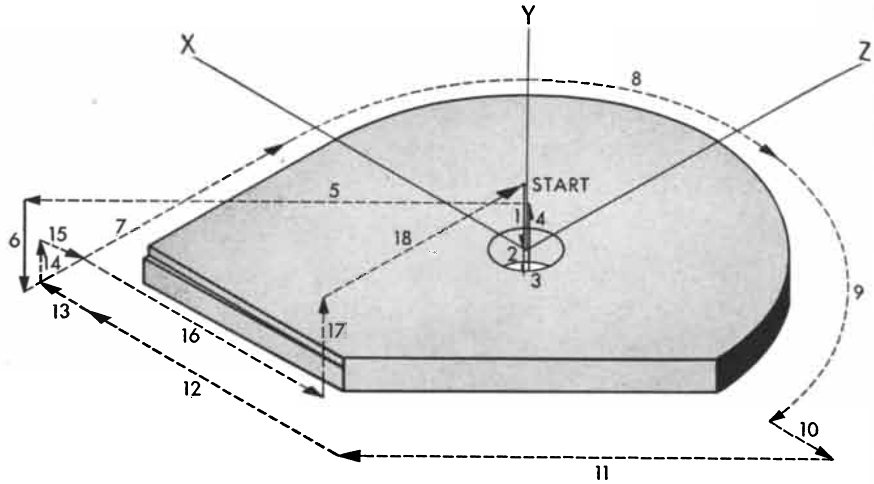
THE M.I.T. system combines digital and analogue processes under feedback control to govern a milling machine whose cutting tool moves in three planes relative to the work piece. In this case the "model" of the object to be fabricated is supplied to the machine in the form of a perforated paper tape similar to that used in teletype systems. For a typical operation, 10 feet of tape will keep the machine busy for an hour.

The components of the M.I.T. system are grouped into two major assemblies. The first of these, called the "machine," comprises the milling machine itself, the three servo-mechanisms employed to operate its moving parts, and the instruments required to measure the relative positions of these parts. The second assembly, called the "director," contains all the data-handling equipment needed to interpret the information on the tape and to pass it on as operating commands to the machine. The director contains three major elements—a data-input system, a data-interpreting system and a set of three decoding servo-mechanisms.

The purpose of the data-input system is to take the original instructions off the tape and feed them into the interpretive and command elements of the director. It consists of a reader, whose metal fingers scan the tape and report the presence or absence of holes by electrical signals, and a set of six relay registers (two for each of the basic machine motions) which store and transmit this information in numerical form. The registers are supplied in pairs, so that while one of them is in control of the machine, the other can receive information from the tape. At the end of each operating interval, command is transferred instantaneously from one register to the other.

The data-interpreting system picks up the numerical instructions stored in the registers and transmits them as pulse instructions to the decoding servo-mechanisms. These pulses are generated by an electronic oscillator, the "clock," which acts as the master time reference for the entire system. By means of a series of flip-flop switches, and in accordance with the instructions stored in the registers, these pulses are sent on to each of the three decoding servo-mechanisms.

Up to this point in the process, information has been handled in digital form. The three servo-mechanisms now convert the instructions to the analogue

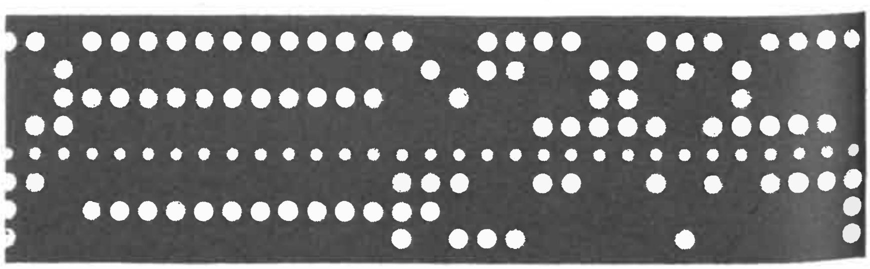


WORK LAYOUT breaks down cam-cutting operation into separate steps for encoding on instruction tape (*below*). Instructions for each motion of the machine may be computed directly from the engineering drawings.

form required by the machine tool. Pulses from the data-interpreting system are translated into the rotation of a shaft—one degree of rotation for each pulse. The shafts are connected to synchro transmitters which are themselves connected to the drive servo-mechanisms of the machine. A feedback circuit, inserted at this point in the director, makes certain that the conversion from digital to analogue information has been accurately carried out. It works as follows:

The mechanical element of each decoding servo-mechanism consists of the shaft connected to the synchro transmitter, a unit called a "coder" and a small two-phase induction servo-motor with appropriate gearing. The coder generates a feedback signal in the form of one electrical pulse for each degree of shaft rotation. The number of these feedback pulses is then compared with the number of pulses emanating from the data-interpreting system by a device called a "summing register." If the two counts agree, the summing register is at zero; if they do not agree, an electric voltage is generated and the two-phase servo-motor rotates the shaft to bring the count to zero. Thus a feedback path makes certain that the output shaft position faithfully corresponds with the series of command pulses from the frequency divider. Information, coded first on tape, converted to digital and then to analogue form, is now transmitted to the working elements of the machine.

Each motion of the machine is accomplished by a lead screw driven by a hydraulic servo-mechanism (*see diagram on page 106*). The motor converts electrical commands received from the decoding mechanisms into the mechanical motions of the machine. Feedback is again introduced at the point of actual cutting to make certain that each element moves according to the instructions of its own decoding mechanism. A standard synchro receiver is coupled to each of the moving elements of the mill in such a way that each .0005 inch of tool travel causes the shaft of the synchro receiver to rotate one degree. The feedback signal derived from this shaft position is compared with the shaft position of the synchro transmitter at the decoding mechanism. Any difference of position between the two shafts appears as an alternating-current voltage which controls the speed of the hydraulic transmission. Thus the ma-



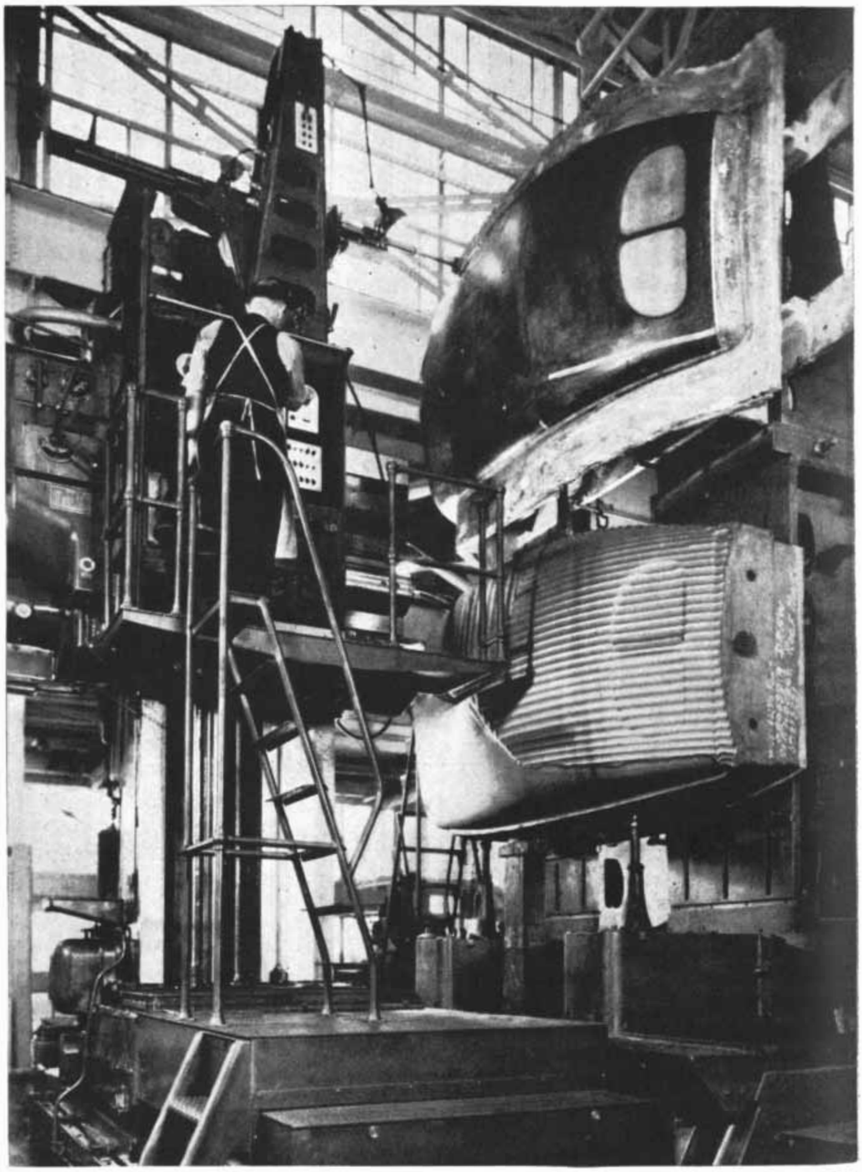
TAPE encodes commands in punch holes. The three lower horizontal rows contain commands for cross-slide, head and table motions, from top to bottom. Small holes in center engage sprocket drive of tape reader; four upper rows contain checking signals. The vertical line of four holes at either end and middle are "block" signals dividing commands into steps as shown in work layout above. Commands are for steps 6 and 7.

chine element follows continuously the rotations of the synchro transmitter in the ratio of .0005 inch of linear travel to each degree of rotation.

How ARE the instructions for the machine's job put on the tape? The desired path of the cutting tool over the work is reduced to incremental straight-line segments; the segments are specified by numbers, and these are then translated into a code which can be punched on the tape.

The cutting path and the speed at which the work is to be fed to the machine are based on a number of factors: the amount of stock to be removed, the sequence of the machining operations, the setup of the work on the machine, spindle speeds, and so on. After the human operator determines the locus of the cutter center which will produce the desired cutting path, he divides the locus into a series of straight-line segments. They should be as long as possible without differing from the ideal tool-center locus by more than the machining tolerance. The dimensions of each straight-line segment are then resolved into components parallel to each of the three directions of motion of the machine. For each straight-line segment, a time for execution is chosen to produce the desired feed rate. All this—the cutter motions and the time—is tabulated in a predetermined order to form a single set of control instructions. A separate set of instructions is made for each segment, in the order in which they will be used by the machine. The instructions, translated into patterns of holes, are punched in the paper tape by a special typewriter keyboard.

By inserting a new reel of tape for



KELLER MACHINE shapes die for an auto top. Via a feedback loop, contour follower on surface of model at top guides cutting tool on work below.

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each job to be performed, the milling machine can be converted from one manufacturing task to the next with little more effort than is required to change a phonograph record. And for every job that a given machine has ever performed, there is left a permanent record, in the shape of a tape containing full instructions. Another great advantage of the machine is that it produces continuously; unlike a machine tool run by a human operator, it does not need to be stopped for periodic measurements and adjustments.

THE PERFORMANCE of this M.I.T. model shows that fully automatic machine tools are not only possible but are certain to be developed in practicable form. It is surely startling (how much more startling it would have been to Maudslay and the other pioneers!) to think of versatile machine tools which

single product. Huge investment must be written off on mass production.

will perform any kind of work without the guidance of a human hand. The possible economic effects of such machines, on many industries besides metal-cutting, are beyond prediction. Automatized general-purpose machine tools, combined with high-production special-purpose tools, would make possible the automatic metals-fabricating factory. Nor are we restricted to metals. With digital machines in control we can conceive of factories which will process, assemble and finish any article of manufacture.

It is unlikely that the automatic factory will appear suddenly. Like the machine tool itself, it will just grow by steps until eventually it is here.

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