A Numerically Controlled Milling Machine

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A MILLING machine which is controlled by numerical instructions is now in operation at the Servomechanisms Laboratory of the Massachusetts Institute of Technology. Figure 1 shows the entire system. The machine tool is located at the right of the picture and the control equipment is housed in the L-shaped structure at the left. The controls, which employ approximately 270 vacuum tubes, 170 telephone-type relays, and 300 germanium diodes, have been arranged on vertical panels for maximum accessibility of all parts.

Operation

In the operation of any milling machine, the complete path of the tool over the work must be controlled. In the machine shown, the path of the tool is controlled by instructions from punched paper tape. New instructions are provided whenever the direction of the path changes. Each instruction will cause the tool to move from one specified point on the work to the next along a straight line, and also will prescribe the time interval which is to be consumed in executing that straight line. The straight lines are generated by a suitable combination of the three orthogonal motions of the machine tool (the table, the head, and the cross-slide), which form a Cartesian coordinate system. One may then state the input-output relationship of the system as follows:

Input. Numerical specification of the x, y, and z components of the motion which the tool is to execute and the time interval required for that motion.

Output. Straight-line motion of the tool from where previous instructions have placed it to the newly specified point.

The flow of information through the system is shown in Figure 2. The machine instructions are read from punched paper tape under supervision of the control circuits and routed via stepping switches to the appropriate storage relays. Storage is shown as divided into three assemblies, one collecting the instructions for the table of the milling machine, one the instructions for the head, and one the instructions for the cross-slide. Each assembly can store two commands, called the A and B numbers. As the A number controls the machine, the B number is being read in from the tape so that when the A number has been executed, the B number is fully assembled in storage and ready for use. Upon switching control to the B number, the next instruction is read in from the tape and stored in the relays which had been cleared upon completion of the original A command. By thus alternating between the two registers, continuous control of the machine is achieved.

The next step in the flow of information consists of generating a set of three pulse trains, one for the control of the milling-machine table motion, one for the control of the head motion, and one for the control of the cross-slide motion. Each pulse train consists of as many pulses as are specified in the instructions and each is distributed over the same interval of time, also specified by the instructions. These three pulse trains are generated by the pulse generator and distributor shown in the center of Figure 2.

Finally, the three pulse trains are translated into three machine motions. This operation involves two steps. Step 1 is carried out by the decoding servomechanisms which translate the pulse trains into shaft rotations. Step 2 is carried out by the power servomechanisms located remotely at the machine tool proper, and consists of transmitting the shaft rotations and translating them into linear motions of the machine ways.

The units of greatest interest are the pulse distributor and the decoding servomechanisms. The remainder of the system is sufficiently conventional to require no further discussion.

Pulse Distributor

Consider first the single flip-flop shown in Figure 3. The flip-flop is so connected that it changes its state with every input pulse. If the flip-flop is initially assumed to be in the 0 state, then all the odd input pulses cause the flip-flop to switch from 0 to 1, and all the even pulses cause it to switch back from 1 to 0. By connecting a differentiating circuit to each of the tube plates, one output will give a positive pulse for the 0 to 1 transition, and the other output will give a positive pulse for the 1 to 0 transition. The pulse generated by a 0 to 1 change is called a non-

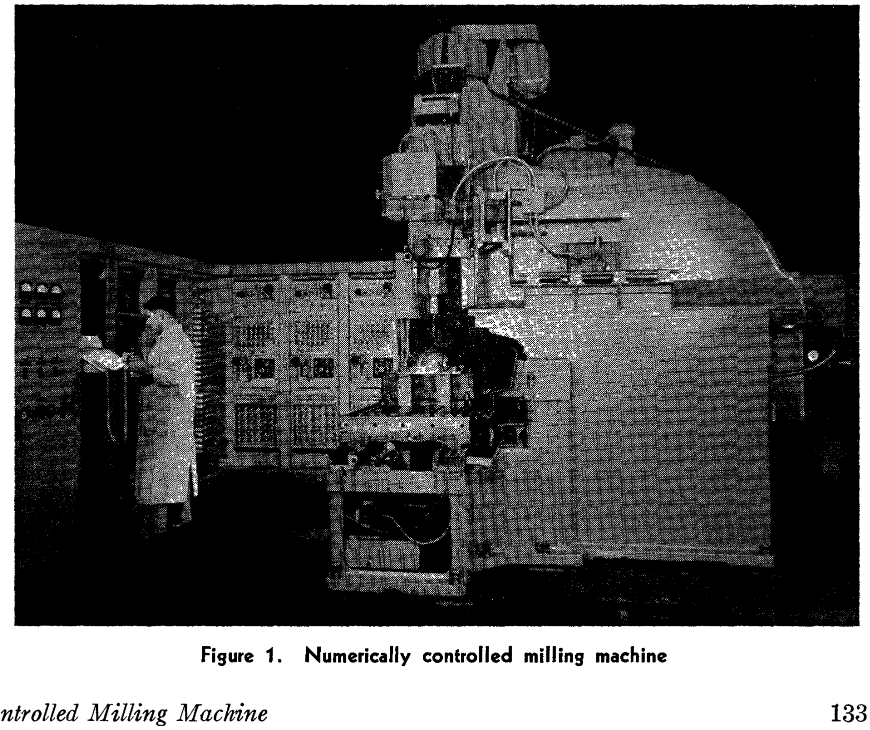

Figure 1. Numerically controlled milling machine

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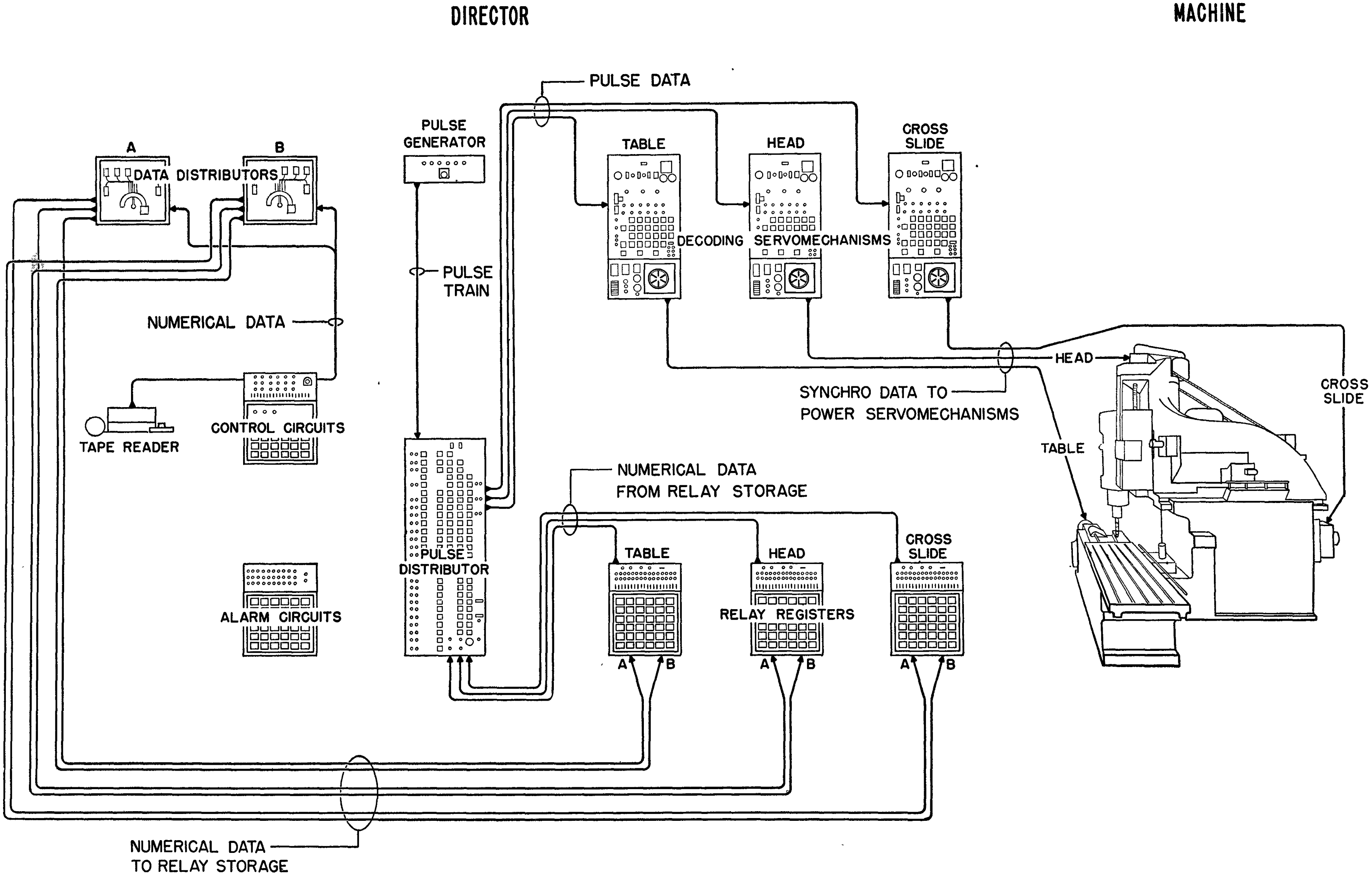


Figure 2. Flow of information

carry pulse. Hence, a noncarry pulse is generated for every odd input pulse, and a carry pulse is generated for every even input pulse.

Consider now a set of three flip-flops interconnected as shown in Figure 3, that is, the carry pulses from each flip-flop are connected to the input of the next flip-flop and the noncarry pulses appear on the vertical lines still not designated. If the remarks made in connection with the top flip-flop are now kept in mind, it is readily verified that when eight pulses appear at the input to the 3-stage counter, four (1,3,5,7) appear at the noncarry output of the first stage, two (2,6) appear at the noncarry output of the second stage, and one (4) appears at the noncarry output of the third stage. The addition indicated in Figure 3 shows that of the eight input pulses to the counter, seven are recovered on the noncarry lines. It can also be observed from Figure 3 that the noncarry pulses from the various stages never coincide in time. It will be shown later that this is a most valuable feature.

If the end-carry pulse is used to stop the input to a counter having S stages and the counter is originally preset to 0 it receives exactly 2^S pulses at the input. Of these, 2^{S-M} pulses are recovered at any one stage on its noncarry line, where M indicates the serial number of the stage. Since the noncarry pulses from the various stages never coincide in time, it is possible to mix, that is, add, the outputs in any combination to obtain the desired number of output pulses. The largest number of pulses that may be so obtained from 2^S input pulses is 2^S-1. For example, the 3-stage counter of Figure 3 supplies five pulses if the outputs of flip-flops 1 and 3 are mixed.

The pulse distributor used in the director of the numerically controlled milling maching utilizes the type of interconnection just discussed. Consider first only the main part of the distributor, shown in Figure 4. Here, a 10-stage counter similar to the previous 3-stage example is drawn. The 10-stage counter has a capacity of 2^{10} or 1,024 input pulses. The input of the counter is shown connected to a 512-pulse-per-second source, so that the counter will give an end carry every 2 seconds. During every 2-second interval, the noncarry outputs can supply a maximum of 1,023 pulses, of which 512 appear at the output of the 10th flip-flop, 256 appear at the output of the 9th flip-flop and so forth. These pulses are generated regardless of the particular instructions to the machine. We will call them potential command pulses.

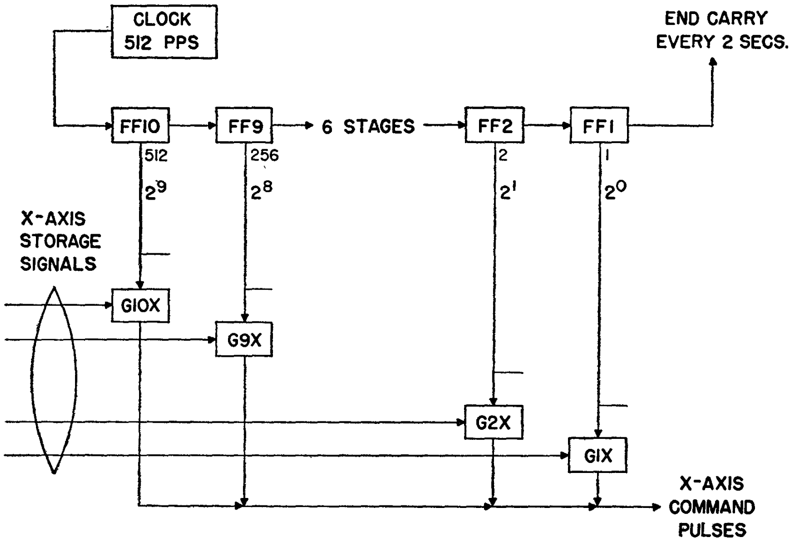


Figure 4. Basic pulse distributor

Actual command pulses for a decoding servomechanism are derived from the potential command pulses by gating the outputs of the flip-flops. For example, if the desired pulse train is to contain 515 pulses, gate $G10$, $G2$, and $G1$ pass pulses from their respective flip-flops, while $G3$ to $G9$ are cut off. The gating signals for the gate tubes are the commands which are held in storage. The resulting deviation from a uniform pulse repetition rate is subsequently smoothed in the decoding servomechanism.

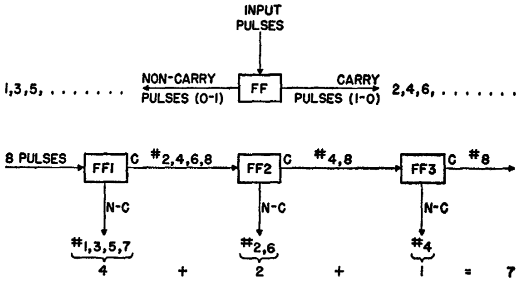
For the sake of simplicity, Figure 4 shows only the X-axis gate tubes. The Y- and Z-axis gate tubes have one input connected where the horizontal bars are shown and the other input controlled by the Y and Z storage registers in a manner identical to that discussed for the X axis.

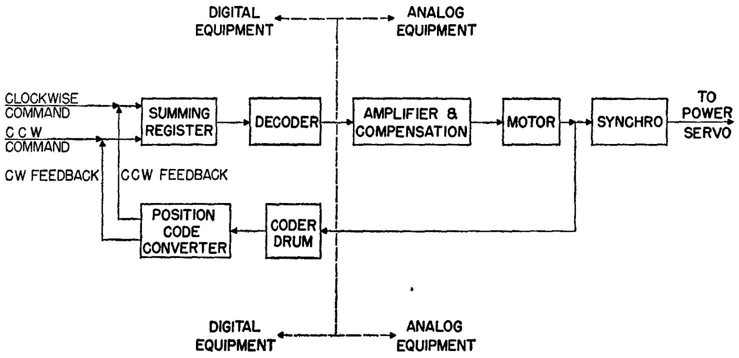
The pulse distributor used in the system differs from the one shown in Figure 4 by the addition of seven flip-flops (numbers 11 through 17) which are connected ahead of flip-flop 10. Clock pulses are gated to any one of the eight flip-flops numbered 10 to 17. If the clock pulses are applied to flip-flop 11, for example, an 11-stage counter results which gives an end carry every four seconds and decreases the pulse repetition rate at each of the flip-flops 1 to 10 by a factor of 2. By thus selecting the number of counter stages used, the following two results are achieved:

1. The average pulse repetition rate of a given desired command pulse train can be varied by factors of 2, hence the time required to execute a given command can be made to be 2, 4, 8, 16, 32, 64, 128, or 256 seconds.

Figure 3 (below). Flip-flop connections

Figure 5 (right). Decoding servomechanism





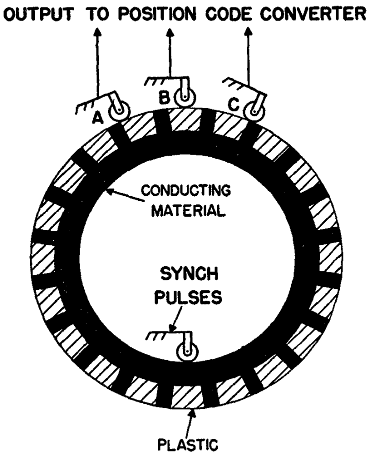


Figure 6. Coder drum

Decoding Servomechanism

The operation of the decoding servomechanism, shown in block diagram form in Figure 5, can be seen by considering an example. Let us assume that there is a train of input pulses on the clockwise-command line. As each pulse arrives, it is added to the contents of the summing register, a reversible binary counter. The new contents of the summing register cause a change in the output voltage of the decoder. The output of the decoder is amplified and drives the motor.. A coder drum, to be described, turns with the motor shaft and sends out a pulse for every degree of rotation. These pulses are interpreted by the position-code converter which, since the motor is turning clockwise, sends out the pulses on the clockwise feedback line. Pulses on the clockwise feedback line reduce the count in the summing register. When there are as many feedback pulses as there are command pulses, the count in the summing register is zero, the decoder voltage is zero, and the motor stops.

The dynamic elements of this servomechanism were designed to provide minimum bandwidth consistent with reasonable transient-response specifications. The purpose of this approach was to provide maximum smoothing of the slightly irregular output from the pulse distributor.

A simplified drawing of the coder drum is given in Figure 6. Since the summing register handles both command pulses and feedback pulses but cannot add and subtract simultaneously, it is readily recognized that command pulses and feedback pulses must never coincide in time. For that reason, all pulses originating from the coder drum must be derived from a train of pulses generated externally and known never to coincide with possible command pulses. A source of such pulses, called synchronizing pulses, is connected to the input of the coder drum and applied to a commutatorlike ring by the roller shown on the inside of the drum. Hence, the synchronizing pulses are available at any of the teeth, which are separated by an insulating plastic. For the configuration shown in Figure 6, the synchronizing pulses appear continuously at output roller *C*. If the drum now turns clockwise, the next roller to make contact is *A*, and further motion results in roller *B* making contact with the commutator. For counterclockwise rotation starting with the configuration shown in Figure 6, the next roller to make contact with the commutator is *B* followed later by *A*. Hence, for this rotation the sequence is *CBA*. Thus *C* followed by *A* implies clockwise rotation, *C* followed by *B* implies counterclockwise rotation, and *C* followed by *C* implies no rotation. Similar statements can be made about any other sequence of events.

Having now examined the operation of the coder, the rule for interpreting its output can be stated as follows: Identify the sequence in which the output pulses from the three rollers occur and decide if it represents clockwise, counterclockwise, or zero motion. The interpretation of the outputs of the coder is carried out by the box called position-code converter in Figure 5. While the interconnections are complex, only three flip-flops and six gate tubes are used in the unit.

Programming

The steps in the preparation of the instructions for the Massachusetts Institute of Technology machine include determination of the desired tool path over the work, reduction of that path to incremental straight-line segments, numerical specification of the end points of the segments, translation of the specification into a form which can be punched on paper tape, and, finally, perforation of the tape.

In more detail, the programming procedure is as follows. On the basis of the drawings and specifications of the part to be machined, the desired cutting paths and feed speeds to be used in machining the work are determined. Since this determination involves the conventional decisions as to cutter type, sequence of machining operations, setup of work on the machine, and so forth, it requires a sound knowledge of machining practices.

The locus of the tool center which will produce the desired cutting paths is next determined by making proper allowance for the geometry of the tool. This locus is then divided into a series of straight-line segments. The segments should be as long as possible without differing from the desired tool center locus by more than the machining tolerance. Each straight-line segment requires a separate instruction. Hence, the longer the segments, the smaller the number of instructions. As the segments need not be parallel to the machine ways, their dimensions must be resolved into components parallel to each of the three orthogonal motions of the machine. The time to be consumed in executing each straight-line segment at the desired feed rate is then specified. The foregoing steps vary in difficulty of computation with the particular part to be made. They can be reduced to routine computations for many useful types of work.

Finally, the three components and the time interval for each segment are coded and punched on paper tape.

The computational and coding steps can frequently be performed by machines. The use of digital computers in programming becomes particularly advantageous in those cases where the work surface can be conveniently described in terms of equations. Several parts have been machined on the numerically controlled milling machine which were programmed by Whirlwind I, the digital computer developed at Massachusetts Institute of Technology. Whirlwind I is capable of supplying at its output tapes which can be used directly to machine parts. International Business Machines (IBM) equipment also has been employed in programming. Equipment modifications are planned which will permit the use of IBM-prepared instructions without further processing.

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2. Depending upon the number of counter stages used, the command numbers may have a length of from 10 to 17 digits.

Discussion

A. Liebersohn (Government Division, Philco Corporation): What is the possibility of receiving better tolerances than 0.001 inch?

Mr. Susskind: In a process of this nature, the only thing that limits the accuracy of the machine parts is the basic tolerances in the machine tool proper. Any slop in the gibs of the machine, any misalignment of the ways, any tool wear will show up in the finished work. We are not considering this system as being applicable only to a milling machine, but we feel it has a great many applications entirely unrelated even to machine tools. If you give me a Swiss jig borer and we agree to put it in an air-conditioned room, the chances are we might get work better than 0.001 inch. We have always been able to make the control information more accurate than the machine tool.

Mr. Liebersohn: What is the possibility of controlling power servos directly from digital data?

Mr. Susskind: Briefly, we feel that it is not economical to tie up a large-scale computer, like our Whirlwind, with a little machine tool in another building. This would be inefficient. We have tried to strike a reasonable compromise between the computing ability within the machine tool and that which is external to it. The present machine is equipped only to carry out linear interpolation. We left the machine control very stupid, giving it new instructions whenever it changes direction. The division into a decoding servo and a power servo was dictated by development considerations. It is entirely possible to have a single closed loop rather than two closed loops in cascade.

Mr. Liebersohn: What is the time response of the power servo in terms of the resonant frequency?

Mr. Susskind: It is, roughly, 3 cycles.

Summary and Forecast

S. N. ALEXANDER

I WOULD like to call attention to the significance of the theme chosen for this year: the characteristics of the input-output systems and the equipment that has been incorporated into several typical electronic digital computing systems. Pertinent auxiliary equipments needed to supplement the input and output functions in approaching a fully automatic data-processing system have been covered in the conference. The choice of this theme and the enthusiastic response given this choice are indicative of the tempo at which digital data-processing equipment is being extended from a specialized tool solely for the scientist into equipment that is going to be extremely useful to the managers of commercial, industrial, and governmental activities. A few remarks regarding the forces that have been at work accelerating this trend may be of interest.

A similar conference held in Philadelphia in December 1951 created the assurance that arithmetic, control, and fast storage functions had been achieved by more than one approach. Furthermore, it appeared that these basic units had exhibited initial reliability that was fully as unexpected as it was gratifying. Because there had been many discouraging delays in the progress of the first computer projects, it was natural that the completion of machines which performed reliably should engender great elation. In fact, in this elation, a certain development tended to be overlooked—the attainment, much sooner than expected, of a level of effectiveness for the internal machine functions that was outstripping the ability to get the information into and out of the machines. There was a backlog of significant computations that need little communication with the outside world and this tended to obscure the situation. This initial elation was short-lived in the face of the mental audacity of the men who began posing problems for the machines that required input-output performance not yet available. Beyond these scientific needs there was an accumulating pressure from potential users of these devices who planned to use them more as generalized information processors than as digital calculating machines.

Perhaps this might be considered to be a distinction without a real difference. I believe not, because the generalized information processor application naturally places emphasis on the input-output characteristics so that the system can function effectively on tasks for which numerical manipulations have a secondary role. A pioneering example in this area has been set by the Bureau of the Census in their recent tabulation of a portion of the 17th Decennial Census with electronic equipment. Incidentally, this role of pioneer in data-processing techniques is not a new role since Census was the first organization to make major use of the punched card techniques developed by Hollerith and Powers at the turn of the century. Census' experience with their initial electronic installation has served to emphasize the weight that needs to be allotted to the characteristics of the input-output features in estimating the effectiveness of digital equipment for data processing.

With this background, it seemed entirely appropriate for this conference to be devoted to the characteristics of the input and output equipment that is now available for use with both computing and data-processing systems. The program for the first part of the conference was selected mainly to provide an orientation for comparing the features of the input-output facilities now available on complete machines. Following this, the specific installations selected for presentation represented several ways to approach the organization of the input-output equipment. In addition, these presentations contained information on equipment that has been completed and, in most instances, equipment for which operational experience is available. There is a host of ingenious ideas which relate to improved performance of such equipment and which deserve attention. However, the limitations of time at this conference required that they either be included in the survey papers or left unmentioned. The fact that certain systems and equipments were given space on the program does not necessarily imply superiority of their approach over that of others known to be in development, but rather a commendation for the energy and zeal of their creators in making them available at this early date. The evident importance of this class of equipment is certainly a provocative

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