The Numericord Machine-Tool Director

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WHAT is numerical control of machine tools? I would answer by saying that it is a system of machine-tool control in which the machining operation is guided by instructions in the form of coded numbers. These instructions may be inserted via punched cards, punched tape, magnetic tape, or other suitable means. A complete sequence of operations is predetermined and programmed in a coded form which is understandable to the controller or the director, as it is called.

As divided into their broad classifications, the two types of numerical machine-tool controls are:

1) Positioning controls. A sequence of positions of a tool is controlled, some operation occurring at each position before the tool continues to the next position. Here, it is generally unimportant by which route and at which speed the tool progresses from one position to the next. The tool is not in contact with the workpiece when moving between positions.

2) Path controls. The tool is made to follow a prescribed path over the surface of the workpiece at a prescribed, but not necessarily constant, velocity. Depending upon the particular control system, the path may be in two or three dimensions.

The numericord machine-tool director, about which I am going to talk, is a path control system. While it differs in some respects from other path control systems, a study of its functioning will serve to demonstrate the processes involved in path control.

When I speak of the machine-tool director system, I am not including the machine tool itself with its power servomechanisms and error-detecting and amplifying circuits. That is separate equipment. I am talking about the data-processing and digital-to-analog conversion equipment which is necessary to provide real-time continuous-control signals in response to the numerical instructions inserted into the director. In the Numericord system there is no physical interconnection between the director system and the machine-tool controls. The continuous-control signals are recorded on magnetic tape and are subsequently played back at the machine tool. The interposition of the recording and playback functions in the sequence of control makes possible the divorcing of the director system from the machine tool. Therefore, a magnetic tape may be repeatedly used to produce several identical parts on the machine tool. Meanwhile, the director system is recording tapes for other machine tools. Fig. 1 shows the director system.

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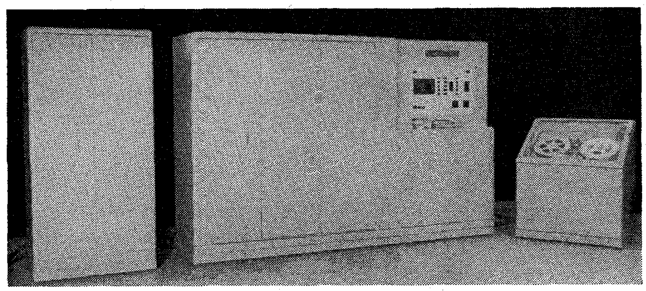

Fig. 1—The director system.

The Numericord director has punched paper tape as its input. Coded numbers on this tape prescribe the path of the cutting tool center in five axes. Thus, for example, a milling machine on which the milling head has two rotational degrees of freedom as well as orthogonal X, Y, and Z degrees of freedom may be controlled. The punched paper tape does not specify the path at all points, therefore it is necessary for the director to interpolate between specified points. That is, the continuous-control signals for the five axes must direct the cutting tool along some path between the points specified on tape.

The amount of data that is required on the input tape for any numerical system depends upon the interpolation method used in that system, and, in general, the amount of data decreases with increasing complexity of the interpolator. If you were to define positions on paper tape successively at one-thousandth intervals on the workpiece, no interpolation between defined points would be necessary at all in order to attain a reasonable degree of accuracy. On the other hand, if the director will interpolate linearly between defined points, that is, if the director directs the machine tool to cut a straight line between defined points, then the paper-tape input need define only the end points of all straight-line cuts. Here, however, a curve must be defined as a series of straight-line segments, the number of the segments depending upon the prescribed accuracy. If, for instance, you were required to cut half of an inside circle of six-inch diameter with a two-inch diameter cutter maintaining an accuracy of one thousandth, linear interpolation would require that the paper tape input specify 78 straight-line cuts. More elaborate interpolation schemes are possible, which pass higher degree curves through a number of specified points. Depending upon the type of cutting to be done, these systems may reduce considerably the amount of data required at the director input at the expense of a greater amount of equipment within the director. All considerations being taken, the Numericord designers were led to the choice of a linearly interpolating system.

The interpolator has five output lines, one for each axis. On each of the output lines discrete "command" pulses appear. One pulse represents a fixed increment of displacement at the machine tool, the amount of displacement being referred to as the quantization level of the system. The Numericord director has a quantization level of one eighth of a thousandth of an inch. Thus, the occurrence of 8000 command pulses in succession on the X-axis output line would drive the tool one inch over the workpiece in the X direction. Since the power servomechanisms at the machine tool respond to analog signals and not to pulses, a pulse-to-analog conversion must take place. This occurs in the "decoder." The output from the decoder consists of five command synchro signals. These are recorded on magnetic tape. When played back at the machine tool, the signals provide the command positions for five servodrives.

A block diagram of the director system is shown in Fig. 2.

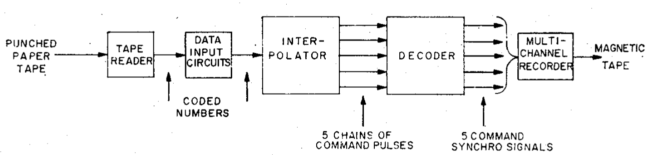

Fig. 2—Block diagram of a Numericord system.

Data Input

The terminal point of each straight-line segment of the programmed tool path is specified on the paper tape by coding the distance in each axis from the terminal point of the previous straight-line segment. In addition to the incremental distances for the five axes, a time-of-cut, or command time, is specified for each straight-line segment, and a direction-of-cut or sign code is inserted at the beginning of each dimension. One line of tape is required for each coded decimal digit or sign. The arrangement of data is such that the command time appears first. Three lines of tape are allocated to command time so that the command time is three decimal digits long. The command time is followed by a sign and seven decimal digit codes for the X axis, then by a sign and seven decimal digit codes for the Y axis, and so on for each of the five axes. The seven decimal digits indicate hundreds of inches, tens of inches, units, tenths, hundredths, thousandths, and tenths of thousandths of inches. The seventh digit is either a zero or a five so that distances are programmed in multiples of a half of a thousandth. The director will handle a maximum distance of 399.9995 inches in all axes. Of course, when the fourth and fifth axes are used to control rotations, a conversion must be made from angular degrees to linear inches so that the programming can be done in inches.

The command-time and command-distance information for a single straight-line cut comprise one "block" of paper-tape information. At the director, each block is read serially, line by line, each line being translated into a four-digit binary code and stepped into four magnetic-core stepping registers. The first digit of the four-digit code is weighted five, the second is weighted two, and the third and fourth are each weighted one. The binary code for seven, therefore, is the binary 1100. Each of the four stepping registers is associated with one of the four binary digit columns in the translated number. One register is designated the "five" register. Into it goes the most significant binary digit. The next register is designated the "two" register, and it receives the second most significant digit. The third and fourth registers are the "one-A" and "one-B" registers respectively.

Table I demonstrates the coding.

TABLE I
Coding

	5		2		1_A		1_B		
0	0×5	+	0×2	+	0×1	+	0×1	=	0
1	0×5	+	0×2	+	0×1	+	1×1	=	1
2	0×5	+	1×2	+	0×1	+	1×1	=	2
3	0×5	+	1×2	+	0×1	+	1×1	=	3
4	0×5	+	1×2	+	1×1	+	1×1	=	4
5	1×5	+	0×2	+	0×1	+	0×1	=	5
6	1×5	+	0×2	+	1×1	+	0×1	=	6
7	1×5	+	1×2	+	0×1	+	0×1	=	7
8	1×5	+	1×2	+	0×1	+	1×1	=	8
9	1×5	+	1×2	+	1×1	+	1×1	=	9

As each character is read, the appropriate code is set into the shift registers and advanced one position into the registers. When one block of tape has been read, the registers are full, and the tape reader stops. The numbers read first are stored in the magnetic cores farthest down the stepping registers. The stepping registers have between them a group of four cores (one core per register) to store each coded decimal digit of the three command-time digits; they have a group of four cores to store each coded decimal digit of the seven command-distance digits for each axis, and they have a group of four cores (some of which are redundant) to store each of the signs. So there is a total of 12 command-time cores, 140 command-distance cores, and 20 sign cores.

Fig. 3 shows the stepping register with the command time, 200 seconds, and with the command distance, —250,9645, stored as an example. Note that the arbitrary choice was made to use the same code for minus as for two. A limitation on the command-time code is that not more than one command-time core contains a binary "one." The reason for this will be seen as we progress. The allowable command times are 200, 100, 50, 20, 10, 5, 2, 1, and 0.5 seconds.

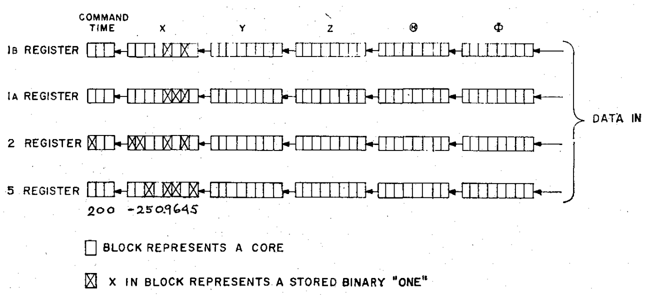

Fig. 3—Magnetic core shift register.

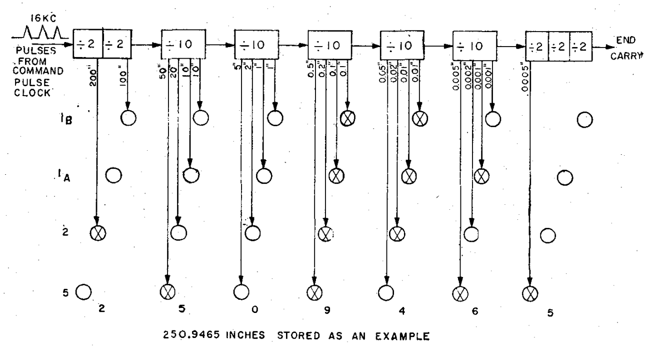

Fig. 4—Arrangement of interpolation counter in relation to storage cores of a typical axis.

Interpolation

Upon the occurrence of an internally generated signal, the contents of the dimersion-storage cores of the four stepping registers are transferred in parallel to a second set of storage cores. Simultaneously, the sign and command time cores are reset, causing pulse outputs from cores which had been storing ones. The stepping registers are thus freed to receive another block of information while the coded dimension numbers of the previous block are available to be operated upon in the second set of cores.

Let us consider of what this operation must consist. We are attempting to convert a coded number into a corresponding number of discrete pulses at a rate of one pulse per eighth of a thousandth, or a rate of four pulses for our least programmable distance, one half of a thousandth. Thus, let us interrogate nondestructively the core in which the half-thousandth bit is stored. If this core contains a binary "one," a pulse output will occur each time we interrogate it; if we interrogate it four times during the processing of the block, four output pulses will occur. We see that we can weight the binary digit stored in any core by fixing the number of times that that core is interrogated during the programmed command time. The cores storing binary "ones" weighted at 0.001 inch will be interrogated eight times during any command time; the cores storing binary "ones" weighted at 0.002 inch will be interrogated 16 times during a command time, a 0.005-inch core 40 times, and so forth. The outputs of the cores for one axis are buffered onto a common output line so that the command pulses on that line are a result of contributions from all the cores which have "ones" stored in them in that axis.

It would appear that the weighting functions for the core-stored dimension could be generated by a counting chain, and this is just what is done. A counting chain composed of cascaded binary and decade scalers is used. Fig. 4 shows how this counting chain, called the interpolator counter, is arranged with respect to the core storage for one axis. The decade circuits consist of four flip-flops connected so that, for 10 pulses entering a decade, there occur 5 carry and 5 noncarry transitions of the first flip-flop, 2 carry and 2 noncarry transitions of the second flip-flop, and 1 carry and 1 noncarry transition from each of the third and fourth flip-flops. The noncarry transitions of each flip-flop trigger an interrogate pulse which results in a command pulse out, if a binary "one" is contained in the magnetic core being interrogated. Although Fig. 4 shows the cores of only one axis, each flip-flop in the interpolator counter interrogates the five corresponding cores of the five axes. With a divide-by-four circuit beyond the half-thousandth flip-flop, the half-thousandth core is interrogated four times for every end carry. The end carry signals the end of the straight-line motion.

It is interesting to note two properties of the interpolation counter without which this system of linear interpolation would not work.

1) No two cores of any axis are interrogated simultaneously, and hence, the command-pulse contributions of the various cores appear as separate discrete pulses on the command-output line. This is because each oscillator pulse propogates down the chain as carry transitions until the first flip-flop ready for a noncarry transition is reached. The noncarry transition of that flip-flop does not result in any action farther down the chain. Hence, only one noncarry transition can occur anywhere in the chain for each input pulse to the chain.

2) It can be shown that, regardless of what pattern of "ones" and "zeros" exists in the storage system, that is, regardless of what number has been stored, the resulting pulse distribution is such that the displacement vs time for any axis never varies from a perfect ramp by more than one quanta.

Our command-pulse clock-oscillator frequency in the Numericord system is 16 kc. Referring again to Fig. 4, we see that 3.2-million oscillator pulses are required for each end carry. At an input rate of 16 kc, it would require 200 seconds to cycle through or cause an end carry. However, if we feed in our 16-kc clock pulses farther down the chain, it will require less time for the counter to cycle through. The Numericord system feeds clock pulses to nine gates, only one of which is open at a time. So pulses are fed to one of nine input points along the interpolator counter. The nine command times available are, as I previously mentioned, 200, 100, 50, 20, 10, 5, 2, 1, and 0.5 seconds. These gates are controlled by flip-flops, one of which is set by the pulse output of the appropriate command-time storage core.

The end carry from the interpolation counter clears the storage register and resets the command-time flip-flop so that no more oscillator pulses are admitted to the counter. When the clearing action is complete, the next command dimension is dumped in the storage register from the stepping register. Simultaneously, the nine command-time storage cores are reset resulting in an output pulse from the one core holding a "one." This pulse sets the appropriate command-time flip-flop. Clock pulses are now entered into the counter at a point in accordance with the new command time. Command pulses continue to appear on the output line after the end carry, but at a rate determined by the new command time and the new command distance. So there may be a discontinuity in command-pulse rate and, therefore, a discontinuity in command velocity at the end of one straight-line cut and the beginning of the next.

In programming an excessively large velocity step in any axis, the programmer may use a special code which will automatically reduce the clock rate as the end of the cut leading into the velocity step is approached. So the velocity step occurs at a much lower clock-pulse level and consequently results in a much lower velocity step at the machine tool. After the velocity step has passed, the clock rate rises to normal.

You can see in Fig. 5 that when clock pulses are entered into the counter at a point other than through the 200-second gate, not all cores will be interrogated. For instance, a 50-second command time results in the 100-inch and 200-inch cores not being interrogated. Therefore, a restriction must be placed on the programmer so that the programmed distance for 50 seconds is not more than 99.9995 inches in any axis. In fact, the restriction for any command time is such that the maximum vector component of feedrate in each axis is two inches per second.

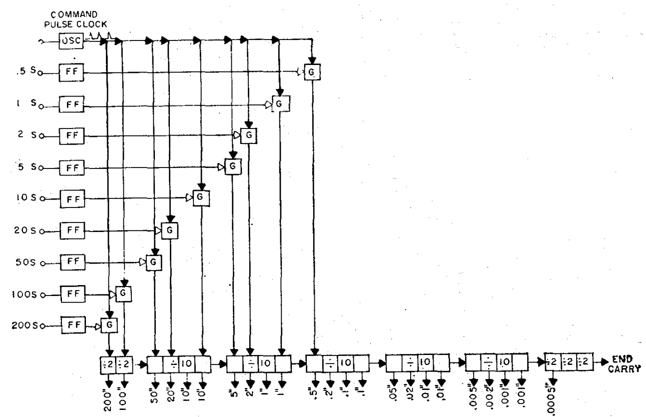

Fig. 5—Interpolation counter with command-time gates and flip-flops.

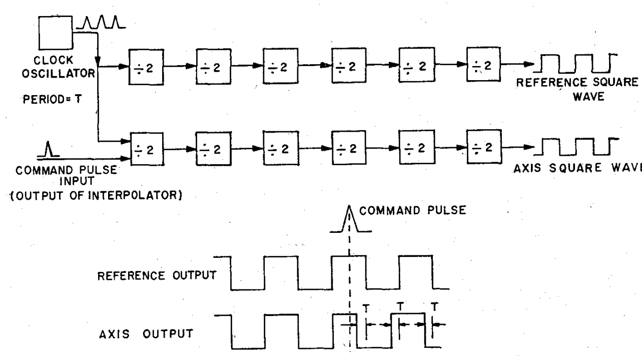

Fig. 6—Sample decoder.

Decoding

Since a synchro signal is well suited to the control of position, the Numericord system was designed to produce command synchro signals from the command-pulse outputs of the interpolator. This is done in the electronic phase-shift decoder. This decoder produces six 200-cps square wave outputs, one for each axis, plus one for a reference. The axis signals are phase shifted with respect to the reference by an amount proportional to the command distance. The decoder output is similar to the output of a rotary command synchro where the stator windings are excited by two or three phase reference voltages, and the phase of the rotor signal with respect to any one of the stator-phase voltages is proportional to the mechanical angle of the rotor.

The mechanism by which the phase shift is produced in response to a command pulse is best understood through reference to Fig. 6. Here, two binary-counting chains of equal length are shown. Both have inputs from a common high-frequency oscillator, the carrier-clock oscillator. One of these counting chains has an additional input which is the command-pulse line. If pulses only appear on the clock-oscillator input line, and if both counting chains initially start with all flip-flops reset to a common state, then the square-wave signals appearing on the plates of the last flip-flop in each chain will be of the same frequency and will be in phase with each other. Now, if a command pulse appears on the command line at a time between the occurrence of two clock pulses, the first flip-flop of this claim will become 180 degrees out of phase with the first flip-flop of the other chain. One less clock pulse will be required for this chain to cycle through a complete count than is required for the other chain. Therefore, the transition of the last flip-flop occurs sooner for this chain, by the amount of time between clock pulses. If no more command pulses appear, the two chains continue counting, and the phase of the square-wave signal of the last flip-flop in the second chain remains advanced by T microseconds with respect to the first chain. (T = clock-pulse period.) The first chain is the reference chain, and the square-wave signal from the plate of its last flip-flop is the reference-output signal and is essentially the signal which excites the stator of the feedback synchro. The second chain is the axis chain and its output is the phase-shifted signal to be compared with the phase of the rotor signal on the feedback synchro. The reference signal must, of course, be filtered to a sine wave and converted to 2 or 3 phase.

When the direction of machine-tool travel is negative, the command pulses are made to delete incoming clock pulses, one for each command pulse. So the phase of the axis counter lags the reference by further fixed increments with every command pulse.

In the Numericord system, there are five counting chains in addition to the reference chain so that five motions may be simultaneously controlled. Each chain is a combination of cascaded binary and decade scalers so that the total reduction of frequency is by a factor of 800 in each axis. The clock frequency is 160 kc and, therefore, the nominal output frequency is 200 cps. Since command pulses may be entered (added or subtracted) at the high-frequency end of the scalers at a rate of up to 16,000 pps, it is possible to modulate the output phase at a rate of 7200 degrees per second, or, in other words, to modulate the frequency at a rate of 20 cps. Each command pulse shifts the phase by one 800th of a cycle or by 0.45 degrees. Eight-hundred pulses or 0.1 inch of command causes the phase to shift one cycle.

The carrier-clock oscillator and command-clock oscillator are not synchronized. It could happen that a command pulse and a carrier-clock pulse could appear simultaneously at the input to a decoder axis counting chain if the precaution were not taken to avoid this. A circuit which we call the chronizer circuit prevents this from happening. In Fig. 7, we see that a command pulse sets a flip-flop to the "one" state, which after a short delay, opens a gate. The next carrier-clock pulse that occurs passes through this gate and resets the flip-flop. A pulse is produced at a fixed interval after the reset transition of the flip-flop. The time that this pulse can occur with respect to the time that carrier-clock pulses occur is determined by the setting of the delay. The delay is adjusted so that the pulse occurs between two carrier-clock pulses. The pulse will either be added to the carrier-pulse chain entering the axis counter, or it will generate a gating potential of sufficient length to prevent the next carrier pulse from entering the counter, depending on the state of the add-subtract flip-flop.

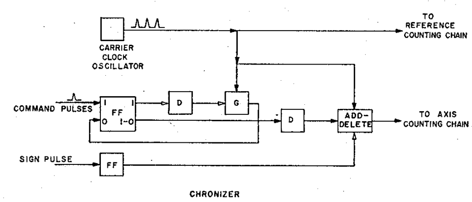

Fig. 7—Chronizer.

I have attempted to explain the operation of the essential feed-forward elements of the Numericord system. There are many auxiliary features, an explanation of which time does not permit. There is an indication scheme by which a continuous decimal-digit display of the actual phase between any axis and the reference is presented to the operator. There are area alarms which point to specific areas in the equipment when a fault occurs.

You can appreciate that the director is a very special purpose type of computer, and I think you will appreciate that much computation may be necessary in the initial paper-tape preparation. These computations include determining tool-center offsets, since it is the contour of the point of tangency between the tool and the workpiece that is of interest, whereas it is the path of the center of the tool that must be programmed. The computations also include determining the straight-line segments necessary to approximate a specified curve with a given degree of accuracy. A general-purpose computer lends itself to these computations, while the real-time problem of interpolating and rate generating is the special province of the director.