Logical Organization of the DIGIMATIC Computer

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System Specifications

PRECEDING the design of the original DIGIMATIC computer and control system, Electronic Control Systems Inc., (ECS) performed technical and economic surveys to determine the requirements for successful entry into the commercial automatic machine-tool market. The results may be summarized as follows.

1) A three-axis milling machine, with any two of the three slides simultaneously controlled, was the most logical tool to be adapted.
2) Cost and complexity of the control apparatus directly associated with the machine tool must be minimized, and reliability maximized. This dictated the elimination of the computing or interpolation function from the tool, with only the control function remaining.
3) From the standpoint of flexibility, accuracy, reliability, cost, and bandwidth, the only form of precomputed memory consistent with the above was magnetic tape recorded in digital incremental form.
4) The programming process by which part-drawing data is converted to magnetic-tape commands in a special-purpose computer must be rapid, accurate, economical, and easily accomplished by regular machine-shop personnel.
5) To satisfy the bulk of shop needs (about 95 per cent of commercial parts), the computer must generate (interpolate) linear or true circular paths with an accuracy of ±0.001 inch, without accumulation of error, from data already present on drawings or from those readily obtainable from drawings.

Mathematical Requirements—Straight Lines

As in most engineering projects, the most difficult task was defining the problem; once this was accomplished, the technical solutions were evolved fairly readily. Since this paper deals mainly with the computer portion of the system, it is possible to derive the input data, its code, and the input device from 4) and 5) above. Part drawings normally define a piece by the decimal coordinates of the start and end of each segment of the contour, and for circular arcs, usually include the radius and decimal coordinates of the center. Thus, the computer should accept contour breakpoints in decimal form; if code conversion is necessary prior to interpolation, it should be accomplished automatically.

The input mechanism, for reliable use by shop people, should be extremely simple and provide means for verification. A decimal keyboard device (such as that on an adding machine) with print-out tape is familiar to nearly all such personnel.

Let us begin by examining the case of a straight-line segment in the X-Y plane. The general equation of such a line

$$y = mx + b, \tag{1}$$

must be solved by the computer, and given the start and end points of the desired segment (which lies on this line).

Since it is fair to assume that a workpiece will contain continuous contours, the constant b may be eliminated from (1) due to the fact that the cutting tool has been brought to the proper start point for this path as a result of the completion of the previous segment.

Now m represents the slope, or tangent of the angle between the desired line and the X axis. By definition, the tangent is equal to the change in Y from the start point (P_1) to the end point (P_2) divided by the change in X over the same interval. It is exactly expressed as follows:

$$m = \frac{y_2 - y_1}{x_2 - x_1}. \tag{2}$$

Eq. (1) has therefore been reduced to the form

$$y = \frac{y_2 - y_1}{x_2 - x_1} x + b, \tag{3}$$

and for the reason indicated above, b need not be computed. This expression is illustrated graphically in Fig. 1. The line to be traversed has now been expressed in terms of the data normally furnished on a part drawing.

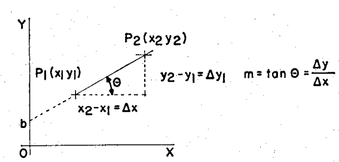

Fig. 1.

Engineering Solution—Straight Line

Quantities y_1, y_2, x_1, and x_2 are constants over the entire line, and are known before the interpolation begins. Since differences $y_2 - y_1$ and $x_2 - x_1$ need be calculated only once for the entire segment between P_1 and P_2, these subtractions may be performed on a relatively slow mechanical adding machine without any undue time penalty, inasmuch as subtraction time is less than keyboard entry time.

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Some keyboard device to receive data is unavoidable, so it may as well be an adding machine.

Therefore we will insert quantities y_2 and y_1 (in that order) into an adding machine, then order it to find the difference, and automatically store y_2 and y_1 in an electrical register (relays). Next, x_2 and x_1 will be entered, and $x_2 - x_1$ will be stored in another relay register. Let us call these differences Δy and Δx, respectively.

An electronic counter can be used to divide input pulses by an integral quantity which may range from one up to the counter capacitance; in such service it is usually termed a predetermined counter. Most commercial predetermined counters using a binary or modified binary code, are preset mechanically and require a considerable interval after recognition to be reset to an initial condition and to be ready to accept further input pulses.

However, a high-speed all-decimal predetermined counter can be designed around the magnetron beam-switch tube. Each target may be connected to a coincidence gate. When the total count in the multistage counter has proceeded from 0 to the integer by which the input pulses are to be divided, recognition will occur, an output pulse will be generated, and the entire counter rapidly reset to 0 via the spades. One microsecond is sufficient for reset; thus, the input pulse rate may be as high as 1 megacycle and still permit reliable counting and resetting. We term the process dividing, and such a counter, a divide counter. Fig. 2 shows the logic of a divide counter.

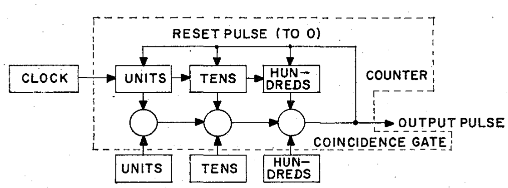

Fig. 2—Divide counter, register containing quantity by which the clock pulses will be divided.

Suppose we feed pulses from a common clock into two divide counters, one dividing the clock rate by Δx, the other by Δy, as pictured in Fig. 3. If the clock frequency f is constant, a train of uniformly spaced pulses will emerge from each divide counter; the output frequency of the first counter will be $\frac{f}{\Delta x}$, that from the second counter will be $\frac{f}{\Delta y}$, and the ratio between these rates will be

$$\frac{\frac{f}{\Delta x}}{\frac{f}{\Delta y}} = \frac{\Delta y}{\Delta x}, \tag{4}$$

which is exactly the slope of the line connecting P_1 and P_2. Assuming each output pulse represents a motion of 0.001 inch by a machine-tool slide, the interpolation process must continue until the Y-axis drive receives a pulse total of Δy, the X-axis drive a total of Δx. Two additional counters and three recognition gates as shown in Fig. 4 monitor this process and turn off the clock when recognition signifies P_2 has been reached. Simultaneously the pulses from the divide counters are recorded on appropriate tracks of an eight-track magnetic-tape recorder for later use in controlling the machine-tool table.

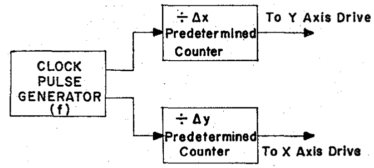

Fig. 3—Straight-line generator.

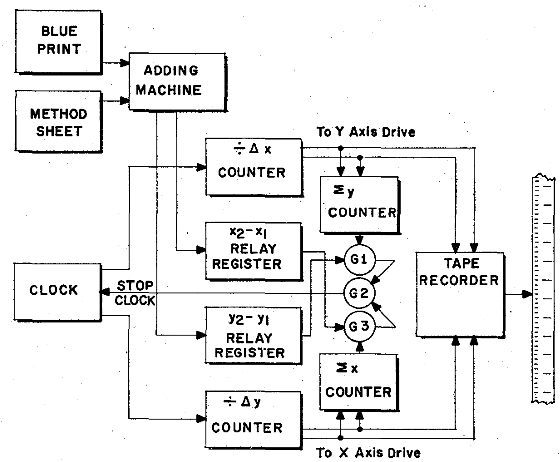

Fig. 4—Straight-line generator.

Since each of the two output pulse trains will have uniform pulse spacing, they will be periodic, and therefore optimum for driving servomechanisms at constant velocities. The description of the DIGIMATIC computer as a linear interpolator requires but one further embellishment to be complete. For vector machine table feed rates to be controlled automatically, the two output pulse trains are sampled by analog pulse rate discriminators, combined in quadrature, and the resultant voltage compared to that commanded by a feed-rate potentiometer calibrated in inches per minute. The difference voltage operates a clock frequency control system in a closed loop, so that the desired feed rate results.

Mathematical Requirements—Circles

The engineering solution given above describes a means for generating a line of constant slope by producing two pulse trains whose frequencies are constant, and are related so that

$$\frac{f_y}{f_x} = m. \tag{5}$$

Now let us examine the mathematical characteristics of a circle. The general equation for a circle with its center at point (a,b) in the XY plane is

$$(x - a)^2 + (y - b)^2 = r^2. \tag{6}$$

We can derive the exact expression for the instantaneous slope at any point by first taking differentials

$$2(x - a)dx + 2(y - b)dy = 0. \tag{7}$$

Separating variables we reduce it to

$$(y - b)dy = -(x - a)dx, \tag{8}$$

and finally the slope is expressed by

$$\frac{dy}{dx} = -\frac{x - a}{y - b}. \tag{9}$$

Engineering Solution—Circles

In the solution for first-degree equations, predetermined dividing counters were utilized to divide the common clock-pulse source by two constant quantities. Referring to the expression for slope of the circle given in (9), it can be seen that if quantities $x - a$ and $y - b$ can be made available at all times, the predetermined counters mentioned earlier can be used to divide the clock-pulse rate f by these varying quantities, and a circle can be generated by continuously changing the slope to fit the above equation.

Inasmuch as the slope changes in sign four times during the generation of a complete circle, it becomes necessary to keep track of the magnitude and sign of the quantities $x - a$ and $y - b$. This can be accomplished by the use of reversible counters which can add and subtract pulses, instead of simple monodirectional counters which would have sufficed for performing the pulse-summing operation in Fig. 4. We call such counters "sum" counters, and we have obtained economy of components and sufficient counting speed by using decimal glow-transfer counter tubes of the Erikson type. Since it is necessary to present the quantities $x - a$ and $y - b$ in parallel decimal form to the inputs of the divide counters, reversible gas-tube GS10C, which has all of its ten cathode electrodes brought out to the tube socket, was chosen.

In the case of the circle, the input commands to the divide counters have to be switched from the output terminals of relay registers, as described for a straight line, to the output terminals of sum counters. In addition, direction gates must be added between the output of the sum counters and the tape-recording channels, and must be commanded by the sign of the appropriate sum counter, to make the logic completely consistent with the mathematical requirements of a circle. The logic of a circle generator, which receives as input information the coordinates of the start point, end point, center, and instructions as to whether the circle is to be generated in a clockwise or counter-clockwise direction, is given in Fig. 5.

To convert the straight-line generator of Fig. 4 to a circle generator of Fig. 5, it is necessary to provide a 100-pole double-throw relay, which switches the 50 input terminals of each 5-decade divide counter from a relay register to a sum counter. Some changes in the method of handling input data must also be incorporated, to permit the sum counters to be initially preset to the actual quantities $x_1 - a$, $y_1 - b$ at the start of the circular arc.

Mention should be made of the singularities which occur four times during the generation of a complete circle. The instantaneous slope of the circle twice goes to zero and twice becomes infinite. The former cases correspond to the quantity $x - a$ becoming equal to zero, and the latter cases occur when $y - b$ becomes zero. If the clock frequency is divided by zero at these times, an infinite output rate should be produced by the predetermined counters. However, as soon as one additional pulse at this infinite rate is emitted and added into the previous total of zero in the reversible counter, the appropriate total changes from zero to either plus one or minus one, and the predetermined counter is then asked to divide by a finite integer. The problem can be resolved by setting up a system of logic which causes the predetermined counter to emit one pulse without receiving a pulse from the clock, if it is ready to be preset by the total in the reversible counter and finds this total to be zero. By thus generating a pulse with no input from the clock, we can simulate an infinite ratio of output to input at the point of singularity. Fig. 5 assumes the use of this type of predetermined counter.

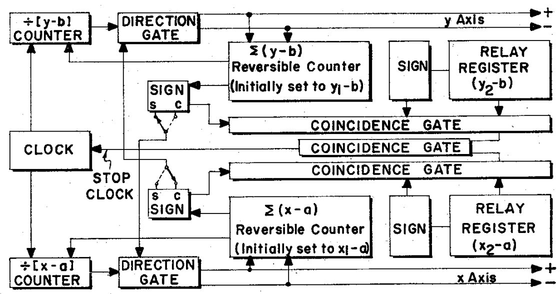

Fig. 5—Circle generator. *Note 1*—In sign block of reversible counters, the letter s refers to the true sign, the letter c refers to the complement of s. *Note 2*—With switches on the sign outputs of the above counters set as shown by the solid lines, the circle will be generated in a clockwise direction. If they are set as shown by the dashed lines, the circle will be generated in a counter-clockwise direction.

To illustrate the operation of this all-decimal interpolator, Fig. 6 shows the path described on graph paper by the occurrence of pulse outputs in the case where the center of the circle is at (0,0) and the radius is 10 increments. Although the appearance of the outline is not smooth, in practice a smooth contour is machined because of the smoothing action of the servomechanisms which drive the slides of the machine-tool table. Furthermore, the example was chosen for simplicity, since a circle with such a small radius is somewhat academic. Standard milling tools are available only in diameters of 1/16 inch (0.0625 inch) and higher.

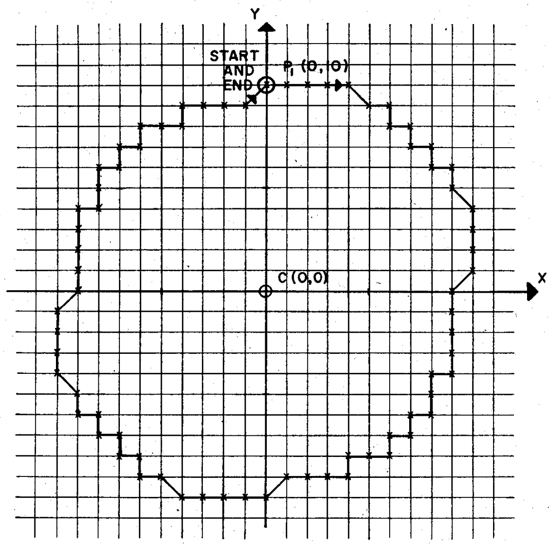

Fig. 6—Interpolated circle. (Radius 10 increments.)

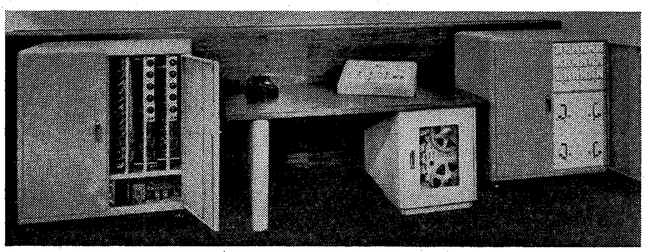

Fig. 7—Model 120 DIGIMATIC computer.

Thus additional smoothing will be provided by the large size of the periphery of the cutting tool compared to the value of an increment, which in our case is 0.001 inch.

The DIGIMATIC Model 120 computer, which follows the logical principles described above, is pictured in Fig. 7. The relay register, clock, divide counters, and sum counters are housed in the cabinet at the left. The desk contains the magnetic-tape handler and some input distribution circuits, while the control console (including adding machine) may be seen on the desk top. The cabinet on the right contains only power supplies.

A close-up of the control console is shown in Fig. 8. Fig. 9 is a photograph of a triangle, circle, and parabola which was machined from tape prepared by the 120 computer.

Generation of Other Curves

The technique of using two divide counters to generate a curve of continually changing slope can also be applied to other second-degree curves. As an example, the equation for a parabola (principal axis parallel to the X axis) is

$$(y - k)^2 = 2p(x - h). \tag{10}$$

In this case k, p, and h are constants. The instantaneous slope is

$$\frac{dy}{dx} = \frac{p}{y - k}\,. \tag{11}$$

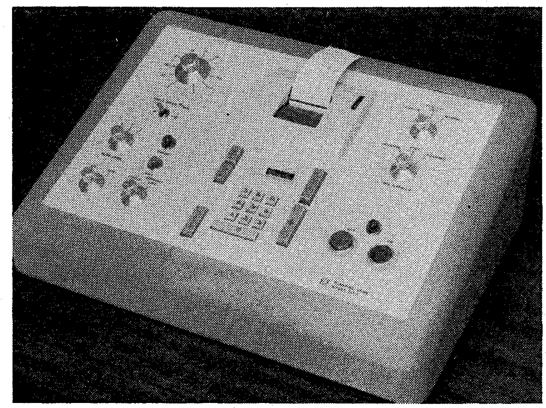

Fig. 8—Model 120 DIGIMATIC computer.

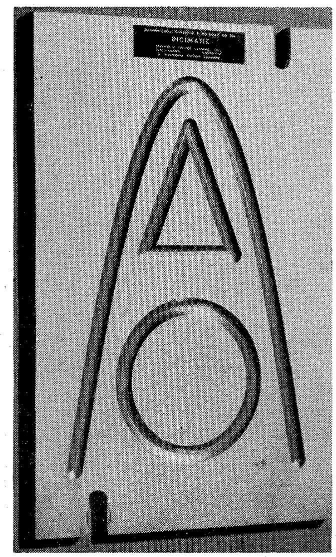

Fig. 9—Geometric contours produced by model 120 DIGIMATIC computer.

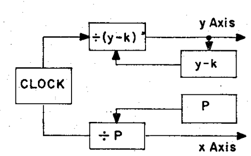

Fig. 10—Parabola generator.

It may be seen that it differs from the slope of a circle only in the respect that the numerator is a constant instead of a variable. Fig. 10 indicates the logic of an interpolator for this kind of parabola. In practice, we have generated parabolas by entering the information as if a circle was desired, and preventing x-axis command pulses from reaching the X sum counter (by removing a driver tube).

The case of an ellipse can be analyzed as follows. The general equation is

$$\frac{(x - h)^2}{a^2} + \frac{(y - k)}{b^2} = 1. \tag{12}$$

From this the slope is derived

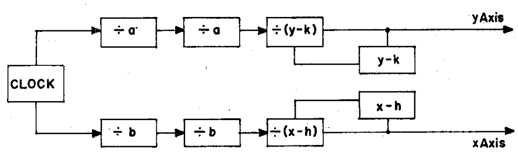

Fig. 11—Ellipse generator.

$$\frac{dy}{dx} = -\frac{(x-h)b^2}{(y-k)a^2}. \qquad (13)$$

Fig. 11 shows how this could be implemented. Since two additional constants occur, *a* and *b*, additional divide counters would be necessary, as well as memory registers to retain the quantities for presentation to the extra divide counters.

This computing philosophy can be extended to accommodate higher order equations. As an example, consider this fourth-degree curve

$$y = 5(x-10)^4. \qquad (14)$$

It has the instantaneous slope

$$\frac{dy}{dx} = 20(x-10)^3, \qquad (15)$$

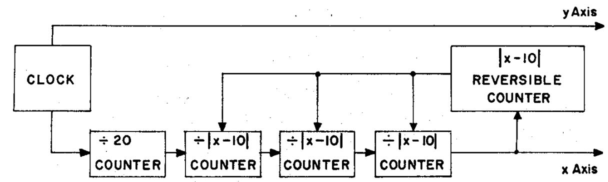

Fig. 12—Higher order curve generator.

which can be generated by the computer logic given in Fig. 12.

Conclusion

A special-purpose, high-speed, digital computer has been described which operates completely in the decimal system, and contains built-in programs for straight lines and circles, selection being made by the turn of a switch. The input data required is inserted very simply, and is either already present or may be simply derived from information on part drawings. This computer could be described as a function generator, which generates analytically expressed relationships in a digital manner. Similar computing principles are being applied to control problems outside the machine-tool field.

Discussion

Question: What is the reliability of the Electronic Control Systems Director and mean time to failure?

Answer: Well, the most unreliable component of our Director is the human operator and unfortunately he breaks down pretty often. The entry of numerical data from a planning sheet is a fairly tedious process and we find that monotony is the chief producer of errors. It is a little hard to answer this accurately, since we have been operating a laboratory system, not an industrial one.

I will say that the mean free time is beyond one day. We have some peculiarities in the Los Angeles climate which control this. We use standard telephone-type relays and whenever there is a strong dust storm from the desert, it plays hob with the relays and we have to clean them out. In general, the mean free time is more influenced by electromechanical than electronic components.

Question: What is the least count, least programmable increment of the ECS system? What is the maximum feed rate of any axis?

Answer: In our present system, one pulse equals one thousandth of an inch, so this is the least programmable increment. Our computer controls the vector feed rate, so that the maximum feed rate in one axis is not necessarily the actual cutting feed rate. To put it another way, our maximum clock-pulse frequency is 500 kc and if you will go through the mathematics and logic of our system, it works out that for most typical cuts on our prototype Bridgeport Mill we must limit the feed to 15 inches per minute. The manufacturer of the original machine provided power feeds up to this rate.

We designed our DIGIMATIC computer to produce feed rates up to 15 inches per minute. There are some cuts that we could make much faster. However, the machine-tool servos could not follow them. To put it another way, the feed rate must depend on the type of material and depth of cut. Our new Director, now near completion, will interpolate at eight times real time for feed rates up to 50 or 100 inches per minute.

Question: Do you verify the tape before you use it for direction of the machine tool, and if "yes," by what means?

Answer: At the present time, we make a pulse count. Our magnetic tape contains six control channels, a plus and minus channel for each of the feeds, *X, Y,* and *Z,* and for each segment of the cut we perform a pulse count for each axis. This is a fairly tedious process, so what we usually do, unless the part must be made to unusually close tolerances, is simply machine a part. It would be possible to play the tape back into the sum counters of our computer. We did not provide for it in the present system. We will in the forthcoming ones.

Question: Do you have a stored program for the interpolation process, or is it made by hardware?

Answer: We have only two programs for this computer, both of them built in. The selection of linear or circular interpolation is controlled by a number of relays which change the input lines to our divide counters. In the case of straight lines, the relays connect the divide counter inputs to numerical relay storage. In the case of circles, these inputs are connected to the sum counter outputs.

This is about the only meaning that I can place on the question.