

May 6, 1958

J. ROSENBERG ET AL

2,833,941

AUTOMATION SYSTEM

Filed Nov. 2, 1955

17 Sheets-Sheet 1

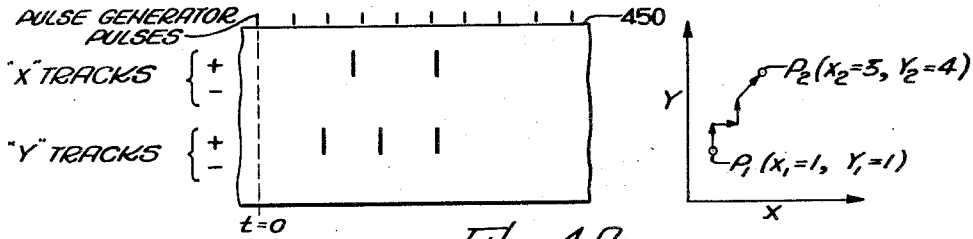


FIG. 4A.

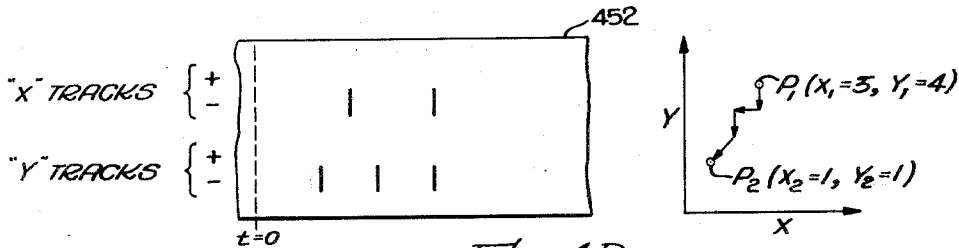


FIG. 4B.

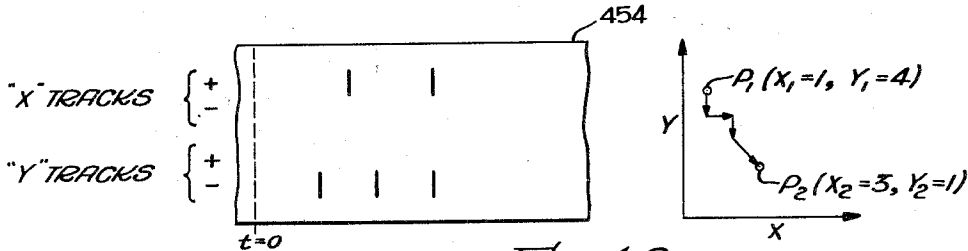


FIG. 4C.

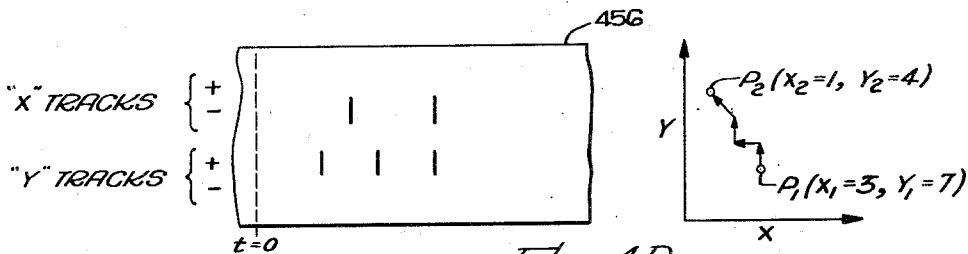


FIG. 4D.

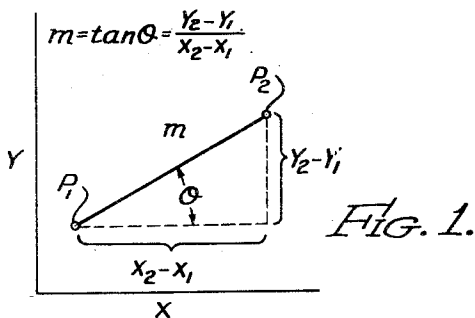


FIG. 1.

JACK ROSENBERG
ALEXANDER F. BREWER
THOMAS J. SCIUITTO
INVENTORS

BY
J. L. Bowser
ATTORNEY

May 6, 1958

J. ROSENBERG ET AL

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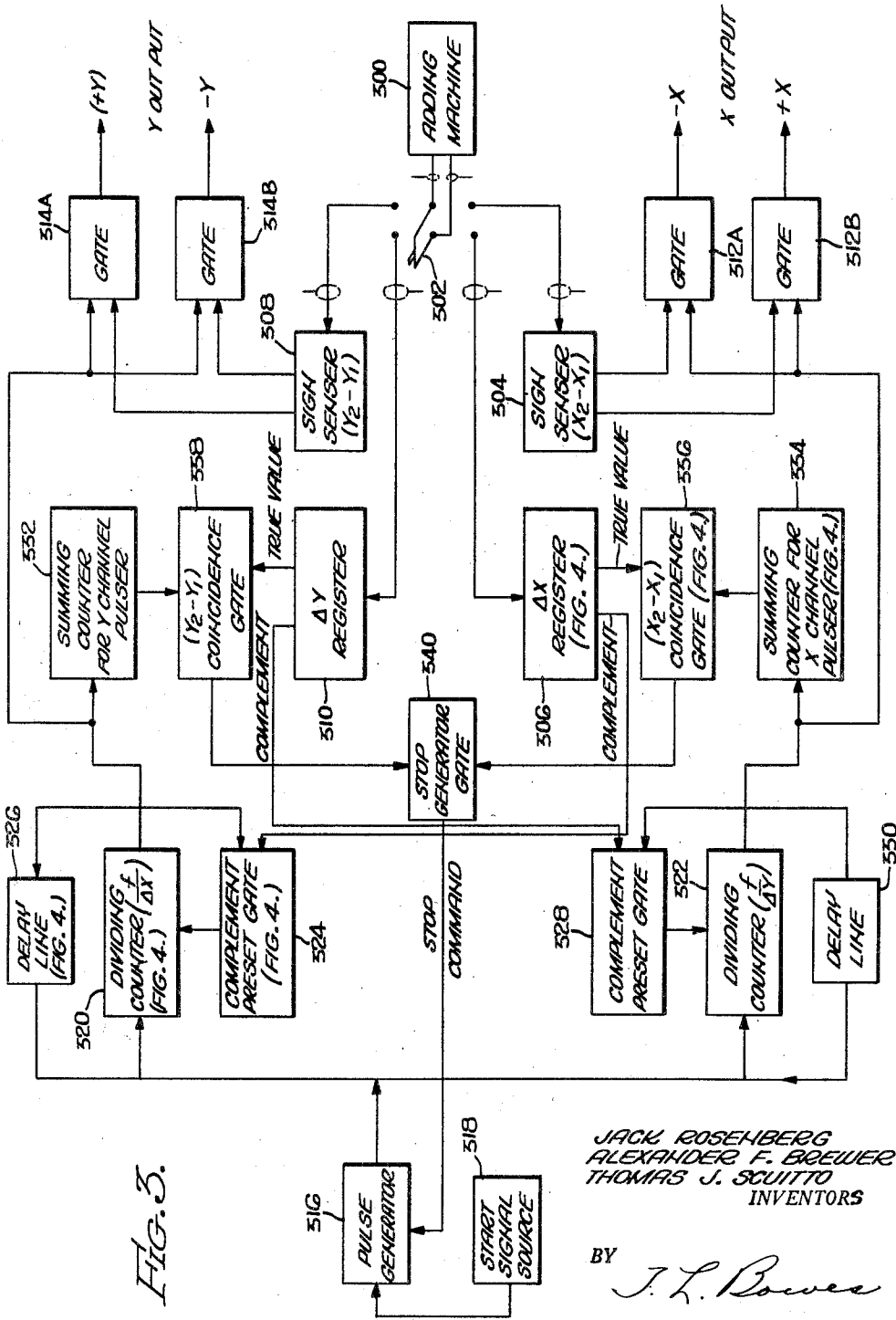


FIG. 3.

JACK ROSENBERG
ALEXANDER F. BROEWER
THOMAS J. SCUITTO
INVENTORS

BY *J. L. Bowes*
ATTORNEY

May 6, 1958

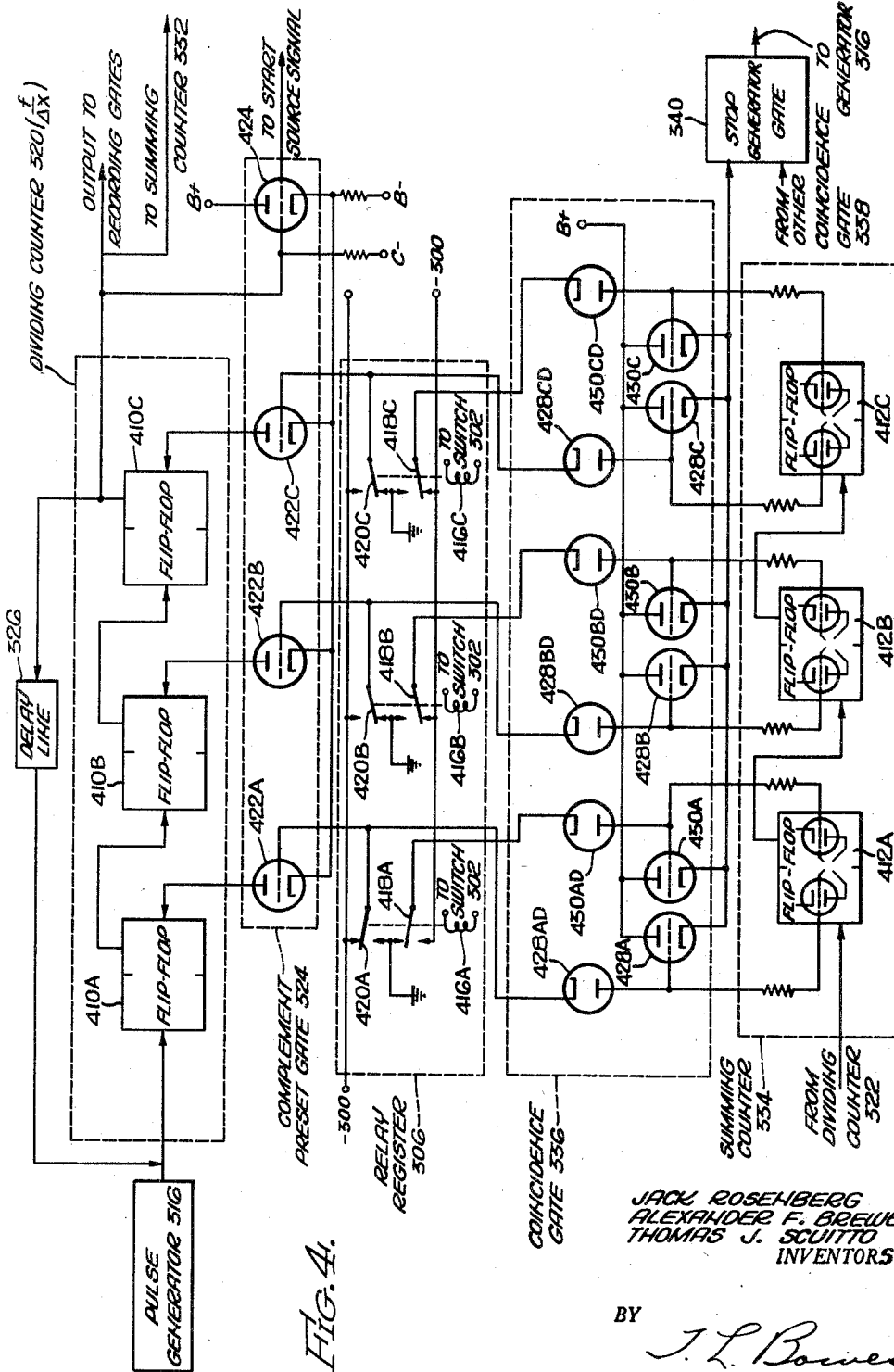
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JACK ROSENBERG
ALEXANDER F. BREWER
THOMAS J. SCUITTO
INVENTORS

BY

J. L. Bowler
ATTORNEY

May 6, 1958

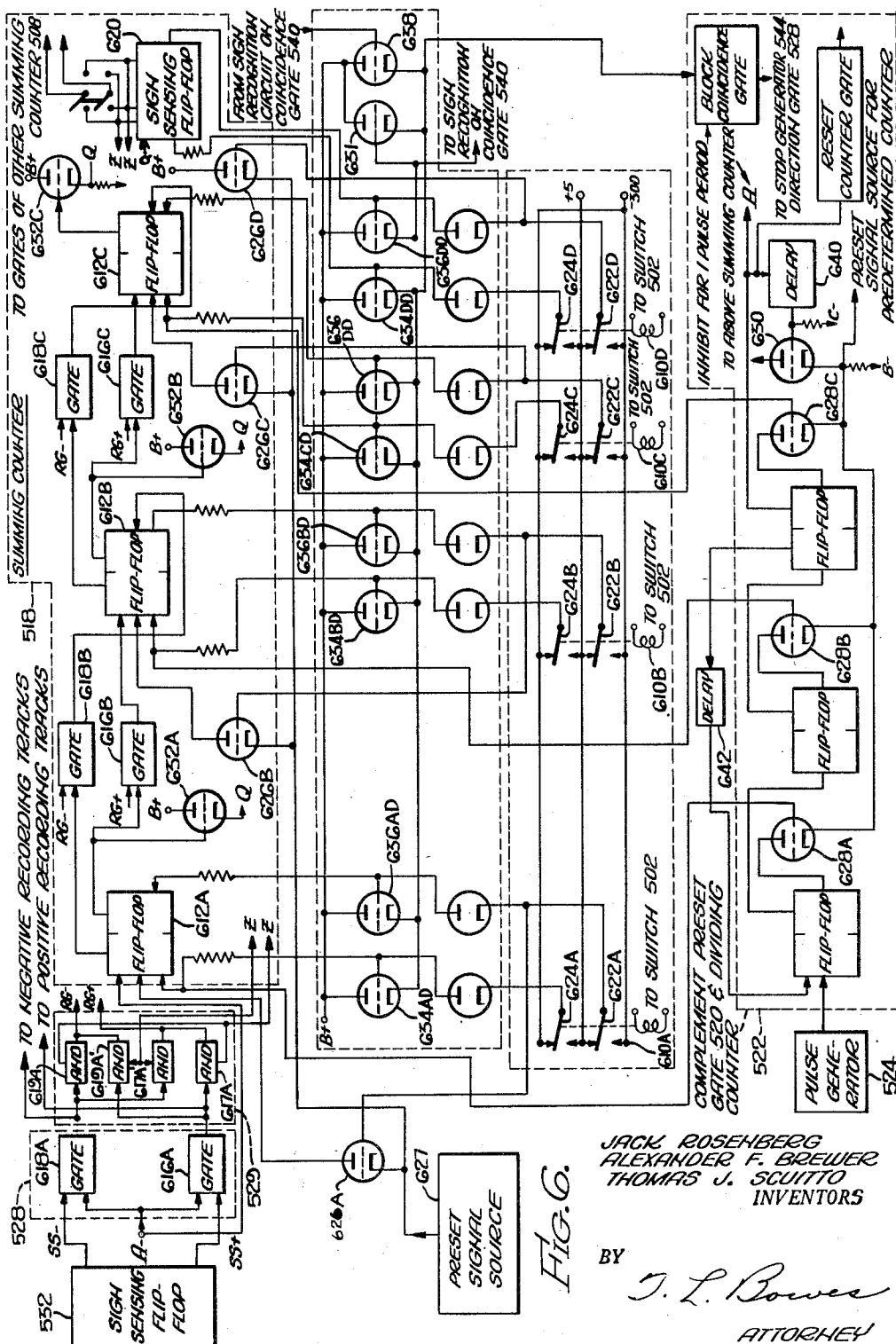
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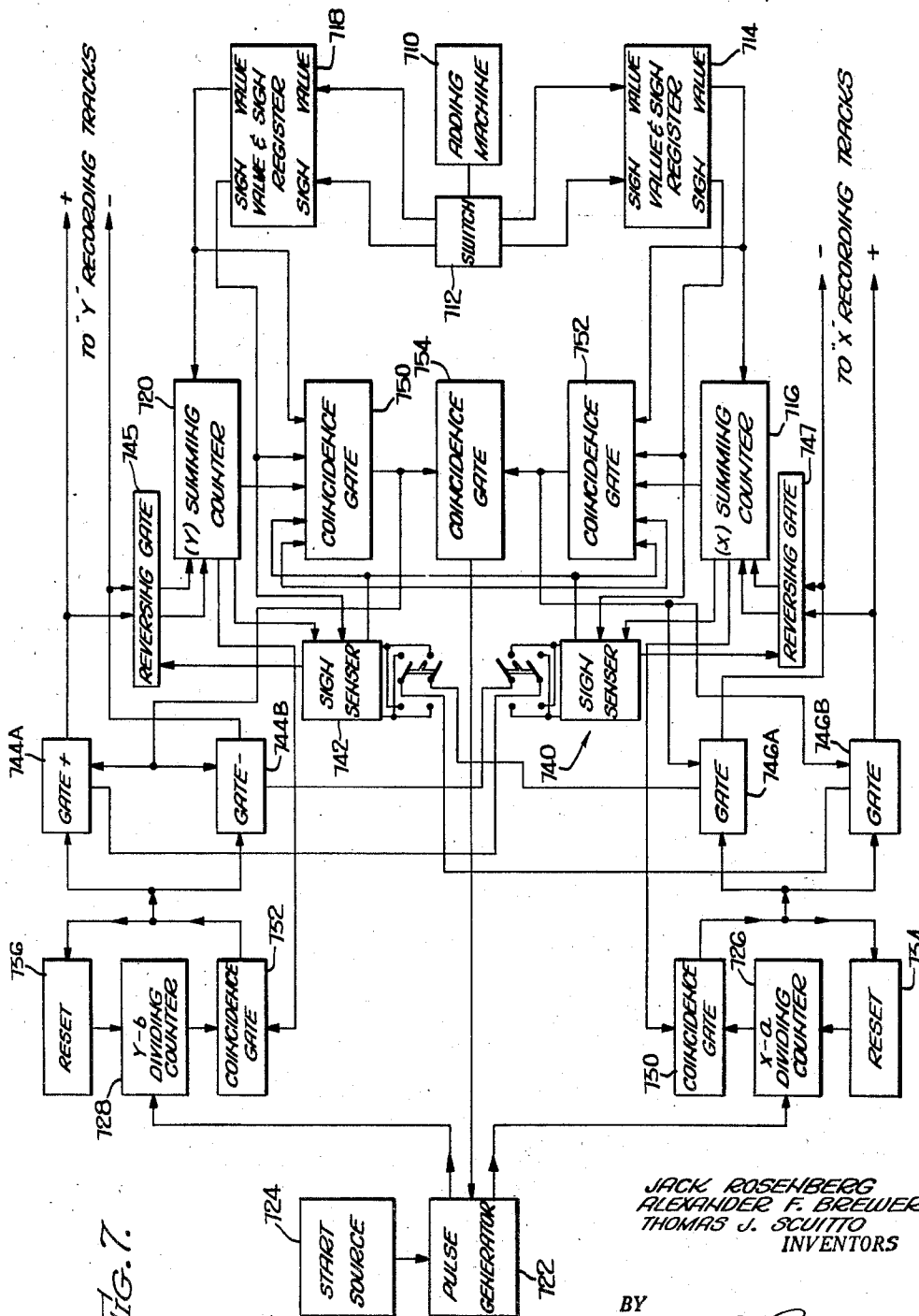


FIG. 7.

JACK ROSENBERG
ALEXANDER F. BREWER
THOMAS J. SCUITTO
INVENTORS

BY

J. L. Bowser
ATTORNEY

May 6, 1958

J. ROSENBERG ET AL

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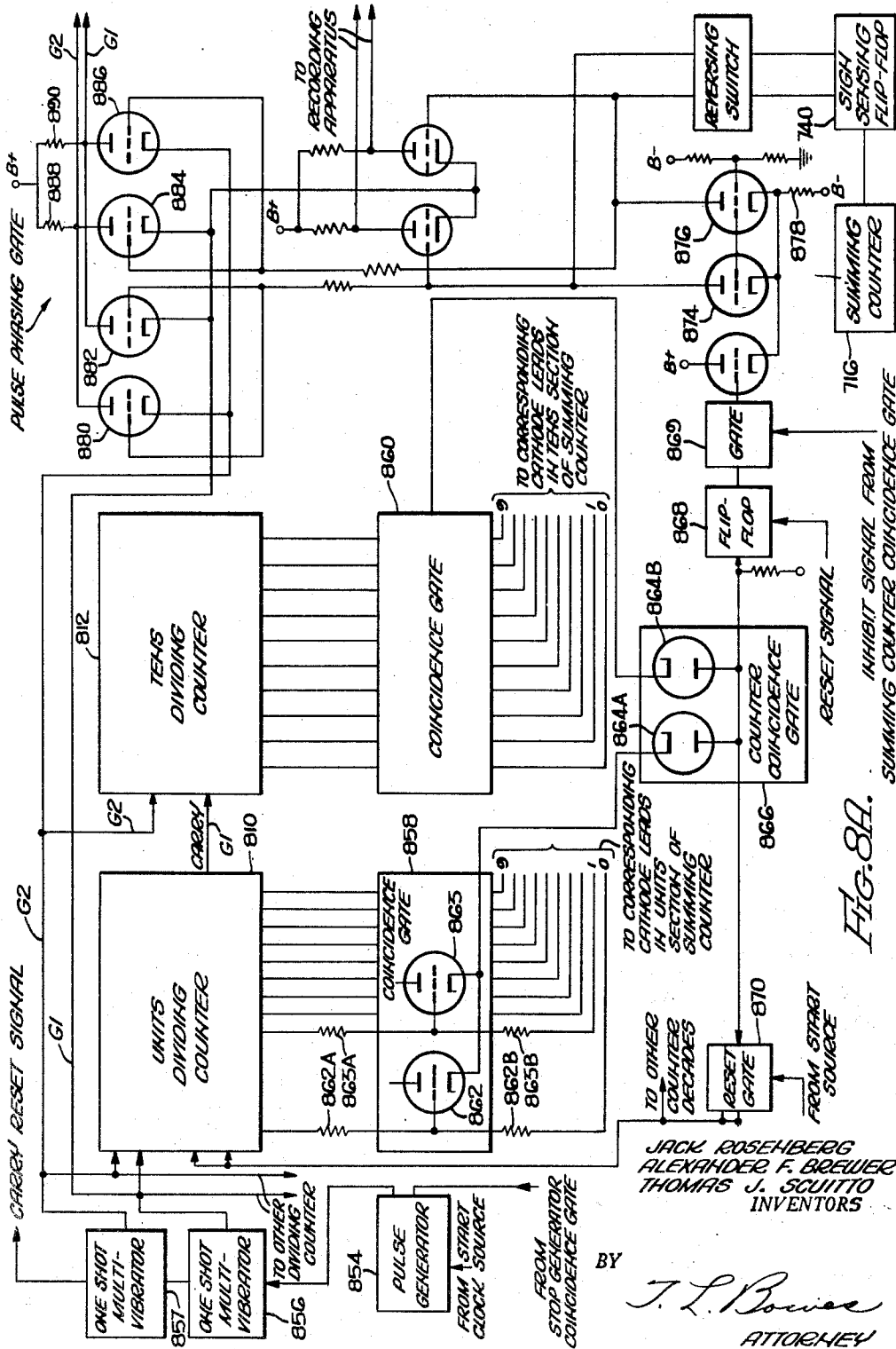


FIG. 8A.

JACK ROSENBERG
ALEXANDER F. BREWER
THOMAS J. SCUITTO
INVENTORS

BY

J. L. Bowler
ATTORNEY

May 6, 1958

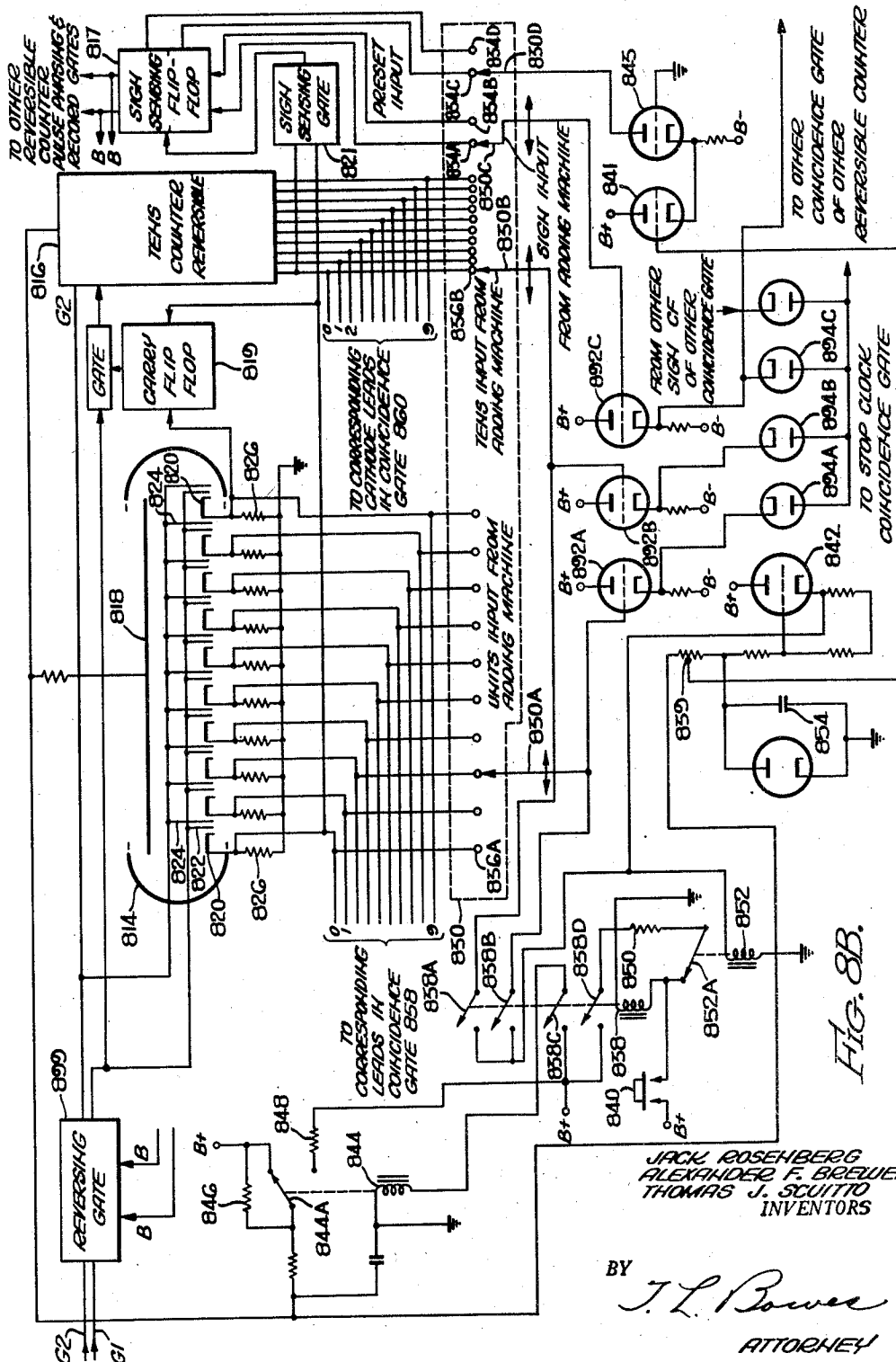
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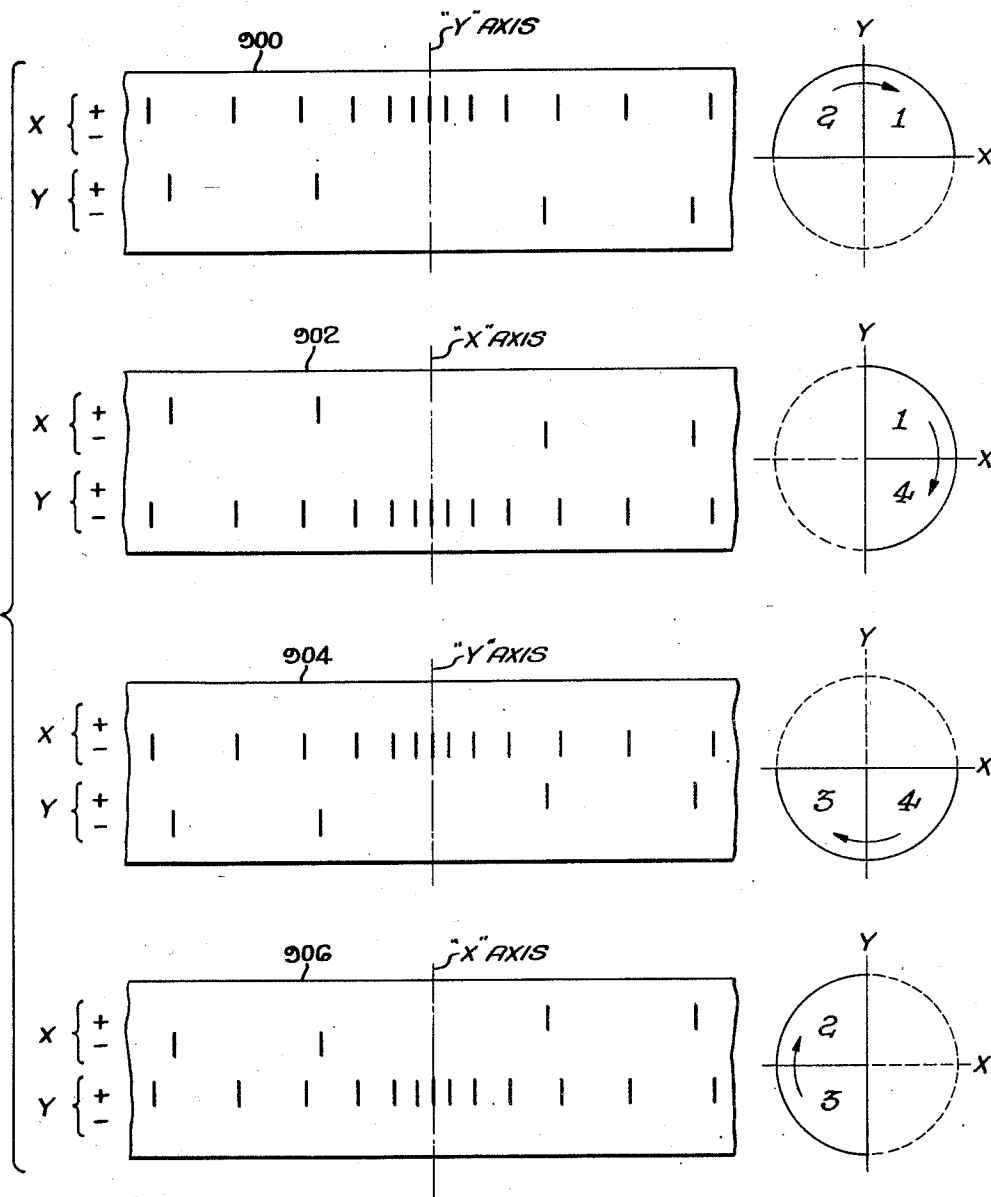


FIG. 9.

JACK ROSENBERG
ALEXANDER F. BREWER
THOMAS J. SCUITTO
INVENTORS

BY
J. L. Brewer
ATTORNEY

May 6, 1958

J. ROSENBERG ET AL

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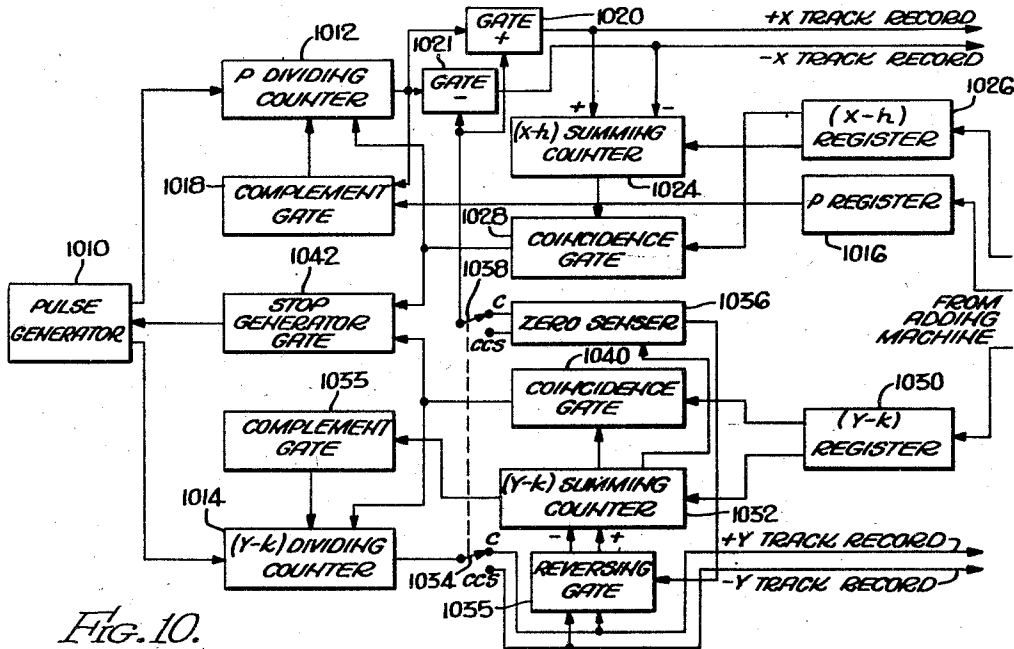


FIG. 10.

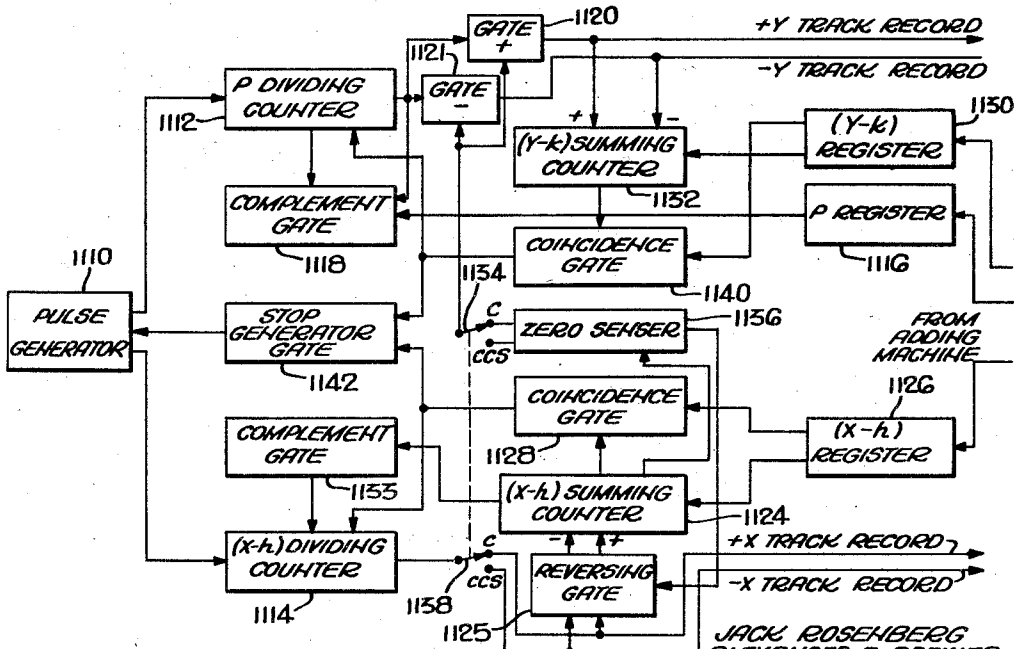


FIG. 11.

JACK ROSENBERG
ALEXANDER F. BREUER
THOMAS J. SCUITTO
INVENTORS

BY

J. L. Bowes

ATTORNEY

May 6, 1958

J. ROSENBERG ET AL

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FIG. 12.

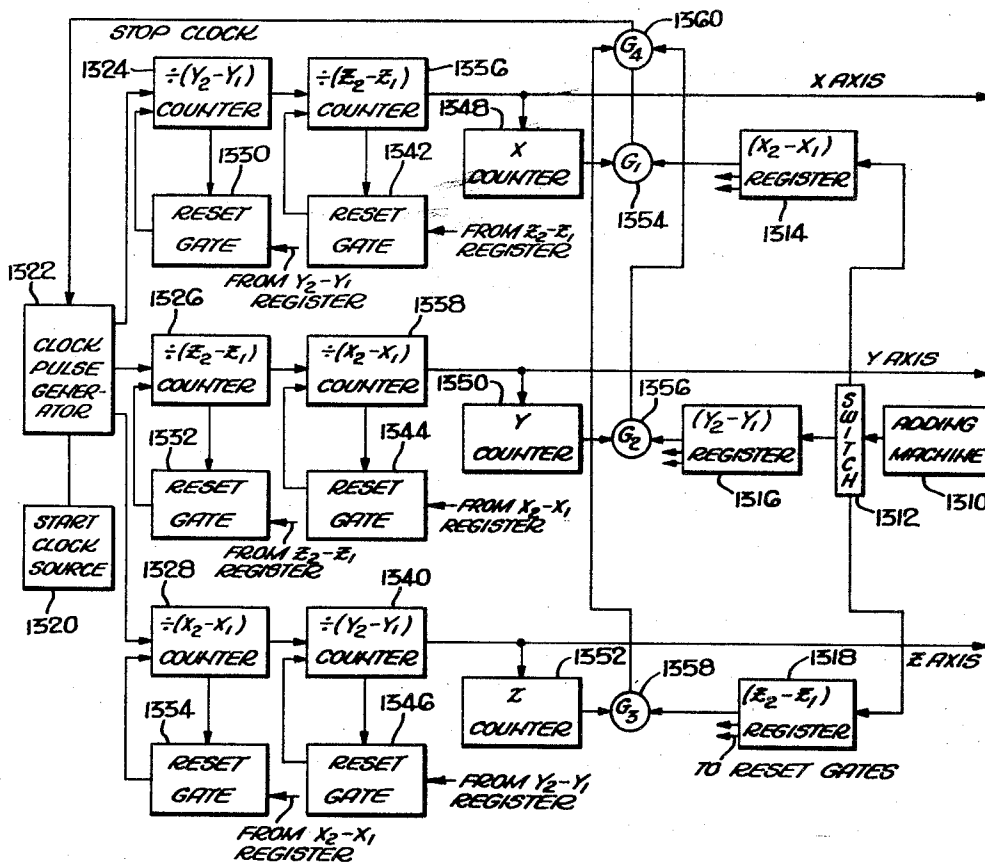
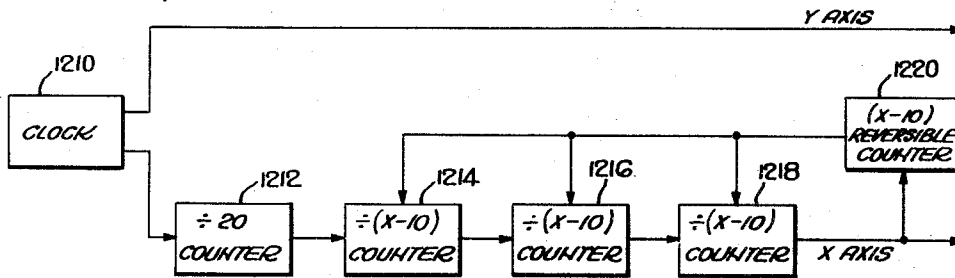


FIG. 13.

JACK ROSENBERG
ALEXANDER F. BREUER
THOMAS J. SCUITTO
INVENTORS

BY

T. L. Bowes

ATTORNEY

May 6, 1958

J. ROSENBERG ET AL

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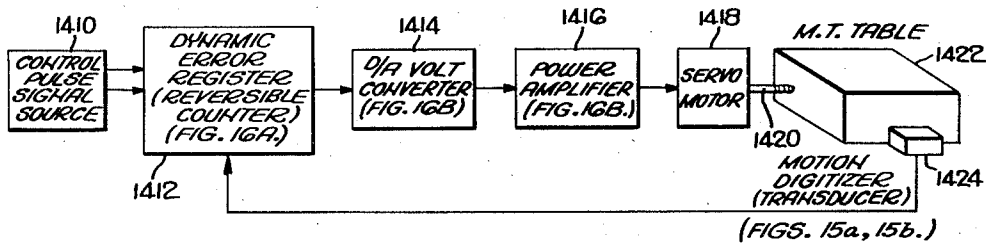


FIG. 14.

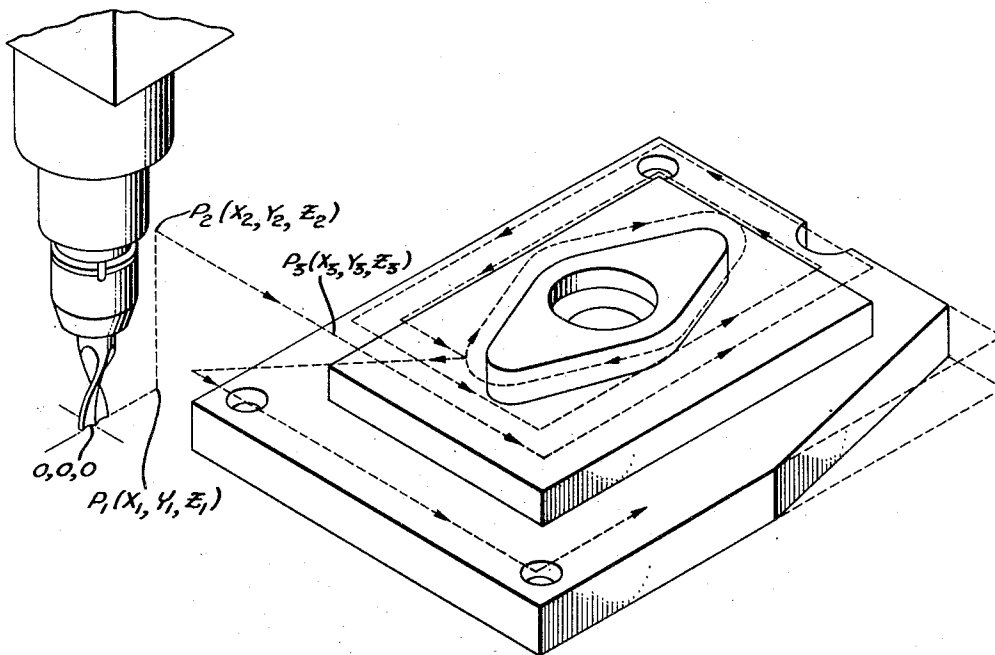


FIG. 17.

JACK ROSENBERG
ALEXANDER F. BREWER
THOMAS J. SCUITTO
INVENTORS

BY *J. L. Bowes*
ATTORNEY

May 6, 1958

J. ROSENBERG ET AL

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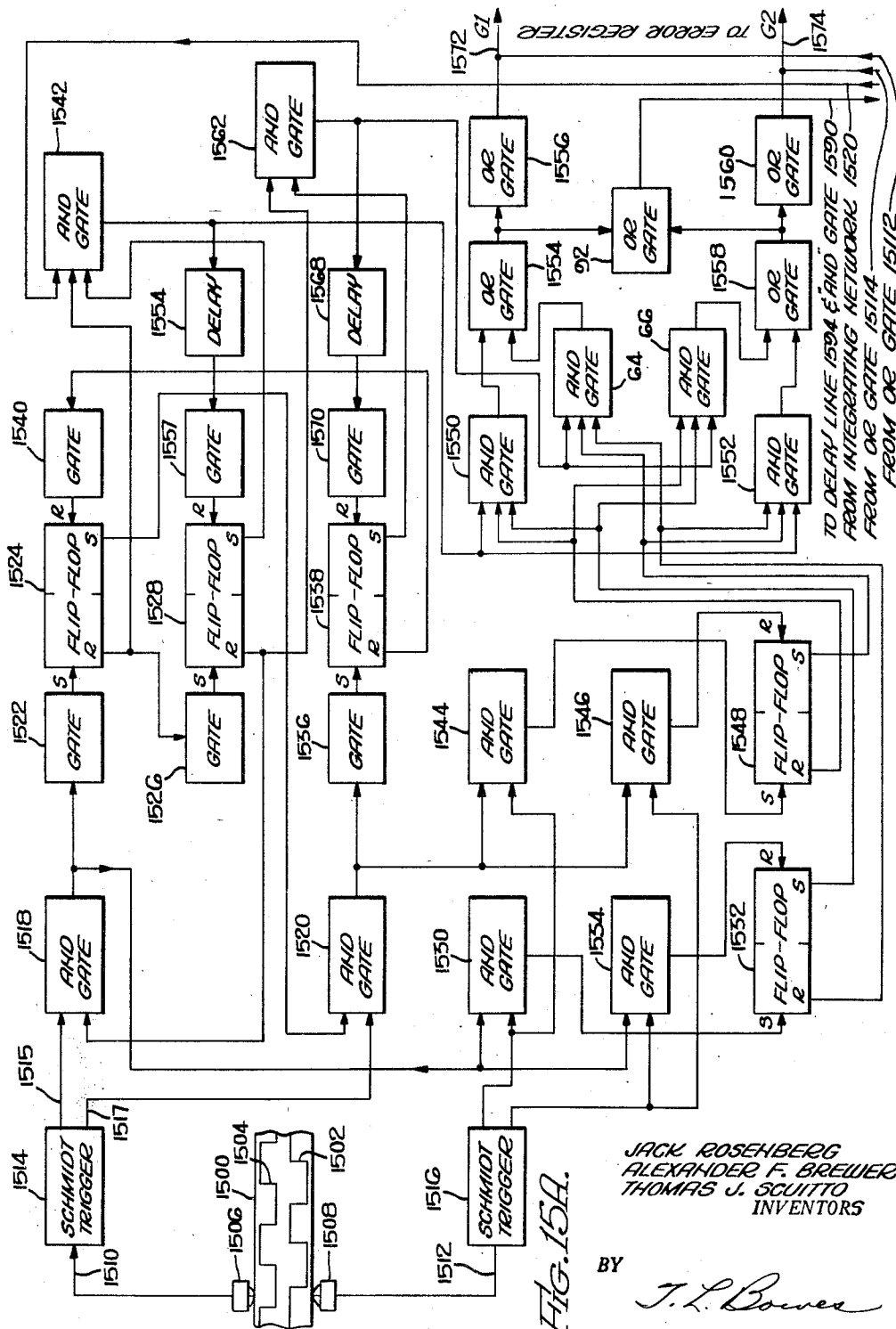


FIG. 15A.

JACK ROSENBERG
ALEXANDER F. BREWER
THOMAS J. SCUITTO
INVENTORS

BY

J. L. Bower
ATTORNEY

May 6, 1958

J. ROSENBERG ET AL

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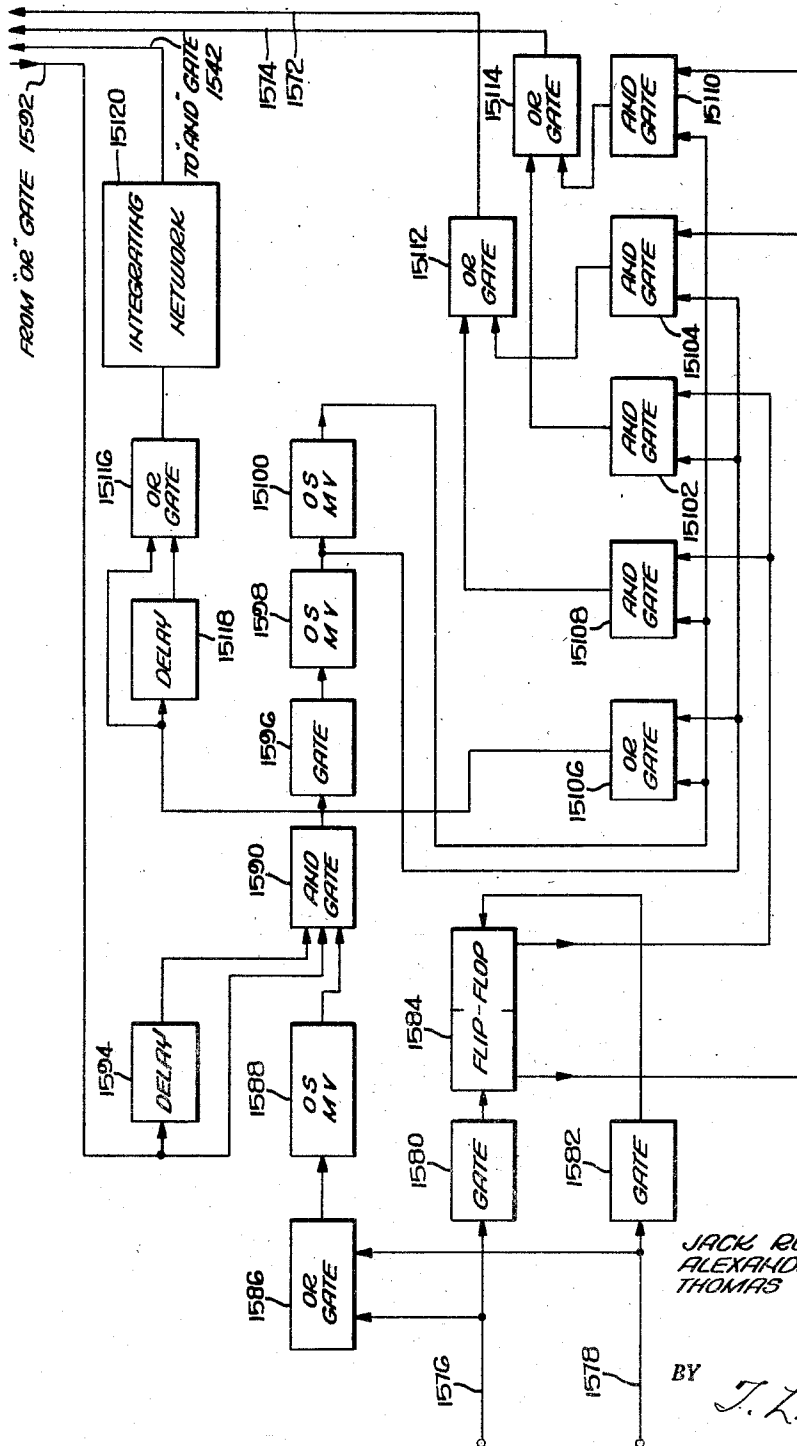


FIG. 15B.

JACK ROSENBERG
ALEXANDER F. BREWER
THOMAS J. SCUITTO
INVENTORS

BY *J. L. Bowes*
ATTORNEY

2,833,941

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**JACK ROSENBERG
ALEXANDER F. BREWER
THOMAS J. SCUITTO
INVENTORS**

BY

T. L. Bowes

ATTORNEY

May 6, 1958

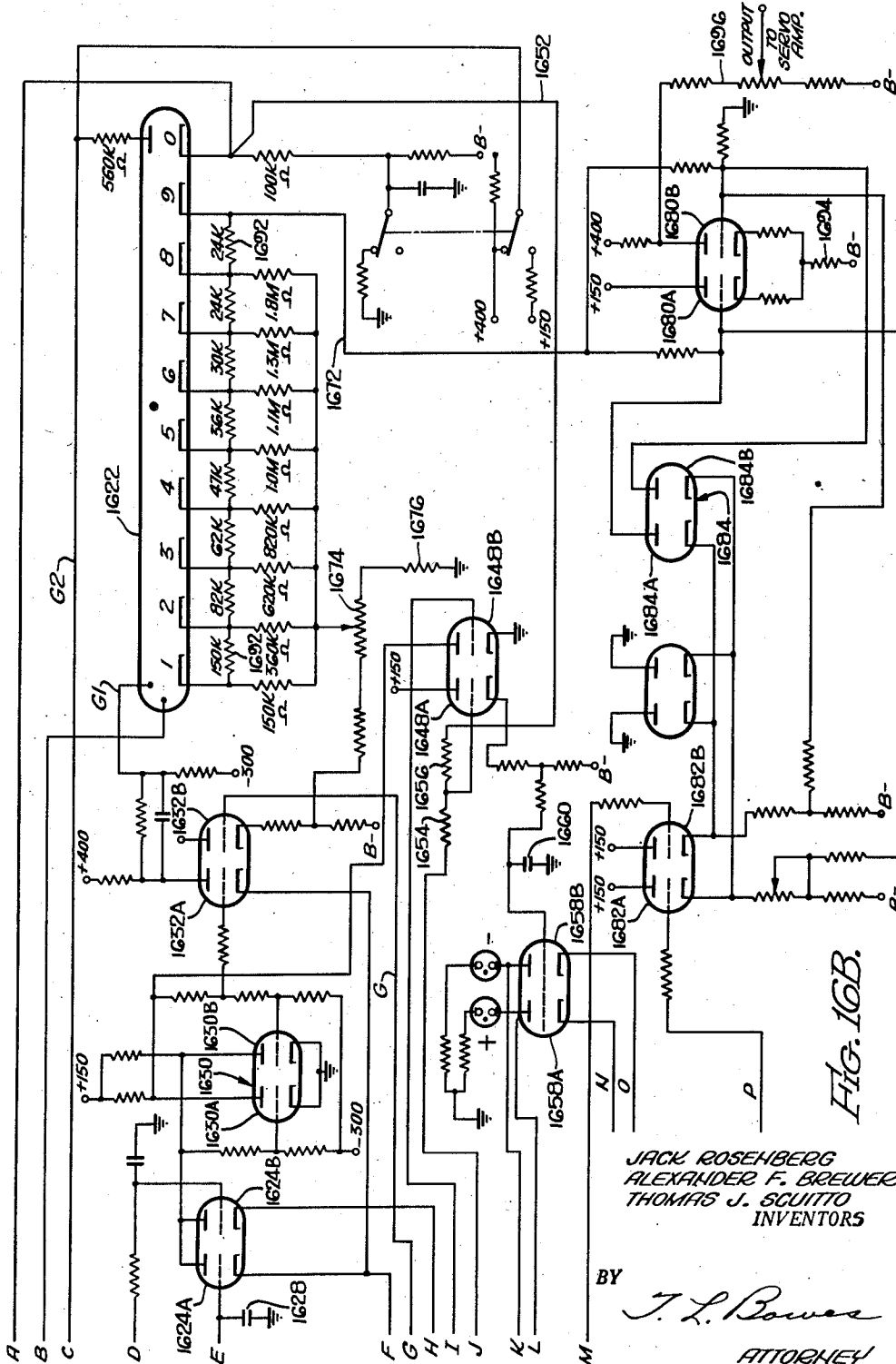
J. ROSENBERG ET AL

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AUTOMATION SYSTEM

Jack Rosenberg and Alexander F. Brewer, Pacific Palisades, and Thomas J. Scuitto, Santa Monica, Calif., assignors to General Dynamics Corporation, Rochester, N. Y., a corporation of Delaware

Application November 2, 1955, Serial No. 544,478

46 Claims. (Cl. 307—149)

This invention relates to automation systems and, more particularly, to an improved arrangement for automatically controlling machine tools.

In the typical machine shop, the machining of a piece of metal to obtain a finished product having a desired form requires that a methods man lay down the procedures for cutting the metal into the required shape in considerable detail. These procedures are then followed by one or more machine-tool operators. Where a large number of the same item must be made, it would appear that the function of operators to continually supervise and control the cutting operations of a machine tool can be economically obviated by some form of control device which directs a machine tool through a cutting sequence. A number of systems have been both proposed and built for the purpose of automatically controlling the operation of machine tools. Thus, the replacement of the machine-tool operator by the automatic-control system is one type of automation. "Automation" may be defined as the utilization of machinery to perform an operation automatically which was previously performed by human beings.

The automation systems for controlling motion which have been built hitherto have not been finding too great commercial success for a number of reasons. One of these is that the cost required for the installations is considerable. Another reason is that the accuracy of the results obtained is not as great in many instances as is required by the kind of product being machined. Still another great drawback on the mass use of these automation machines is that the instructions to the automation machine in the steps to be followed in order to effectuate a desired finished product from the raw stock attain such complexities as to discourage and deter any prospective users. The process of instructing the automation-control apparatus to follow or proceed along certain cutting paths is akin to the process of programming a computer. In actual machine-shop practice, the directions to be followed by the machine-tool operator are laid out in detail by the methods man, who, as a result of his vast experience, knows what sequence of cuts or cutting paths should be followed to produce the desired result.

An object of this invention is to provide an automation system which is simpler and faster to program than those heretofore.

Still a further object of this invention is to provide an automation system which is simpler to operate than those heretofore.

Yet another object of the present invention is to provide an automation system which is simpler to construct than those heretofore.

Still another object of the present invention is to provide an automation system which is more inexpensive than those heretofore.

The presently known automation systems usually employ a medium, such as magnetic tape or perforated paper tape, upon which signals are recorded. The function of the recorded signals is to direct motors, for example,

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which control the motion of a table upon which a workpiece is mounted relative to a cutting tool. The apparatus required in the machine shop to interpret the signals recorded in order to properly control the relative cutting tool and workpiece motions has been quite complex. This is not a desirable feature, since the vibration and noise attendant a machine-shop operation is usually such as to prevent or deter the continued operation of all but the most rugged types of equipment. While this invention, in those instances where a record is desired, may also employ a recording medium for the purpose of containing the instructions to be applied to the motion-controlling equipment, a further object of the present invention is to reduce considerably the complexities of the apparatus required at the location of the machine tool which is being controlled.

These and further objects of the present invention are achieved by providing a system wherein the programming information is very simply prepared and, further, the apparatus required for interpreting the programmed information is also extremely simple. For the programming of the computer, the layout man goes through substantially the identical procedure as he now goes through without automation apparatus. In other words, he proceeds to determine the desired operational sequence of cuts or cutting processes or motion paths for a tool relative to the workpiece which are required and prepares the drawings required. Each drawing may then be considered as being in a co-ordinate system, since dimensions from reference lines or edges are always provided.

The apparatus comprising an embodiment of the invention may include a source of periodic pulses from which pulses are applied to two divider means. The first of these divides the number of pulses obtained from the source by the differential of the equation of the desired motion path with respect to one of the co-ordinates. The second divider means simultaneously divides the number of pulses from the source by the differential of the equation of the desired motion path with respect to the other of said co-ordinates. The outputs from these dividing means may be directly utilized or may be recorded for future utilization. The data for finding the differential for each path is obtained by subtracting the co-ordinates at the beginning and at the ending of a path. These differences may be used to provide the numerical value of the dividers. Each divider means provides a train of pulses. Each pulse represents an incremental motion along a path such as that of the tool being controlled relative to the workpiece along one of the co-ordinates. Each train of pulses contains as many pulses as there are increments of motion required along a co-ordinate to complete the required operation which is the resultant of the motion along said two co-ordinates.

The pulse trains may be separately recorded, and the apparatus required at the machine tool may consist of a motor to drive the workpiece relative to the tool along each of the co-ordinates the required number of increments for which a pulse train is provided. Apparatus may be provided to furnish an output pulse for each increment of motion the workpiece is moved relative to the tool along a co-ordinate. A separate counter counts the recorded pulses which are applied to the separate driving motors. This counter (one for each co-ordinate) also counts the pulses obtained from the moving machine tool, subtracting pulses resulting from motion in the commanded direction and adding those resulting from motion in the opposite direction. Accordingly, it may be readily established, for example, whether or not the machine tool has effectuated a required cut amplitude, and any shortage or surplus of pulses due to machining difficulties or cutting-tool troubles or other causes can provide an alarm.

It should be appreciated that where only a single co-ordinate-path motion is required, one divider means is able to provide the output necessary for directing such motion. Also, where three co-ordinate-path motion is required, three divider means may be employed for providing the necessary control signals.

The novel features that are considered characteristic of this invention are set forth with particularity in the appended claims. The invention itself, both as to its organization and method of operation, as well as additional objects and advantages thereof, will best be understood from the following description when read in connection with the accompanying drawings, in which:

Figure 1 shows a straight-line graph to assist in an understanding of the invention;

Figure 2 shows an arrangement for deriving required number-representative signals from an adding machine;

Figure 3 is a block diagram of an embodiment of the invention employed to generate pulse trains for ordering motion along a straight line;

Figure 4 is a schematic and block diagram showing some circuit details for the embodiment of the invention shown in Figure 3;

Figures 4A through 4D show typical pulse trains which may be derived from this embodiment of the invention shown in Figure 3;

Figure 5 is a block diagram of an embodiment of the invention for generating control pulses for ordering motion along a circular path;

Figure 6 is a schematic and block diagram showing some circuit details for the embodiment of the invention shown in Figure 5;

Figure 7 is a block diagram of another embodiment of the invention for generating control pulses for ordering circular motion;

Figures 8A and 8B are schematic and block diagrams showing some circuit details for the embodiment of the invention shown in Figure 7;

Figure 9 shows typical pulse trains which may be derived from the embodiment of the invention shown in Figure 7;

Figures 10 and 11 are block diagrams of embodiments of the invention showing pulse generators for pulses for ordering parabolic motion;

Figure 12 is a block diagram of an embodiment of this invention showing a generator for control pulses for ordering a higher order curve motion;

Figure 13 is a block diagram of an embodiment of this invention showing a generator for control pulses for ordering a three-dimensional straight-line motion;

Figure 14 is a block diagram of an embodiment of the invention for executing the paths ordered by the control pulses generated;

Figures 15A and 15B are schematic diagrams of a motion digitizer and apparatus to prevent control pulses and motion-digitizer pulses from interfering with each other which are required in the embodiment of the invention shown in Figure 14;

Figures 16A and 16B are circuit diagrams of an error register and a digital-to-analog converter required in the embodiment of the invention shown in Figure 14; and

Figure 17 shows a typical workpiece mounted on a table, and the required cutting paths.

Straight-line generator

In order to facilitate an understanding of this invention, it will first be explained in connection with generating and effectuating straight-line paths or motion for a tool relative to the workpiece. Its utilization for various types of curved cutting paths will readily become apparent from the explanation that follows. Furthermore, the explanation will be directed to the automation of a machine tool, such as a milling machine, where the relative motion of the cutting tool and workpiece is effectuated by having a cutting head, which is stationary, and a table which moves to perform the required motion.

This should not be construed as a limitation upon the invention, since the principles explained here can readily be extended towards the automation of other machine tools or such diverse systems such as automatic displacement recording and reproducing systems or an automatic pen controlling system.

From elementary algebra, it can be established that the formula of a straight line is $y=mx+b$. The slope of the straight line can be obtained by differentiating y with respect to x , whereby

$$\frac{dy}{dx}=m$$

is obtained; m is the value of the slope which for any given straight line is a constant. Considering Figure 1, it can also be readily established that the slope of a straight line, m , which extends between two points, p_1 and p_2 , which have as their co-ordinates respectively (X_1, Y_1) , (X_2, Y_2) is equal to the tangent of the angle θ between the desired line and the x -axis. Mathematically, this can be readily expressed as

$$\tan \theta = m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\Delta y}{\Delta x}$$

Therefore, $\Delta y = y_2 - y_1$, $\Delta x = x_2 - x_1$. Therefore, to go from point p_1 to point p_2 , we can move simultaneously along the x - and y -axes Δx and Δy in the relationship

$$\frac{\Delta y}{\Delta x}$$

These co-ordinates are normally provided in a blueprint where measurements are provided from reference lines or edges. Thus, to effectuate a desired straight-line cut, if the co-ordinates of the beginning and ending of the path are known, the table of a milling machine may be directed simultaneously to move distances along the respective two co-ordinate axes, as expressed by the differences $(x_2 - x_1)$ and $(y_2 - y_1)$, to effectuate such a resultant cutting path.

At the outset, it is desired to move the workpiece and cutting tool relative to one another in response to pulses an increment of motion for each pulse. A suitable increment may be considered as 0.001 inch. For the purpose of controlling the machine tool, a separate pulse train may be provided for motion along each co-ordinate. According to this invention, a pulse train has as many pulses as increments of motion are required.

Thus, if a straight-line cut of 10 inches along, for example, the x -axis, is required, then 10,000 pulses would be required in the pulse train. Similarly, if a straight-line cut of 5 inches along the y -axis is required, then 5,000 pulses in the pulse train are required. A milling-machine table may be driven along the x - and y -co-ordinates by two separate drive screws. A pulse-responsive driving mechanism may be employed to drive each screw. The driving mechanism employs motors which preferably are servo motors. It can be appreciated that in order to make a desired straight-line cut, both co-ordinate motion motors are simultaneously excited with a separate pulse train, whereby each train represents the motion required along a co-ordinate to provide a resultant relative table and cutting-tool motion to effectuate the required cut on the workpiece.

The problem now presented is to obtain two pulse trains, one for each co-ordinate motion driving motor, the pulse trains having the requisite number of pulses corresponding to incremental motions along a co-ordinate axis, which are required to obtain the proper resultant cutting path. These co-ordinates may be established when measuring a specimen by referencing dimensions to two co-ordinate baselines. A layout blueprint shows a required cut referenced to two baselines which may be relatively rectangularly disposed with the distances to the point at which the cut is to begin and the point at which it is to end being shown. Thus, $x_2 - x_1$ and $y_2 - y_1$ may be readily determined if the two rectangularly related

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baselines to which the starting and ending points are referenced are considered as the x - and y -axes. It is seen that to generate a line having the required slope m , a division is necessary.

It is well known that the output of a pulse generator may be readily divided by a counter. As an illustration, a generator may provide 1,000 pulses per second, and a counter may be set to count ten pulses before providing an output pulse. The counter then provides 100 output pulses per second when the generator output is applied thereto. Thus, effectively, the generator output has been divided by 10. If we apply pulses from a pulse generator to two counters, we may derive from each of the counters a train of pulses which equals the number of pulses applied thereto from the generator divided by the count of the counter, or the number set into the counter for the purpose of determining the amount of the division. Expressed another way, the pulse rate " f " of the generator is divided by the scale of the counter. If one dividing counter is set to divide its input f by Δy , and the other of the counters is set to divide its input f by Δx , there will emerge from the Δx counter a train of uniformly spaced pulses at one rate

$$\frac{f}{\Delta x}$$

while from the Δy counter will emerge a train of uniformly spaced pulses at another rate

$$\frac{f}{\Delta y}$$

If we examine the ratio between these two rates, we see that

$$\frac{\frac{f}{\Delta x}}{\frac{f}{\Delta y}} = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}$$

This is exactly the slope of the desired cut between points x_1, y_1 and x_2, y_2 . To obtain such a path, a machine-tool table which interprets each pulse as an order to move by 0.001 inch along a co-ordinate must have simultaneously applied a y -axis drive totaling Δy pulses and an x -axis drive totaling Δx pulses.

The two output pulse trains from the respective dividing counters may be recorded for this purpose so that whenever the same operation is required, the recording can be employed for repeating it without further effort. The recording medium may be of any type, but magnetic tape on which the electrical pulses are recorded is preferred. Because of the nature of the counting process, the two pulse trains recorded on the magnetic tape are periodic in nature, which is to say that in any one direction pulses will be spaced uniformly in time. This is an advantage when considering the output motion of a servomechanism which is to be employed to drive the cutting table in response to the pulse train. It is much easier to achieve smooth motion with periodic pulses than with an aperiodic drive.

It should be appreciated that the slope of a straight-line cut can be positive or negative. The directions to the servomechanisms employed for driving the worktable can order it to go in one direction for positive-slope cuts and in the opposite direction for negative-slope cuts. Accordingly, instead of two channels upon which two pulse trains for the respective two co-ordinates are recorded, four channels may be employed, two for each co-ordinate, one of the two being for positive motion direction and the other for negative, or the opposite, motion direction. The determination of in which of the two channels (two for X and two for Y) a pulse is to be recorded may be derived by sensing whether $x_2 - x_1$ or $y_2 - y_1$ provides a positive or negative difference.

As an illustration of one preferred source of input to the system, adding machine apparatus which may be modified in the manner shown in Figure 2 is used. This

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is employed to calculate the differences $x_2 - x_1$ and $y_2 - y_1$. As previously explained, $x_2 - x_1$ is the difference between one of two co-ordinates denoting the beginning and ending of a straight line and $y_2 - y_1$ is the difference between the other of two co-ordinates denoting the beginning and ending of the same straight line.

Actually, for each subtraction, two separate electrical outputs are derived from the adding machine apparatus, one being signals representative of the co-ordinate difference ($x_2 - x_1$ or $y_2 - y_1$) and the other being the sign of the difference. The most significant digit position of the adding machine is reserved and employed to provide sign information. By a most significant digit of a number is meant the highest order digit. For example, the most significant digit of 6,352 is 6. The most significant digit of 3,259,875 is 3. The most significant or highest digit position of the adding machine which is reserved for indicating the sign is the highest digit position of which the machine is capable. It should be noted that adding machines may be made to have any digit-handling capacity desired. Regardless of this, the principles to be described apply. If a subtraction is made and the difference or answer is positive, the highest digit position will remain a zero, provided that the numbers being handled are not of a size to include the highest digit position. If a subtraction is made and the difference or answer is negative, then the highest digit position will be a nine or less, dependent upon how large the negative difference is. This will become more apparent from the following description of Figure 2.

Figure 2 is a drawing which represents by way of illustration how the differences which are obtained by employing an adding machine are converted into an electrical output which may be entered into a register shown in Figure 3. By way of example and to maintain simplicity in the drawing, only three of the many answer wheels in an adding machine are shown. The answer wheels are the wheels which are read when the answer to a calculation is required. The first answer wheel represents the units answer wheel; the second wheel represents the tens answer wheel; the third wheel represents the representative of the answer wheel in the highest digit position of which the adding machine is capable. Thus, there are shown a tens and units answer wheel and the answer wheel from which there is derived the information as to the sign of the answer.

In performing the required subtraction function, first there is entered into the adding machine the minuend from which a second number, or subtrahend, is subtracted. Next, the subtrahend is entered and the subtraction process performed. The answer to the subtraction is represented by the angular position of the various answer wheels. These wheels bear numbers on their peripheries and represent the answer as seen through an opening in the housing of the adding machine (not shown). Regarding the answer wheels shown in the diagram more closely, these have been modified by placing insulating material (not shown) on the sides thereof and electrical contacts on the insulating material, one of which is positioned opposite each one of the digits represented on the periphery of the answer wheel except the "0" digit. These contacts are then all connected together by a common bus bar. The contacts and bus bar may be applied to the answer wheel sides, using printed circuit techniques or by any other suitable means. All the answer wheels employed in the adding machine are thus modified.

The answer wheel for the highest digit position has a slightly different arrangement. It has the plurality of contacts as shown for the other answer wheels, except that there is also provided a contact at the zero position which is not connected to the common bus connecting the other contacts. Furthermore, the zero contact is larger than the others. Three fixed position brushes are employed with the highest-digit

position answer wheel. One of these, 218, is positioned to touch the contact for the zero position on the wheel when it is the digit which is indicated as a result of the arithmetical subtraction which has been completed. This brush is shorter than the others and can only make a connection with the oversize "zero" contact. The brush 219 serves the purpose of contacting any one of the remaining contacts. A third stationary brush 220 is employed in association with the highest-digit-position answer wheel for the purpose of energizing the contact which is at the answer position (shown as the position of brush 218 in the drawing). This third brush is connected to an adding machine reset key 221. This adding machine reset key, in turn, is connected to a source of potential. Thus, when the adding machine reset key is depressed after a subtraction has been performed, either brush 218 is energized (indicative of a positive answer) or brush 219 is energized (indicative of a negative answer). Both the brushes are connected through a switching device to a sign register in the manner shown in Figure 3.

The adding machine reset key is also connected to the bus on each one of the remaining answer wheels. Each of the answer wheels has associated therewith a stationary brush 224, 226 which can be energized through the contacts on the wheel. The stationary brush 224 for the units answer wheel is connected to a units reversible decimal counter 228; the stationary brush for the tens answer wheel is connected to a tens reversible decimal counter 230. It is to be understood from this that each answer wheel except the highest-digit-position answer wheel 214 has a stationary brush connected to the input of an associated reversible decimal counter.

The reversible decimal counter stages may be of a type to be found described and shown later in this application or of the type described and shown in an article by V. H. Regener. The article is entitled "Reversible decade counter"; it is found in the magazine, *The Review of Scientific Instruments*, volume 17, pp. 375-376, of the issue of October 1946. This reversible decade counter is one which can count to ten in an additive direction or count back to zero in a subtractive direction. There are two inputs provided for this operation. One of these inputs, to which each associated stationary brush is connected, is the additive input for the stage. The other input is a subtractive input. Pulses applied thereto are subtracted from whatever count has previously been inserted into the counter stage by the other input. An oscillator 232 generates pulses when it is enabled by an "enter switch" 234. These pulses are applied to both a plus-gate 240 and a minus-gate 242. The one of these two gates which is open to pass these pulses is determined by a flip-flop 244. Plus-gate 240 applies its output to the add input of the units counter; minus-gate 242 applies its output to the subtract input of the units counter.

Flip-flop 244 is a two-stable-state trigger circuit of the type described and shown on pp. 96 et seq. of the book *Electronics*, by Elmore and Sands, published by the McGraw-Hill Book Co., Inc., in 1949. It is tripped to one of its stable states by an output from the stop-gate 236. At this time, it opens a minus-gate 242. An output from the lead which indicates that the number has a negative sign trips the flip-flop to its other stable state, at which time plus-gate 240 is opened and minus-gate 242 is closed. Pulses passed through minus-gate 242 to the units counter are subtracted from the count already present in the units counter as a result of pulses applied from the stationary brush 224. Suitable gates, such as the stop-gate or plus- and minus-gates, are well known as coincidence gates or coincidence circuits and, as an illustration, are shown and described in the above-noted book *Electronics* on pp. 117 et seq.

Between the units and tens counter stages are a plus-gate 240' and a minus-gate 242' which are similar to gates 240 and 242 and function similarly with respect to the tens reversible counter. A similar pair of gates would

be provided between each of the higher order stages of the counter. All the plus-gates and all the minus-gates are controlled from the flip-flop 244 in the same manner as are plus-gate 240 and minus-gate 242. However, the pulses which are applied to these gates, such as 240' and 242', consist of carryover output from the preceding stage. A carryover output pulse is derived from a counter stage when it passes through the count of nine.

Thus, the arrangement for the reversible counter stages is such that input from each answer wheel is additively inserted into each associated counter stage. Then, by means of the plus- and minus-gates as controlled by the flip-flop 244, the various counter stages are interconnected into a serial counter so that pulses from the oscillator 232 are either added to or subtracted from the total count represented by all the counter stages.

A subtraction having been performed on the adding machine, the adding machine reset key 221 is actuated. This serves the purpose of either manually or automatically resetting all the wheels of the adding machine to the zero position, as well as applying potential to the busses which are used to interconnect the contacts on the sides of the various answer wheels. The answer wheels are all reset to zero by being rotated in the same direction back to zero. This is in a decreasing-number manner. This occurs whether the answer is positive or negative. Thus, when the answer wheels are rotated back to their zero position, each one of the contacts will generate a pulse when it connects with the associated stationary brush which, in turn, applies it to the associated decimal counter stage. Thus, if, for example, with the arrangement shown, an answer of +22 were obtained, the units wheel would rotate and generate two pulses which would be entered into the units reversible decimal counter. The tens wheel 212 would generate two pulses in being rotated back to zero. These two pulses would also be entered into the tens reversible decimal counter. The highest-digit-position answer wheel would remain stationary, thus providing a pulse on the brush 218. If, for example, 25 is subtracted from 23, the answer by the adding machine would be 9 . . . 98. The 9 in the highest-digit-position would be detected upon pressing the reset key indicative of a negative answer. In being reset, the units answer wheel would generate eight pulses, and the remaining answer wheels would generate nine pulses each.

After the adding machine answer wheels have been returned to zero, the store key 234 is depressed. This store key 234 causes the oscillator 232 to commence delivering pulses to the plus-gate 240 and the minus-gate 242. If the answer to the subtraction is positive, then the minus-gate 242 is open and the oscillator pulses are subtracted from the units-counter input. When the units counter passes through its nine count, it emits an output known as a carryover pulse. This is applied through the two gates 240', 242' to the tens counter stage to be added or subtracted as determined by the control flip-flop 244. If the answer is positive then the minus-gate 242' is open and the carryover pulse is subtracted. This arrangement also obtains for all the higher order counter stages (not shown). If the answer to the subtraction is negative, flip-flop 244 opens all the plus-gates 240, 240' and closes all the minus-gates 242, 242'. Thus the pulses from the oscillator 232 as well as the carryover pulses are added to the count in the counter.

To illustrate the necessity for the above operation, assume that it is necessary to subtract 15 from 32. The answer is 17. In being reset the answer wheels introduce seven pulses into the units counter and one pulse into the tens counter. The store key is then depressed. The oscillator then delivers pulses to the units counter through the minus-gate 242, which pulses are therefore subtracted from the seven count. Thus, after eight pulses have been delivered the units counter passes through its nines count condition, providing a carryover pulse which is subtracted from the one count in the tens counter stage.

After nine more pulses from the oscillator, or a total of 17 pulses, the counter stages are in their zero count condition. This is sensed by the stop-gate 236. It then proceeds to stop the oscillator. The 17 pulses are also entered into a binary counter 238. This provides an output consisting of the binary representation of the number 17. This output is applied through a switching circuit to a storage register, as is more fully shown in Figure 3.

Consider now, as an illustration of the operation of the device shown in Figure 2, a subtraction which results in a negative answer; for example, 28 from 17 is 9 . . . 989. The actual difference required is 11. The answer shown on the adding machine is the complement of 11. When the adding machine is reset, 9 . . . 989 is entered into the various counter stages. However, since the answer is negative, the negative lead is excited. This will trip the control flip-flop 244 so that the plus-gates 240, 240' are opened and the minus-gates 242, 242' are closed. Thus the oscillator pulses will be added to the count in the counter stages when the store key 234 is depressed. Since only eleven pulses are required to fill the counter whereupon all stages attain a zero count condition after these 11 pulses are received, the stop-gate will render the oscillator inoperative. Upon an output being obtained from the stop-gate, the control flip-flop 244 is reset to the condition where it opens minus-gates 242 and 242'.

The adding machine described generates pulses from each of its answer wheels when it is reset which equal in number the number indicated by the answer wheel. Other forms of adding machines exist which return the answer wheel to zero by the shortest possible rotation or which, when they have a negative answer, start going in a positive direction after reaching zero instead of continuing on in the negative direction. These machines may also be modified to provide a number of pulses as indicated by the number on the answer wheel in the same manner as has been described above. However, in the case of the adding machine which reverses direction of the answer wheel for a negative answer, the number of pulses generated by a wheel for a negative answer is the required number, and no provisions for gates or a control flip-flop are required, since the pulses from the oscillator are always subtracted from the count in the counter. The adding machine with answer wheels which proceed to zero by the shortest possible direction require modification to operate as one of the other types. There is still another type of adding machine wherein the answer wheels return to zero from one direction for a positive answer and from the opposite direction for a negative answer. These adding machines can be operated with the arrangement shown in Figure 2, except that when a negative answer is obtained the pulses from the answer wheels must be entered into the associated counters as a complement. That is, when the answer as shown by the wheels is 9 . . . 989, the answer wheels would generate pulses, which if permitted would enter 1 . . . 121 in the respective counter stages. By appropriate switching, however, this is entered into the counter stages as complements or 9 . . . 989. The arrangement for doing this is not difficult but will not be shown here, since it is not a favored embodiment of the invention in view of the simplicity of the arrangement shown and described. A showing of the further required arrangement for this embodiment would only add to the complexity of the explanation and is not believed required in view of the foregoing explanation.

As explained above, the number of pulses entered into the decimal counter are also entered into the binary counter. In effect, what has been accomplished is a conversion of the answer of the adding machine, which is in decimal code, into a binary code. The output of the binary counter is the binary code. A suitable binary counter of this type is described and shown in an article

entitled "Electronic counters," by I. Grosdoff, in the September 1946 issue of the RCA Review, vol. 7, pp. 438 et seq.

Figure 3 is a block diagram of a straight-line generator in accordance with this invention. A rectangle 300 represents the adding machine and the associated circuitry required to convert its output from decimal to binary form, which is shown in Figure 2.

The output from the adding machine may be connected through a switching device 302, when the difference $(x_2 - x_1) = \Delta x$ is found, to an $(x_2 - x_1)$ sign sensor 304 and to a Δx register 306. The output from the adding machine may also be connected through the switching device 302, when the difference $(y_2 - y_1) = \Delta y$ is found to an $(y_2 - y_1)$ sign sensor 308 and to a Δy register 310. It is possible to eliminate the switching device 302 by employing two adding machines, one supplying the difference $(x_2 - x_1)$ and its sign directly to the respective associated register 306 and sign sensor 304, the other supplying the difference $(y_2 - y_1)$ and its sign directly to the respective associated register 310 and sign sensor 308. Each of the sign sensors may consist of a flip-flop circuit of the type shown and described on pages 96 et seq. of the book Electronics, by Elmore and Sands, published by the McGraw-Hill Book Company, Inc., in 1949. These flip-flop circuits are triggered into one or the other of their stable states, depending upon which of the sign output leads from the adding machine is energized (see Figure 2). The registers 304 and 306 may be any suitable type of memory device, either relay, magnetic, or electronic, which can store and can provide as an output not only the true digital value of the input but also as an additional output the complement of the input. A preferred type of relay register is shown and described in Figure 4.

The embodiment of the invention shown in Figure 3 employs the binary system although the decimal system or any other desired numeric system may also be employed without departing from the spirit and scope of the invention. In the binary system, a complement of a binary number is obtained by replacing the ones in the number by zeroes and the zeroes by ones. This complements the number with respect to another number having as many digits as the number being complemented and wherein all the digits in that other number are ones. Thus, if a four-digit binary number such as 1000=8 is complemented, its complement is 0111=7. The four-digit binary number having all ones is 1111=15. As another example, 0101=5. Its complement is 1010=10.

The $(x_2 - x_1)$ sign sensor 304 opens either gate 312A or 312B, depending on the condition in which the sign sensor was placed by the adding-machine output. Similarly, the $(y_2 - y_1)$ sign sensor 308 opens either gate 314A or 314B, depending on the condition in which it was placed by the adding-machine output. These gates determine in which of the two channels (two for x and two for y) a pulse is to be recorded for determining the slope of a cut. This will be explained subsequently in more detail.

A pulse generator 316 provides a train of periodic pulses at a frequency F . The pulse generator may be a free-running-blocking oscillator or free-running multivibrator of the type described and shown on pages 81 et seq. of the above-noted book Electronics. These circuits are capable of being started and stopped by the application or removal of a bias voltage applied from external apparatus. Thus, the pulse generator is enabled to start oscillations by a signal from a "start source" 318 which may be a mechanical key or electronic apparatus which is operated when it is desired to commence the operation of the apparatus.

The pulses from the pulse generator are applied to two counters 320, 322 which perform the function of dividing and thus are hereafter referred to as dividers, or dividing counters. These counters may be of the type

shown on page 18 of the book *High-Speed Computing Devices*, by Engineering Research Associates, and published by the McGraw-Hill Book Company, Inc., in 1950. These dividers 320, 322 respectively divide the number of pulses applied thereto by (x_2-x_1) and by (y_2-y_1) . These dividing counters are operated in this embodiment of the invention in a manner known in the art as a predetermined counter. The numbers by which they are to divide are those which are entered in the Δx and Δy registers.

To illustrate the operation of a predetermined counter, let it be assumed that $(x_2-x_1)=3$ or 011 in the binary code. Let dividing counter 320 be a three-stage binary counter with a maximum capacity of seven. If the counter is initially cleared to zero, its stages represent 000. As pulses are applied, the following numeric sequence is represented by the counter stages 001, 010, 011, 100, 101, 110, 111, 000. This is a totalling process and such a counter may be termed a summing counter. It is seen that after eight pulses the counter returns to its initial state. In so doing, it emits an output pulse from the last or highest order stage, which occurs when the counter goes from the 111-representative condition to the 000-representative condition. This last stage represents the most significant digit of the binary number.

The quantity $(x_2-x_1)=3$ or 011 in binary form may be expressed as a complement, as previously explained, by replacing the zeroes in the number with ones and the ones with zeroes, giving 100. If this complement is inserted into the counter and pulses are applied to the counter, it would take four pulses to restore the counter to zero from the number 100 which is set into it. If, however, before applying these pulses an additional pulse was applied to the counter so that it represents 101, only three pulses are required to restore the counter to 000. The first complement (100) is known as a "one's complement" and, when one pulse is added (101) there is provided a "two's complement." When a two's complement of a binary number is inserted into a binary counter, only a number of pulses equal to that number need be applied to the counter to restore it to a 000 condition.

The above describes the method of operation of the dividing counters. The complement output of the Δx register 306 is transferred by a complement preset gate 324 at the proper time into the first divider 320, which has previously had entered therein a single pulse, in order to complete the establishment of a two's complement. The means for inserting the single pulse is a delay line 226. The delay line may be any of the types which are well known in the art, suitable types of which are described and shown on pp. 38-47 of the above-noted book *Electronics*. The delay line is connected between the highest order stage and the input or lowest order stage of the counter. When the counter goes from its filled state to its empty state, as described previously, an output pulse may be derived from the highest order stage. This is applied to the delay line from whence after a suitable interval it is applied to the counter input to complete the required "two's complement" of the number being inserted from the complement preset gate. This operation is described in greater detail in connection with the description of Figure 4. The second divider 322 is also associated with a complement preset gate 328 and a delay line 330. This complement preset gate 328 receives a "one's" complement output from the Δy output which is transferred thereby at the proper time into the second divider. The delay line 330 serves the function of inserting a pulse into the counter also at the proper time to convert the one's complement to a two's complement. The output pulses from the respective dividers are also employed to actuate their associated complement preset gates to insert the one's complement into the dividers.

As thus far described, an adding machine is employed to determine the numeric values of the terms Δx and Δy .

These are stored in respective Δx and Δy registers. The registers enter these values into respective Δx (first) and Δy (second) dividers. Upon a signal applied from the start source, the pulse generator supplies pulses to both dividers at a frequency F . The number of these pulses, or, alternatively expressed, the frequency, is divided by both dividers by the quantities Δx and Δy , as was described previously. Each time a division by Δx or Δy occurs, an output pulse is provided by each which re-establishes the respective quantities in the respective dividers and which are subsequently recorded in a manner to be described. Sign-sensing circuits 304 and 308 which sense the signs of the respective terms Δx and Δy serve to control the opening and closing of gates 312A, 312B—314A, 314B, whereby the output pulses of the second and first dividers are directed into the proper x and y co-ordinate control channels. Thus, trains of pulses are provided for controlling x co-ordinate and y co-ordinate motion increments simultaneously to provide a resultant straight-line path having a desired slope.

The remaining apparatus to be described in Figure 3 functions to terminate the pulse trains being generated when the length of the straight-line path equals that of the straight line from which the information applied to the input adding machine was derived. To accomplish the function of terminating the generation of further control pulses, two summing counters 332, 334 are provided. One of these, 332, counts the number of output pulses obtained from the first divider

$$\left(\frac{f}{\Delta x}\right)$$

The second of these 334 counts the number of output pulses obtained from the second divider

$$\left(\frac{f}{\Delta y}\right)$$

The summing counters are binary counters and may have the same structure as the dividing counters. Both actually operate in the same number as far as input from a pulse source is concerned. For the dividing counters, the pulse source may be considered as the pulse generator; for the summing counters the output from the associated dividing counters can be construed as "pulse source" outputs. The respective relay registers 310, 306 have their respective "true value" outputs applied as one set of inputs to the respective coincidence gates 338, 336. A second set of inputs to these gates comprises the counts of the respective summing counters 332, 334. The circuit details of a preferred arrangement for these gates are shown in Figure 4. These gates are well known in the art as coincidence or recognition gates. They require a coincidence of all their inputs to provide an output. Other suitable coincidence gate arrangements are found described in the book *Waveforms*, pp. 364 et seq., by Chance et al., published by the McGraw-Hill Book Company in 1949. Accordingly, outputs from the respective coincidence gates are obtained when the associated summing counter count and the true value of the register are the same. The coincidence gate outputs, in turn, are applied to a second coincidence gate 340, also called a stop-generator gate. This gate, upon receiving a coincidence of inputs, provides an output which is applied to the pulse generator 346 to cause it to stop.

The number of pulses counted by the respective x and y summing counters 334, 332 equals the number in the respective Δx and Δy registers 306, 310. Each one of these pulses represents an increment of motion along the co-ordinate axis, and, therefore, there are as many pulses required as there are increments of motion required for generating the resultant required straight line. The predetermination of the size of an increment of motion to be derived responsive to a pulse determines the number of pulses required for generating the straight line. Thus to generate a line 10 inches long parallel to one of the

axes, where a pulse represents .001 inch, 10,000 pulses are required. If a pulse represents 0.0001 inch, then 100,000 pulses are required. In using the adding machine, if the points x_1 , y_1 and x_2 , y_2 are in inches, they are each multiplied by a factor

$$F = \frac{1}{K}$$

where K is the incremental distance represented by a pulse, before being entered into the adding machine.

Referring now to Figure 4, there may be seen more detail of the arrangement for the straight-line generator shown in Figure 3. Due to the symmetry of the apparatus, as may be appreciated from Figure 3, in Figure 4 there is shown the schematic for a dividing counter 320 or 322, a register 306 or 310, a summing counter 332 or 334, a coincidence gate 336 or 338, and a complement preset gate 324 or 328. Their interconnections are also shown in accordance with this invention. It should be appreciated that two of the circuits shown in Figure 4 are required for the complete system, as is shown in the block diagram of Figure 2.

The dividing counter 320 and the summing counter 332 each have three flip-flop stages. This is not to be considered as a limitation but is merely shown by way of example. The actual operation of and interconnections of the dividing counter and the summing counter comprising a number of flip-flop stages in series in performing the function of counting input pulses is the same as any other binary counter, is well known, and is described, for example, in the previously mentioned article by Grosdoff. Thus their interconnections for the purpose of counting need not be recited here.

A relay register 306 is shown, also consisting of three stages. The adding machine (not shown here) by its output either exciting or not the relay coils 416A, 416B, 416C sets the relay register to represent a binary number equal to the difference between two co-ordinates as computed by the adding machine. Each relay in the register is provided with two movable double-pole, double-throw contacts 418A, 418B, 418C—420A, 420B, 420C. One contact is always grounded when the other is connected to -300. Thus, one set of contacts represents the one's complement of the number represented by the other set of contacts. As shown in the drawing, both movable contacts are simultaneously moved when the associated relay coil is excited. Allowing, arbitrarily, the lower tier of relay contacts 418A, 418B, 418C to always represent the binary number corresponding to the difference value from the adding machine, then the upper tier of relay contacts 420A, 420B, 420C represents its one's complement.

The three flip-flop stages 410A, 410B, 410C of the dividing counter 320 have the number which is represented by the upper tier of the contacts set into it by means of three presetting tubes 422A, 422B, 422C, which form the complement preset gate 324. These three presetting tubes have their control grids connected respectively to each of the relay contacts 420A, 420B, 420C, representing a one's complement. The output of each tube is applied to one side of an associated dividing counter flip-flop stage 410A, 410B, 410C to drive it. The cathodes of the three tubes are connected to the cathode of a gate tube 424, which, by virtue of the positive bias applied to its control grid, conducts current and maintains the three presetting tubes cut off. When this single tube is made nonconductive by an output from the dividing counter 320 when it fills, those of the presetting tubes which have their grids connected to ground potential by the associated relay contacts will be rendered conductive. The others, which have their grids connected to the -300 volt potential by the associated relay contacts cannot conduct. The conductive ones of the presetting tubes cause the associated flip-flops to be set in a corresponding condition, if they are not already in such condi-

tion. Thus, the one's complement number is transferred into the predetermined counter. It should be appreciated that a flip-flop has two stable states and one of them is with its left side or left one of the two tubes conductive. The other is with its right side or the right one of its two tubes conductive.

Once the one's number complement is set into the dividing counter, an additional pulse is required to be set into the counter. As previously stated, the two's complement of a number must be set into the dividing counter in order to obtain the required division by that number, since the counter is a binary operating one. This two's complement is obtained by adding one to the complement of the number entered into the dividing counter from the register. The pulse for performing this is obtained from the last stage 410C of the counter when it goes from its one to its zero state. This is delayed for the time required for the counter to be preset by the delay line 326.

A start pulse is applied to the gate tube 424 to enter the number complement and then the clock-pulse source is enabled. The counter proceeds in well-known fashion to count from the number which has been set into it until the counter is filled. The three-stage counter shown is filled upon completing a count of eight. If the number in the lower bank or tier of the relay register is three, then the dividing counter had the number five set into it. Upon the eighth count, the last stage of the predetermined counter provides an output pulse which enables the gate tube to lower the cathodes of the three presetting tubes, whereby the predetermined counter is reset to the number four. An output pulse has also been obtained from the last stage of the flip-flop when it reaches its full count condition. This is delayed until the counter has been preset, at which time it is applied to the first stage of the counter to complete the two's complement. The dividing counter then proceeds to count again the output from the clock-pulse generator.

Each pulse which emanates from a dividing counter, when it is filled, is applied to a summing counter. The dividing counter 320, which divides the clock pulses by Δx , applies its output to the y summing counter 332, and the dividing counter 322, which divides the clock pulses by Δy , applies its output to the x summing counter 334. When the three flip-flop stages 412A, 412B, 412C of the counter 334 attain the identical value, as is represented by the lower-tier contacts 418A, 418B, 418C of the relay register 306, the coincidence is sensed by the coincidence gate 336, and a pulse is applied to the stop-generator gate 340.

The coincidence-sensing arrangement for the coincidence gate includes two triode tubes which are associated with each counter stage. Thus, stage 412A has associated tubes 428A and 430A, stage 412B has associated tubes 428B, 430B, and stage 412C has associated tubes 428C, 430C. The grid of tube 428A is coupled to the grid of one of the two tubes in counter stage 412A and through a diode 428AD is coupled to the relay arm 420A. The grid of tube 430A is coupled to the grid of the other of the two tubes in counter stage 412A and through a diode 430AD to relay arm 418A. The other tubes 428B, 430B, 428C, and 430C are similarly coupled to the grids of the tubes in the associated stages of the counter and through diodes 428BD, 430BD, 428CD, and 430CD to the respective associated relay arms 420B, 418B, 420C, 418C.

The cathodes of all the tubes 428A, 430A—428B, 430B, 428C, and 430C are connected together and to the stop-generator gate. When all the grids of these tubes are driven down, or negative together, a large negative pulse is applied to the stop-generator gate 340. This occurs when there is coincidence between the number in the register and that in the summing counter. It is known that when a flip-flop, which comprises each stage of the summing counter, is in one stable condition, one of its grids is positive and the other is negative. When it is in its other

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stable condition, the voltage on the grids is reversed. Since, considering the first stage of the summing counter, the diodes 428AD and 430AD will couple these flip-flop grids to either —300 volts or ground potential, one or the other of the diodes is made to conduct. Thus, diode 428AD is conducting because its anode is connected to a slightly negative grid in the flip-flop stage 412A and its cathode is connected to a far more negative potential (—300 volts); the diode 430AD is not conducting because its cathode is connected to ground and its anode is connected to a grid which is substantially also at ground. The digit represented by the stage 412A does not correspond to the digit represented by the associated relay contacts 418A and 420A. However, if the flip-flop stage 412A is tripped to its other stable condition then the diode 428AD remains more conductive, since it is coupled to a positive grid in the flip-flop stage. The grid of triode 428A is thus effectively still at —300 volts, being coupled thereto by the diode 428AD. The diode 430AD is now not conducting, since its anode is coupled to a negative grid in the flip-flop stage. Therefore, the grid of triode 430A is also negative. This occurs when the digit represented by the register relay and the digit represented by the associated flip-flop stage is the same. Thus, it should be apparent how, when the binary number stored in the relay register and the one attained by the summing counter are the same, a negative voltage is delivered to the stop-generator gate from the coincidence gate.

It should also be noted that the straight-line generator is self checking. Unless both summing counters coincide in coincidence with their associated registers simultaneously, then there is an error and the function should be rerun. An alarm indication may readily be made, using the fact of output from one of the coincidence-sensing gates 542 without a coincidence-indicating output being received from the other 540.

To review the operation of the straight-line generator system shown and described above, a desired straight-line cut to be made on a workpiece has the location of the beginning and the ending of the straight-line path in a system of co-ordinates determined either from the blueprint used for making the part or from the part itself. An adding machine is used to subtract x_2 from x_1 , which designates the beginning and ending of the cut, and this difference (Δx) as voltages representing a binary number is entered through a switch into one relay register (Δx). This relay register then sets the complement of the number into one of two dividing counters

$$\left(\frac{f}{\Delta x}\right)$$

The sign of the difference is also sensed and this opens a gate for recording output in either a positive or negative recording channel for the particular co-ordinate (x) for which a pulse train is being generated. The switch at the output of the adding machine is then reversed. The difference between the remaining two co-ordinates ($y_2 - y_1$) marking the beginning and ending of the desired cut is also calculated, using the adding machine. This difference also has its sign sensed, and the proper positive or negative (y) recording channel is then opened. The difference (Δy) is entered as voltages representing a binary number into the proper relay register (Δy). A second dividing counter

$$\left(\Delta y\right)$$

then has the complement of this difference set into it. A clock-pulse generator is then started from a start-command source 248. It applies pulses to both dividing counters simultaneously. Each time a dividing counter fills it emits an output pulse which (1) is counted by the associated summing counter, (2) is recorded in the proper x or y channel, (3) actuates the preset gate to reset the counter, and (4) is added to complete the two's complement in the dividing counter. When the number of

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pulses derived from each of the respective dividing counters which are added in the summing counters equal the numbers stored in the respective relay registers, this is sensed by the connecting gates which through a stop-gate turns off the pulse generator.

The pulses derived for the x and y channels may be used directly for directing motion in a manner to be described later, or may be recorded for subsequent use. The recording medium may be any type desired, such as paper tape, magnetic drums, or magnetic tape. Magnetic tape is preferred, however.

Although one adding machine is described for determining the differences ($y_2 - y_1$) and ($x_2 - x_1$), and its output is switched to the Δy or Δx register, the switching function can be eliminated by providing an adding machine and its accompanying decimal-to-binary-code conversion apparatus for each register. Furthermore, although the straight-line generator is described using the binary system this is not to be construed as a limitation on the invention, since the decimal system or any other desired number system may be employed without departing from the scope or spirit of the invention. Use of the decimal system eliminates the requirement for decimal-to-binary-code conversion at the adding machine output. Further, the dividing counters, summing counters, and other apparatus would be decimal operating instead of binary operating.

Figures 4A through 4D show typical pulse trains obtained from the straight-line generator as a result of entering co-ordinate data for points p_1 and p_2 shown on the accompanying graphs. Figure 4A shows pulses derived for the x and y channels when p_2 ($x_2=3$, $y_2=4$) is greater than p_1 ($x_1=1$, $y_1=1$) and the slope of the straight line is positive. The tape fragment 450 shown has four tracks, two for x and two for y . One of the x and y tracks is for pulses representative of increments of motion in a positive direction; the other of the x and y tracks is for pulses representative of increments of motion in a negative direction. As shown on the tape 450, two positive x co-ordinate increment pulses and three positive y co-ordinate increment pulses are represented, the last of the x and y co-ordinate increment pulses occurring simultaneously. The motion generated responsive to these pulses is as shown in the graph to the left of the tape. Starting at p_1 , a single positive y pulse orders a vertical motion of one increment. Then a single positive x pulse orders a horizontal positive motion of one increment. The single positive y pulse again orders a vertical positive motion of one increment. The simultaneously occurring x and y positive pulses produce a resultant ending at p_2 , which is one increment vertically upward and one increment to the right of the previous point.

In Figure 4B, a typical pulse record is shown which is derived when p_1 ($x_1=3$, $y_1=4$) is larger than p_2 ($x_2=1$, $y_2=1$) and the slope of the straight line is still positive. As shown on the tape fragment 452, the x and y pulses are recorded in the negative tracks. The motion increments depicted on the graph to the right of the tape fragment proceed from p_1 to p_2 , are negative, and are the reverse of that shown for Figure 4A.

Figure 4C represents a typical pulse record where p_1 ($x_1=1$, $y_1=4$) is greater than p_2 ($x_2=3$, $y_2=1$) but the straight-line slope is negative. The required x co-ordinate motion increments are positive, and therefore the x pulses are recorded in the positive x track. The required y co-ordinate motion increments are negative, and the y pulses accordingly are recorded in the negative y track. The motion increments directed as a result of these pulses is shown in the graph alongside of tape fragment 454.

Figure 4D shows a typical pulse record on a tape fragment 456 for the situation where p_2 ($x_2=1$, $y_2=4$) is larger than p_1 ($x_1=3$, $y_1=1$) and the slope is negative. Since the required x motion increments are negative the

x pulses are recorded in the negative track for the x channel. The required y motion increments are negative and accordingly are recorded in the negative track for the y channel. The motion increments generated responsive to those pulses are shown on the graph to the left of the tape fragment 456. Generator pulses, from which the x and y pulses shown were derived, are shown at the top and bottom of the tape fragments 450—456.

The tape-recording apparatus employed may be any of the commercially available types. The tape speed is immaterial, since it is the relative frequency of the x and y pulse trains which is important. These may be secured by recording all four tracks on the single tape. The pulse trains are periodic. Any number of straight-line cutting paths may be recorded in sequence by the above-described apparatus.

Circle generator

The straight-line generator generates two pulse trains which are respectively representative of the differential with respect to x and the differential with respect to y of the formula for the straight line. Motion commands carried out in response to these pulse trains can recreate the straight line. The circle generator to be described employs the same basic principles of operation.

Using a similar technique, the dividing properties of two dividing counters can be used to generate curved lines. At any instant of time the ratio between the frequencies of pulse trains emerging from the dividing counters will be inversely equal to their division rates. If, instead of repeatedly dividing by the same quantity as is done in the straight-line generator, the quantity by which each dividing counter divides pulses from the generator is varied in time in accordance with a proper function, pulse trains which can order a circle can be generated. It is known that the general equation for a circle with its center at point a, b in a co-ordinate system is $(x-a)^2 + (y-b)^2 = r^2$; the instantaneous slope can be derived by differentiating this equation, which produces

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

If the predetermined quantities $(x-a)$ and $(y-b)$ can be made available at all times, the dividing counters can be caused to divide the clock-pulse rate f by these quantities. The divider outputs are pulses which have a relative occurrence for controlling incremental motion along x and y co-ordinates from which a circle can be generated. The motion increments along both axes occur so that the slope of the path or cut made by the tool on the workpiece is always changing so that it always equals the ratio dy/dx for the circle.

The equation obtained when the frequency f of the pulse generator is divided by dy/dx is as follows:

$$\frac{f}{\frac{dy}{dx}} = \frac{dy}{dx} = -\frac{x-a}{y-b}$$

Since the slope of the cut will change sign four times as a complete circle is traced out, it becomes necessary at all times to keep track of both the magnitude and sign of the quantities $(x-a)$ and $(y-b)$. This can be accomplished by use of reversible counters for the summing counters which can both add and subtract pulses. It also becomes necessary to make provision for positive and negative recording tracks, as was previously the case, to take care of the negative slopes.

The necessity for keeping track of magnitude and sign of the quantities $(x-a)$ and $(y-b)$, which are always present in the summing counter, may be better understood from the following. Assume that it is desired to generate a circle in a clockwise direction with its axis on $x=0, y=0$ ($a=0, b=0$) so that the circle lies in all four quadrants. Starting at any point in the first quadrant

(where x is positive and y is positive), as the circle is generated x is positive and motion in the x direction is in an increasing or positive direction. This can be represented by $+x \rightarrow +$, which is read as x is positive and going in an increasing x direction; y is positive but motion in the y direction is in a decreasing or negative direction represented by $+y \rightarrow -$, read as y is positive and going in a decreasing y direction. At the x axis, x is a positive maximum and y is zero. A table may be set up as follows for a clockwise generation of a circle:

First quadrant.....	$+x \rightarrow +$	$+y \rightarrow -$ (x and y are positive)
At x axis.....	$+x = \text{max.} +$	$y = 0$
Fourth quadrant.....	$+x \rightarrow -$	$-y \rightarrow -$ (x is positive, y is negative)
At y axis.....	$x = 0$	$-y = \text{max.} -$
Third quadrant.....	$-x \rightarrow -$	$-y \rightarrow +$ (x is negative, y is negative)
At x axis.....	$-x = \text{max.} -$	$y = 0$
Second quadrant.....	$-x \rightarrow +$	$+y \rightarrow +$ (x is negative, y is positive)
At y axis.....	$x = 0$	$y = \text{max.} +$

The following table may be set up for the counterclockwise generation of a circle:

First quadrant.....	$+x \rightarrow -$	$+y \rightarrow +$ (x is positive, y is positive)
At y axis.....	$x = 0$	$y = \text{max.} +$
Second quadrant.....	$-x \rightarrow -$	$+y \rightarrow -$ (x is negative, y is positive)
At x axis.....	$x = \text{max.} -$	$y = 0$
Third quadrant.....	$-x \rightarrow +$	$y \rightarrow -$ (x is negative, y is negative)
At y axis.....	$x = 0$	$y = \text{max.} -$
Fourth quadrant.....	$+x \rightarrow +$	$-y \rightarrow +$ (x is positive, y is negative)
At x axis.....	$x = \text{max.} +$	$y = 0$

Another fact is worthy of note from the above table which is pointed out later herein. Whenever the circle crosses one of the axes, whether traveling clockwise or counterclockwise, the direction of motion along one of the co-ordinate axes reverses while the other co-ordinate value passes through zero. Thus, when in the course of generating pulse trains for subsequently directing a circular motion, the fact that one of the co-ordinate values passes through zero can be utilized to reverse the direction of motion being generated along the other co-ordinate axis. This is made more clear by the explanation for Figures 5 and 6.

An embodiment of the invention in schematic form is shown in Figure 5 for generating pulse trains for directing a circular cut from input information consisting of the co-ordinates of the starting point (x_1, y_1) , ending point (x_2, y_2) , and center of a circle (a, b) , as well as information as to whether the circle is to be generated in a clockwise or counterclockwise direction. The location of the beginning and ending of a circle, as well as the location of the center of the circle, can always be determined from the layout drawing for a part to be made by machining. The co-ordinates of the center of the circle are designated as a, b . Accordingly, initially an adding machine arrangement 500, of the type described in Figure 2 for the straight-line generator, is employed in the manner described for the straight-line generator to establish the difference $(x_1 - a)$. This is obtained by subtracting the quantity a from the value of the x co-ordinate of the starting point of the circle. This difference is entered both in value and sign through the switch 502 into the relay register 504 and the sign register 506. From the relay and sign register the numerical value of $(x_1 - a)$ is transferred into an x summing counter 508 and sign of $(x_1 - a)$ into sign sensor 532. The complement of $(x_1 - a)$ is then entered from the reversible counter through a complement preset gate 510 into the dividing counter 512. The adding machine 500 is next used to compute $(x_2 - a)$. x_2 is the x co-ordinate at the end of the circular path to be generated. This value is entered into the sign and value registers 504, 506, replacing $(x_1 - a)$. The switch 502 is then thrown so that the next value to be computed on the adding machine, which is $(y_1 - b)$, will be entered into the sign and value register 516, 514. This number is then transferred into the y summing counter 518 and y sign sensor 534. From the y summing counter the complementary value of $(y_1 - b)$ is entered through the complement preset gate 520 into the $(y - b)$ dividing counter 522. Then the adding machine is used to determine $(y_2 - b)$, which is then entered into the sign and relay register, replacing $(y_1 - b)$.

A pulse generator 524 is provided which generates periodic pulses at a desired frequency rate. Upon application of a signal from the start signal source 526, the pulse generator starts to provide output pulses. The output of the pulse generator 524 is applied simultaneously to the two dividing counters 522, 512. The dividing counters which previously had the complements of the quantities $(x_1 - a)$ and $(y_1 - b)$ entered therein will count up to these quantities and then emit output pulses. The outputs from the respective dividing counters are applied to direction gates 528, 530, which are controlled to determine whether the pulses applied to them are to be recorded on a positive or negative track and, also, whether the pulses applied to them are added to or subtracted from the number which was previously inserted in the summing counters 508, 518. These direction gates are controlled by sign sensors 532, 534. The sign sensor 532 holds the sign of the number in the y summing counter 508. The sign sensor 534 holds the sign of the number in the x summing counter 518. The sign sensor 534 controls the direction gate 530 to determine whether the control pulses for the x channel are recorded on the positive or negative track. Sign sensor 532 controls the direction gate 528 to determine whether the control pulses for the y channel are recorded on the positive or negative track. The direction gates 528, 530 are also controlled by the associated sign sensors to determine whether the pulses from the dividers being recorded are added to or subtracted from the number in the summing counters 518, 508.

The summing counters, as previously explained, are reversible counters. Thus, when counting through zero, they will count as follows: 2, 1, 0, 9 . . . 99, 9 . . . 98, etc. This is a complementary count and is not a proper operation, since what is actually required is 2, 1, 0, 1, 2, etc. with the sign sensors preserving the proper sign of the value in the summing counter. This can be appreciated from the following. Assume that the difference $(x_2 - a)$ is -120. With the typical reversible counter in counting from a positive number to -120, the count would proceed as above through 0, 9 . . . 99, 9 . . . 98 to -120. What is actually needed here is to count 0, 1, 2 . . . 120. To assure this type of operation the output of the direction gates 528, 530 are respectively applied to the respective summing counters 518, 508 through respective reversing gates 529, 531. These reversing gates are respectively controlled from sign sensors 534 and 532. The details of the reversing gates and their operation are shown in Figure 6. In brief, however, when the sign sensor senses that its associated summing counter is passing through zero to a negative count, it controls its associated reversing gate to reverse the sense of the direction gate output being applied. Thus, negative output pulses are added by the summing counter so that it counts 1, 2, 3, although the sign sensor indicates that this is a negative value. Positive output pulses from the direction gate are subtracted from the value in the counter. When a sign sensor indicates that the value in the summing counter has a positive sign, then the reversing gate is controlled so that it does not affect the instructions of the direction gates to the summing counter. In other words, when the sign sensor indicates the contents of the summing counter are positive, the output from the direction gates is not reversed.

Pulses from the pulse generator are continually applied to the dividing counters. The respective dividing counters 512, 522 first divide the number of pulses from the clock generator by $(y_1 - b)$ and $(x_1 - a)$ which was first set into them. As soon as the generator pulses respectively totalling $(y_1 - b)$ and $(x_1 - a)$ have been applied to these respective counters, they are filled. An output pulse is derived from each of the counters which is channeled through each of the direction gates to the proper polarity track for the channel which is determined by the sign sensed for the number in the opposite sum-

ming counter. Thus, the sign of the number in the x summing counter determines the track polarity for recording the pulse emitted by the $(y - b)$ dividing counter, as well as whether this pulse is added to or subtracted from the number in the y summing counter. The sign of the number in the y summing counter determines the recording track polarity for the x channel, in which is recorded the pulse emitted by the $(x - a)$ dividing counter, as well as whether the pulse is added to or subtracted from the number in the x summing counter. The reversing gates operate when the value in the summing counter is negative to provide a true value count and not a complementary value count.

In recapitulation therefore, when each of the dividing counters fills it emits a pulse. This is (1) recorded in a proper track as outlined above, (2) entered into the proper summing counter as outlined above to change the number therein, and (3) enables the associated complement gate to set the complement of this changed number in the summing counter into the proper dividing counter. This is the same dividing counter into which the complement of the previous number in the summing counter was entered. The dividing counters will then divide the generator pulses by this new or changed number, and the pulses which are emitted when these dividing counters again fill are again recorded, the summing counter numbers are again changed by one in a positive or negative direction as determined by the direction gates, and these new numbers are again entered into the predetermined counters.

When the connection between the direction gate and the sign sensor is on the terminal designated as "s," the circle is being generated in a clockwise direction, and when it is on a terminal designated as "c" the circle will be generated in a counterclockwise direction. These s and c terminals merely reverse the polarity of the output of the sign sensor, thereby changing the polarity of the track in which a pulse is recorded as well as changing the polarity of addition of the pulse to the number in the summing counter. That this is proper may be seen by reference to the tables shown previously.

This cycle of operation will continue until the coincidence sensing gates 540, 542 indicate a coincidence between the sign and value of the numbers in the respective summing counters 508 and 518 and the sign and value of $(x_2 - a)$ and $(y_2 - b)$ which were previously established in the relay registers. Upon a single coincidence, the coincidence gate output is used to block further output being received from the dividing counter supplying its associated summing counter with pulses. Upon a double coincidence, the gate 544 is enabled by the simultaneous outputs from the two coincidence sensing gates and emits an output which stops the pulse generator. Thus, the circle generator generates two trains of pulses which may be subsequently employed to direct servomechanisms to simultaneously move a cutting head and table relative to each other along two co-ordinates so that a circular cut is effectuated upon the workpiece.

The block diagram of the invention shown in Figure 6 is suitable for use with counters operating in decimal, binary, or any other system of numbers. However, since most adding machines operate in the decimal system, if other systems of numbers are used, then a code converter is required between the output from the adding machine and the input to the relay registers. A converter arrangement for decimal-to-binary code is shown in Figure 2.

The similarity between the circle generator and the straight-line generator should be noted. Both use two dividers to divide the frequency of the pulse generator in accordance with quantities established therein. The divider outputs are recorded, added into the quantities in the summing counters, and, when coincidence is achieved between the quantities in the summing counters and those in the registers, the pulse generator is stopped. The dividing quantities are the differential with respect to x and

the differential with respect to y of the formula for the line or curve.

As was the case for the straight-line generator, there is symmetry also present in the apparatus of the circle generator. Two dividing counters, two summing counters, two relay registers, etc., are required. Accordingly, to render the explanation and drawings more clear, only one of the required components and its interconnections will be shown in more detail in Figure 6.

Figure 6 is a schematic and block diagram showing an arrangement whereby the number (x_1-a) or (y_1-b) stored in the relay register 610 is entered into the summing counter 612, and the number in the summing counter is entered into the predetermined counter 614 each time it completes a count. This operation continues until the summing counter has a number therein which is equal both in value and in sign to a second number (x_2-a) or (y_2-b) which is stored in the relay register in place of (x_1-a) or (y_1-b) once these numbers have been entered into the dividing counters. The summing counter for the circle generator must be reversible—that is, it must add or subtract input pulses in much the same fashion as the counter described in connection with the adding machine in Figure 2. Binary operating reversible counters are well known and are found described in the literature. A suitable summing counter which is reversible is described, for example, in a patent to Flory et al., for Electronic Counters, Patent No. 2,462,275. Briefly described, however, the reversible summing counter employed here may comprise a series of flip-flop stages. The flip-flop, as is well known, provides two outputs, one from each of the two tubes contained therein. In the usual counter, when any one of these stages has received two input pulses, an output is taken therefrom after the second pulse has been received which is applied to the input of the succeeding stage to drive it from one to the other of its stable conditions which may be designated as zero and one. Thus, each stage of the counter is driven from a zero to a one state and then back to a zero state, and, upon receiving two pulses, applies an output pulse to the succeeding stage which counts two pulses before it, in turn, provides an output to drive a succeeding stage.

In a reversible counter, gates are inserted between each flip-flop output and each of the inputs to the succeeding flip-flop, in a manner so that when one of the gates is enabled a succeeding flip-flop is changed from one state and back by outputs from the preceding flip-flop. When the other of the gates is enabled, a succeeding flip-flop is changed in a reverse manner by outputs from the preceding flip-flop. Accordingly, depending upon which of the gates is enabled, successive pulse inputs to the first stage of the reversible counter will increase or decrease the count in the counter. These gates perform the function represented by the direction gates 528, 530 shown in Figure 5.

In summary, therefore, the direction in which the counter counts, whether positive or negative, is determined by which one of the two gates for the summing counter 518 indicated in Figure 6 as plus-gates 616B, 616C or minus-gates 618B, 618C are enabled. A sign-sensing flip-flop 620 (corresponding to sign senser 532 or 534 in Figure 5) is included with each summing counter. It will be recalled that the sign-sensing flip-flop 532 for the x reversible counter, as shown in Figure 5, determines through the reversing gates whether the plus-gates or minus-gates are open on the y summing counter, and the sign-sensing flip-flop for the y summing counter 534 determines through the reversing gates whether the plus- or minus-gates are open on the x reversible counter.

As previously described, initially a number is entered into the relay register 524 from the adding machine. The structure of this relay register is similar to that described for the relay register employed with the straight-

line generator in Figure 4 and consists of a relay 610A, 610B, 610C for each stage of the counters, each having two ganged, movable contacts, the lower tier of which 622A, 622B, 622C are arranged to present the true value of the binary number being entered therein and the upper tier of which 624A, 624B, 624C presents the complement of the number. In addition, another relay 610D is included which performs the function of storing sign information provided from the adding machine. This relay is identical in structure with the other in the register. Biasing voltages are applied to the fixed contacts of all these relays so that when one of the ganged contacts is at +5 volts, the other is at -300 volts. The output of the adding machine after it has been converted to the binary code is applied to the relay coils of the register to condition the relays to be representative of the adding machine output.

For purposes of simplification of the drawings, there is not shown either in Figure 6 or Figure 4 means for enabling the relays to retain their operated position after the source of excitation (adding machine) is removed. Means for making relays remain operated, such as extra contacts or other relays, are well known in the art and therefore are omitted.

The number in the relay register is transferred into the summing counter from the relay register by means of transfer tubes 626A, 626B, 626C. The sign of the number is transferred into the sign-sensing flip-flop 620 by means of transfer tube 626D. These transfer tubes all operate in a manner similar to the complement preset gate in Figure 4. The tubes all have their outputs coupled to one side of the flip-flops and their grids connected to the relays which are associated with each one of the flip-flop stages. The cathodes are all connected to a preset signal source 627, which may provide a negative pulse derived from a "preset-signal source" for the reversible counter. This may simply be a switch which is closed when a transfer is required. This applies a single pulse from a charged condenser for enabling the transfer tubes. This enables the sensing tubes to conduct or not, depending upon the grid voltages received from the associated relays, and thus the flip-flop stages receiving the outputs from the transfer tubes are driven to a condition which corresponds to the binary number stored in the relay register and its sign.

The output of the sign-sensing flip-flop 620 is applied to control the plus- and minus-gates of the other summing counter 508 in the circle generator (not shown in Figure 6). As soon as the number (x_1-a) or (y_1-b) has been entered into the reversible counter, a second group of preset tubes 628A, 628B, 628C are primed by means of grid connections with the flip-flops of the summing counter stages in accordance with the complement of the number (x_1-a) or (y_1-b) , now in the summing counter. These preset tubes receive their driving signals from the zero sides of the summing counter flip-flop stages but drive the one sides of the dividing counter stages to correspond, thereby establishing into the dividing counter the complement of the binary number in the summing counter. The preset tubes 628A, 628B, 628C comprise the complement preset gate 520 in Figure 5. These preset tubes have their cathodes connected in common to the cathode of an enabling tube 630, whose function is the same as was described previously for tube 424 in the straight-line generator, which is to enable the preset tubes to transfer the complement of the number in the summing counter 518 into the dividing counter 522 each time the predetermined counter completes its count. The common line of the cathodes for these preset tubes at the outset receives a negative pulse input from a preset signal source for the dividing counter after that applied to the transfer tubes for the summing counter, in order to permit the entry of the first number therein. This preset signal source may also be a switch which connects the common cathode line to a charged condenser. Otherwise,

the preset tubes 628A, 628B, and 628C have a signal applied to their common cathode line, which enables them to transfer the one's complement of the number in the summing counter into the dividing counter, from the cathode of the enabling tube 630. This tube is driven by an output pulse from the dividing counter, which is received through the delay line 640.

The pulse generator may now be started. The dividing counter fills and provides an output pulse to terminal A, which connects with input terminal A of the summing counter. Whether the plus- or minus-gates are opened and, thus, whether the pulse is added or subtracted is determined by the sign sensor 532 of the other summing counter 508 (not shown here), and by the reversing gate 529 (comprised of gates 619A, 619'—617A, 617') which is responsive to sign-sensing flip-flop 620.

The sign of the number in the summing counter is sensed by means of sign-sensing tubes 632A, 632B, 632C, one of which is provided for each stage. Before describing these, an understanding should be had of the singularities which occur four times during the generation of a complete circle. The instantaneous slope of a circle twice goes to zero and twice becomes infinite. The former case corresponds to the quantity $(x-a)$ becoming equal to zero twice, and the latter case occurs when $(y-b)$ becomes zero twice. For the situation where a and b are zero, as occurs when the center of the circle is on the origin, the instantaneous slope is infinity when the circle crosses the x axis and is zero when the circle crosses the y axis. If the pulse frequency is divided by zero at these times, an infinite output ratio should occur between the dividing counters. However, as soon as one additional pulse at this infinite rate is emitted and added into the previous total of zero in the summing counter, the appropriate total changes from zero to either plus one or minus one, and the dividing counter is then required to divide by a finite integer. This singularity is resolved by setting up a system of logic which causes the dividing counter to emit one pulse, without receiving a pulse from the pulse generator, when it is ready to be preset to the number in the reversible counter and finds this number to be zero. By thus generating a pulse with no input from the clock, an infinite ratio of output to input is simulated at the point of singularity.

From the above, it will also be appreciated that when passing through the two zero-slope and the two infinity-slope points, the sign of the slope will change. This may be verified from the table previously shown herein. Since the summing counters pass through zero from minus one to plus one, or vice versa, the sign indicated for the number in the counter must change. The circular path will proceed only either in a clockwise direction or in a counterclockwise direction, as previously determined. It will be seen, therefore, that for such a case, all that is necessary to completely control a sign-sensing flip-flop is to determine when the number in its associated summing counter is passing through zero. The sign-sensing flip-flop can then be tripped to indicate a reversal in sign of the number, which thereafter is represented by the summing counter stages. Thus, in going in a clockwise direction, the x summing counter reverses the sign of the number therein at one point from plus to minus and at the other point from minus to plus as the slope passes through two infinity points. The y summing counter will likewise reverse the sign of the number contained therein at one point from minus to plus and at the other point from plus to minus, as the counter passes through the two zero-slope points going in a clockwise direction.

When the predetermined counter is at zero, all the stages assume an identical one of the two stable conditions which is the zero condition. Merely by sensing this coincidence of zero conditions, an output may be derived for use in controlling the sign-sensing flip-flop properly.

The sign-sensing arrangement thus comprises a tube 632A, 632B, 632C for each reversible counter stage which has its grid connected to the same output side of the associated flip-flop stages. The grids of all of these tubes will be simultaneously rendered negative when all the flip-flops are in their zero conditions. All the cathodes of these tubes are connected in common, as designated by "Q," to input "Q" on the sign-sensing flip-flop, so that when the grids of all these tubes are driven negative a negative pulse of sufficient magnitude is applied to the sign-sensing flip-flop to trip it to its opposite condition.

The reversing switches 572, 574 shown in Figure 5 serve the function of determining whether the apparatus is providing control pulses for a clockwise or a counter-clockwise circular cut (respectively c and s terminals). These switches merely reverse or not the control effects applied to the plus- and minus-gates and the recording gates, as determined by the direction desired for the circular cut.

The reversing gate 529, or 531, includes four two-input And gates illustrated in Figure 6 by rectangles 619A, 619A', 617A, 617A'. Direction gate 528 is illustrated in Figure 6 by the two And gates 618A and 616A. The input to these gates besides output from the dividing counter is also output from the sign-sensing flip-flop 532. When sign-sensing flip-flop 532 is in its positive representative state, its output, designated by SS+, enables gate 616A to pass the next pulse from the dividing counter to And gates 617A and 619A', as well as to the positive recording track. The output from sign-sensing flip-flop 620 (designated as BB) determines which of these And gates 617A and 619A' can pass the signal received from gate 616A. If the sign-sensing flip-flop is in its positive representative state, then And gate 617A is opened by its output. This results in gates 616B and 616C (via RG+ lead) being enabled and the summing counter functions to add the pulse being applied thereto to its contents. If sign-sensing flip-flop 532 were in its negative representative state, then And gate 619A is opened by positive output from sign-sensing flip-flop 620. This would enable gates 618B and 618C (via RG- lead), whereby the summing counter subtracts the input pulse from its contents. Thus, when the sign of the number in the summing counter 518 is positive, as determined by the sign-sensing flip-flop 620, the reversing gate does not reverse the instructions from the sign sensor 532 to the summing counter 518.

When the sign-sensing flip-flop 620 is in its negative-sign representative condition, it enables And gates 617' and 619' to pass any signals received. And gate 619' has its output connected to energize the RG- lead to cause the summing counter to subtract. Since the other required input to And gate 619' is from And gate 616A, effectively the direction of sign sensor 532 to the summing counter to add is reversed. Similarly, an output from And gate 618A is applied through And gate 617A' to the RG+ lead, thus instructing the summing counter to add. Therefore, the instruction from sign sensor 532 to the summing counter is reversed when the sign of the value in the summing counter is negative and is not altered when the sign of the value in the summing counter is positive.

The determination of the time when the number in the register (representative of (x_2-a) or (y_2-b)) coincides with the sign and value of the number in the summing counter and the sign of the number in the other summing counter is achieved by the same type of coincidence sensing as was described for Figure 4; namely, two coincidence-sensing triodes 634A, 634B, 634C, 634D, 636A, 636B, 636C, 636D for each stage have their respective grids coupled to the grids of the corresponding flip-flop stage in the summing counter. The sensing tube grids are also coupled through associated diodes 634AD, 636AD—634DD, 636DD to the relay register. Coincidence-sensing triodes 637 and 638 provide the sign inputs

from both the sign sensors 532 and 534. The operation of the sensing triodes and diodes has previously been discussed in connection with Figure 4, and reference is made thereto for the details thereof. Thus, when the flip-flop stages and the relay register achieve coincidence in the numbers represented (including coincidence in sign of both summing counters) the common cathodes all go sufficiently negative to apply a pulse to the stop generator gate 544, and an inhibit pulse to direction gate 528 which prevents further output from dividing counter 522 to the y recording tracks and to the y summing counter 518. It will be understood, of course, that to completely stop the generator a pulse is also required from the other summing counter.

Thus, to review the above, there is shown a relay register, a summing counter, and a dividing counter. First, for example, the difference $(x_1 - a)$ and its sign is entered into the relay register. A preset signal source then transfers this number and its sign into the summing counter and into its sign-representative stage. Another preset signal source then transfer the complement of the number in the reversible counter into the predetermined counter. The number $(x_2 - a)$ and its sign is then entered into the relay register, replacing $(x_1 - a)$ and its sign. The pulse generator is then started to provide pulses to the dividing counter. The dividing counter, each time it fills, supplies an output pulse to the summing counter to be counted and also to be recorded in the proper track on tape. The output pulse is also employed for generating an additional pulse in the predetermined counter to provide a true two's complement. It should be noted that the output from gates 616A and 618A goes to the positive and negative tracks of the recording medium for recording.

The count, which the summing counter achieves by the addition of the pulse from the dividing counter, is entered into the dividing counter plus a two's complement pulse. The dividing counter proceeds to count pulses again until it fills. The pulse input to each summing counter is added or subtracted as determined by the sign-sensing flip-flop associated with the other summing counter. When the summing counter attains the value and sign of the number stored in the register, an output is obtained which blocks the direction gates and thereby prevents further output from the dividing counter. When both summing counters have attained coincidence with the sign and value in the associated registers, the process is stopped. When in the course of counting pulses a summing counter adds or subtracts a pulse which drives it into a zero count, this zero count is attempted to be transferred into the dividing counter, which, however, upon finding itself in the zero state, supplies an output pulse which is applied to the dividing counter to enter therein a one count. This, in turn, is transferred back into the dividing counter. Thus, a pulse is obtained from the dividing counter without a generator pulse being applied thereto. As stated above, this is necessary in order to pass through the zero-slope and infinity-slope conditions.

The reason the dividing counter provides an output when the summing counter is in its zero condition is that the dividing counter fills when it reaches the condition at which all its stages are in zero condition. When the zero condition of the summing counter is entered into the predetermined counter in a complementary manner, all the dividing counter flip-flops are driven to the one state. This is followed by the two's complement pulse driving the dividing counter to zero again. Thus an output carry pulse is obtained without a clock pulse being required.

A block coincidence gate 638 at the output of the coincidence circuit 542 is provided because, when an occasion requires that a complete circle be generated, the coincidence gates 540, 542 can immediately provide an output pulse and thus stop the operation practically be-

fore it commences. To prevent this, the outputs of coincidence gates 540 and 542 are blocked until the first output from their respective divide counters are received. A slight delay is provided by the delay line 640 between the output of the dividing counter and the enabling tube which enables the summing counter number to be preset complementary-wise into the dividing counter. The reason is to enable the output of the dividing counter to be counted by the summing counter and for the summing counter to settle before transferring its count. The delay by the delay line 642 is provided in the two's-complement pulse feedback line, also to enable the dividing counter to settle after the summing counter count is entered therein before the two's-complement pulse is added.

Figure 7 is a block diagram of another embodiment of the invention for generating a circle. Although with this arrangement the binary system may be used, the decimal system is preferred. There are a number of advantages to be derived by using the decimal system. Apparatus for converting the usual decimal output from an adding machine to a decimal-to-binary-code-converting arrangement is eliminated. Decimal output may be taken directly from the counter stages 223, 240, shown in Figure 2. Besides this, the remaining apparatus required may be considerably simplified. The theory of operation of the over-all arrangement, however, is still the same.

As previously described, an adding machine 710 is used to determine and enter the required differences into the system. First $(x_1 - a)$ is calculated and through switch 712 is entered into the first relay register 714, both in sign and value. As before, from the first relay register the number $(x_1 - a)$ and its sign are entered into the first summing counter 716 and sign-sensing flip-flop 740. The value of $(x_2 - a)$ is calculated and then entered in sign and value into the relay register 714, replacing $(x_1 - a)$. The adding machine is then used to calculate the value and sign of $(y_1 - b)$, and the switch 712 is actuated to enter this into the relay register 718. From the second relay register, this value and its sign is transferred into the second summing counter 720 and its associated sign-sensing flip-flop 742. The value $(y_2 - b)$ is then calculated and entered into the second relay register 718 both in sign and value, replacing $(y_1 - b)$. The pulse generator 722 is then started by an impulse from a start source 724. The generator output is then applied to two dividing counters 726, 728, which are respectively designated as $(x - a)$ and $(y - b)$ dividing counters. As soon as the respective dividing counters count a number of pulses equal respectively to the number $(x_1 - a)$ and $(y_1 - b)$ in the associated summing counters, associated coincidence-sensing gates 730, 732 are each actuated to provide an output pulse—each of which actuates a reset gate 734, 736, which resets the two dividing counters to zero. The output pulse from the coincidence gate 732 is also applied to two gates 744A and 744B. The one of these which is open is determined by sign sensor 740. The open gate applies the pulse in an additive or subtractive manner through a reversing gate 745 controlled by the sign sensor 742 to the summing counter, and also determines whether the pulse is recorded in a positive or negative track of the y channel. The output pulse from the coincidence gate 730 is also applied to two gates 746A, 746B, which are controlled by sign sensor 742. One of the gates applies the output pulse to the summing counter through a reversing gate 747 controlled by sign sensor 740, and to one of the tracks of the y recording channel in accordance with the direction of the sign sensor 742. The dividing counters again count the number of pulses received and again, upon coincidence, an output pulse is emitted from each of the coincidence gates which is added to the number in the respective summing counters, and the dividing counters are reset to zero.

When either coincidence gate 750 or 752 alone senses coincidence in value and sign of the associated summing

counter and register, the coincidence gate output is applied to inhibit the coincidence gate 732 or 730 from supplying further pulses for recording and counting by the summing counter first attaining coincidence. The other dividing counter continues providing pulses for storage and counting.

Upon the numbers in both summing counters equaling the value and sign of the numbers stored in the associated relay register, the coincidence is respectively sensed by the gates 750, 752. The occurrence of coincidence in sensing by gates 750, 752 is sensed by the gate 754, and its output serves to stop the pulse generator.

Figures 8A and 8B show in more detail a preferred arrangement for a circle generator in accordance with the arrangement shown in block diagram form in Figure 7. Again, in view of the symmetry of the apparatus (the same apparatus being required for obtaining pulses for the y channel as for the x channel), substantially one-half the required apparatus will be shown in detail to provide clarity and simplicity. The decimal counters and reversible decimal counters required for the embodiment of the invention may be of any of the well-known types. However, for reasons of economy, a decimal-counter tube which is sold commercially by Sylvania Electric Products, Inc., and is known as Type 6476, is preferred. This tube is described in the Sylvania engineering data Service Publication 6476. This preference, however, is not to be construed as a limitation upon the invention.

Each one of the large rectangles 810, 812 (Figure 8A) which comprise the dividing counter and the one in the second stage 816 (Figure 8B) of the summing counter are representative of tube 814, which is shown schematically as the first stage of the reversible counter. The tube has a common anode 813 about which are disposed thirty cathodes. Ten of these are main cathodes; the remainder are divided into guide cathodes and are known as first and second guide cathodes 822, 824. These are interspersed between the main cathodes. The tube operates on the principle that the ionization, or starting voltage, of gas-filled tubes is lower if ions or electrons are already present in the anode-cathode gap. Under these conditions, a glow discharge can be made to move from one cathode to an adjacent one by means of a relatively small negative pulse on the new cathode, provided that electrons or ions are able to diffuse in this new anode-cathode gap. With a series of cathodes about a common anode, the discharge can be made to move in succession along the cathode series by application of successive voltage pulses to each cathode. Thus, the two guide cathodes 822, 824 are employed to determine the direction of the glow discharge. Thus, with a glow present on a main cathode, if a negative pulse is applied to the adjacent first guide cathodes, then to the adjacent second guide cathode, then upon termination of the second pulse because the main cathodes are biased below the guides the glow will be transferred to the succeeding main cathode. By reversing the sequence of application of negative pulses as first to all second guides and second to all first guides, the glow is transferred in a reverse direction to a preceding main cathode.

Cathode load resistors 826 are in series with all main cathodes. A positive signal is obtained across this resistor when the associated main cathode has the glow discharge. A count may be inserted by lowering the anode voltage, thus extinguishing the arc, and then lowering the voltage at whatever one of the cathodes it is desired to have the glow discharge, and then again raising the anode voltage.

Returning now to an explanation of the apparatus shown in Figures 8A and 8B, an adding machine (not shown) is employed to calculate and enter the signs and values of (x_1-a) or (y_1-b) into the sign and value register 830 (Figure 8B). This register will have ten contacts 836A, 836B for each decade 814, 816 in the reversible counter and four contacts 834A, 834B, 834C, 834D for the sign-sensing flip-flop 817.

Each register section, instead of consisting of separate storage relays as was shown previously in Figure 6, may be of the stepping selector-switch type, with pulse signals from the adding machine being employed to step the selector arms 830A, 830B, 830C, 830D to the proper contacts. In any event, the selector arms are positioned to represent the decimal number value and sign of the value of the differences calculated by the adding machine. Each one of the contacts 836A, 836B is connected to an associated main cathode 820. Each one of the main cathodes is connected to ground through a separate resistor 826. Only one of the contacts in each decade is connected to a selector arm to represent the value of the adding machine output. For the purpose of transferring the number stored in the register into the summing counter, each of the selector arms 830A, 830B is connected to a separate relay contact 838A, 838B, which is normally open. When a set button 840 is pressed, it applies a current to the relay coil 838. This closes relay contacts 838A, 838B, 838C, and 838D. This applies a negative potential through the selector arms 830A, 830B from the cathode of tube 842 to a selected cathode in each decade of the summing counter.

When contact 838C closes, it energizes relay coil 844, thus moving its contact 844A to a second position, whereby a resistor 846 is inserted in series between B+ and the anode of each decade tube, thereby lowering the anode voltage and extinguishing the glow in the tube which is immediately re-established at the one of the main cathodes which is connected to the negative bias via a selector arm 830A, 830B. After a time, determined by the discharge tube of condenser 854, tube 842 is rendered nonconductive, thus causing relay 852 to become excited, whereupon it is operated and relays 838 and 844 are released. A negative signal that appears at resistor 839 drives a cathode follower tube 841, which, in turn, causes amplifier tube 843 to conduct. The plate of tube 843 is connected through sign-sensing contacts 834C, 834D to the plates of sign-sensing flip-flop 817. Therefore, the conduction of tube 843 sets sign-sensing flip-flop 817 in a state which represents the sign derived from the one of contacts 834C, 834D to which movable contact 830D is set.

The value of (x_1-a) or (y_1-b) has thus been set into the summing counter decades. The sign has been entered into the sign-sensing flip-flop 817 directly from the contacts in the register. Next the adding machine is used to compute the value (x_2-a) or (y_2-b) and its sign, and this is entered into the register to replace (x_1-a) or (y_1-b) .

A start source, which may be a switch or enabling amplifier, is actuated to start the generator 854 (Figure 8A). Since two pulses in sequence are required to make the type of tubes used to form the decade counter described here advance, the output of the generator is applied to a first one-shot multivibrator 856, which generates a first pulse. The end of the first pulse energizes a second one-shot multivibrator 857, which generates a second pulse. These first and second pulses, respectively designated as pulse one and pulse two, are applied to the first and second guides of the units dividing counter 810 to advance its count. The second, or ten's counter decade 812, only receives pulse two from the second one-shot multivibrator which is applied on guide 2. In the absence of a preceding or a following pulse applied to guide 1 of the ten's decade, this is not enough to transfer a count because of electrode spacing in the tube. When the unit counter fills—that is, the last main cathode receives the glow—a carry pulse is obtained which may be suitably inverted and applied as a pulse to guide 1 to advance the count of the decade tube comprising the ten's decade of the dividing counter. The units decade then can start counting from the beginning again.

The cathodes of each decade of the dividing counter

are each coupled to a separate decade coincidence gate 858, 860. Each of the corresponding decades of the summing counter are also coupled to these decade-coincidence gates. Any of the well-known coincidence-detecting devices may be employed which emit an output when there is coincidence between the value in the dividing counter and the value in the summing counter. An illustration of a suitable coincidence device is one wherein ten tubes, such as 862, 863, are provided for each decade in the counter. Each tube has its grid coupled through resistors 862A, 862B—863A, 863B, between the corresponding main cathodes of the dividing counter and the summing decade counter. All the cathodes of the ten tubes in each decade coincidence gate are coupled together and to a separate diode 864A, 864B. These diodes make up a counter coincidence gate 866.

When an arc is established in the counter tubes, the cathode in the path of that arc is positive by about 35 volts. Therefore, in the absence of coincidence between the summing and dividing counter values, two of the tubes in the decade coincidence gates have a positive potential applied to their grids by virtue of current flowing through the resistors coupling the cathodes to the coincidence-gate tube grid and the cathode lead resistor connecting the tube cathodes to ground. However, this voltage (assuming 35 volts on the energized cathodes of both summing and dividing counters and resistors 862A, 862B, 863A, 863B are equal and much larger than the cathode resistors of the gas tubes) on the energized tubes will be raised to only 17 volts. Thus, the diode 862A or 862B in the counter coincidence gate generates an output voltage of only 17 volts by virtue of the potential being applied from the conducting coincidence tube cathode. Upon counter coincidence, the voltage on the conducting tube is raised to 35 volts, since the corresponding cathodes in both the dividing-counter decades and reversible-counter decades all attain the same potential simultaneously. Thus, all the coincidence-gate cathodes have 35 volts applied to them, causing the output to rise from 17 to 35 volts to enable flip-flop circuit 868.

The output pulse obtained at coincidence must (1) energize a reset gate 870 to reset all the dividing counter decades to zero count, (2) must be applied to the summing counter in a manner to be added or subtracted from the count already there, as determined by the sign-sensing flip-flop for the other summing counter, and (3) must be recorded in the proper track of a channel as determined by the sign-sensing flip-flop. The reset gate 870 may comprise, for example, the relay apparatus previously described for setting a count from the relay register 830 into the summing counter decades 814, 816; only, of course, the number set into the dividing counter, upon reset, will always be zero.

The apparatus for properly applying the coincidence pulse to the gate for the summing counter and recording apparatus includes a carry storage flip-flop, a stop gate, an enabling gate, and a pulse-phasing gate. The enabling gate includes three tubes 872, 874, 876. All of these tubes have their cathodes coupled through a load resistor 878 to a source of B—. Two of these tubes 874, 876 have their grids connected to a source of negative potential. The anode of one tube 874 is connected to the plus, or add, side and the anode of the other tube is connected to the minus, or subtract, side of the sign-sensing flip-flop 740 of the other summing counter. The tubes are biased so that when a coincidence pulse is applied to the first tube 872 from carry storage 868, both tubes 874, 876 are rendered nonconductive, allowing the potentials appearing at their plates to rise to values determined by the sign-sensing flip-flop. Thus, the plates of tubes 874, 876 are enabled after a coincidence pulse. However, the sign-sensing flip-flop allows only one plate of tubes 874, 876 to rise (depending on the sign in the flip-flop), enabling either the minus or plus grids of the pulse-phasing gate. After pulse one and pulse two have

been passed through the pulse-phasing gate, giving the carry to the summing counter, carry storage flip-flop 868 is reset by the ending of pulse two, as generated by the second one-shot multivibrator 857, which causes plates of tubes 874, 876 to conduct, cutting off the pulse-phasing gate until the occurrence of the next coincidence pulse. Gate 869 serves as a stop gate to prevent further application of coincidence output pulses from the divide counter at the end of circle generation.

The pulse-phasing gate consists of four tubes 880, 882, 884, 886. Two of these, 882, 884, have their cathodes coupled to one-shot multivibrator 856, providing the first pulse of the pair of pulses. The other two tubes have their cathodes connected to one-shot multivibrator 857, providing the second pulse of the pair of pulses. Tubes 880 and 882 have their grids coupled to the anode of tube 874, hereafter designated as the plus tube; tubes 884 and 886 have their grids coupled to the anode of tube 876, hereafter designated as the minus tube. Tubes 880 and 884 have their anodes connected to a load resistor 888 and to the second guides of all the reversible counters; tubes 882 and 886 have their anodes connected to a load resistor 890 and to the first guides of the first decade of the reversible counter.

To understand the operation of the pulse-phasing gate, assume that tubes 874, 876 are both rendered non-conductive as a result of a coincidence pulse which was applied to tube 872, and assume further that the plus side of the sign-sensing flip-flop is high. The G_1 — G_2 pulses coming from the pulse-phasing gate as a result of an application of G_1 — G_2 pulses from the one-shot multivibrators 856, 857 will have the order required to advance the count. When the sign-sensing flip-flop is in its minus state, the order of the pulses from the pulse-phasing gate in response to a G_1 — G_2 pulse input is reversed to G_2 — G_1 , which is the order required to reverse the count. This is accomplished by virtue of the cathode-anode connections in the pulse-phasing gate which reverse the output obtained in response to the G_1 — G_2 pulse input. The reversing gate 899 receives the G_1 — G_2 pulse output from the pulse-phasing gates and, as determined by the signal received over leads B—B from the sign-sensing flip-flop 817, applies them to the summing counter in the order received (when the value in the counter is positive) or reverses the order of the G_1 — G_2 pulses (when the value in the counter is negative). It will be recalled that this operation is necessary to prevent the summing counter from counting in complementary fashion for negative counts. The structure of the reversing gate is identical with that shown and described for the pulse-phasing gate except that the order of the pulse output from the reversing gate is determined by the sign represented by sign-sensing flip-flop 817.

As may be seen in Figure 8B, a carry flip-flop 819 is provided between each two decades of the summing counter. This serves the purpose of applying a carry pulse from one decade to the next when the decade fills. The carry flip-flop is reset when a nine count is obtained and provides an output pulse when the decade goes from 9 to 0 again. The timing of the carry pulse is made coincident with a G_1 pulse, so that the pulse-phasing gate as modified by the reversing gate will send a G_2 pulse to the ten's counter decade 816 either ahead of or behind the carry pulse, as determined by the sign-sensing flip-flop of the other reversible counter. Thus, addition or subtraction of the carry pulse is achieved in the succeeding decade.

The rules determining the sign of the number in the reversible counter are the same as were discussed with the binary-operating embodiment. Thus, when the reversible counter passes through zero, the sign of the sign-sensing flip-flop 817 must be reversed. A sign-sensing gate 821 senses a coincidence of the fact that all the zero cathodes of the reversible counter are at a positive potential (of about 35 volts) signifying that the count

is at zero. The sign-sensing gate then supplies an output which reverses the state of the sign-sensing flip-flop 817.

The sensing of coincidence of the value and sign of the number in the summing counter with (x_2-a) or (y_2-b) , the number and its sign in the relay register is achieved by coincidence gate tubes 892A, 892B, 892C, each of which has its grid connected to the movable arm 830A, 830B, 830C of the register. Thus, when all of the cathodes of the summing counter which are connected to these arms through the contacts are made positive simultaneously by virtue of the glow being transferred to them, the coincidence gate tubes all conduct simultaneously, thus simultaneously raising the cathodes off all the diodes 894A, 894B, 894C, whereby they are all prevented from conducting. A pulse is thereby obtained at their common anode connection which is applied as an inhibit pulse to stop gate 869 of the associated divide counter, which prevents further output to the following summing counter and tape. When coincidence has occurred in both summing counters, the pulse generator is stopped which completes the computing process.

To illustrate the arrangement of control pulses obtained on tape with the circle generator described previously, Figure 9 is included to show the arrangement of pulses derived for a circle, as shown, being generated in a clockwise direction. The first tape section 900 shows some typical pulses in the x and y channels which are derived when going from the second to the first quadrant. The motion along the x axis approaches a maximum velocity as the y axis is approached and begins to decrease as it is passed. Thus the pulses in the plus- x track increase in number as the y axis is approached and begin to decrease as it is left behind. The motion along the y axis approaches zero as the y axis is approached and then begins to increase as it is left behind in the reverse direction. Thus the y pulses decrease as the y axis is approached and, after it is crossed, begin again in the negative track.

The second tape section 902 illustrates the pulses obtained in going from the first to the fourth quadrant. Here in crossing the x axis the motion along the x axis goes through zero and then begins to increase again, but in a negative direction. The motion along the y axis approaches a maximum as the x axis is approached and then begins to decrease after it is crossed. Thus, the x -channel pulses are seen to become fewer in the positive track, then stop, and then begin again in the negative track. The y pulses are seen to increase and then to decrease before and after crossing the x axis.

The next tape 904 shows the control pulses obtained in going from the fourth to the third quadrant. Here the situation is reversed from what it was in going from the second to the first quadrant. Thus, the motion along the x axis increases in a negative direction as the y axis is approached and decreases in a negative direction after it is passed. The minus- x track pulses increase and then decrease to effectuate this motion. The motion along the y axis decreases to zero from negative direction motion and after the y axis is passed commences again in a positive direction. The y -channel pulses, thus, after decreasing in number in the minus- y track, begin to increase in the plus- y track.

The next tape section 908 depicts the control pulses obtained in going from the third to the second quadrant. Here motion along the x axis approaches zero from a negative direction as the x axis is approached and then begins to increase positively again after it is passed. Thus the pulses are first in the minus- x track and then, after crossing the x axis, are in the plus- x track. The motion along the y axis goes through a maximum as the x axis is crossed. This may be seen by the greater density of pulses in the plus- y track as the x axis is crossed.

Other curves

Although the straight-line and circle generators are

shown separately, it should be appreciated that they may be readily combined by means of suitable switching apparatus to provide pulse trains for ordering circular or straight-line paths in any desired sequence by actuating a switch to achieve the arrangement required. The basic apparatus required is substantially the same for both; it is only their interconnections that are changed.

The principles described heretofore are also applicable for generating other second-degree or conic curves. For example, for a parabola with its principal axis parallel to the x axis the formula is $(y-k)^2=2p(x-h)$, and the slope

$$\frac{dy}{dx} = \frac{p}{y-k}$$

For a parabola with its principal axis parallel to the y axis, the formula is $(x-h)^2=2p(y-k)$, and the slope

$$\frac{dy}{dx} = \frac{x-h}{p}$$

Figures 10 and 11 show the generalized block diagrams whereby the control pulse trains for generating these two types of parabolic cuts may be achieved. The values of p , h , and k are constants which are readily obtained from the equations for the curves. In Figure 10, the frequency of the pulses from the pulse generator 1010 is divided by two dividing counters 1012, 1014. One of these 1012 divides by p to provide the x -track control pulses and the other divider 1014 divides by $(y-k)$ to provide the y -track control pulses. An adding machine is used to enter the value p into the register 1016. From the p register the complement of the value of p is entered into the dividing counter 1012 through the p -complement gate 1018. Every time the p -dividing counter fills and emits a pulse this pulse, amongst other things, is used to actuate the complement gate 1018 to preset the dividing counter to the complement of the value of p , operating in the manner described for the circle or straight-line generator. The output of the p -dividing counter is applied to a pair of gates 1020, 1021. These gates are used to determine whether the x pulses are recorded in a positive or negative track. These gates also determine whether the x pulses are added to or subtracted from the value in an $(x-h)$ summing counter 1024.

The value of (x_1-h) is calculated on the adding machine and entered into the $(x-h)$ register 1026. From the register the value (x_1-h) is transferred into the $(x-h)$ summing counter. The value of (x_2-h) is next calculated on the adding machine and entered into the $(x-h)$ register in place of (x_1-h) . When the count in the summing counter reaches the value in the $(x-h)$ register the coincidence is sensed by a coincidence gate 1028 which then produces an output. The summing counter, the register, and the complement gate will be recognized as the same apparatus employed in the circle generator.

Similarly, a $(y-k)$ register 1030 is employed into which first the sign and value of (y_1-k) is entered. This value is next entered into the $(y-k)$ summing counter 1032 and from thence through the complement gate 1033, as a complement of (y_1-k) , into the $(y-k)$ dividing counter 1014. Then (y_2-k) and its sign are calculated and entered into the $(y-k)$ register to replace the value and sign of (y_1-k) previously entered.

The parabolic path can be generated in a clockwise direction or in a counterclockwise direction. The motion required along the y axis will always be in one direction for clockwise operation or always in the opposite direction for counterclockwise operation. Thus switch 1034 is set for clockwise operation C or counterclockwise operation CCS. For clockwise operation motion along the y axis in a positive direction is required, y is always increasing, and, therefore, y pulses are recorded in the positive track and are always added to the quantity in the summing counter 1032. For counterclockwise operation,

the opposite is true and operating switch 1034 to the CCS position insures that pulses are recorded in the negative track and are subtracted from the quantity in the $(y-k)$ summing counter. A reversing gate 1031 is employed, controlled by zero sensor 1036, to insure proper operation of the $(y-k)$ summing counter when it counts negative values.

A slightly different arrangement for summing and recording the pulses in the x track is required. It should be noted that motion along the x axis reverses as a transition is made from the upper to the lower portion of a parabola. Such reversal actually occurs at the vertex of the parabola, which is the point at which y is equal to k . This point is established when $(y-k)$, the quantity in the summing counter 1032, equals zero. Thus, a zero sensor 1036, similar to the sign sensor used in the circle generator, emits a pulse when the summing counter 1032 is at zero. This reverses the condition of gates 1020 and 1022, so that the one that was opened is closed and the one that was closed is opened. The proper one of the gates that is operated is determined by switch 1038, which applies the output of zero sensor 1036 to both gates with a polarity which is determined by whether a clockwise or counterclockwise parabola path generation is desired. Switch 1038 and switch 1034 are gauged to prevent any conflict in their setting.

When the value in the $(y-k)$ register equals the value in the $(y-k)$ summing counter, this coincidence is sensed by coincidence gate 1040. The outputs of coincidence gate 1040 and coincidence gate 1028 in general will not occur simultaneously. Therefore, coincidence of the summing counters is handled in the identical manner as is done in the circle generator. When one of the summing counters reaches coincidence with its respective register, the output of its divide counter is inhibited. When both summing counters reach coincidence, this is detected by stop-generator gate 1042, which then provides an output to stop the pulse generator 1010.

To review the operation of the parabola generator, first a determination is made as to whether clockwise or counterclockwise path generation is required and switches 1034 and 1038 are operated accordingly. Next the value of p is entered into the p register 1016 and from there through the complement gate 1018 into the dividing counter 1012 in complementary form. The value of (x_1-h) is calculated and entered into the $(x-h)$ register 1026. From there it is transferred into the $(x-h)$ summing counter 1024. Then the value (x_2-h) is calculated and entered into the $(x-h)$ register in place of (x_1-h) . Next the value (y_1-k) is calculated and entered into the $(y-k)$ register 1030. From there it is transferred into the summing counter. The complement of the value is also entered into the $(y-k)$ dividing counter 1012 through the complement gate 1033. Next the value (y_2-k) is calculated and entered into the $(y-k)$ register.

The pulse generator 1010 is then started and the output pulses from the two dividers are added in the respective summing counters, the zero sensor 1036 reversing the sign of the addition occurring in the $(x-h)$ summing counter and the track in the x channel on which the x -control pulses are recorded whenever the value in the $(y-k)$ summing counter reaches zero. Upon coincidence between the value and sign in the $(y-k)$ summing counter, the $(y-k)$ register, the $(x-h)$ summing counter, and the $(x-h)$ register, the pulse generator is stopped.

Figure 11 is a schematic diagram of the apparatus required to generate control pulses for the parabola having the equation $(x-h)^2=2p(y-k)$. It will be seen that the apparatus required is substantially identical except that the functions of the $(y-k)$ summing counter and the $(x-h)$ summing counter are interchanged.

Thus the operation of the system shown in Figure 11 is as follows. First a determination is made as to whether clockwise or counterclockwise path generation is required

and switches 1134 and 1138 are operated accordingly. Next the value of p is entered into the p register 1116 and from there through the complement gate 1118 into the dividing counter 1112 in complementary form. The value of (y_1-k) is calculated and entered into the $(y-k)$ register 1130. From there it is transferred into the $(y-k)$ summing counter 1132. Then the value (y_2-k) is calculated and entered into the register in place of (y_1-k) .

Next the value (x_1-h) is calculated and entered into the $(x-h)$ register 1126 in sign and value. From there it is transferred into the summing counter. The complement of the value is also entered into the $(x-h)$ dividing counter 1114 through the complement gate 1133. Next the value (x_2-h) is calculated and entered into the $(x-h)$ register.

The pulse generator 1110 is then started, and output pulses from the two dividers are added in the respective summing counters, the zero sensor 1136 reversing the sign of the addition occurring in the $(y-k)$ summing counter and the track in the y channel on which the y -control pulses are recorded whenever the value in the $(x-h)$ summing counter reaches zero. The zero sensor also controls the reversing gate 1125. Upon coincidence between the values in the respective summing counters and their associated registers, the coincidence gates 1128 and 1140 operate to inhibit the output of their respective divide counters. The stop-generator gate 1128 acts to stop the pulse generator 1110 when both summing counters have reached coincidence.

The general equation of an ellipse is

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

The slope,

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

The previously explained principles apply to providing a generator for the ellipse; namely, divide the output pulse from a pulse generator by the differential with respect to x and the differential with respect to y to provide two pulse trains which may be used to guide relative tool and workpiece motion along the two co-ordinates to generate a parabolic cut. The divisions by the product terms such as $(x-h)(b)^2$ is accomplished by employing three counters $\div b$, $\div b$, and $\div (x-h)$ in series to divide down the output of the pulse generator.

Another extension of the interpolation principles as illustrated by this invention is the automatic interpolation of higher-order equations. For example, it is desired to make a cut of a curve having the following equation in two variables: $y=5(x-10)^4$. This curve has the instantaneous slope:

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

As shown by the block schematic diagram in Figure 12, the pulse generator 1210 will deliver pulses to generate a series of control pulses for the x -co-ordinate motion through four counters in series, the first being a fixed $\div 20$ counter 412; the second, third, and fourth counters 1214, 1216, 1218 each divide by $(x-10)$. They are each set and reset to the proper dividing values by means of a summing counter 1220 which counts the output pulses of the dividing chain until it has counted the pulses required to go from (x_1-10) to (x_2-10) , at which time the clock is stopped as well as the direct recording of the number of clock pulses on the y -control track.

Three-dimension control

Figure 13 is a block diagram showing an arrangement for generating control pulse trains for three co-ordinates to effectuate a straight-line cut in three dimensions. Similar division techniques are employed. For example, assume the general case where the cutting path desired is from point p_1 , whose co-ordinates are (x_1, y_1, z_1) ,

to point p_2 , whose co-ordinates are (x_2, y_2, z_2) . The slope of the line connecting p_1 and p_2 , referred to each of the three reference planes, and defined by the ratio of pulses fed to the individual axes, is:

$$\frac{fy}{fx} = \frac{\frac{f}{(x_2-x_1)(z_2-z_1)}}{\frac{f}{(y_2-y_1)(z_2-z_1)}} = \frac{y_2-y_1}{x_2-x_1}, \text{ for the } x-y \text{ plane}$$

$$\frac{fz}{fx} = \frac{\frac{f}{(y_2-y_1)(x_2-x_1)}}{\frac{f}{(y_2-y_1)(z_2-z_1)}} = \frac{z_2-z_1}{x_2-x_1}, \text{ for the } x-z \text{ plane}$$

$$\frac{fz}{fy} = \frac{\frac{f}{(x_2-x_1)(z_2-z_1)}}{\frac{f}{(y_2-y_1)(x_2-x_1)}} = \frac{y_2-y_1}{z_2-z_1}, \text{ for the } y-z \text{ plane}$$

In Figure 13, as before, an adding machine 1310 is employed to calculate the required co-ordinate difference (x_2-x_1) , (y_2-y_1) , and (z_2-z_1) for the cut and to enter them through the switch 1312 into the respective (x_2-x_1) register 1314, (y_2-y_1) register 1316, and (z_2-z_1) register 1318. A start source 1320 is used to start the pulse generator 1322 supplying pulses simultaneously to three counters 1324, 1326, 1328, respectively designated as first $\div(y_2-y_1)$ counter, first $\div(z_2-z_1)$ counter, and first $\div(x_2-x_1)$ counter. These counters count pulses until there is a coincidence detected with the numbers entered into the associated registers, at which time the respective reset gates 1330, 1332, 1334, detect this and reset the associated counters. As previously indicated, a method of dividing a source of pulses by a product is to employ counters in series, each dividing by one of the terms in the product. Thus second counters 1336, 1338, 1340, respectively $\div(z_2-z_1)$, $\div(x_2-x_1)$ and $\div(y_2-y_1)$ each respectively receives output from the first counters $\div(y_2-y_1)$, $\div(z_2-z_1)$ and $\div(x_2-x_1)$. These second counters count the respective outputs from the first counters and when any of the respective associated reset gates 1342, 1344, 1346 detect coincidence with the number in an associated register, an output is emitted which resets the counter again to the value in the register.

Thus, the outputs of the second counters are recorded on magnetic-tape tracks for controlling motion in the direction of the x axis, the y axis, and the z axis. The $\div(z_2-z_1)$ second counter output is recorded on an x track and counted by an x counter 1348. The $\div(x_2-x_1)$ second counter output is recorded on a y track and counted by a y counter 1350. The output of the second counter $\div(y_2-y_1)$ is recorded on a z track and counted by a z counter 1352. Coincidence between the count in the x counter and the number stored in the (x_2-x_1) register is detected by a gate 1354; likewise, coincidence in count between the y and z counters and the numbers stored in the (y_2-y_1) register and the (z_2-z_1) register are respectively detected by the coincidence gates 1356 and 1358. The outputs of the three coincidence gates enable a single coincidence gate 1360 which stops the pulse generator. From the above description, it should also be apparent how three-dimensional cutting paths for other than straight-line configurations may be generated employing the principles described.

Two other worthwhile operations may be easily achieved with any of the previously described systems. One of these solves the problem of stopping the motion at a desired point. It does not suffice to issue a stop command to a machine-tool table when it has reached its intended endpoint, because to stop it instantaneously involves the use of an infinite amount of force. When cutting an outside contour on a piece of work this overshoot, for which the servomechanism can eventually compensate, does not result in a serious error. When making an inside cut, however, overshoot will cause material

to be removed which cannot be put back and, therefore, cannot be compensated. The proper way to attack this is by providing for gradual deceleration before the endpoint is reached. In manual operation, the machine-tool operator anticipates the end and slows down the rate of hand feed.

Automatic slowdown can be accomplished with the embodiments of the invention described herein by recognizing when the number of pulse commands to an axis has come within a stated amount of the total required for an interval. For the case of a straight line, during all but the last part of the cut it is desired that the table move at the highest permissible cutting velocity, but, just before the end, it is desired to decrease the table velocity to a value, say, one-tenth the previous value. This may be handled as follows: At the time of entering x_2 into the adding machine, there is subtracted from it 0.100. In turn, x_1 is subtracted from this difference. Thus, the difference $x_2-0.100-x_1$ is stored in an extra register. The rest of the program is handled in the manner described previously. A set of coincidence gates can recognize when the quantity in an x -true-value counter and the value of the number in the extra register coincide. The output of these coincidence gates can be used to either slow down the pulse generator by a factor of ten or enable a counter which divides the pulse output by ten. Thus, reducing the pulse frequency will automatically result in slowing down the velocity of the table, since this spaces the control pulses further apart. In an analogous manner, when the table is being accelerated from a standstill to maximum velocity along a new path, the clock frequently can be increased in two steps, in the reverse manner, to provide for a gradual instead of sudden acceleration. Thereby, the load on the driving motors is eased and the tendency toward hunting, which a sudden command can produce, is reduced.

Control pulse command execution

Figure 14 is a schematic diagram of a tool-control arrangement which is capable of receiving and utilizing the control pulse trains. The apparatus shown is that required to move the table along one axis. It must be duplicated for each axis along which motion control is desired. Schematic circuits for the components required on Figure 14 are shown in Figures 15A, 15B and 16A, 16B.

The control-pulse signal source 1410 represents a source of control signals of the type derived from the generators previously described herein. Thus, the control signals may be reproduced from the medium on which they were recorded or directly fed from the generators. Where the pulses are recorded on magnetic tape, a transducer head is provided over each track, the control pulses in a positive and negative track for a channel being provided as output from the control-pulse signal source 1410. For each axis there is provided a separate dynamic error register 1412 which is substantially a reversible counter. A digital-to-analog converter 1414 generates a voltage whose amplitude is proportional to the count of the counter. The polarity of this voltage is determined by the sign of the count in the counter. The output of the digital-to-analog converter is applied to a power amplifier 1416, the output of which is used to drive a servomotor 1418. The servomotor turns a screw 1420, or a gear train, an amount and in a direction determined by the amplitude and polarity of the voltage it receives which, in turn, is determined by the sign and count in the reversible counter. The screw drives a table 1422. The table is actually driven an incremental amount for each one-count in the counter which is caused by a single pulse. A workpiece (not shown) is fastened to the table, and a cutting tool may be positioned over the table so that as the table is moved the tool operates on the workpiece. It will be appreciated that the screw which is driven can perform other operations than driving a table.

The table motion direction is determined by whether

the track from which a pulse is read is a positive or negative one. It will be recalled that to handle a negative slope, the sign of the differential is sensed and used to determine on which track a pulse is to be recorded. The significance given to these tracks is that pulses in one of them represents motion opposite to motion represented by pulses in the other of them.

The system thus far described is an open loop system. No control exists over the input from the output. To close the system, a motion digitizer 1424 is used. This is a transducer which generates a pulse for every increment of motion made by the table. These pulses are applied to the error register to reduce the count therein occurring either by reason of the input pulses from the control-pulse signal source or as a result of table-motion error which requires correction. The motion digitizer also provides pulses which are added to or subtracted from the count of the reversible counter, as determined by direction of table motion and as required to reduce the counter count. Thus, an indication is provided as to the progress of a cut. The reversible counter thus provides an error count, which truly represents the difference between motion command and motion execution, and the servomotor is driven in response to this error count. Each single-error count calls for a single increment of motion by the table which generates a pulse which cancels the error count.

The motion transducer or motion digitizer can be an antibacklash step-up gear train and an instrument-synchro transformer, which signals back the motion of the machine tool. Alternatively, this may be done with linear photographic gratings and photocells. Preferably, the motion transducer may be a magnetic system whereby the pulses are prerecorded on a magnetic medium attached to the table and a flux-responsive transducer head is used to pick up pulses from a moving table. An illustration of suitable types of flux-responsive transducer heads are described in "Survey of flux-responsive magnetic reproducing heads by Otto Kornei," Journal of Audio Engineering Society, vol. 2, No. 3, July 1954. The logic for determining whether a pulse should be added to or subtracted from the number in the counter may be performed in many ways; for example, by employing two heads and two tracks, it is possible to energize one or the other of the outputs from the heads either from the sense of the motion-controlling input pulse or from phase detection of the pulses obtained at the moving table.

The motion transducer

Figures 15A and 15B comprise a block diagram of an arrangement for generating pulses from the motion of the table holding the workpiece. These figures show the apparatus required for the motion digitizer 1424. The pulses from the motion digitizer are generated in a manner so that they will cause the error register 1412 to add counts responsive to a motion in one direction by the table and to subtract counts responsive to motion of the table in the opposite direction. It will be recalled that one of the possible methods previously described for detecting table motion was to affix a strip of magnetic tape 1500 to the side of the table. This has two tracks thereon which are adjacent to one another. Pulses are recorded on both tracks, but the pulses 1502 on one track are displaced 90 electrical degrees from the pulses 1504 on the other track. Two reading heads 1506, 1508 are positioned side by side over the tracks. The output of one of the magnetic reading heads 1506 will be applied to terminal 1510; the output of the second reading head 1508 will be applied to terminal 1512.

The output of terminal 1510 is applied to a Schmitt trigger circuit 1514, which serves the function of squaring the wave shape of the signal applied thereto. Similarly, Schmitt trigger circuit 1516 serves the function of squaring the wave shape of the pulse applied thereto. The

Schmitt trigger circuit is a well known type of trigger circuit and is described in an article by O. H. Schmitt, entitled "A thermionic trigger," which is in the Journal of Scientific Instruments, vol. 15, pp. 24-26, January 1938. It has two stable states, one of which it assumes as long as a pulse is applied to its input. It returns to remain in the other when its input is removed. The output derived as long as a pulse is applied to the trigger circuit is designated as the "on" output 1517, the other output derived when no pulse is applied to the Schmitt trigger circuit is known as the "off" output 1515. The "off" output is applied to the subsequent And gate circuit 1518. The "on" output 1515 of the Schmitt trigger circuit 1514 is applied to an And gate circuit 1520. Thus, when pickup head 1506 does not detect a pulse on the tape, Schmitt trigger circuit 1514 applies an output to And gate 1518. When a pulse is detected by the pickup head 1506, Schmitt trigger circuit 1514 applies an output to And gate 1520. Thus, similarly, when pickup head 1508 does not detect a pulse, Schmitt trigger circuit 1516 applies its "off" output 1519 to both And gate circuits 1530 and 1544. When a pulse is detected, the Schmitt trigger circuit 1516 "on" output 1521 is applied to both And gate circuits 1534 and 1536.

The And gate circuits shown in Figure 15, unless otherwise designated, are the coincident type of And gate circuits described previously, which require a coincidence, or simultaneous presence, of all of their indicated inputs before an output can be derived therefrom. Flip-flop 1528 provides the second required input to And gate 1518 when in one of its stable states. Let it be assumed that flip-flop 1528 is in the one stable state in which it provides such required input. Accordingly, when And gate 1518 has both the required inputs from this flip-flop 1528 and from Schmitt trigger circuit 1514, the output of the And gate is applied to a single input gate 1522, which applies this output to a flip-flop 1524. Flip-flop 1524 is driven to a second stable condition, whereupon it provides an output which is applied to a single input gate 1526. Gate 1526 has its output applied to flip-flop 1528. Flip-flop 1528 is driven by this output to its other stable condition, whereby it terminates the output to And gate 1518.

The output of And gate 1518, in addition to being applied to gate 1522, is also applied to And gates 1530 and 1534. Because of pulse spacing on the tape 1504, And gate 1530 will have an output applied thereto from Schmitt trigger circuit 1516 for a time when And gate 1518 comes on and applies a second output thereto. When this happens, And gate 1530 is enabled and applies its output to flip-flop 1532. The output from And gate 1530 is terminated when the output from And gate 1518 is terminated.

And gate 1534 can also provide an output to flip-flop 1532 to drive it to the condition opposite to the one it is driven by And gate 1530. Since when the Schmitt trigger circuit 1516 has no pulse applied it enables And gates 1530 and when in the other condition it enables And gate 1534 (in the presence of an output from And gate 1518), flip-flop 1532, which is driven by the respective And gates to one or the other of its stable conditions, effectively follows the state of the Schmitt trigger circuit 1516 and stores that state, in the presence of output from And gate 1518.

Attention is now directed to And gate 1520. And gate 1520, it will be recalled, has an output 1517 from the Schmitt trigger circuit 1514 when a pulse is applied to the Schmitt trigger circuit input. The second required input for And gate 1520 is obtained from flip-flop 1524. As previously described, flip-flop 1524 was turned over by receiving an output from And gate 1518. An enabling output from the flip-flop is applied to And gate 1520. When Schmitt trigger circuit 1514 is driven by a pulse from the table, And gate 1520 will apply this pulse to single input gate 1536 and to And gates 1544 and 1546. Single input gate 1536 can then drive flip-flop 1538,

whereby an output is supplied to single input gate 1540. This single input gate 1540, by its output, drives flip-flop 1524, which closes And gate 1520 and terminates the output derived therefrom.

The output from And gate 1520 is also applied to two And gates 1544 and 1546, which are connected in similar fashion to the output of the Schmitt trigger circuit 1516, as are And gates 1530 and 1534. The output of And gates 1544 and 1546 are applied to control the state of a flip-flop 1548. In effect, flip-flop 1548 also duplicates the condition of Schmitt trigger circuit 1516 substantially as does flip-flop 1532, except this occurs in the presence of output from And gate 1520 instead of in the presence of output from And gate 1518, as was the case previously. It should be pointed out however that this should not be taken to mean that the flip-flops 1532 and 1548 at every instant will have the identical storage conditions, since they indicate the condition of the Schmitt trigger circuit either when And gate 1518 is enabled when flip-flop 1532 can function or when And gate 1520 is enabled when flip-flop 1548 can function.

The signals being applied from the two tracks to the Schmitt trigger circuits 1514 and 1516 are 90° out of phase with one another. Accordingly, one Schmitt trigger circuit will be turned over before the other one if motion proceeds in one direction; the reverse situation occurs if motion proceeds in the opposite direction. The previously described circuitry functions to reflect this condition by the condition of flip-flops 1532 and 1548 relative to one another. Flip-flop 1532 will have one stable condition when motion is proceeding in, for example, a positive direction; flip-flop 1548 will have one stable condition when motion is proceeding in a negative direction. The reverse is true when the directions are reversed. When the table is oscillating about a central or stationary position, the flip-flops will have substantially the same condition. This oscillation should be on the order of less than half a motion increment. The flip-flop have substantially the same condition when one of the Schmitt trigger circuits, either 1514 or 1516, is flipping from one to the other of its stable conditions and the other Schmitt trigger circuit is not being flipped from one to the other of its stable conditions.

The circuitry to be described now performs the function of utilizing the relative conditions of flip-flops 1532 and 1548, which indicate the direction of motion and pulses generated by the motion to direct the error register 1412 to add or subtract these pulses. Circuitry is also provided which effectively prevents a conflict which can arise by the simultaneous arrival at the error register of pulses from the control-pulse signal source 1410 and from the motion digitizer.

And gate 1542 receives three inputs; one of them comes from the circuitry associated with the control-pulse signal source. This input is not present when pulses are being read from the control-pulse source into the error register 1412. The second input is received from flip-flop 1524, upon its being reset from flip-flop 1538, and the third input is received from flip-flop 1528. The input from flip-flop 1528 is received when it is in its nonrestored condition after having been driven by flip-flop 1524. Thus, when these conditions are all present, And gate 1542 provides an output to two following And gates 1550 and 1552 and also to a delay line 1554. The output of the delay line 1554 is applied to a single input gate 1557. The output of this gate 1557 restores flip-flop 1528 to its initial condition. The purpose of the delay line 1554 is to generate a pulse of a required duration out of And gate 1542 to feed the slower error-register counter.

And gates 1550 and 1552 have three inputs which are required to be present before they will provide an output. The input to And gate 1550 consists of two opposite grids in flip-flops 1532 and 1548. The input to And gate 1552 consists of the remaining two opposite grids in flip-flops 1532 and 1548. In effect, this insures that

either And gate 1550 or And gate 1552 will provide an output (when the third required input from And gate 1542 is received) when flip-flops 1532 and 1548 are in one or the other sets of opposite conditions.

And gate 1550 output goes through two Or gates 1554 and 1556. The outputs from Or gate 1556 is directly applied to guide 1 of the tubes used in the error register (Figure 16A). And gate 1552 applies its output to two Or gates 1558 and 1560. Or gate 1560 applies its output to guide 2 of the tubes used in the error register (Figure 16A). Thus a pulse is applied to guide 1 before guide 2 or to guide 2 before guide 1, dependent upon the motion of the table which determines the order of the signals being applied to the Schmitt trigger circuits. It will be recalled that the order of exciting guide 1 and guide 2 determines whether pulses are added or subtracted by the error register. It should also be noted here that when flip-flop 1528 is restored to its initial condition by output from And gate 1542 it applies a second required input to And gate 1562. Output from And gate 1562 is applied to delay line 1568, which delays it for a time sufficient to obtain an output of a required duration from And gate 1562. The output of the delay line 1568 then resets flip-flop 1538, thus terminating the output from And gate 1562.

And gates 1564 and 1566 are also three-input And gates similar to And gates 1550 and 1552. However, the inputs required to operate And gates 1564 and 1566 are opposite to the inputs required to operate And gates 1550 and 1552. It will be recalled that And gate 1542 provides an output which turns over flip-flop 1528, thereby terminating And gate 1542 output. Flip-flop 1528, when it is turned over, applies its output to And gate 1562, which can then provide an output to And gates 1564 and 1566. Therefore, And gate 1562 provides an output after the output from And gate 1542 has terminated. Therefore, an output will be derived from either of the And gates 1564 or 1566 subsequent to the derivation of an output from either of the And gates 1550 or 1552. Which of the And gates 1564, 1566 or 1550, 1552 provides an output is determined by the conditions of the flip-flops 1532 and 1548.

The Or gates 1554 and 1558 apply the outputs of And gates 1564 or 1566 respectively to guide 1 and guide 2 in sequence, dependent upon the sequence of operation of flip-flops 1532, 1548. To summarize the above circuitry operation principles, the error register employed herein requires two pulses to change its count. This count is a positive one if the two pulses have one sequence (G_1-G_2), and the count is negative if the pulses have the reverse sequence (G_2-G_1). The motion of the table in one direction causes flip-flops 1532 and 1548 to operate in one sequence from which pulses are derived in G_1-G_2 order by And gate 1542 enabling And gates 1550, 1552 to derive these pulses from the flip-flops. When the table motion is reversed, flip-flops 1532, 1548 operate in reverse sequence from which pulses G_2-G_1 are derived by And gate 1562 enabling And gates 1564, 1566 to derive these pulses from the flip-flop. It will be recalled that the error register consists of a gas tube having a single anode and ten cathodes. The cathodes are spaced or separated by two guides. The direction in which the arc which is ignited between the single anode and one of the cathodes can be made to move depends upon the one of the two guides which receives a negative pulse first. Thus, the direction of the error register is controlled by the signals which are applied to guide 1 and guide 2.

Reference is now made to Figure 15B, which is a schematic diagram of circuitry for preventing pulses from the control-pulse signal source from interfering with pulses from the motion digitizer. Terminals 1576 and 1578 respectively represent the inputs from the reading heads positioned over two tracks in a channel. One input is received from the plus channel on tape and the second in-

put is received from the minus channel on tape. There will be a pulse on either the plus or the minus channel, but never on both simultaneously. The output from the terminal 1576 is applied to a single-input buffer gate 1580. The output from the terminal 1578 is applied to a single-input buffer gate 1582. Gates 1580 and 1582 serve to drive flip-flop 1584 to one or the other of its stable conditions. Thus, flip-flop 1584 by its state represents which of the channels has just provided a pulse input to the tape unit. The two terminals 1576 and 1578 are also connected to an Or gate 1586. The output from the Or gate 1586 is applied to a one-shot multivibrator 1588. This multivibrator is driven from a stable to an unstable condition, where it remains for an interval determined by the value of its circuit elements; then it returns to its stable condition.

The output of multivibrator 1588 is applied to an And gate 1590. And gate 1590 has two other inputs applied thereto. These inputs, however, are not enabling inputs; they are inhibiting inputs. That is, output is obtained from And gate 1590 when the one-shot multivibrator is driven, except if either of the other inputs to the And gate are excited. The signals for these other two inputs is derived from Or gate 1592 (Figure 15A). Or gate 1592 will provide an output in response to an input from either Or gate 1554 or Or gate 1558. Accordingly, in the presence of an output from the control-pulse signal source, And gate 1590 will supply an output, but this output will be prevented from occurring as long as there is an output received from Or gates 1554 or 1558 which occurs as a result of table motion. The delay line 1594 serves the function of prolonging the inhibiting of And gate 1590 for a short period after termination of the pulse from Or gate 1592.

The output of And gate 1590, which is present when the pulse is received from either the positive or negative track from the control signal source, is applied to a single-input buffer gate 1596. The gate 1596 applies its output to a first one-shot multivibrator 1598. This multivibrator in being driven generates a pulse at the termination of which a second one-shot multivibrator 15100 is driven. Thus, two pulses are generated in sequence. The output of one-shot multivibrator 1598 is also applied to an And gate 15102, an And gate 15104, and an Or gate 15106. The output of one-shot multivibrator 15100 is applied to Or gate 15106 and to And gates 15108 and 15110. Flip-flop 1584 provides all the second required inputs for And gates 15102, 15104, 15108, and 15110. However, as seen in the drawing, the flip-flop inputs are applied to the And gates so that they will be enabled only in accordance with the condition of flip-flop 1584. Thus, only one of And gates 15102, 15104, 15108, and 15110 will provide an output pulse at any given instant. That one is determined by the condition of flip-flop 1584, as well as which of the one-shot multivibrators 1598 and 15100 is providing an output. The arrangement is such that if flip-flop 1584 primes And gates 15104, 15110, one-shot multivibrator 1598 provides an output pulse which is applied to Or gate 15112 through And gate 15104. This is followed by an output from one-shot multivibrator 15100 which is applied to Or gate 15114 through And gate 15110. If flip-flop 1584 primes And gates 15102, 15104, then the pulses to the Or gates occur in a reverse sequence, namely, Or gate 15114 receives a pulse first from one-shot multivibrator 1598 and Or gate 15116 receives a pulse second from one-shot multivibrator 15100. Thus, if an input to flip-flop 1584 is derived from the positive track of the control signal source, the G_1 - G_2 pulse sequence to add a count in the error register is obtained at the output of Or gate 15112 first and Or gate 15114 second. If an input pulse is received from the negative track, then the G_2 - G_1 pulse sequence to subtract a count from the error register is obtained at the output of Or gate 15114 first and Or gate 15116 second. Therefore, the sequence of pulses

(whether to guide 1 first and then guide 2 or to guide 2 first and then guide 1) is determined by which of the two tracks in the control pulse source provides the pulse.

The output of Or gate 15106 is applied to a second Or gate 15116, both directly and indirectly through a delay line 15118. The delay line 15118 serves the purpose of stretching the input to the Or gate and thereby its output for a time beyond the termination of the output from the Or gate 15106. Output from Or gate 15116 is applied to a fast-charging integrating network 15120. This network has the function of maintaining its output for an interval beyond the interval of the input. The output of the integrating network 15120 is applied to And gate 1542 in Figure 15A and serves the function of inhibiting it to prevent any output being derived therefrom during the interval of operation of the one-shot multivibrators 1598, 15100 and for a short time thereafter. This effectively blocks any output being derived from the motion digitizer while output is being applied as a result of control source pulses.

The reason for requiring this operation is to insure that the error register will receive pulses from the control pulse unit in preference to pulses from the motion digitizer on the table. However, the information from either the tape unit or the motion detector is not lost, since in view of the flip-flops employed in the network, the information is stored for a time until it can be applied to the error register. If information is being applied to the error register from the motion digitizer when control-pulse information is received, then the information from the control pulse source is stored in flip-flop 1584 and one-shot multivibrator until the motion-digitizer information has been utilized. If information is received from both the motion digitizer and the control pulse source simultaneously, in view of the fast-charging operation of the integrating network 15120 as opposed to the slower-operating network in the motion digitizer shown in Figure 15A, the information from the control pulse source receives priority and is fed to the error register first.

The error register and digital-to-analog converter

Reference is now made to Figures 16A and 16B which are circuit diagrams for the error register 1412, the digital-to-analog converter 1414, and the power amplifier 1416. The error register is connected through appropriate circuitry to terminals 1572 and 1574 of Figure 15A. Assume first that information being received from either the motion digitizer or the control pulse source is to the effect that a positive count should be added to the one in the register. This requires an input of pulses in the order G_1 - G_2 . In order to effectuate this, a pulse is received first on the guide 1 terminal 1572 and second on the guide 2 terminal 1574. The pulse received at the guide 1 terminal is applied from there to the cathodes of tubes 1610A and 1610B. The grids of tubes 1610A and 1610B are biased in accordance with sign information, which is received from the grids of flip-flop 1620 (consisting of tubes 1620A and 1620B). The sign information is determined by the count in the counter tubes; in other words, if the count is a positive one, the sign information is positive, and, if the count is a negative one, the sign information is negative. The stable condition of sign trigger 1620 is determined by the sign information derived from the counter. The output from sign flip-flop 1620 is applied to the grids of tubes 1610 and 1612, so that the one of the sides A or B of these tubes which is rendered conducting is in part determined by the condition of flip-flop 1620. The other determining factor which controls which of the sides of tubes 1610 and 1612 is conducting is determined by their cathode connections to guide 1 and guide 2.

The output from tube 1620 (when the sign is positive) is applied to side A of tube 1610 and side A of tube 1612. Thus, when the G_1 pulse is received on guide 1, side A

of tube 1610 is rendered conductive. When a pulse is received on guide 2, side A of tube 1612 is rendered conductive. When a positive input is received from the motion digitizer and the sign of the register is positive, first side A of tube 1610 is rendered conductive. The output from tube 1610A is applied to a cathode follower 1614B. The output of the cathode follower is applied, in turn, to an amplifier 1616B. The output therefrom is applied to guide 1 of the error-register tube 1618.

When a G_2 pulse is received on terminal 1574, then tube 1612A is rendered conducting. Its output is applied through a cathode follower 1616A to guide 2 of the error-register tube 1618. Thus, the sequence of pulses applied to the error register is first guide 1, then guide 2, and, as explained previously, the tube will add a count. If the order of pulses received on terminals 1572, 1574 is the reverse, denoting a subtraction is required, with the sign flip-flop indicating that the contents of the register are positive, then tube 1612A would conduct first, which would actuate tube 1616A to apply a pulse to guide 2 of the error-register tube, followed by the conduction of tube 1610A in response to a pulse from terminal 1572, which would cause tube 1616B to apply a pulse to guide 1 of the error register. If flip-flop 1620 is in a negative-indicating condition because the contents of the register are negative and a positive input (G_1-G_2) is received from the terminals 1572, 1574, the input to the error register must be subtracted from the count. The pulse on terminal 1572 will now cause tube 1610B to conduct which excites tube 1616A whereby guide 2 in the register tube is excited. A G_2 pulse on terminal 1574 causes tube 1612B to become conductive, which, through cathode-follower tube 1614B and amplifier 1616B, excites guide 1 of the register. Thus the G_1-G_2 input on terminals 1572 and 1574 is reversed to a G_2-G_1 sequence as actually applied to the error register tube. This reduces the count in the register by one, as it should. If the order of pulses on the terminals 1572, 1574 is G_2-G_1 , then the order of application to the error-register tube is reversed by tubes 1610 and 1612, and a count will be added to that in the register. Since the contents of the register are negative, a positive count must be subtracted from those contents and a negative count must be added to those contents. This is achieved by reversing the order of the guide pulses received when the register contents are negative.

The description that follows now is that of the operation of the error register. This, effectively, is a reversible counter. This reversible counter must be able to either add or subtract counts which are applied thereto. This is taken care of by the priority of inputs to the guide 1 and guide 2 grids in the register. In view of the fact that a register is made of a number of separate decades, there must be provided structure which insures a proper carryover between the decades. Thus, the register shown consists of two decades, the first being enclosed in tube 1618, the second (Figure 16B) being enclosed in tube 1622. The decade 1618 is the units decade, and the decade 1622 is the tens decade. The size of the error register may be as large as is desired. However, the two decades shown can handle counts up to 99, which may be sufficient for the required purpose.

Pulses which are received as G_1-G_2 on guide 1 and guide 2 cause the count in the units decade to increase from one up to nine in the manner described previously herein. When the glow is at the ninth cathode of the tube 1618, the flow of current causes the cathode thereof to become positive by about 35 volts. The positive signal is applied over lead E to the grid of tube 1624A (Figure 16B). The tube, however, cannot be rendered conductive until a negative signal is applied to its cathode from the lead F. This lead receives a negative pulse from the cathode of tube 1614B. As previously described, tube 1614B is excited by a signal from either tube 1610A or

1612B. Condenser 1628, which is connected to the grid of tube 1624A, serves the function of preserving the signal applied to the grid when the signal derived from the ninth cathode of tube 1618 is removed. It should be noted that in operation, the count may pass through nine rapidly; thus, it is necessary to hold the grid of tube 1624A positive for a time to store this fact and to insure proper circuit operation responsive thereto.

The output from tube 1624A is applied to a flip-flop 1630. The plate load for tube 1624A is common with the plate load for the tube 1630B of flip-flop 1630, and, therefore, it serves to cause tube 1630B to be rendered conductive when tube 1624A is rendered conductive. In effect, tube 162A operates as a plate follower. When tube 1630B of flip-flop 1630 is conductive, an output signal is derived and applied to tube 1632A. This tube has its cathode also connected to lead F and tube 1614B. Therefore, tube 1632A is in a position to be rendered conductive when a guide pulse is received from tube 1614B. When this occurs, a negative signal from the plate of tube 1632A is applied to guide 1 in the ten stage of the reversible counter. It is to be noted that the guide 2 pulse is applied to both the units and tens stages of the counter simultaneously. The control of this stage of the counter is determined by the application of the guide 1 pulse, which may occur either before or after the guide 2 pulse selectively.

For an example of the operation here, assume that the count in the counter is 20. In this situation, there is conduction at the zero cathode in the unit stage and there is conduction at the two cathode in the ten stage. It is desired to subtract a count from that in the counter. This requires the ten stage to go from two to one and the unit stage to go from zero to nine, thus representing a count of 19. In order to effectuate this, when the unit stage goes from zero to nine, a carryover pulse is applied to the ten stage, which is subtracted from the count already in the ten stage. This may be effectuated as follows: when the zero cathode of the units stage is in the path of the glow, a signal is applied over lead D to tube 1624B. The cathode of tube 1624B is connected by lead F to the cathode of tube 1614A. Thus, this lead is made negative by pulses from tube 1614A, which is driven by either tube 1610B or 1612A. For subtraction, this is a G_1 pulse occurring after a G_2 pulse. Thus, lead H enables tube 1624B to be rendered conductive from tube 1614A, whereby flip-flop 1630 is driven in the same manner as previously described. The flip-flop drives tube 1632A, which is rendered conductive when its cathode receives a pulse over lead F. Tube 1632A then applies this pulse to the G_1 guide of the ten stage of the counter. Since the original instruction was for a subtraction, a G_2 pulse occurred on lead 1574 before a G_1 pulse on lead 1572. This resulted in lead H being energized before lead F. Thus, a G_2 pulse was applied to tube 1622 before a G_1 pulse. The result is that a subtraction, or a transfer of the glow from the two cathode to the one cathode is effectuated in the tens counter. Meanwhile, a subtraction also occurs in the units counter, which goes from zero to nine. The flip-flop 1630 must be restored after each operation. In order to effectuate this, a diode 1640 (Figure 16A) serves the function of providing a signal which enables such restoration. This diode is, in effect, an Or gate. One of its cathodes is connected via lead 1642 to the grid of tube 1614B. The other of its cathodes is connected through lead 1644 to the grid of tube 1614A. Thus, the output of the diode is provided when either one of these grids is made negative. This enables the diode to draw current through resistor 1646. When this occurs, a negative signal is applied over lead I to tube 1648B. The tube 1648B is normally conducting; when a negative signal is applied to its grid, it is rendered nonconducting. Tube 1648B is a plate follower of tube 1630A in the flip-flop and, thus, when it conducts, it restores flip-flop 1630 to its

initial condition. Thus, flip-flop 1630 is restored to its initial condition whenever there is an absence of guide 1 and guide 2 pulses.

From the above, it will be seen that the reversible counter can add or subtract counts and can transfer carry pulses in a proper manner to insure that the registers store the proper count. The next function to be described is that of the determination of the sign of the count stored in the register. The reason for this requirements is that in view of the fact that the register stores a count without any inherent ability to indicate the sign of the count stored, supplemental means must be provided to indicate whether or not such count is positive or negative.

If a count is initially a positive one, in order to proceed to a negative count, the count must pass through the zero count. Thus, by sensing when the counter is zero, and, further, by sensing whether or not the count following that zero is in a negative direction (by determining that G_2 occurs after G_1) or determining that the count is to go in a positive direction (by determining that G_1 precedes G_2) a means is available for determining the algebraic sign of the absolute count. For sensing the time at which both the tens and the units sections of the counter are on zero, connections are made from the zero cathodes of the units and tens stages over leads J and 1652 through resistors 1654 and 1656 to the grid of tube 1648A. When both cathodes are positive, indicative of the fact that the counters are on the zero stage, the grid of tube 1648A is raised sufficiently to make the tube conductive. Tubes 1658A and 1658B have their grids connected to the cathode of tube 1648A. Thus, when the cathode of tube 1648A goes positive as a result of the tube being rendered conductive, a positive signal is applied to the following tube grids. The cathodes of tube 1658A and 1658B are respectively connected over leads N and O to the respective terminals 1574 and 1572. Thus, whether tube 1658A or 1658B is rendered conductive first is determined by whether or not, following the positive signal being applied to their grids, a guide 1 or a guide 2 pulse is required.

If a guide 1 pulse is received first, then tube 1658B is rendered conductive. The plate of tube 1658B is connected over lead K to the plate of tube 1620 and, thus, when tube 1658B goes conductive, it pulls current through the plate load of tube 1620B, and thus the sign flip-flop is set with tube 1620B conducting. This represents a positive sign, or the fact that the count in the counter is positive. If a guide 2 pulse is the first received, tube 1658A is rendered conductive. Tube 1658A has its anode connected over lead L to tube 1620A of the sign flip-flop. As previously described, tube 1658A will make tube 1620A conductive, thus setting sign flip-flop 1620 in a negative indicating sense for the count in the counter. A condenser 1660 is employed which is connected between ground and the grids of tube 1658 to insure some storage effect of the input thereto. The condenser value is selected to insure that the storage is not longer than the period of one pulse. Such storage is necessary because of the rapid operation of the counter tube.

For digital-to-analog conversion purposes—that is, for transforming the count of the counter into a voltage having a representative amplitude and sign—the following apparatus is employed. A series of resistors 1690, 1692 are connected to form a ladder network. This ladder network consists of resistors 1690, 1692 which are connected as a voltage divider between the cathodes of the stages of the units counter and the tens counter. In the preferred embodiment of the invention, the resistors have the values shown in the drawing. This is not to be construed as a limitation on the invention, since other values may be used, if desired, and will provide satisfactory operation. With a voltage tap-off point taken at the nine cathode of the decade stage, the closer to the nine cathode the location of the conducting arc

in the tube, the fewer resistors between the cathode in its path and the tap-off point, and, therefore, the higher the tap-off voltage will be. Therefore, the amplitude of this voltage depends upon how close the conducting cathode in the tube is to the point of takeoff of that voltage. Thus, as an arc is ignited at each cathode, in turn increasing direction toward the top of that ladder, the voltage at the top will increase; as an arc is ignited at each cathode, in turn going away from the top of that ladder, the voltage at the top will decrease. Thus, this tap-off voltage is an analog representation of the count in the counter.

A ladder is provided for each stage in the counter. Lead G is connected through a network to tap off a voltage from the units counter stage resistance ladder; lead 1672 is used to tap off a voltage from the tens counter stage resistance ladder. Lead G connects to the grid of tube 1632B. The resistance ladder of the tens stage of the counter, instead of being brought directly to ground through the cathode resistors, as was the case in the units stage, is brought through the cathode resistors to a potentiometer 1674. The potentiometer has one end of its fixed resistor connected through a resistor 1676 to ground; the other end of the potentiometer fixed resistor is coupled to a point on the cathode load resistor of tube 1632B. Thus, in effect, the cathode of tube 1632B is placed in series with the resistance ladder of the tens counter tube 1622.

The state of conduction of tube 1632B is determined by the voltage applied to its grid, which, in turn, is determined by the voltage derived from the units-counter tube resistance ladder. Thus, the grid voltage of tube 1632B is determined by the voltage or the count of the units stage. This voltage is added at the cathode to the voltage derived from the resistance ladder of the decimal stage. A total output voltage is accordingly obtained at the tap-off point at lead 1672, which has its amplitude determined by the total count in the units and the decimal stages.

Lead 1672 is connected to the grids of tubes 1680A and 1680B. The total analog voltage derived from the resistance ladder is applied by lead 1672 to the grids of tubes 1680A and 1680B.

Tubes 1680A and 1680B serve the function of providing a current which will drive the servomotor, which, in turn, drives the table. In order to obtain the proper operation of the motors—that is, to move the table in one direction for positive counts and in the opposite direction for negative counts—the current to be derived from tubes 1680A and 1680B should be positive for positive counts and negative for negative counts, even though the voltage derived from the resistance ladders has only one polarity. Accordingly, the sign-sensing flip-flop 1620 is employed to control the output of tube 1680, whereby the negative output current is obtained when the sign of the count in the counter is negative, and a positive output current is obtained when the sign in the counter is positive.

In order to effectuate this, connections are made to tubes 1682A and 1682B over leads M and P from both plates of the sign-sensing flip-flop 1620. One or the other of the two tubes 1682A and 1682B will be rendered conductive responsive to the sign-sensing flip-flop condition. Diode 1684 serves as a means of coupling the cathodes of tubes 1682A, 1682B to the grids of tubes 1680A and 1680B. In this manner, when tube 1682B conducts, the cathode of tube 1682B is rendered positive, which cuts off the diode 1684A or prevents it from conducting. This enables tube 1680A to be rendered conductive by the input voltage from lead 1672. Since tube 1682A is not conductive at this time, diode 1684B is enabled to be conducting. By this means, the grid of tube 1680B is clamped to the voltage of the cathode of tube 1682A, and thus it cannot be affected by the voltage being applied from lead 1672. However, there is a common

cathode coupling resistor 1694 between the cathode of tubes 1680A and 1680B. The current through tube 1680B is varied as a result of this common cathode coupling inversely as the current varies through tube 1680A. Thus, the output which is obtained from the plate of tube 1680B will be a positive output when side 1680A is permitted to follow voltage being received from lead 1672; it will be a negative output when side 1680B is permitted to follow the voltage from lead 1672. This output is applied through the tap-off potentiometer 1696 to the servo-amplifier and controls it accordingly. This output voltage is the analog representation of the count in the counter and its sign.

It should be remembered that for each co-ordinate of motion to be controlled a set of the circuits described above is required, namely, one error register, one digital-to-analog converter, one power amplifier, and one motion digitizer.

The velocity of the table along the desired path can be expressed by the equation:

$$v = f(\delta^2) \frac{\sqrt{(\Delta x)^2 + (\Delta y)^2}}{\Delta x \cdot \Delta y}$$

where f is the pulse rate in pulses per second and δ is the distance the table must move to generate a single pulse in the position transducer. The above equation may be solved for f as a function of v giving:

$$f = \frac{v(\Delta x)(\Delta y)}{\delta^2 \sqrt{(\Delta x)^2 + (\Delta y)^2}}$$

From this it can be seen that table speed can be readily controlled by control of the pulse generator frequency during interpolation. As previously described, this can be used for automatic speedup or slowdown of the table.

Figure 17 shows a typical workpiece 1710 which is to be milled along the cutting paths shown by the dotted lines using the previously described invention. From a drawing of the piece, the methods man determines the location, with respect to a fixed reference point, of the beginning and end of each cut. He also determines the speed of table travel.

Calling the offset from the reference point at the start of the cut along the longitudinal feed x_1 and along the crossfeed y_1 , similar offsets at the end of the cut are x_2 and y_2 . For vertical feed control, the initial offset will be called z_1 and the final offset z_2 .

For a straight-line path, the straight-line generator set-up of the invention is used. The required cutting speed is established by fixing the pulse generator frequency at a value which provides this speed. This can be readily determined from the formula for velocity shown above. Assuming the cutting tool is at the origin (O, O, O), the values of x_1 , y_1 , z_1 will be first entered and the pulse generator frequency set to a proper value. The table speed and frequency can be quite high until the cutting path is actually started.

Then the methods man will enter the differences $(x_2 - y_1)$, $(y_2 - y_1)$, and $(z_2 - z_1)$. The system is again set in motion to record the directions for the table to bring the cutting head to point p_2 . As soon as the proper recording is finished, he will continue to enter the next required difference and frequency into the system to generate pulses to direct the next segment of travel. This will continue until all the paths are generated, segment by segment. Where circular paths are required, the system may be switched from the straight-line to the circular configuration with entries made in the manner previously described.

An adding machine can print out on paper tape the various calculations made. With programming completed, this paper tape can be checked against the drawing. The reel containing the recording on magnetic tape may be placed in the tape player, and the blank workpiece mounted on the milling-machine bed in a reference

position as determined by a single jig. Then, by merely pressing a start button, the milling machine will be controlled by the playback and control units through a cutting cycle, which will result in a finished workpiece.

Since all required instructions are on magnetic tape, a library of these may be produced with relative ease. The problem of programming is simple, being done from ordinary drawings and methods-sheet information. All programming is finished when the tape is finished, so that the shop installation for reproducing the tape and controlling the machine tool is simple and inexpensive. The system automatically guides a machine table along circles and other second-degree curves instead of approximating these by a series of straight-line paths.

There has accordingly been shown and described herein a novel, useful, and relatively inexpensive system for programming and automatically controlling machine tools. The programming system is effectively a digital-function generator which obtains a digital manifestation of any given path. The digital function may then be subsequently carried out by the pulse command execution portion of the system.

Although the invention has been described employing as an input device an adding machine or two adding machines, it is within the scope of this invention to store the calculated differences on punched cards or tape and to put these storage mediums into a reading device which feeds these to the registers of the invention to effectuate a generation of control pulses. Alternatively, such information can be supplied from other forms of calculating machines.

Although the output is described as controlling machine tools, it is well within the skill of those versed in the art to use the output to drive curve-drawing equipment or the controls of a vehicle to follow a predetermined path.

While particular embodiments of the present invention have been shown and described, it is apparent that various changes and modifications may be made therein without departing from the true spirit and scope of the invention. Accordingly, it is intended that the appended claims cover all such changes and modifications as fall within the true spirit and scope of the invention.

We claim:

1. A digital-function generator for obtaining digital functions representative of a path in a co-ordinate system comprising a source of periodic pulses, separate means for dividing the number of pulses issuing from said source by a factor equal to the differential of the equation of said path with respect to each one of the coordinates in said system to obtain a separate series of pulses for each co-ordinate, and means to utilize each of said series of pulses.

2. A digital-function generator for obtaining digital functions representative of a path in a co-ordinate system comprising a source of periodic pulses, separate means for dividing the number of pulses issuing from said source by a factor equal to the value of the differential of the equation of said path with respect to each one of the co-ordinates in said system to obtain a separate series of pulses for each co-ordinate, means to prevent further pulses from issuing from said source when the number of pulses in each of said separate series of pulses represents the extent of displacement from the beginning to the ending of said path along a different co-ordinate axis in said co-ordinate system, and means to utilize said pulses.

3. A digital-function generator for obtaining digital functions representative of a path in a co-ordinate system comprising a source of periodic pulses, means for dividing the number of pulses issuing from said source by a factor equal to the differential of the equation of said path with respect to one of the co-ordinates in said system to obtain a first series of pulses, means to divide the number of pulses issuing from said source by a factor

equal to the differential of the equation of said path with respect to another of the co-ordinates in said system to obtain a second series of pulses, means to prevent further pulses from issuing from said source when the number of pulses in said first and second series of pulses respectively represents the extent of displacement along the respective co-ordinate axes in said co-ordinate system from the beginning to the ending of said path, and means to store said first and second series of pulses.

4. A system for generating signals for controlling motion along separate co-ordinate axes to describe, as a resultant of all said co-ordinate motions, a desired path, said system comprising a plurality of separate means to generate a separate train of control pulses for each co-ordinate axis, each pulse in a train representing an increment of motion along the co-ordinate, a plurality of separate means for establishing the correct number of control pulses to provide a required motion along each co-ordinate axis for describing said path, and means for controlling each of said means for generating a separate train of control pulses with a separate one of said plurality of separate means for establishing the number of control pulses for deriving separate trains of control pulses for each co-ordinate axis having the correct number of control pulses.

5. A system for generating signals for simultaneously controlling motion along separate co-ordinate axes to describe as a resultant of all said motions a desired path, said system comprising a separate variable frequency means for each co-ordinate for generating a train of control pulses, each control pulse in a train representing an increment of motion along the co-ordinate, a separate means for controlling the frequency of each said separate variable frequency means for generating a train of control pulses responsive to the value of the differential of the equation of said path with respect to one of the co-ordinates of said system, a separate means for each co-ordinate axis for establishing the correct number of control pulses required for said motion along said co-ordinate axis for said path, means for controlling each of said variable frequency means for generating a train of control pulses responsive to a different proper one of said means for establishing the correct number of control pulses required for motion along the related co-ordinate axis to derive control pulse trains for each co-ordinate having the correct number of pulses, and means to utilize said control pulse trains.

6. A system as recited in claim 5 wherein said means to utilize said control pulse trains includes for each co-ordinate axis, an error register, means to convert the value in said register and its sign to a representative voltage means to move along a co-ordinate axis responsive to said representative voltage, motion transducer means to generate a pulse responsive to an increment of motion along said co-ordinate, and means to apply said pulses from said control pulse train and said pulses from said motion transducer means generated responsive to the control pulses of said train to said error register in a manner to provide opposite changes to the value in said register.

7. A system for generating signals for simultaneously controlling motion along separate co-ordinate axes to describe as a resultant of all said motions a desired path, said system comprising a source of periodic pulses, a means for each co-ordinate for deriving from said source a train of control pulses, each control pulse in a train representing an increment of motion along a co-ordinate, each of said means including a means associated with a co-ordinate for dividing the number of periodic pulses from said source by the differential of the equation of said path with respect to the associated co-ordinate of said system, a separate means for each co-ordinate axis for establishing the correct number of control pulses required for said motion along said co-ordinate axis for said path, means responsive to one of said means to establish the

correct number of control pulses to block further output from each of said means for deriving a train of control pulses when the number of control pulses in said train equals the correct number for the co-ordinate motion to be controlled by said train, and means to utilize said control pulse trains.

8. A system as recited in claim 7 wherein each said means for dividing the number of periodic pulses from said source includes a dividing counter, and means to derive an output from said dividing counter when the number of pulses counted equals the value of the differential of the equation of said path with respect to the co-ordinate with which said counter is associated.

9. A system as recited in claim 8 wherein each said means to block further output from each of said means for deriving a train of control pulses when the control pulses in said train equals the correct number of the co-ordinate motion to be controlled by said train includes a summing counter, means to apply the output from one of said dividing counters to said summing counter, means to compare the sign and value of the quantity in the summing counter with the quantity and value in the one of said means for establishing the correct number of control pulses required for said motion along the co-ordinate axis for said path for which said dividing counter output is utilized, and means to prevent further output from said dividing counter responsive to said means to compare indicating a coincidence.

10. A system as recited in claim 7 wherein said means to utilize said control pulse trains includes for each co-ordinate axis, an error register, means to convert the value in said register and its sign to a representative voltage means to move along a co-ordinate axis responsive to said representative voltage, motion transducer means to generate a pulse responsive to an increment of motion along said co-ordinate, means to apply pulses from said control pulse train to said error register to change the value in said register, means to apply pulses from said motion transducer means generated responsive to the pulses from said control pulse train to said error register to provide changes in the value in said register opposite to those effectuated by pulses from said control pulse train, and means to prevent the simultaneous application to said error register of pulses from said motion transducer and said control-pulse train.

11. A system for generating signals for simultaneously controlling motion along a first and second co-ordinate axes to describe as a resultant of all said motions a straight-line path, said system comprising a source of periodic pulses, a first dividing counter, a second dividing counter, means to apply pulses from said source to the inputs to said first and second dividing counters, means to derive output from said first dividing counter each time it counts a number of pulses equal to the value of the differential of the equation of said path with respect to said first co-ordinate to obtain a first train of pulses for controlling motion along said second co-ordinate, means to derive output from said second dividing counter each time it counts a number of pulses equal to the value of the differential of the equation of said path with respect to said second co-ordinate to obtain a second train of pulses for controlling motion along said first co-ordinate, each pulse in said first and second train of pulses representing the same increment of motion along the respective second and first co-ordinate axes, first means to establish the number of motion increments required along said first co-ordinate axis, second means to establish the number of motion increments required along said second co-ordinate axis, first means to count the number of pulses in said first train, second means to count the number of pulses in said second train, and means to terminate further pulses from said periodic pulse source when the number of pulses counted in said first and second pulse trains respectively equal the num-

bers established in said second and first means to establish the number of motion increments required.

12. A system for generating signals for simultaneously controlling motion along a first and second co-ordinate axis to describe as a resultant of all said motions a circular path, said system comprising a source of periodic pulses, a first dividing counter, a second dividing counter, means to apply pulses from said source to the inputs to said first and second dividing counters, means to derive an output pulse from said first dividing counter each time it counts a number of pulses equal to the value of the differential of the equation of said path with respect to said first co-ordinate at each of successive spaced points along said circular path to obtain a first pulse train, means to derive an output from said second dividing counter each time it counts a number of pulses equal to the value of the differential of the equation of said path with respect to said second co-ordinate at each of said successive spaced points along said circular path to obtain a second pulse train, each pulse in said respective first and second trains representing the same increment of motion along the respective first and second co-ordinate axes, a first summing counter having a first sensing means to sense the sign of the quantity in said first summing counter, a second summing counter having a second sensing means to sense the sign of the quantity in said second summing counter, means to establish in said first summing counter and its sensing means the value and sign of the differential of the equation of said path with respect to the first co-ordinate at the beginning of said circular path, means to establish in said second summing counter and its sensing means the value and sign of the differential of the equation of said path with respect to the second co-ordinate at the beginning of said circular path, means to apply pulses from said first dividing counter to said first summing means under control of said second sensing means, means to apply pulses from said second dividing counter to said second summing means under control of said first sensing means, and means to terminate pulses from said pulse source when the sign and value of the quantities in the respective first and second summing counters attain the sign and value of the respective differentials of the equation of said path with respect to each of said co-ordinates at the termination point of said circular path.

13. A system for generating signals for simultaneously controlling motion along a first, second, and third co-ordinate axis to describe as a resultant of all said motions a straight-line path comprising a source of periodic pulses, first, second, and third pairs of dividing counters, means to apply pulses from said source to one of said first, second, and third pairs of dividing counters, means to apply output from said one of said first to the other of said third pair of dividing counters, means to apply output from said one of said third to said other of said first pair of dividing counters, means to apply output from said one of said second to said other of said third pair of dividing counters, means to derive an output from each of said first pair of dividing counters each time it counts a number of pulses equal to the value of the differential of the equation of said path with respect to said first co-ordinate, means to derive an output from each of said second pair of dividing counters each time it counts a number of pulses equal to the value of the differential of the equation of said path with respect to said second co-ordinate, means to derive an output from each of said third pair of dividing counters each time it counts a number of pulses equal to the value of the differential of the equation of said path with respect to said third co-ordinate, whereby first, second, and third control pulse trains are respectively derived from said other of said third, first, and second pairs of dividing counters, each pulse in each pulse train representing a motion increment along a co-ordinate axis, means to respectively establish the number of motion increments

required along said first, second, and third co-ordinate axes, and means to terminate further pulses from said source upon a coincidence being achieved in the number of pulses in said first, second, and third pulse trains and the respective numbers established in said means respectively establish the number of motion increments required along said first, second, and third co-ordinate axes.

14. A system for controlling the relative motion of a tool and a workpiece comprising means to generate during the same interval of time a first, a second and a third pulse train having a frequency ratio determined by the slope of the path desired for said relative motion, the total number of pulses in each pulse train respectively representing the relative displacement of said tool and workpiece, along a different co-ordinate to effectuate a desired operation on said workpiece, means to record said first, second, and third pulse trains, means to reproduce said pulse trains from said means to record, and means to relatively move said workpiece and tool a predetermined increment of motion along the respective co-ordinate responsive to each pulse from said reproduced pulse trains.

15. A system for obtaining signals to control the relative motion of a tool and a workpiece along two co-ordinates to effectuate an operation on said workpiece along a desired path comprising a source of periodic pulses, a first dividing counter having its input coupled to said source, a second dividing counter having its input coupled to said source, means to set said first dividing counter to provide an output pulse after counting a number of input pulses equal to the value of the differential of the equation of said path with respect to one of said two co-ordinates to obtain a first series of periodic-control pulses over an interval, means to set said second dividing counter to provide an output pulse after counting a number of input pulses equal to the value of the differential of the equation of said path with respect to the other of said two co-ordinates to obtain a second series of periodic-control pulses during said interval, and means to record said first and second series of control pulses for subsequent utilization for controlling the relative motion of said tool and workpiece.

16. A system for obtaining signals to control the relative motion of a tool and workpiece along two co-ordinates to effectuate a given-length operation along a desired path comprising a source of periodic pulses, a first dividing-counter means, a second dividing-counter means, means to apply pulses from said source to the inputs to said first and second dividing-counter means, means to set said first dividing-counter means to provide an output pulse after counting a number of input pulses equal to the differential of the equation of said desired path for said given length with respect to one of said co-ordinates to obtain a first series of control pulses, means to set said second dividing-counter means to provide an output pulse after counting a number of input pulses equal to the differential of the equation of said path for said given length with respect to the other of said co-ordinates to obtain a second series of control pulses, means to count both said first and second series of pulses, means to terminate the application of pulses from said source of periodic pulses to said first and second dividing-counter means when the counts indicated by said means to count equal the values of said differentials for said desired path lengths, and means to record said first and second series of pulses for controlling the relative motion of said tool and workpiece along said co-ordinates.

17. A system as described in claim 16 wherein said desired path is a straight line and said means to record includes means to record the output of said first dividing counter as a second series of pulses for controlling motion along said first co-ordinate, and said means to record includes means to record the output of said second divid-

ing counter as a first series of pulses for controlling motion along said second co-ordinate.

18. A system as described in claim 16 wherein said desired path is a circle, and said means to count both said first and second series of periodic pulses includes a first reversible counter to count said first series of pulses, a second reversible counter to count said second series of pulses, a first and second sign sensor respectively coupled to said first and second reversible counters to determine the sign of the number in said reversible counter, means coupled between said first reversible counter and said second sign sensor to determine whether pulses received for said first series are to be added or subtracted by said first reversible counter responsive to the sign sensed by said second sign sensor, and means coupled between said second reversible counter and said first sign sensor to determine whether pulses received for said second series are to be added or subtracted responsive to the sign sensed by said first sign sensor.

19. A system as described in claim 16 wherein said desired path is an ellipse and said first dividing-counter means includes first, second, and third counters coupled in series, means to set said first and second counters to repeatedly provide an output upon counting a fixed number of pulses, and means to change by one the count required to provide an output from said third counter after each output, and said second dividing-counter means includes third, fourth, and fifth counters coupled in series, means to set said third and fourth counters to repeatedly provide an output upon counting a fixed number of pulses, and means to change by one the count required to provide an output from said sixth counter after each output.

20. A system as described in claim 16 wherein said desired path is a curve and said first and second dividing-counter means each includes a plurality of counters coupled in series, the number of counters in each said first dividing means being one for every term in the corresponding differential when all said terms are expressed as powers of one.

21. A system as described in claim 16 wherein there is included means to reduce the frequency of the periodic pulses from said source when the counts indicated by said means to count are at a predetermined count from the total count.

22. In a system for controlling with pulse signals the relative motion of a tool and workpiece in a co-ordinate system to effectuate a desired straight-line operation on said workpiece, apparatus for obtaining said signals comprising a source of periodic pulses, a first means to divide pulses from said source during an interval by a first number which is the difference between one of the co-ordinates which locate the beginning and the end of said straight line in said co-ordinate system to provide a first pulse train representative of the difference between another of the co-ordinates which locate the beginning and end of said straight line in said co-ordinate system, said first number being expressed in units which are desired relative tool and workpiece motion increments responsive to pulse signals, a second means to divide pulses from said source during said interval by a second number expressed in the same units as said first number and which is the difference between said another of said locating co-ordinates to provide a second pulse train representative of said difference between said one of said locating co-ordinates, means to separately record both said pulse trains, and means to discontinue pulses from said source to both said dividing means when the total number of pulses in said respective first and second pulse trains are equal to said second and first numbers.

23. In a system as recited in claim 22 wherein said first and second means to divide respectively include a first and second counter; and said means to discontinue pulses from said source to both said dividing means in-

cludes a separate counter connected to the outputs of said first and second counters, and means to sense when said separate counters have counted to said first and second numbers to discontinue pulses from said source.

24. In a system for controlling with pulse signals the relative motion of a cutting tool and a workpiece in a co-ordinate system to effectuate a desired straight-line cut, apparatus for obtaining said signals comprising a source of periodic pulses, a first and second dividing counter, means to apply simultaneously pulses from said source to said first and second dividing counters to be counted, a first and second counter, means to apply said first dividing counter output to said second summing counter, means to apply said second dividing counter output to said first summing counter, a first register, a second register, means to enter into said first register a first number which is the difference between one of the two co-ordinates which locate the beginning and the end of said line in said co-ordinate system, said first number being expressed in units which are desired increments of relative cutting tool and workpiece motion responsive to pulse signals, means to enter into said second register a second number expressed in the same units as said first number which is the difference between another of the co-ordinates which locate the beginning and end of said line in said co-ordinate system, means to set said first dividing counter from said first register to count a number of pulses equal to said first number before being reset, means to set said second dividing counter from said second register to count a number of pulses equal to said second number before being reset, means to sense coincidence between said first register and the count of said second summing counter and between said second register and the count of said first summing counter, means to prevent pulses from said periodic-pulse source from being applied to said dividing counters responsive to said coincidence-sensing means, and means to record the pulse outputs of said first and second dividing counters.

25. A system as recited in claim 24 wherein said means to record includes a positive and negative recording track for the output of said first dividing counter, and a positive and negative track for recording the output of said second dividing counter, means to sense the sign of said first number and to indicate whether it is positive or negative, means to record said second dividing counter output on a positive or negative track responsive to said means to sense said first number indicating a corresponding positive or a negative sign, means to sense the sign of said second number to indicate whether it is positive or negative, and means to record said first dividing counter on a positive or negative track responsive to said means to sense indicating said second number sign as correspondingly positive or negative.

26. A system as recited in claim 24 wherein said means to enter said first and second number respectively into said first and second registers is an adding machine.

27. In a system for controlling with pulse signals the relative motion of a machine tool and a workpiece in a co-ordinate system to effectuate a desired circular operation on said workpiece, apparatus for obtaining said signals comprising a source of periodic pulses, a first and second register, a first and second dividing counter to which pulses from said source are applied, a first and a second reversible counter, a first and a second means to respectively detect the sign of a number in said first and second reversible counters, means to enter into said first reversible counter a first number representative of the difference between one of the co-ordinates denoting the beginning of said desired circular cut and one of the co-ordinates denoting the center of a circle with the periphery of which said desired circular cut coincides, means to set said first dividing counter to count a number of pulses equivalent to the number in said first reversible counter each time the number in said first reversible counter changes, means to apply output from said first dividing counter to said first reversible counter to be

counted, first means to record the output from said first dividing counter, means to enter into said second reversible counter a second number representative of the difference between another of the co-ordinates denoting the beginning of said desired circular cut and another of the co-ordinates denoting the center of said circle, means to set said second dividing counter to count a number of pulses equivalent to the number in said second reversible counter each time the number in said second reversible counter changes, means to apply output from said second dividing counter to said second reversible counter to be counted, second means to record the output from said second dividing counter, and means to prevent pulses from being applied from said source to said first and second dividing counters responsive to said first and second reversible counters respectively attaining counts equivalent to a third and fourth number, said third number being the difference between one of the co-ordinates denoting the end of said circular cut and said one of said co-ordinates denoting the center of said circle, said fourth number being the difference between another of the co-ordinates denoting the end of said circular cut and said another of said co-ordinates denoting the center of said circle.

28. In a system as recited in claim 27 wherein said first and second means to record the output from said dividing counters each includes a positive and a negative recording track, and said first dividing counter output is recorded by said first means in a positive or negative track responsive to said second means to detect the sign of a number in said second reversible counter, and said second dividing counter output is recorded by said second means in a positive or negative track responsive to said first means to detect the sign of a number in said first reversible counter.

29. In a system as recited in claim 27 wherein said means to prevent pulses from being applied from said source to said first and second dividing counters responsive to said first and second reversible counters respectively attaining counts equivalent to a third and fourth number comprises a first register, a second register, means to respectively establish said third number into said first register and said fourth number into said second register, first coincidence gate means to detect coincidence between said first reversible counter and said first register, second coincidence gate means to detect coincidence between said second reversible counter and said second register, and means to prevent pulses from being applied from said source to said first and second dividing counters responsive to a detection of coincidence by said first and second coincidence gate means simultaneously.

30. In a system for controlling with pulse signals the relative motion of a tool and a workpiece in a co-ordinate system to effectuate a desired circular cut, apparatus for obtaining said signals comprising a source of periodic pulses, a first and a second register, a first and a second counter, a first and a second summing counter, a first means and a second means to respectively represent the sign of a number in said first and second counter, means to enter into said first summing counter a first number representative of the difference between one of the co-ordinates denoting the beginning of said desired circular cut and one of the co-ordinates denoting the center of a circle with the periphery of which said desired circular cut coincides, means to enter into said second summing counter a second number representative of the difference between another of the co-ordinates denoting the beginning of said desired circular cut and another one of the co-ordinates denoting the center of said circle, means to enter into said first register a third number representing the difference between one of the co-ordinates denoting the end of said desired circular cut and said one of the co-ordinates denoting the center of said circle, means to enter into said second register a fourth number representing the difference between another of the co-

ordinates denoting the end of said desired circular cut and said other of the co-ordinates denoting the center of said circle, means to apply pulses from said periodic-pulse source to said first and second counters to be counted, means to generate a first output pulse responsive to said first counter counting the same number of pulses as the numbers in said first summing counter, means to add said first output pulse to the number in said first summing counter, first means to record said first output pulse, means to reset said first counter to its initial condition for counting, means to detect a coincidence between the number in said first summing counter and in said first register, means to generate a second output pulse responsive to said second counter counting the same number of pulses as the number in said second summing counter, second means to add said second output pulse to the number in said second summing counter, second means to record said second output pulse, means to reset said second counter to its initial condition for counting, means to detect a coincidence between the number in said second summing counter and in said second register, and means responsive to a coincidence detection by both said means to detect coincidences between said summing counters and registers to interrupt application of pulses from said source to said counter.

31. In a system as recited in claim 30 wherein said means to generate a first output pulse includes a means to detect coincidence between the count of said first counter and the count of said first summing counter, and said means to generate a second output pulse includes a means to detect coincidence between the count of said second counter and the count of said second summing counter.

32. In a system as recited in claim 30 wherein said first and second means to record each includes a positive and a negative recording track and said first output is recorded in the one of said two tracks determined by the sign of the number represented by said second means to represent the sign of the number in said second summing counter and said second output is recorded in the one of said two tracks determined by the sign of the number represented by said first means to represent the sign of the number in said first summing counter.

33. A system for controlling the relative motion of a tool and a workpiece to effectuate a desired operation on said workpiece comprising a source of periodic pulses, first means to move said workpiece relative to said cutting tool along a first co-ordinate a predetermined increment responsive to a pulse, second means to move said workpiece relative to said cutting tool along a second co-ordinate a predetermined increment responsive to a pulse, first means to derive from said source of periodic pulses a first plurality of pulses, the total number of pulses in said first plurality being representative of the total number of increments of motion along said first co-ordinate to effectuate said desired operation, second means to derive from said source of periodic pulses a second plurality of pulses, the total number of pulses in said second plurality being representative of the total number of increments of motion along said second co-ordinate to effectuate said desired operation, and means to simultaneously apply said first and second plurality of pulses to said first and second means to move said workpiece relative to said tool.

34. A system as recited in claim 33 wherein said first means to derive a first plurality of periodic pulses and said second means to derive a second plurality of periodic pulses respectively include a first and a second dividing-counter means, means to set each of first and second dividing-counter means to produce an output from each upon counting a number of pulses from said source equivalent to the number of pulses required to complete the total number of increments of motion along said respective first and second co-ordinate, means to count said output from each of said first and second di-

viding counter means, and means to stop pulses from said pulse means from being applied to said dividing-counter means when said outputs from each of said dividing-counter means respectively equal said first and second plurality of pulses.

35. A system as recited in claim 33 wherein said first and second means to derive a first and second plurality of pulses includes means to record said first and second plurality of pulses, and said means to simultaneously and respectively apply said first and second plurality of pulses to said first and second means to move said workpiece relative to said tool includes means to reproduce said recorded first and second plurality of pulses, first and second reversible counters, means to respectively apply said reproduced first and second plurality of pulses respectively to said first and second reversible counters to be added, means to derive a separate pulse for each increment of relative motion along each co-ordinate, and means to apply said separate pulses to said respective first and second reversible counters to be subtracted.

36. In a system for controlling with pulse signals the relative incremental motion along separate co-ordinates of a tool and workpiece to effectuate a desired operation along a desired resultant path on said workpiece, a single-pulse source, means to derive a train of said pulses for each of said separate co-ordinates from said single-pulse source, means to determine the total number of pulses required in each train to complete said desired operation along said desired path, and means to control the frequency of said single-pulse source to vary the frequencies of the pulses in said pulse train relative to one another at predetermined portions of said pulse trains to determine the speed of the relative tool and workpiece in motion.

37. In a system for controlling with pulse signals the relative incremental motion along separate co-ordinates of a tool and workpiece to effectuate a desired operation on said workpiece comprising an error register to which control pulses are applied to be counted, means to convert the count of said error register to a voltage having a representative amplitude, means to move said workpiece relative to said tool responsive to said representative voltage, motion transducer means to convert increments of said relative motion to error pulses, and means to apply said error pulses to said error register to be subtracted from the count of said control pulses.

38. A system for providing motion increments in response to control pulses comprising an error register to which said control pulses are applied to be counted, digital-to-analog means to convert the count of said error register to a voltage having a representative amplitude and polarity, servomotor means to which said voltage is applied, means driven by said servomotor means, motion transducer means to convert increments of motion of said means driven by said servomotor to error pulses, means to apply said error pulses to said error register to be subtracted from the count of said control pulses, and means to prevent the simultaneous application of a control pulse and an error pulse to said error register.

39. A system as recited in claim 9 wherein each said dividing counter is a decimal system dividing counter, and said summing counter is a decimal system summing counter.

40. A system as recited in claim 11 wherein said first and second dividing counters are decimal system dividing counters, and said first and second means to respectively count the number of pulses in said first and second pulse trains are respectively a first and a second decimal system summing counter.

41. A system as recited in claim 12 wherein said first and second dividing counters are decimal system dividing counters, and said first and second summing counters are decimal system summing counters.

42. A system as recited in claim 24 wherein said first and second dividing counters are decimal system dividing

counters, said first and second summing counters are decimal system summing counters and said first and second registers are decimal system registers.

43. A system as recited in claim 25 wherein said first and second dividing counters are decimal system dividing counters, said first and second summing counters are decimal system summing counters and said first and second registers are decimal system registers.

44. A system as recited in claim 38 wherein said error register is a decimal system error register.

45. A system for obtaining signals to control the relative motion of a tool and workpiece along a first and a second co-ordinate to effectuate a given length operation along a desired path comprising a first decimal system register, a second decimal system register, means to enter into said first and second registers the sign and value of a first and second number, said first and second numbers respectively comprising the difference between the values of the two co-ordinates denoting the end and the beginning of the desired path, a first decimal system dividing counter, a second decimal system dividing counter, a source of pulses, means for controlling the frequency of said source of pulses, means to apply pulses from said source to both said decimal system divide counters to be counted, a first means to sense when said first divide counter has counted a number of pulses equal to said first number in said first decimal system register and to emit a pulse indicative thereof, a second means to sense when said second divide counter has counted a number of pulses equal to said second number in said second decimal system register and to emit a pulse indicative thereof, first and second decimal system summing counters, means for applying pulse output from said first means to sense to said second decimal system summing counter to be counted, means for applying pulse output from said second means to sense to said first decimal system summing counter to be counted, recording means having a first and a second recording channel for respectively recording signals for controlling motion along said respective first and second co-ordinates, each recording channel having a positive and a negative track for respectively controlling the direction of motion along the associated co-ordinate, means to record output pulses of said first means to sense in the track of said second recording channel which corresponds to the sign of said second number in said second register, means to record output pulses of said second means to sense in the track of said first recording channel which corresponds to the sign of said first number in said first register, and means to block further output from said source of pulses when the count in said first and second decimal system summing counters respectively equal the value of the second and first numbers in said second and first decimal system registers.

46. A system for obtaining signals to control the relative motion of a tool and workpiece along a first and a second co-ordinate to effectuate a given length operation along a desired circular path comprising a first decimal system register, a second decimal system register, a first decimal system reversible counter, a first means to sense the sign of the count in said first reversible counter, a second decimal system reversible counter, a second means to sense the sign of the count in said second reversible counter, means to respectively enter the value and sign of a first number in said first decimal system reversible counter and said first means to sense, means to enter the value and sign of a second number in said second decimal system reversible counter and said second means to sense, said first and second number values and signs being respectively those of the differences between the values of the first and second co-ordinates at the beginning of said desired circular path and at the center of a circle which has the same radius as said desired circular path, means to transfer said first and second numbers and their signs into said first and second reversible counters, means to respectively enter the sign and value of a third and a

fourth number into said first and second registers, said third and fourth number values and signs being respectively those of the differences between the values of the first and second co-ordinates at the ending of said desired circular path and at the center of said circle, a first and second decimal system dividing counter, a source of pulses, means for controlling the frequency of said source, means for applying pulses from said source to both said dividing counters to be counted, first means for sensing when the count of said first dividing counter equals the value of the number in said first reversible counter to provide an output pulse indicative thereof, means to apply the output of said first means to sense to said first reversible counter to be added or subtracted to the number therein responsive to the sign of said second sign sensing means, second means for sensing when the count of said second dividing counter equals the value of the number in said second reversible counter to provide an output pulse indicative thereof, means to apply the output of said second means to sense to said second reversible counter to be added or subtracted to the number therein responsive to the sign of said first sign sensing means, recording means having a first and a second recording

channel for respectively recording signals for controlling motion along said respective first and second co-ordinates, each recording channel having a positive and a negative track for respectively controlling the direction of motion along the associated co-ordinate, means for recording output pulses of said first means to sense in the track of said first recording channel which corresponds to the sign in said second sign sensing means, means for recording output pulses of said second means to sense in the track of said second recording channel which corresponds to the sign in said first sign sensing means, and means to block further output from said pulse source when the signs and values of the numbers in said first and second reversible counters respectively equal the signs and values of said third and fourth numbers entered in said first and second registers.

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UNITED STATES PATENT OFFICE
Certificate of Correction

Patent No. 2,833,941

May 6, 1958

Jack Rosenberg et al.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 4, line 41, for "ane" read —one—; column 6, line 18, for "whch" read —which—; column 15, lines 65 and 66, for the equation

$$\left(\Delta y \right) \quad \text{read} \quad \left(\frac{f}{\Delta y} \right)$$

column 18, line 21, for "Third quadrant---- $-x \rightarrow + y \rightarrow -$ " read —Third quadrant----
 $-x \rightarrow + y \rightarrow -$ —; column 25, line 21, for "transfer" read —transfers—; column 29,
line 45, for "counted" read —counter—; column 36, line 32, for "frequently" read
—frequency—; column 44, line 14, for "162A" read —1624A—; column 45, line 44,
for "1620" read —1620B—; column 48, lines 40 and 41, for "inmention" read —inven-
tion—; column 50, line 17, for "number of" read —number for—; column 52, line 5,
after "means" insert —to—; lines 21 and 22, for "co-ordinate" read —co-ordinates—;
column 53, line 73, for "seconds" read —second—.

Signed and sealed this 2nd day of September 1958.

[SEAL]

Attest:

KARL H. AXLINE,
Attesting Officer.

ROBERT G. WATSON,
Commissioner of Patents.

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