IEEE TRANSACTIONS ON

INDUSTRY AND GENERAL APPLICATIONS

MARCH/APRIL 1970 VOLUME IGA-6 NUMBER 2

Published Bimonthly

GUEST FEATURE

PAPERS

Numerical Control of a Lathe

YORAM KOREN, ALEXANDER SHANI, SENIOR MEMBER, IEEE, AND J. BEN-URI

Abstract—**This paper deals with the design of a digital biaxial contouring control system for a lathe, constructed at the Technion—Israel Institute of Technology. The system is capable of simultaneous application to both feed and crossfeed by means of an interpolator (in this case a DDA computer). It comprises a speed-control loop governed by the interpolator, and an incremental position-control loop. The biaxial motion may be linear, circular, or combined. The position and speed signals for each step are fed to the system from a command panel comprising a socket matrix with plugs used for "writing." As soon as a given command has been implemented, the system automatically passes on to the next. Transition from step to step is effected through a counter whose output contains a decoding network. The decoder outputs are connected to the command panel, which is scanned row by row. The axis position is measured by means of rotating encoder emitting 1000 pulses per revolution, of which 125 are utilized in ordinary operation. The required accuracy is 1 pulse, equivalent to 0.01 mm.**

I. General Description

A GENERAL block diagram of the proposed system is shown in Fig. 1. Two control units, one for each axis, are connected to the table, with both inputs fed simultaneously from a command panel. On completion of each segment of the workpiece, signals are fed to the advance circuit, which in turn provides new data for the control units from the command panel. From the short description one can see that the command panel replaces the punched tape usually used in the N/C systems. The command panel is especially suitable for small factories which can buy only one or two N/C machine tools. The command panel gives the operator direct access to the machine, completely eliminating the need for a programming crew. The price to the buyer is much reduced by the elimination of a "flexowriter" and approximately a third of the hardware needed in other systems, i.e., the part needed for the reading of the tape. (For more details see Section V.)

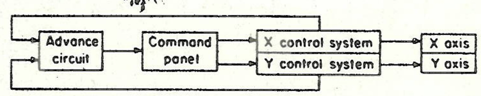


Fig. 1. Block diagram of complete system.

The system comprises an interpolator and two identical pairs of loops for speed and axis-position control. The speed-control loop is governed by the interpolator, which is in turn fed by the command panel. The latter also governs the position-control loop and determines the direction of rotation for the speed-control loop. The position-control loop receives the advance increment prescribed for the table, and on completion of this stretch the loop blocks the speed-control input and simultaneously feeds a signal to the advance circuit.

Advance from step to step is conditional on motion being completed along both axes. In the absence of preliminary information as to which axis movement is completed first, the advance circuit must include a memory element storing this fact and delaying the advance signal until the second axis movement is also completed. (It should be kept in mind, however, that only one of the axes may be active.) The advance circuit itself has a single input, and outputs in the same number as that of rows in the command panel (which is also the maximum possible number of steps per workpiece). With

Paper 68 TP 106-IGA, approved by the Machine Tools Industry Committee of the IEEE IGA Group for publication in this Transactions. This paper is based on part of Y. Koren's M.Sc. thesis which was presented to the Senate of the Technion—Israel Institute of Technology, Haifa, in April, 1968. Manuscript received October 15, 1968; revised May 25, 1969.

Y. Koren and J. Ben-Uri are with the Faculty of Electrical Engineering, Technion—Israel Institute of Technology, Haifa, Israel.

A. Shani was with Elbit Computers Ltd., Haifa, Israel. He is now with ALEF Research and Development Ltd., Haifa, Israel.

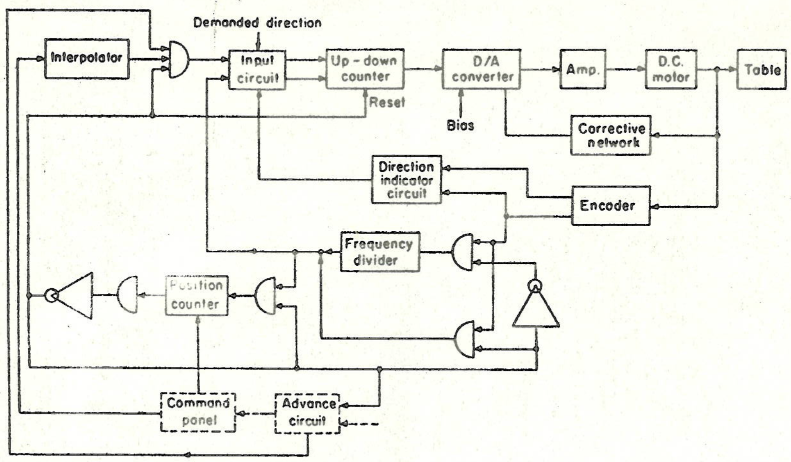


Fig. 2. Control system for one of the axes.

every signal at the circuit input, the command is passed on to another row, until all rows have been covered. In addition, the circuit is capable of restoring the system to the first row and initiating a new scanning cycle.

II. Control Systems

A control system for one of the axes is shown in Fig. 2. Speed control is effected in a closed loop, as any speed deviation entails a position deviation and affects the shape of the workpiece. A five-stage up–down counter serves as equalizer in the loop, with the pulses from the interpolator received at one input and those from the encoder at the other. The encoder is of the optical rotating type, emitting one pulse per 0.01 mm table advance. The pulse-number difference between the inputs is the instantaneous position error, fed to a D/A converter (consisting of weight resistors) whose bias is such that the motor is at rest when the counter is set at 1 0 0 0 0. The converter output voltage is fed in turn to an amplifier feeding a dc motor.

The counter is preceded by a circuit directing the interpolator pulses to one channel and the encoder pulses to the other for one direction of motor rotation, and interchanging them for reversed rotation in accordance with suitable signals from the command panel and the direction indicator. A device is also included for eliminating simultaneous pulses in both channels.

In order to save counter stages and reduce the position error, the open-loop gain of the system is set at 100, necessitating a corrective network (tachometer and differentiating circuit) feeding back an acceleration-proportional voltage.

The function of the three-stage frequency divider is prevention of overshoot exceeding the prescribed accuracy. It operates only under normal working conditions. Once the position command has been implemented, it is short-circuited and the encoder emits pulses at every one eighth of 0.01 mm. In these circumstances the system may overshoot the stop point by 8 pulses without exceeding the accuracy limit, whereas without this circuit it would be exceeded even by a single-pulse overshoot. An additional advantage of the circuit is that it reduces the cumulative error.

Position control is effected by a 14-stage up–down counter (receiving parallel signals from the command panel), with its input connected to the frequency-divider output so that received pulses are subtracted successively to zero. Zeroing actuates a circuit which, inter alia, closes the counter input, so that the counter remains inactive pending the next position command. With the position counter thus excluded, its role is assumed by the counter in the speed loop. With the former zeroed, input from the interpolator to the speed counter is discontinued and it is set at 1 0 0 0 0, the correct position reading at that moment. The speed counter continues in this role, with each pulse again equivalent to one eighth of 0.01 mm, until the system is finally stopped, or pending a new rotation command for the axis in question.

All stage outputs of the position counter are connected to an AND gate, whose output generates a pulse on zeroing, with the following results:

1) setting of the speed counter at 1 0 0 0 0,
2) blocking of the position-counter input,
3) disconnection of the speed-control loop from the interpolator,
4) a pulse to the advance circuit, indicating completion of the step for one of the axes,
5) inactivation of the frequency divider.

III. Interpolator

The interpolator [Fig. 3(a)] consists of two integrators of a DDA computer and is capable of linear and circular interpolation, in accordance with signals from the command panel.

In *linear* interpolation each integrator functions separately. The command panel feeds the y register a number

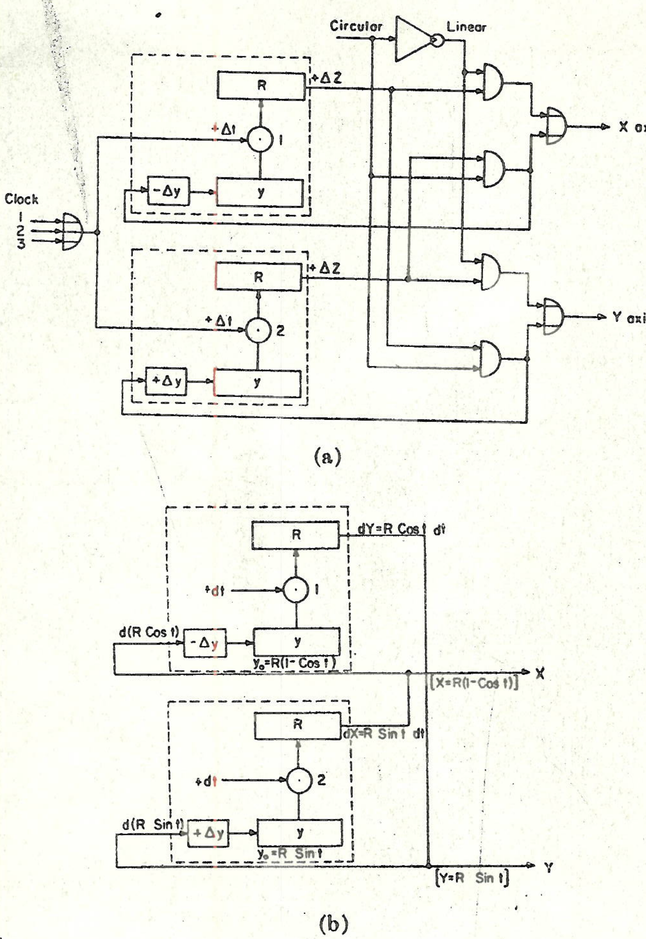


Fig. 3. (a) Interpolator. (b) Circular interpolator.

proportional to the speed required from the axis. The pulses from $+\Delta z$ are fed directly to the speed control system and serve as commands to the motor, with integrator 1 controlling the X axis and 2 the Y axis. For a conical workpiece with path lengths a and b along the X and Y axes, respectively, these numbers must be fed to the respective registers. If the larger of the two numbers fails to occupy all stages, they may be magnified by multiples of 2 until the most significant digit between the two numbers is unity. This method permits the advance rate to be adjusted to the necessary level. (An alternative method is based on clock interchange, also effected from the command panel.)

In *circular* interpolation [Fig. 3(b)], the following equation is satisfied:

$$(X - R)^2 + Y^2 = R^2 \tag{1}$$

where

$$X = R(1 - \cos t)$$

and

$$Y = R \sin t. \tag{2}$$

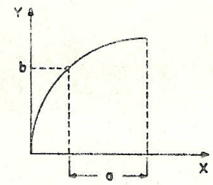


Fig. 4. Initial conditions of circuit.

The integrator outputs are

$$dX = R \sin t \, dt = -d(R \cos t) \tag{3a}$$

and

$$dY = R \cos t \, dt = d(R \sin t). \tag{3b}$$

On feeding the initial conditions to the y registers, care should be taken that the integrator emitting $R \sin t$ receives $R(1 - \cos t)$ and vice versa. The y register of integrator 1 belongs to the X-axis section on the command panel; hence it receives the number a which is the initial condition for $R(1 - \cos t)$ (see Fig. 4). At the integrator output we have the value $R \sin t$, which by (2) should be connected to the Y axis. Accordingly, integrator 2 (belonging to that axis) will receive the value b, the initial condition for $R \sin t$. Its output, $R(1 - \cos t)$, is connected to the X axis.

The output of integrator 2 is connected to $-\Delta y$ of integrator 1, so as to secure sign reversal in (3a); similarly, that of integrator 1 is connected to $+\Delta y$ of integrator 2.

The feed rate is set by a clock connected to $+\Delta t$ in the integrators. Three clocks are provided for a given workpiece, and selected as required by the program written on the command panel. The clocks may be set for the required feed rates before processing begins.

As an illustration, assume that a circular quadrant with radius r is to be produced, with initial conditions $a = r$, $b = 0$. The number r is fed to the y register of integrator 1 and connected to its R register in every cycle, so that the integrator 1 initially emits pulses at a high frequency. The reading on y is gradually reduced by pulses entering $-\Delta y$, and the output frequency drops until $y = 0$.

By contrast, a zero value is connected initially to the R register of integrator 2, but its y register is gradually filled up with pulses from integrator 1, and the output frequency increases accordingly.

As the output of integrator 1 is connected to the Y axis and vice versa, and as the motor speed is directly proportional to the output frequency of the interpolator, the Y axis motor starts at a high speed and decelerates ($dY/dt = R \cos t$), while that of the X axis starts at zero speed and accelerates ($dX/dt = R \sin t$). Since the position of the axes is the integral of the motor's speeds, the movement of the axes will be according to (2), so that the required circuit is obtained.

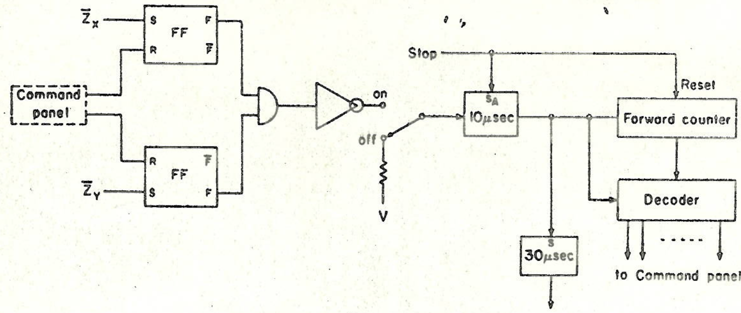


Fig. 5. Advance circuit.

IV. Advance Circuit

The advance circuit (Fig. 5) receives a pulse from each axis on reaching the required position. Following the second pulse, the circuit emits its own pulse, indicating that the system as a whole is at the required position. To allow for the possibility of single-axis operation, the circuit is given "timely notice" of the active axis by the command panel.

The final pulse actuates a 10-μs delay which feeds a pulse to an up-down counter connected to a decoder (consisting of AND gates) whose outputs are connected to the command panel. The delay (also connected to the decoder) closes all outputs pending setting of the counter at the new position. It also safeguards against a possibility of simultaneous opposite voltage trends at two outputs; otherwise identical commands at both outputs would interfere with the performance of the panel.

The first delay actuates a second delay of 30-μs which disconnects the position-counter stages while being charged from the command panel, and also disconnects the interpolator from the speed-control loop. The 20-μs difference is utilized for data feeding from the command panel to the system.

There is also provision for actuating a "stop" circuit from the command panel for resetting the advance counter and restoring the system to the first row. This is required in the case of automatic supply of material to the lathe. This so-called stop action calls for closing the decoder outputs and for actuating the 10-μs but not the 30-μs delay.

On actuation of the system the advance counter is set at 11 . . . 1; manipulation of the ON–OFF switch (Fig. 5) feeds a pulse to the counter and the system begins to operate. Turning off of the switch causes the system to stop at the end of the corresponding step.

V. Command Panel

The command panel consists of a socket matrix arranged in columns and in rows of 60 sockets in each. Each row is connected to one of the decoder outputs and assigned to a single step. Plugging in of any socket connects a row to a column, each column connected as an OR gate and feeding the information from the row to the system.

In each row on the command panel, the following information is "recorded":

1) state increment of current operation for each axis,
2) direction of advance of each axis,
3) identification of the processed segment—linear or circular,
4) in the latter case, numbers a and b (Fig. 4), defining the radius, are "recorded,"
5) resetting of the system to the first command (the relevant column accommodating only one plug),
6) determination of the feed rate—by activation of the appropriate clock,
7) determination of the spindle speed (chosen from a number of available speeds, including zero),
8) control of the collet.

The rows are scanned successively with the aid of the advance circuit. For each line, a segment of the workpiece is processed, and on completing it the system passes on to the next operation within 30 μs. The panel comprises 25 rows, which is also the number of possible operations on a given workpiece.

The main disadvantage of the command panel compared with punched tape lies in the limited number of steps per workpiece. Other disadvantages are as follows. 1) Punched tapes may be stored pending further use, while if a command panel is used the plug arrangement must be preserved. 2) In the latter case, machine time is wasted while the program is set up, a difficulty obviated by installing twin panels. On the other hand, the panel has the following advantages:

1) simplicity of operation and of the training of operators,
2) much lower cost,
3) errors in programming, and slight errors in lathe operation, are easily corrected,
4) adjustment of the tool to its initial position is effected by the plugs on the first command, without need for accurate adjustment of the tool itself,
5) there is provision for slight adjustment of the program, to correct for tool wear,
6) a memory unit (essential in the case of punched tape) is dispensed with,
7) the system is self-contained, in contrast to its dependence on a computer in the case of punched tape,
8) in the case of DDA computer control of a series of lathes, high-speed input in all channels is essential in order not to delay the computing process.

VI. Experimental Results

The accuracy of the final position up to 4-mm/s speed level (for each of the axes) lay within ±0.01 mm. At higher speeds this accuracy was only maintained as an average, whereas in the 1.5–3-mm/s range the limits were ± 0.005 mm.

In contour turning, errors to ±0.05 mm were observed during the first millimeter (due to starting differences between the unequally leaded motors), after which the limits were ±0.01 mm. The overshoot at 4 mm/s was 0.01 mm at most.

References

[1] S. T. Buckerfield, "Continuous numerical control of machine tools," *Control*, vol. 3, pp. 90–98, June/July 1960.

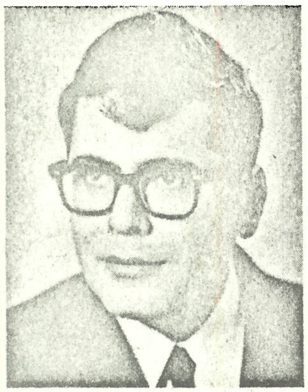
[2] J. T. Evans and L. U. C. Kelling, "Inside the Mark Century numerical control," *Control Engrg.*, vol. 10, pp. 112–118, May 1963.

[3] J. A. Haringx, "A numerically controlled contour milling machine," *Philips Tech. Rev.*, vol. 24, pp. 299–331, September 1963.

[4] F. V. Mayorov, *Electronic Digital Integrating Computers, Digital Differential Analyzers*, English ed. London: Iliffe, 1964.

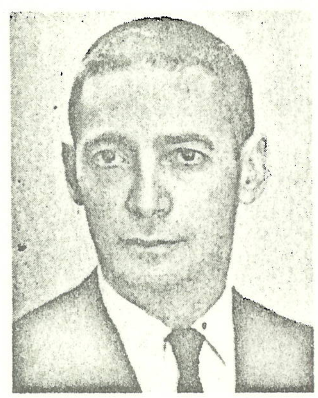
[5] A. K. Suskind, *Notes on Analog-Digital Conversion Techniques.* New York: Wiley, 1957.

[6] Y. Koren, A. Shani, and J. Ben-Uri, "Overshoot correction in digital control system," *Control*, vol. 13, pp. 204–205, March 1969.



Yoram Koren was born in Tel-Aviv, Israel, on August 1, 1938. He graduated from the Technion—Israel Institute of Technology, Haifa, in 1965, received the M.Sc. degree in 1968, and is now carrying out research toward the D.Sc. degree in the area of optimization for numerically controlled machine tools.

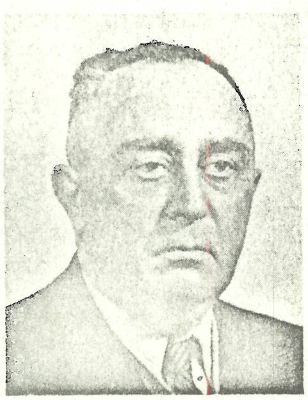
He is presently a Teaching Assistant at the Technican—Israel Institute of Technology. He is also interested in digital control and quantization problems.



Alexander Shani (A'53–M'55–SM'66) was born in Satu-Mare, Romania, on March 4, 1923. He graduated from the Technische Hochschule, Munich, Germany, in 1948. He received the M.Sc. and D.Sc. degrees from the Technion—Israel Institute of Technology, Haifa, in 1956 and 1958, respectively.

He was one of the founders and the first Technical Director of Elbit Computers Ltd., Haifa. He is currently the Manager of ALEF Research and Development Ltd. and part-time Associate Professor at the Technion—Israel Institute of Technology.

Dr. Shani was one of the founders and the first Chairman of the Israel National Committee for Automatic Control.



J. Ben-Uri was born in 1908. He graduated from the Technische Hochschule, Darmstadt, Germany, in 1930 and received the Dr. Ing. degree in 1931.

He then joined the City and Guilds College, London, England. He emigrated to Israel in 1934, where he worked as a Consulting Engineer and was Manager and Chief Engineer of the Shell Butagaz Company. He became Controller of Electrical Industries in the New Israeli Ministry in 1948. He was Manager and Chief Engineer of Ramlah Motor Company and Telrad-Telephone Company, Lydda, Israel. He held a part-time teaching position at the Technion—Israel Institute of Technology, Haifa, in 1952, and was a Visiting Professor at the Carnegie Institute of Technology, Pittsburgh, Pa., from 1958 to 1960. He returned to Israel in 1960 where, at present, he is a Professor at the Technion—Israel Institute of Technology. His main interests are in the fields of electrical drives and the application of semiconductors to them in servo systems and automation.

Dr. Ben-Uri is a member of the Swiss Association of Electrical Engineers and a fellow of the Institution of Electrical Engineers (London).