DESIGNING DIGITAL CONTROL SYSTEMS WITH STEPPING MOTORS

part 1: composing a positional control system

by T. R. Fredriksen
Electroglas, Inc.,
Menlo Park, CA 94025

A digital positioning system is the natural subordinate of a digital computer. In a most realistic way, the stepping motor serves as the computer's working arm, analogous to those sections of the human control system associated with basic motion. The movement of an arm, the clenching of a fist, operate from a stored program in the brain, learned and debugged by experience.

The composition of a digital positioning system must have the same structure as the human arm, where all motions are executed on a sense and control basis. In order of priority levels, the gross elements are:

- Stored program that lists the sequence of motions,
- A set of control points that, by selective combination, give rise to all motions necessary to fulfill the program,
- A set of sense points that indicate the physical states necessary for unique motion control.

Computer Interface Selection Since all control elements, apart from coil drivers and sensors, employ standard binary logic, there is a choice, theoretically, where to divide the total system into **processor** and **motion controller.** Until this division is made, the input versus output, with respect to sense and control, cannot be defined. As far as the stepping motor is concerned, the **interface** between controller and processor can be drawn at many levels. In general, the more logic included in the controller, the less frequently it will need attention from the processor. The decision is largely one of economics, optimizing cost of memory for the stored program versus cost of logic in the controller. Regardless of how many other external devices are to be time shared, each controller must receive adequate attention so that the motions can be executed reliably.

Three parties normally involve themselves in equipment selection: the user, whose process needs mechanization by the total control system, the computer (processor) manu-

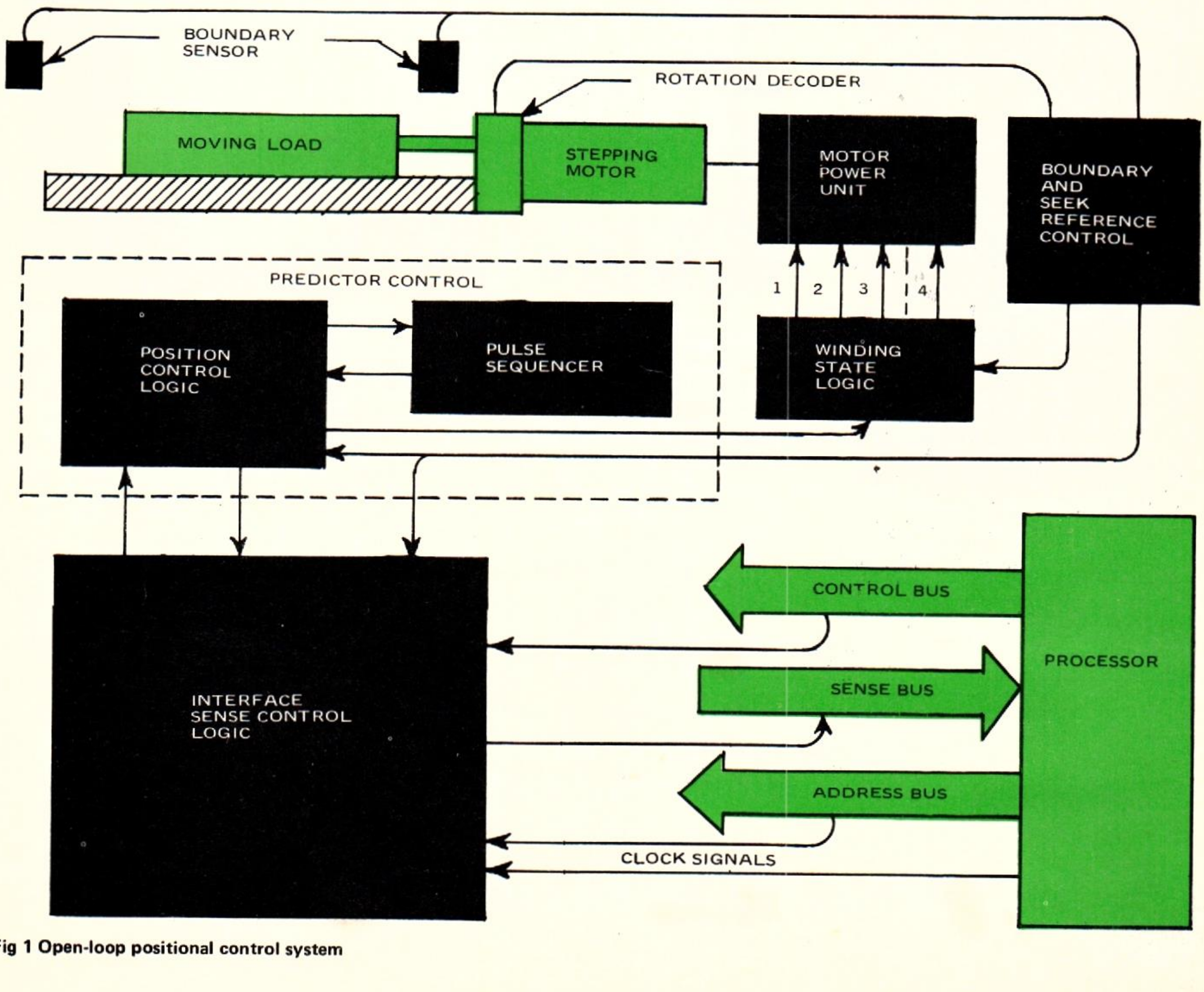


Fig 1 Open-loop positional control system

facturer and the positional control system supplier. The user invariably must control a process adequately at minimum cost, while the equipment suppliers must sell their units and make an adequate profit. A practical solution to this situation is to standardize the interface and assign the process options and flexibility as programming tasks within the computer. This allows both supplier and user to eliminate special engineering, which is costly and restrictive from all points of view.

Using a controller with 16-bit input-output channels, the minicomputer sends 16-bit signal combinations to an external device that initiates a motion. The computer, in turn, receives a 16-bit signal combination back as input, reporting the dynamic state of the motion. The processor interface must also include an address channel that permits the selection of one external device for operation and, finally, a set of clock signals that initiates the transfer of information between the processor and motion controller.

Mechanical Output Criteria The productive output function of a positional control system is some form of mechanical motion. This motion, restricted by physical bounds within the process equipment, is not only necessary to control the shaft motion of the stepping motor, but also to relate it to geographical limits within the actual equipment. To achieve optimum reliability, uniqueness of position must be ensured. This essentially means the exclusion of analog elements.

Using the stepping motor as a basic reference, all motions are defined in terms of steps. For simplicity, assume that a stationary position point is synonymous with a locked step of the motor. These step positions must now be related to unique positions within the bounds of the processing equipment, and moreover, the processor is required to establish this reference without human intervention. Thus, the overall criteria for a digital positional control system is **total automation**, giving the computer the ability to power up the system, as well as setting it up for a fixed reference position.

Control Elements A number of well defined control elements translate commands from the interface into mechanical motion. Many of the elements are similar for both open and closed loop control, but generally, more electronics are required for the closed-loop system.

Both open-and closed-loop systems present a linear load within drive motor and electronic limits (boundary detectors). The step motor is driven from a basic motor control, which consists of motor power drivers and appropriate logic. For the open-loop system (Fig 1), the winding state logic accepts inputs in the form of pulses and direction signals, while in the closed-loop system (Fig 2), the minor loop logic operates an ON-OFF command, sending actual step pulses back to the position control.

The open-loop predictor control converts the new position command into a direction signal and a train of pulses from which the basic motor control produces motor action. The closed-loop system works as a servo and the

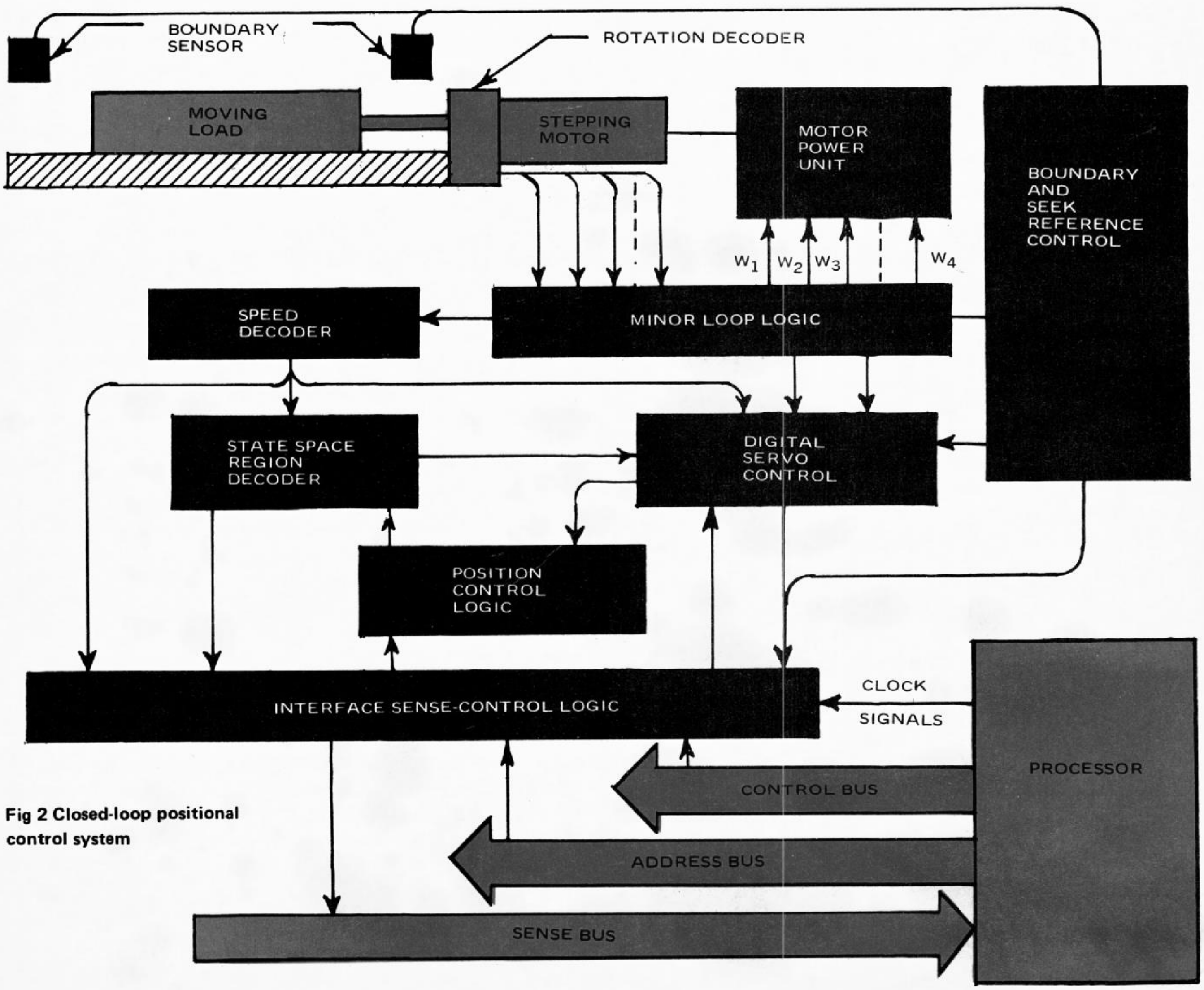


Fig 2 Closed-loop positional control system

control logic starts the motor via the minor loop. Then, as motion takes place, pulses representing actual measured steps feed back to the position control, reducing the error toward zero.

The seek reference control (SRP) is similar for both open-loop and closed-loop systems. When the computer commands the SRP, the positional control forces the motor to seek a predetermined reference step regardless of present position. The reference step is approximately one-half rotation of the motor shaft, from one of the electronically detected limits. In the SRP mode, both systems are open loop when searching for the reference step, and both are essentially closed loop when locking in on the reference

interface design

The overall system's interface must match the computer, and give it access to all necessary control inputs and state variables of the positioning system. In other words, the computer must be able to monitor (sense) the state of

U and V include the basic motion requirement of a positioning system, namely; how far to move the load from present position (U), direction of move (ν_5, ν_6, ν_7). In addition, two diagnostic control points are included that enable the processor to stop all motion (ν_4) regardless of previous commands and the seeking of reference point (ν_8), that enables the computer to restart the system from a known geographical point within the travel boundary.

For the purpose of explanation, it is easier to think of V as five separate control inputs, even though the computer transfers them all at the same time. Thus, we have

$$V' = \begin{bmatrix} \nu_5 \\ \nu_6 \\ \nu_7 \end{bmatrix} = (\nu_5, \nu_6, \nu_7)$$

while the other components of ν retain their individual notation since they are single control points.

Open Loop Sense Point Definitions The necessary set of sense points for a predictor control is derived directly from the state plane trajectories shown in Fig 3. Here, the points

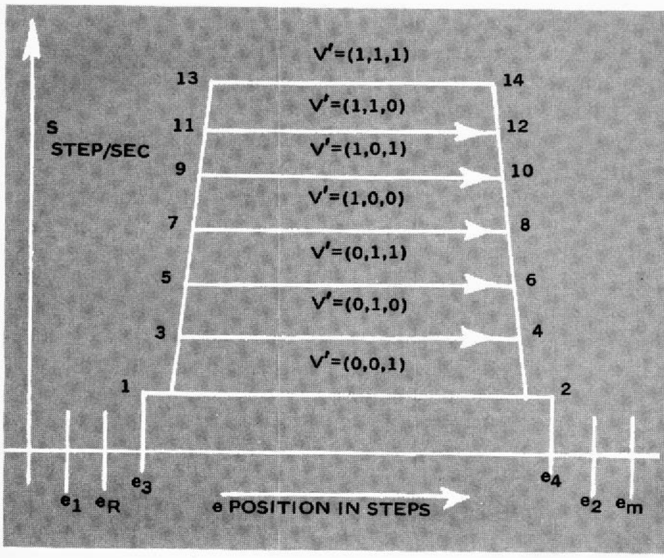


Fig 3 Open loop trajectories in state plane.

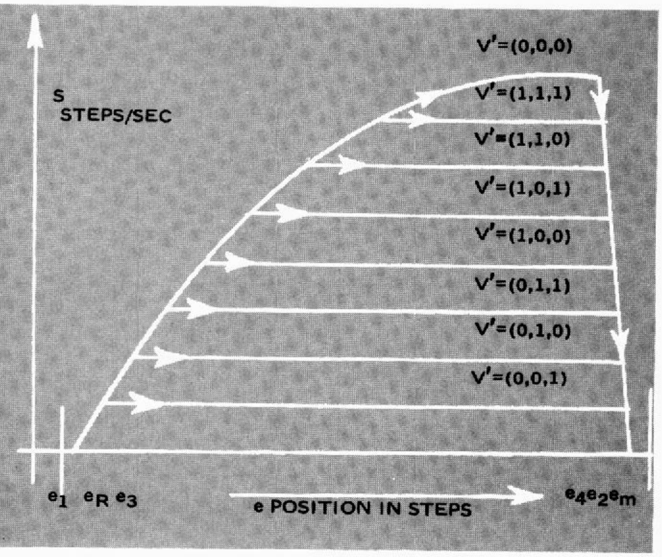


Fig 4 Closed loop trajectories in state space.

the system in sufficient detail to always make adequate control decisions. The interface logic operates on the regular computer input-output channels and establishes communication when the computer selects the positional control system via the address code. You must take care here to stay within channel loading specification; otherwise, subtle transmission reflections can create hard to find errors.

Control Point Definitions The control functions are the same for both open- and closed-loop systems. Defining U and V as two sequential 16-bit data words,

$$U = \begin{bmatrix} u_1 \\ u_2 \\ \cdot \\ \cdot \\ \cdot \\ u_{16} \end{bmatrix} = (u_1, u_2 \ldots u_{16}) \quad V = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \cdot \\ \cdot \\ \cdot \\ \nu_{16} \end{bmatrix} = (\nu_1, \nu_2 \ldots \nu_{16})$$

where $U \equiv$ |motion in motor steps|

$\nu_1 \equiv$ sgn|motion|

$\nu_4 \equiv$ Halt motion

$\left.\begin{matrix} \nu_5 \\ \nu_6 \\ \nu_7 \end{matrix}\right\} \equiv$ maximum speed selection

$\nu_8 \equiv$ seek reference point

and ν_2, ν_3, $\nu_9 \ldots \nu_{16}$ are unused. (In a two axis system, these bits can be applied to the second axis of control.)

$P = (e, o)$, where $e = 0, 1, 2 \ldots e_m$

represent the absolute maximum set of stable terminal positions. The practical boundaries (e_1 and e_2) are placed inside the physical limits to prevent damage to the equipment. Thus, it is necessary to detect the two limit zones and define two sense points X_1 and X_2 where

$X_1 = 1,\ 0 < e \leqslant e_1 \qquad X_2 = 1,\ e_2 \leqslant e < e_m$

$X_1 = 0,\ e_1 < e \qquad X_2 = 0,\ e < e_2$

The point $P = (e_R, 0)$ is defined as reference position and detected by a third sense point, X_3 *where*

$X_3 = 1,\ e = e_R$

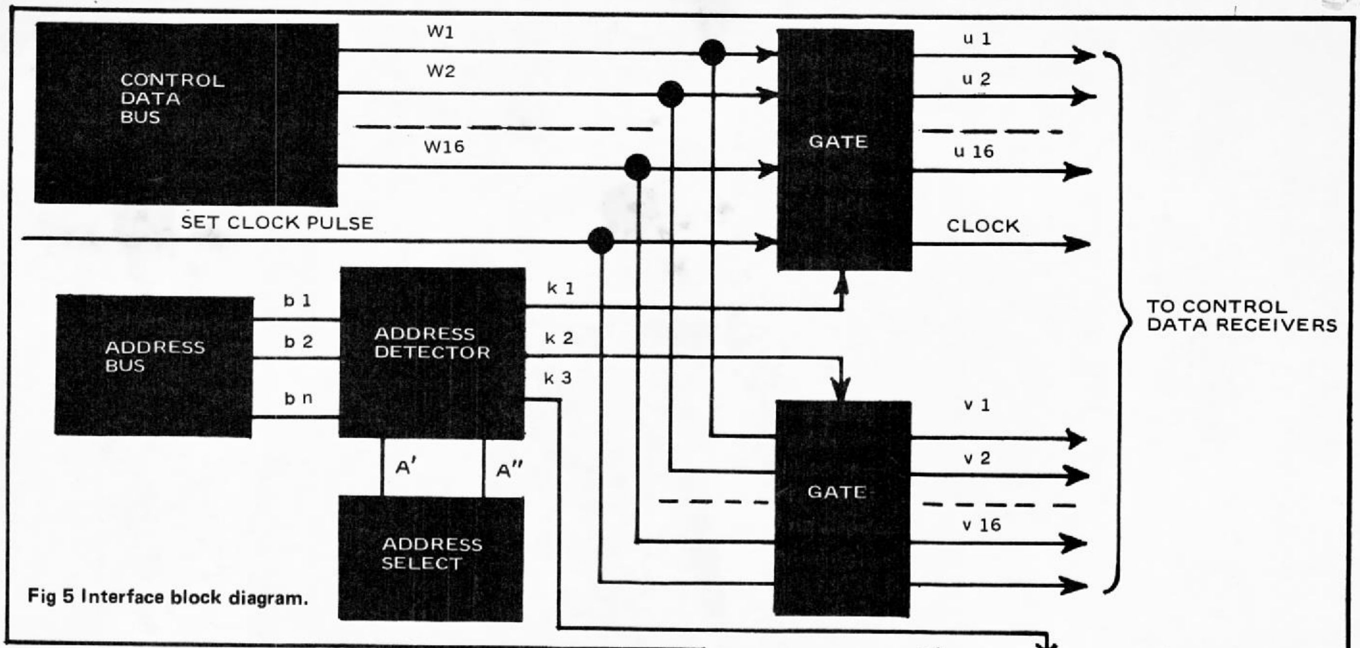
$X_3 = 0,\ e \neq e_R$

The dynamic trajectories from e_3 to e_4 are responses to the control input U and V where the speed component of V, V', takes on the binary format as shown in Fig 3. These trajectories are predetermined by the predictor control; the stepping motor is slaved to follow a particular pattern. The whole open-loop control fails if the motor does not follow. X_4 is the only required sense point, which indicates whether a pulse train is being generated. If $t = 0$ at e_3 and $e_4 - e_3$ pulses have been produced by $t = t_1$ then

$X_4 = 1,\ t \geqslant t_1$

$X_4 = 0,\ 0 \leqslant t < t_1$

Closed-Loop Sense Point Definition A typical closed loop set of trajectories is shown in Fig 4. The previous



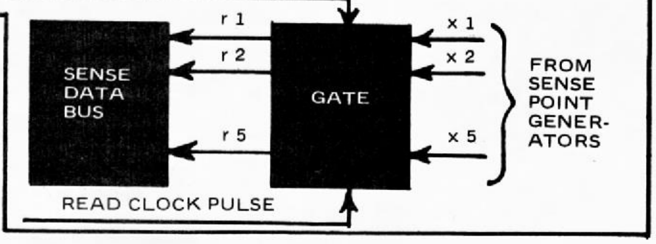


Fig 5 Interface block diagram.

definitions of X_1, X_2 and X_3 hold for this situation as well. but the dynamic side is now controllable. The system will not necessarily fail if e_4 is reached at other than $s = 0$; simple load changes could make this happen. It is necessary, therefore, to add a sense point for zero velocity detection, but because there is no true zero sensor, X_5 is defined as:

$X_5 = 1, S < S_1$

$X_5 = 0, S \geqslant S_1$

The "motion complete" sense point X_4, has a different meaning in closed-loop control. Rather than being pre-timed, X_4 now depends only on whether the target has been reached, thus:

$X_4 = 1, e = e_4$

$X_4 = 0, e \neq e_4$

The closed loop stepping motor is not, of course, a true second order system. Other state variables could be added for more optimum control; however, our objective is "adequate function at minimum cost" and that rules out all but two dimensional control.

Addressing Definition The interface is not complete without giving the processor the ability to select a particular device for sense-control operation. Referring to Figs 1 and 2, the device needs to respond to two combinations of the address function A' and A''. Either A' or A'' is sufficient to connect the sense lines to the device, while A' and A'' channel the control data from the processor into the U and V recievers, respectively. If W is the control data from the processor, R is sense data returned to the processor and B is the address work from the processor, then:

$$U = W \cdot k_1 \quad V = W \cdot k_2 \quad R = X \cdot k_3$$

The constants k_1, k_2 and k_3 are generated by the device address detector, such that:

$k_1 = 1$ when $B = A'$

$k_1 = 0 \quad B \neq A'$

$k_2 = 1$ when $B = A''$

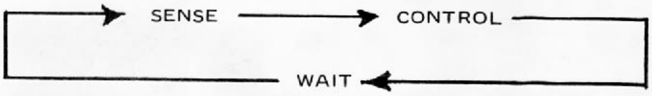
$k_2 = 0 \quad B \neq A''$

$k_3 = 1$ when $B = A'$ or $B = A''$

$k_3 = 0$ when $B \neq A'$ or $B \neq A''$

Interface Hardware The block diagram of the interface sense-control logic is shown in Fig 5. Here, the components of the column matricies W, U, V, R, X and A now correspond to parallel sets of signal lines. The address detector contains three comparators where A' and A'' are matched to the B input components. The k_1, k_2 and k_3 outputs are one or zero, depending on the composition of B. The set clock pulse from the computer strobes the data in the appropriate counters or registers within the control elements. Similarily, the read clock pulse gates the sense word onto the sense bus at the appropriate time in the computer input cycle. The read pulse need not necessarily go to the device, since this gating function is often performed within the processor.

System Operation The actual operations conducted by the computer are sequential chains of:



During "wait", the computer concerns itself with other devices or tasks. Then, when the previous motion is completed, the sense points are checked on a more frequent basis until the expected state comes true or the system is overdue and probably malfunctioned. The first condition results in the execution of a new control, while a set of diagnostic routines are consulted for the second condition. The diagnostic solution may simply say "try again", but it can also demand complete restart (SRP), or if nothing succeeds, it can sound alarms and call for the operator to intervene.

For the systems described here, the sense function consists of reading the X word until it matches the expected combination (i.e., 0, 0, 0, 1 for open loop and 0, 0, 0, 1, 1 for closed loop).

Next month, Part 2 will detail the mechanical output configuration of a positional control system using stepping motors.