interface in 164.25 microsec. EXC 16 will write the BCD character in the LINC accumulator onto the incremental tape in 159 microsec, while EXC 3 will transfer contents of Clock 1 to the LINC accumulator in 156.75 microsec. When an external device requests a program interrupt, the device is serviced and control returned to the LINC processor within 170 microsec. These execution times can be reduced, but it has not been necessary when only two independent paradigms have been operated simultaneously. Most of the time, the computer is idling while waiting for real-time external events to occur every second or two. Clock rates are usually 100 to 1,000 Hz.

Interfacing to a Massey Dickinson³ solid-state control system is handled through level converters and Schmitt triggers. Relay closures are handled directly through Schmitt triggers. Interfacing the LAB-K is handled in the same manner. Flip-flops are used in the LAB-K to isolate noise which may be introduced on long cable runs. Similarly, the level converters, Schmitt triggers, and buffer flip-flops in the computer interface keep noise from entering the computer logic. A major concern with the discrete component computer logic is to observe rise time requirements.

The following observations are based on 3 years' experience of using a laboratory computer in a behavioral laboratory. Tasks should be implemented with stand-alone hardware when possible. Thus, the specialized computer is not tied up on meaningless tasks and is free to be exploited on tasks for which it was intended. The potential user should realize that if computer usage is to expand and become more innovative, then time on available systems must always be available for hardware and software development without jeopardizing current user research and teaching programs. Time spent in learning computer hardware is a good investment. Initial time required can be quite large but will pay off in the long run as the user realizes he is not locked to an existing system but can modify it at will to suit present and future needs. Interfacing is straightforward once the fundamental skills are acquired. The user also gains the ability to maintain his system, which, depending on availability of local outside service, can be crucial to the conduct of scientific inquiry. Our approach has been that downtime of more than a few hours is of major concern and potentially a disaster in experiments requiring large investments of time and money.

From the beginning, interfaces should be developed with the intent of

letting the external event signal the computer when information is available. Any interface developed should have indicators, usually lamps, that indicate the status of each input, output, and control bit in order to facilitate debugging hardware and software.

CRT displays in the experimental psychology laboratory*

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The cathode ray tube (CRT) can be used effectively as a general purpose visual stimulus presentation device. It is possible to send information from a minicomputer to a CRT to draw any picture using points or line segments and to do it simply and cheaply. At any instant, the picture consists of a bright fluorescent point appearing on the phosphor-coated surface of the CRT, whose luminous intensity is proportional to the amount of electron beam energy striking that point per unit of time. Any arbitrarily complex picture can be drawn by manipulating the three voltages which determine horizontal (x axis) and vertical (y axis) components of the beam's location and its intensity (z axis). One sweep of the beam creates the appearance of a brief flash. This must be repeated (refreshed) to maintain the appearance of a steady picture.

CRITERIA

Efficiency

The system should be capable of presenting a complex picture (lines of text, for example) with minimal requirements of space for information storage in the computer and of computer processing time to maintain the steady picture. The latter problem can be eliminated by a "storage CRT" which stores the information on the face of the CRT itself until an erase command is given, with a loss of intensity control, some loss of spatial resolution, and timing problems, as discussed below. Multiple independent displays can also be refreshed from their own common rotating magnetic disk memory. However, large-scale

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NOTES

1. Digital Equipment Corporation, Maynard Massachusetts 01754.

2. Engineering drawings of the interface logic and software details can be obtained from the author.

3. Massey Dickinson, Saxonville, Massachusetts 01701.

laboratories whose requirements for multiple independent displays tempt consideration of a single centralized computer should heed Uttal's advice, elsewhere in this issue, not to time share (see also Markowitz, 1969). In general, experimental applications with a need for general-purpose CRT displays can be implemented much more cheaply, simply, and, therefore, quickly if a separate minicomputer is dedicated to controlling each experiment, refreshing the display directly from its core memory.

Selection

The computer should be able to switch instantly (i.e., between one refresh and the next) from one display to another, selected from among a large number of alternative displays. An advantageous solution is thus provided to the n-field tachistoscope problem (Eriksen, Shurman, & Richter, 1969; Lawrence & Sasaki, 1970). This obvious criterion needs to be mentioned because some displays, which change from one picture to another in a gradual roll-down fashion, are commercially available.

Precision

"General purpose" implies the ability to construct a picture precisely as specified by the E, free from inherent restrictions on fine-grain detail. Such precision should be achieved consistent with efficiency and ease of programming.

Timing

For some applications, millisecond-resolution timing capability is required. Different sets of problems are encountered in display onset and offset. A rigid 60-Hz refresh rate may limit display initiation points to every 16-2/3 msec, for example,

whereas display offset is hindered by phosphorescence (persistence of the luminous image after the electron energy has ceased) of the CRT screen itself. Thus, a low persistence phosphor such as P-15 (available from CRT suppliers as a special option) should be selected. Storage CRTs are also eliminated from consideration in these applications, since they erase by flooding the screen with electrons, causing a flash which takes 200-500 msec to subside. Where feasible (fairly simple displays, etc.), millisecond time resolution is obtained simply by initiating a refresh each millisecond.

WAYS TO IMPLEMENT A CRT DISPLAY

Of concern here are design considerations for the hardware necessary to convert information stored in the computer in the form of units ("words") of 12 to 18 binary digits into manipulations of the three analog voltages which specify the x, y, and z axes of the beam. For simplicity, the example of a 16-bit word length will be used here.

Random Access Point Plot

This simple, inexpensive, and popular method of constructing a picture out of a series of discrete points has been described recently by Wojnarowski, Bachman, and Pollack (1971). The location of each point in the display is specified by a computer word as follows: the word is sent to an output buffer from which 8 bits are fed to one digital-to-analog converter (D/A) to provide an analog voltage for the x axis. The other 8 bits are sent to another D/A to determine the y axis. These values are maintained, thus displaying a point for a few microseconds, after which a new word is brought to the output buffer to send the beam to a new point. The z axis is turned on to display each point, then turned off ("blanked") momentarily while the beam is being repositioned. The voltage for the x or y axis has $2^8 = 256$ possible values, giving $2^8 \times 2^8$ possible points in the display. Finer resolution would destroy the great programming convenience and storage efficiency of using one computer word to display each point. However, one extra bit of resolution

(doubling the number of points on each axis or quadrupling the number of points in the display) could be gained by establishing a "quadrant counter" in the interface which increments every time a word of all zeros is sensed and controls the most significant bit of the two (now 9-bit) D/As. This is similar to a suggestion of Wojnarowski et al (1971), except that it is also consistent with Sperling's (1971) advice to present all spatially adjacent points at similar times to help avoid flicker.

Raster Scan Point Plot

Here the interface itself controls the x and y axes to scan the beam in an orderly way across the face of the CRT, much like a television display. The z axis is modulated by turning the beam on or off as appropriate as it passes over each point. Thus, the computer must store only 1 bit of information for each point instead of 16. But note that this procedure is only efficient if a great many points are to be displayed, since every picture must allow for the worst case of a complete scan. Timing is also inflexible in the typical raster scan display, for the same reason.

Stroke Generator

A picture consisting of connected line segments instead of points can be generated simply by sending each of the x and y analog voltages through an integrator (operational amplifier with capacitive feedback). Thus a positive voltage level, when integrated, yields a positive slope over time, and a negative level integrates to become a smoothly decreasing voltage. A given output word, then, would specify an increment or decrement of the x axis in the constant time unit of several microseconds, an increment or decrement in the y axis, and 1 bit to blank the z axis if desired. The stroke that appears (if not blanked) is the resultant of the x and y components. Programming is simplified, since this is a simple, direct way to specify strokes. A picture is specified by an array of stroke commands. When one sweep is complete, the integrator must be reset by discharging the capacitor, which requires a little engineering foresight, since it must be done in a matter of microseconds to achieve a refresh every millisecond.

Less information per axis is required to be output to the D/A than was the case for the random-access point plot, since the endpoint of one stroke must be in a reasonable vicinity of the endpoint of the previous stroke. If 5 bits specify each axis, then 1 of 2^{10} possible strokes may be generated with each stroke command, although shorter strokes will have greater luminous intensity than longer strokes. In a stroke generator on a Nova minicomputer at the University of Connecticut, a 16-bit stroke command uses 5 bits for the x axis, 5 bits for the y axis, 1 bit for the z axis, and a 5-bit count of time units for the interface. A new stroke command is fetched from core storage in the computer automatically by the interface via the direct memory access channel whenever the count for the previous stroke runs out. This means that up to 32 copies of a stroke (i.e., a stroke 32 times as long with the same intensity) may be displayed before more information is required, thus saving considerable processing time and core space.

Vector Generator

This could also be called a random access stroke generator because here the two endpoints of each line are specified. This is a more convenient device for many applications, but it is more expensive and difficult to implement because the analog circuitry is more sophisticated.

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