COMPUTER TECHNOLOGY

Real-time generation of random-element motion displays

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Random-element motion patterns for visual research, in which a set of the elements are shifted uniformly on successive exposures, can be generated in real time on a CRT display, using a relatively low-cost, commercially available display processor (Sigma QVEC). The software achieves economy of time by not rewriting large amounts of the display file for each exposure. Instead it changes only the "chaining addresses" that determine the order in which strips of the display are arranged. Further features of the hardware and software are described.

In a number of recent studies (Anstis, 1970; Bell & Lappin, 1973; Braddick, 1973, 1974; Julesz, 1971; Lappin & Bell, 1976), dynamic random-dot patterns have been found to be a powerful tool in the investigation of the mechanisms underlying stroboscopic motion perception. A typical display consists of a square matrix of cells, up to 100 by 100 elements in size, in which 50% of the cells are filled and 50% unfilled. In successive exposures, or "frames," presented typically at a rate of 10-20 per sec, a subset of the elements is displaced through an integral number of elements' widths. With appropriate spatial and temporal parameters, this gives the appearance of a region of the display moving against a stationary background.

The production of arrays of thousands of elements would be impossibly laborious by hand, so most commonly the individual frames have been generated on a computer-controlled cathode ray tube (CRT) display. However, for most laboratory minicomputers directly driving analog output to a CRT, the process of computation and output of such patterns has been too slow to allow motion displays of any size to be generated in real time. The usual solution has been to photograph the CRT display and to produce the apparent motion effects by exposing the photographs successively via a tachistoscope or cine projector. This paper describes a hardware and software system for generating random-dot motion patterns in real time, using equipment that is readily available commercially and of relatively low cost.

Real-time generation has a number of important advantages: (1) It allows indefinitely long sequences of frames, impossible in a tachistoscope, without the sacrifice in flexibility involved in making up a cine film. (2) It avoids the problem, very acute in a tachistoscope or similar display device, of accurate optical alignment

of the patterns. (Misalignment of less than 1-min arc affects the apparent motion appearance.) (3) In an experiment consisting of many trials in each of which a motion sequence is presented, it can use an independent random-dot pattern for each trial. Experiments using photographed stimuli have often used the same patterns repeatedly because of the great labor involved in preparing many sets of stimuli. This may give the subject undesirable familiarity with particular micropatterns or sequences.

DISPLAY PROCESSOR

The speed, versatility, and convenience of computer-controlled displays are greatly enhanced by the use of a display processor. The system to be described consists of the Sigma QVEC processor¹ driving a Hewlett-Packard CRT display, and linked to a Digital Equipment Corporation PDP-11/10 minicomputer.

The pattern to be displayed is specified by a display file which is set up in the core store of the PDP-11 by a program running in the PDP-11. The display is initiated when the PDP-11 sends two control words to the QVEC, one of which specifies the starting address of the file in core. The QVEC then fetches successive words of the file by direct memory access. Each word is interpreted according to the instruction set of the QVEC, that is, as a coordinate or a vector to be drawn on the display or as the ASCII code for a character to be displayed.

The power of the display processor, as compared with direct control of analog outputs by the main processor, arises from two main sources. First, the display processor can fetch its instructions from core independently of the operation of the main processor. The PDP-11 can therefore continue with computation, for instance updating the display files, while the QVEC simultaneously writes the display on the CRT. Second, the instruction set of the QVEC processor is specifically designed

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for the construction of displays. Operations which would involve a number of instructions for a general-purpose processor such as the PDP-11 can therefore be executed by a single QVEC instruction.

Among the features of the QVEC which make it especially suitable for this application are the following. (1) File chaining: A number of distinct display files can be held in store, with each file specifying the address of the next file to be read. The use of a display made up from files which can be specified in any order is essential to the programming method to be described. (2) Hardware character generation: The elements of the dot patterns generated can be characters; lowercase *o* and *space* are used as "white" and "black" elements, respectively. This allows elements of finite size to be generated by single QVEC instructions. In particular, character scale can be varied with the QVEC; this allows the investigation of the parameter of element size, which has been shown to be an important variable in motion perception (Braddick, 1974). Variation of element size would be inconvenient or impossible with a point-plotting display. (3) Specification of beam position: On the QVEC, the position where a vector or character will be drawn can be specified either absolutely, or relative to the current position, or in "autoincrement mode." In the latter, a specified increment of position in either *x* or *y* is executed automatically before each instruction (e.g., before drawing each character). All three methods are used on different occasions in generating a random-dot display: The auto-increment between each character greatly increases the speed and convenience of generating strings of elements. (4) High speed: The QVEC generates a single character in 5-10 microsec (and plots points or vectors at a similar rate). A double buffer facility allows it to fetch the next instruction while drawing, which largely eliminates any delay in drawing that might occur while waiting for access to core when the PDP-11 processor is active.

A number of other display processors are available (e.g., Digital Equipment VT-11, as incorporated in the GT-40 system, and Imlac PDS-1). In principle, the method to be described could be implemented with any such machine that incorporated a feature equivalent to file chaining, that is, a JUMP instruction that permits transfer of control to a sequence of display instructions that is not contiguous in core.²

The QVEC has the merit of relatively low cost. The processor configuration supplied cost UK £2,617 in April 1976. To this must be added the cost of a suitable CRT display.

SOFTWARE DESIGN

The software is written entirely in FORTRAN, calling library routines to use system facilities such as the computer's line-frequency clock and to initiate and terminate operations of the QVEC (assembler-written

routines supplied by DEC and the QVEC manufacturers, respectively).

The QVEC is capable of displaying a pattern of 50 by 50 elements at a refresh rate of about 50 Hz, which is adequate for displays of the type required. However, the real-time use of random-element motion patterns requires not only that they can be displayed at an adequate rate, but also that the display file can be generated in time for each successive exposure. Generation of random-element motion pattern requires two stages: A single random pattern must be generated, and shifts of some specified region within the pattern must be introduced in each new frame.

With the computer system available, it would not be possible to generate the random sequence within the time required for display of a pattern: Each element requires an entry into a pseudorandom number routine, which is slow on a machine without hardware multiplication. However, the random generation need occur only once, before display of the motion sequence, since each successive pattern is derived from the preceding one without fresh randomization.

The conceptually simplest way to introduce shifts of a set of elements would be to copy those elements to their new positions in the display file, for each exposure. In principle it would be within the capability of the system to do this within the required time. However, it was soon apparent that this would not be possible with a FORTRAN program, if the shifted region was of any size. The alternative method adopted uses the file chaining facility. The random pattern is not generated as a single display file. Rather, each vertical column of elements is represented by a separate display file, and the chain address associated with each of these files points to the file which will generate the next column. If a particular column passes through the region of the pattern which is to be shifted, the shifting part is again represented by a separate file. Thus, the structure of the display files relates to the pattern to be generated in the way shown in Figure 1. The starting position from which any column is displayed is specified incrementally from the finishing position of the preceding column. A shift can now be introduced without moving in the store any of the QVEC instructions that generate elements. This is done by merely moving the chaining addresses from one column's file to another. The chaining address formerly associated with file E_1 is moved to file D_1 . That address points to file E_2 : The column section specified by E_2 is therefore displayed vertically above D_1 . Similarly, the chaining address associated with D_2 , which points to D_3 , is copied into file E_2 , so that D_3 is displayed in the same vertical column. This process is continued throughout the region to be shifted. The effect is to displace all the displayed columns $E_2 F_2 G_2 \dots$ one position to the left, as shown in Figure 1(c). The chaining addresses pointing to and from D_2 are in fact moved so that D_2 appears at the right-hand side of the shifting region, that is, the movement of the region is cyclical,

with columns that "drop off" at one edge reappearing at the other. Thus, the shifting of the displayed sub-columns is achieved by moving in store only two words per column, rather than a word for each element in the subcolumn.

The procedure is slightly complicated by the fact that it is not convenient to alter the display file while it is actually being displayed. This is because the QVEC operates independently of the central processor; it is therefore difficult to insure that a change in the display files will not appear prematurely in the currently displayed frame rather than in the next. This difficulty is avoided by initially setting up two identical copies of the display files. While one copy is being read for display by the QVEC, the computer is moving the chaining addresses in the other copy. The two sets of files are displayed alternately. This duplication has a second consequence of increasing the flexibility of the system: The files A, B, C, D₁, D₃, . . . which specify the non-shifted region of the display need not be identical in the two copies. If their random sequences are uncorrelated, this has the effect of producing incoherent oscillating motion in the surround region of the pattern, with coherent motion of the central region (Braddick, 1974).

The program is written as a FORTRAN subroutine

(named JRT), so that it can be called from a program that schedules an experiment consisting of a series of random-dot motion displays, and logs subjects' responses. The calling arguments can define a wide variety of displays, as follows:

CALL JRT (ELSIZE, MATSIZE, DISP,
XSIZ, YSIZ, OSC, EXPO, ISI, N)

where ELSIZ = size of pattern elements (in QVEC character scale), MATSIZE = size of square pattern (number of elements on a side), DISP = displacement of central region (expressed as a number of elements' widths), XSIZ = horizontal dimension of central shifting rectangle (expressed as a number of elements), and YSIZ = vertical dimension of central shifting rectangle. If OSC is zero, the shifting is continuous, that is, all shifts are in the same direction. If OSC is nonzero, alternate shifts are in opposite directions, and the apparent motion is oscillatory. EXPO = exposure time (in 20-msec units) of each frame, ISI = intervals between successive frames, and N = total number of frames to be exposed before return to the main program. Special facilities are called by setting special values of the argument MATSIZE. If this is negative, the surround

Figure 1. (a) Organization of the display files. Each file contains a "chaining address" pointing to the next file to be displayed: These are symbolized by solid arrows in the figure. (b) Layout of the display produced by the file structure shown in a. Each file consists of a vertical column of random elements (os and spaces) starting at a position specified relative to the end of the previous column. (c) Layout of the display produced by the file structure following the shifting operation.

region displays two alternating uncorrelated patterns, as described above. (In this case, the pattern size generated is the absolute value of MATSIZ). If MATSIZ is zero, the parameters involved in generating the random pattern (i.e., ELSIZ, MATSIZ, XSIZ, YSIZ) are unaltered from the last call, and no new random pattern is generated (but the shift and timing parameters can be changed). This allows a new display to be introduced without the delay of random generation, on occasions when the use of the same random pattern is acceptable.

A listing of the routine is available on request from the author.

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NOTES

1. Manufacturer: Sigma Electronics Systems Ltd., Church Street, Warham, Horsham, Sussex RH12 3QW, England.

2. Two further points should be noted in the selection of a system. (1) A display processor which, unlike the QVEC, has its own dedicated core store will require extra complexity in the transfer of display files, and extra expense in core that cannot be used for other purposes by the host computer. (The routine to be described uses 6,000 words of memory for its display files.) (2) Some graphics display systems are supplied with slow phosphors (e.g., P39) which are quite inadequate for the display of dynamic stimuli in visual experiments.

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