The Design of a Low Cost Video Graphics Terminal*

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We have designed and built a computer terminal that provides low cost, high quality graphics and programmable text processing by taking advantage of the latest memory and microprocessor technology. A microprocessor control element allows most of the control functions to be programmed so that all of the control electronics require less than 100 integrated circuits. The graphic image is generated by a microprocessor which accepts vector commands intended for a Tektronix storage tube display terminal. The microprocessor maps those vector commands into a random access memory, and the resulting bit map of the graphic image is displayed on a standard TV monitor. Reasonable resolution in the graphic image requires a large number of bits in the bit map, but with the use of 4K memory chips, less than 100 integrated circuits are required for the bit map memory in our design. At 1975 small-quantity prices, the parts cost for the terminal is approximately $2000.

1. INTRODUCTION

The desirability of low cost graphics for many kinds of scientific and engineering computations is reflected in the sucess of the small Tektronix storage tube computer terminals. Our experience with that type of terminal, the 4013 in particular, led to a project to overcome the limitations of the storage tube technology for low cost graphics in a convenient terminal format. We have designed and built a computer terminal that uses a microprocessor for control, a random access memory for image storage, and a standard TV monitor for display. This choice of recently available technology results in a terminal with high reliability, low maintenance, and expanded capability compared to the storage tube graphics terminal. In tests, it has been favorably received by many users. Approximately 200 integrated circuits are used for the electronics and the total parts cost for the terminal (in small quantity prices, in late 1975) was approximately $2000. Much of the cost of the terminal is the the electronics and we foresee substantial price reductions in the near future, especially in large quantity purchases.

The image quality of the graphics is comparable to that obtainable on small storage tubes such as those used in the Tektronix 4010-series terminals. Because the graphic image is maintained in random access read/write memory, the image can be selectively erased, a capability not easily obtained with a storage tube. By using the graphic image memory to store character codes for a character generator, we obtain a text mode that is capable of storing 600 80-character lines of typescript. This overcomes some of the traditional objections to "soft copy" terminals. Since the typescript is managed by a programmable processor, the text processing capabilities of the terminal are very general. It is easy to eliminate annoying aspects of text terminals and to adapt the terminal to the needs of the computers to which it is connected and to the needs of its users. In fact, many of the irritating aspects of the terminal interface of computing systems can be masked by suitably programming the terminal. For example, the limitation to half-duplex of our IBM computing system is especially annoying for experienced users when response time is slow. We therefore programmed the terminal to buffer lines of keyboard input and send them to the computer at the appropriate times. With the increasing difficulty of modifying system software, this local masking could be a major benefit to many users.

The terminal has three 128-character character generators. One is a read-only memory containing an extended ASCII character set, and the other two are read/write memories for user-programmable character sets. All characters are generated on either an 8 by 13 or 8 by 16 matrix, so the character quality is high. For an inexpensive display device, we use a standard TV monitor and generate EIA RS-170 composite video [1]. For an inexpensive and versatile control device, we use a standard microprocessor [2]. With the microprocessor and the writable character sets we can easily program the terminal with no hardware changes for unusual applications, such as Arabic text where characters on different lines must sometimes meet and the cursor must go from right to left.

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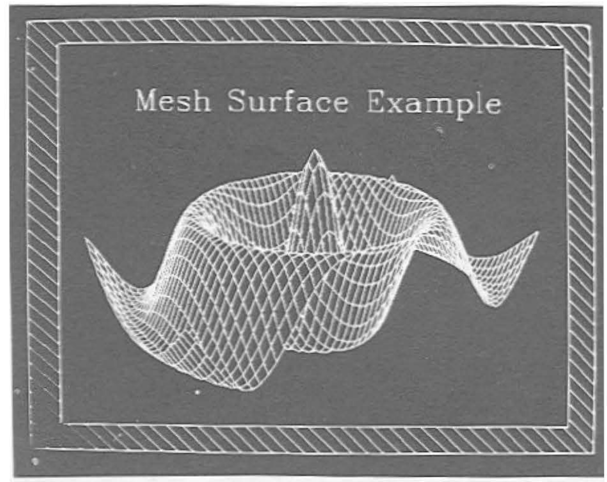
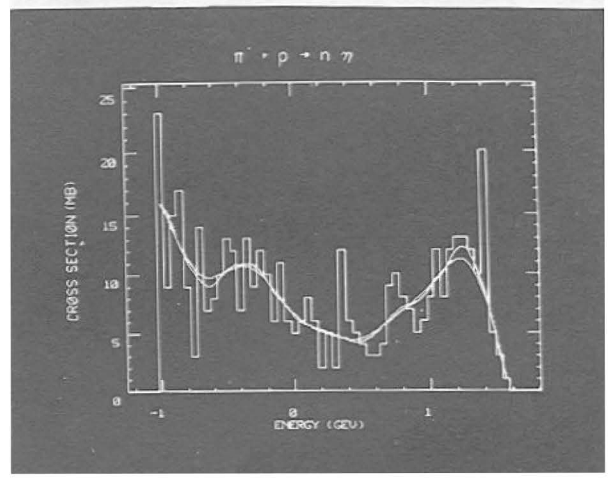
2. THE GRAPHIC IMAGE

Graphics on an American standard TV monitor can be conveniently generated on a 640 by 480 matrix of square dots. By using a large random access memory and a microprocessor to manage the bit map of dots we achieve a very clean and simple design. The bit map consists of 307,200 bits organized as 38,400 8-bit bytes so that it can be easily manipulated by an 8-bit microprocessor. The memory chips used are the widely available 4096x1 bit dynamic RAM's, and at least 80 such chips are required. Even with the minimum number of RAM's, there are 2560 bytes of storage which are not part of the bit map and may be used by the microprocessor for other purposes. It is convenient to use 96 memory chips, so there are 10,752 bytes available for other purposes.

A standard TV picture has 480 visible scan lines and a 3 to 4 ratio of height to width. With the tube mounted in the standard position we then have 480 addressable positions in the vertical direction and 640 addressable positions in the horizontal direction. Using all 480 scan lines for different video information requires that the alternate-frame interlace feature be correctly implemented. Many text-only TV terminals are simplified by generating the same information in both the even and odd frames, and adjusting the timing so that the scan lines are not interlaced. The result is at most 24 lines of text with low image quality and a screen refresh rate of 60 hertz instead of the normal TV standard of 30 hertz. The higher refresh rate is desirable because the standard P4 phosphor appears to flicker badly when high contrast images are displayed and refreshed at 30 hertz. In contrast to that approach, our terminal uses full interlace to get more text and higher quality text and graphics, and compensates for the 30 hertz refresh rate by using a TV monitor with a green P39 long persistence phosphor. The P40 long persistence phosphor with black images on a white background also seems acceptable.





Figures 1 and 2. Photographs of the TV Monitor Image Produced by the VGT.

The 640 by 480 matrix of addressable points of the graphic image is almost exactly five eighths of the 1024 by 780 matrix of visible points on the small Tektronix graphics terminals (models 4006, 4010, 4012, and 4013). Thus we can accept line drawing commands designed for those terminals, scale the coordinates by five eighths (two shifts and an add), and display the expected picture. The resolution of the image is not quite as good, but our superior image contrast seems to more than compensate for the slight loss of resolution. Figures 1 and 2 are photographs taken from the TV monitor which show typical images created from Tektronix graphic commands.

3. TEXT MODE

In text mode, the display image memory is no longer a bit map of what is displayed on the screen but instead is a coded representation of the text that should be displayed. An 8 bit code permits up to 256 different characters to be displayed at one time. The terminal allows the user (or the computer) to select any two of the three 128-character character sets to be active when the terminal is in text mode. By storing a character code instead of an image of the character, we reduce the amount of memory necessary for a screen image by a factor of 13. The large amount of extra memory thus made available is used to keep a long record of the typescript of a terminal session, and "local commands" (key strokes intercepted by the microprocessor) allow the user to scroll backward and forward through this typescript. The microprocessor can easily implement a variety of scrolling modes. We currently have three such modes. One is a "page-turning" mode where a page is one screen (37 lines) of text and successive pages overlap by five lines. Another is a high speed mode that allows the user to rapidly scan the entire 600 lines of text that can be in the locally stored typescript. The third mode is a slow, smooth scrolling that allows the text to be read comfortably as it moves.

4. HARDWARE ORGANIZATION

As in many graphics terminals, it is convenient to think of the electronics as two processors, a display processor and a control processor. Figures 3 and 4 are block diagrams of the two processors. The control processor is an 8 bit microprocessor, the Intel 8080 [2]. The display processor is a simple collection of counting registers and random logic which we call the video generator. The video generator has read-only access to the 48K bytes of graphic image memory. It receives an initial display address from the microprocessor during the vertical retrace of the TV monitor. It then fetches successive bytes beginning from the initial display address and uses those bytes to generate the video image for the current display frame. When the terminal is in graphics mode, the 8 bits from the memory are used directly for the intensity information for one eightieth of a raster line (640/8 = 80).

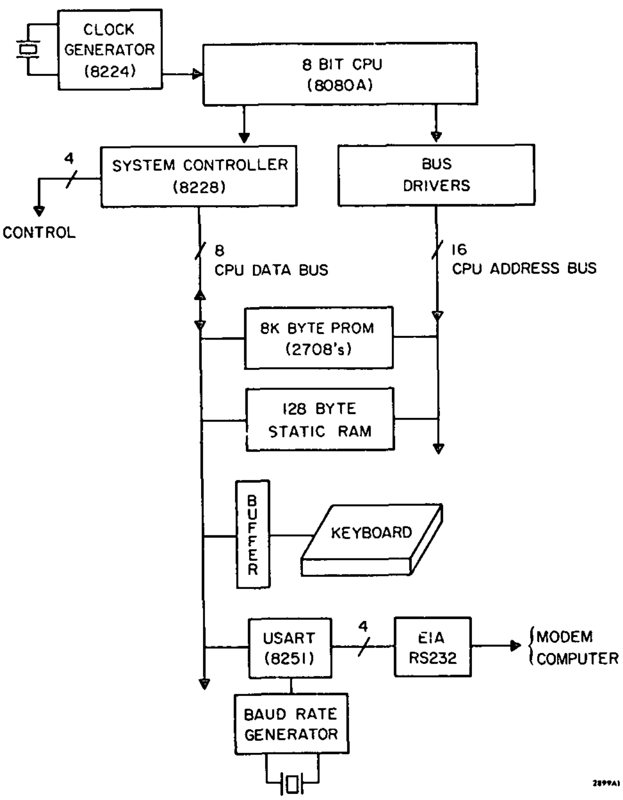


FIGURE 3. VGT Control Processor

When the terminal is in text mode, the 8 bits from the memory together with 4 bits of character row address (maintained by the video generator) are used to address one of the character generators which then supplies eight bits of intensity information for a segment of the raster line. This fetching, decoding (if necessary), and

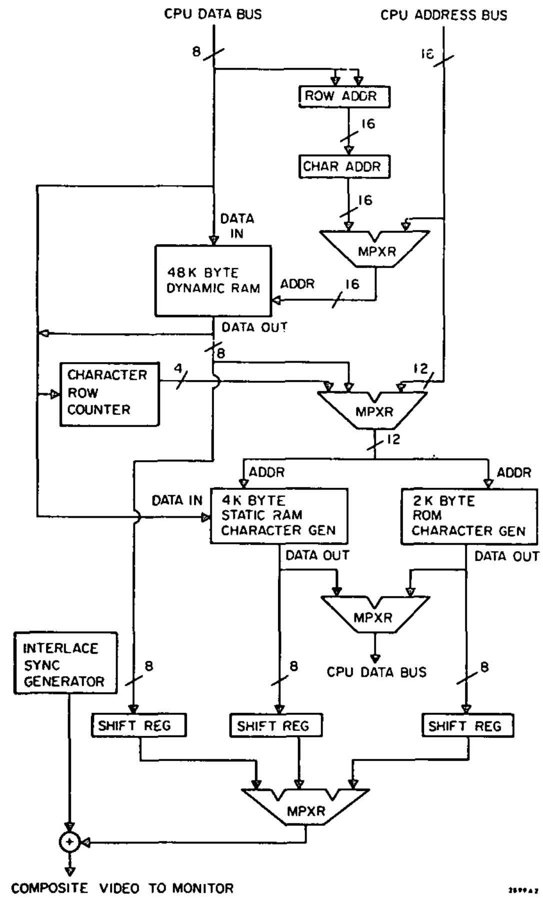


FIGURE 4. VGT Display Processor

displaying of each segment of the raster line is pipelined by the video generator because of the timing requirements of the TV monitor and the relatively slow speed of the memories used. One eightieth of a raster line must be displayed in 650 nanoseconds, but the access time of the memory chip is 420 nanoseconds. Thus the eight bit organization and the speed of the memory fit nicely with the speed requirements of the video generator.

The memory chips used in the terminal have a read cycle time of 700 nanoseconds and are dynamic. We must therefore provide for some form of interleaving to prevent consecutive accesses to individual chips, and memory refresh to prevent the loss of information. The memory is organized into three banks of 16K bytes each and the low order address bit is used to choose between two of the three banks so that an access is possible every 650 nanoseconds. The internal construction of the memory chips is such that 64 bits are simultaneously refreshed when the chip is addressed even if the output is not enabled. By addressing two of the three banks for every sixth or seventh raster line of 80 accesses the video generator can refresh the entire memory at the required rate (once every two milliseconds) with almost no extra hardware or loss of memory cycles.

By not refreshing the memories much more often than is required, power dissipation and therefore heat generation is kept to a minimum.

The read-only character generator is an 8192-bit read-only memory chip organized as 128 64-bit characters. The characters are formed on a 7 by 9 bit matrix and the remaining bit of the 64 determines whether the character is to be descended an extra 3 raster lines ("g", for example). Thus this character generator displays dots on a 7 by 12 submatrix of our 8 by 13 field. The maximum access time of this chip is 500 nanoseconds so that if fits easily into the 650 nanosecond pipeline window. The writeable character set is constructed from eight 4096-bit static memory chips, which allows 256 different characters each on an 8 by 16 matrix. Thus when this character generator is used with our 8 by 13 field, an 8 by 3 submatrix is discarded. These memories have a 400 nanosecond cycle time so that they, too, fit in the pipeline window. Static memory chips, though more expensive than the dynamic chips used for the bit map, are used for the writeable character sets because there is no simple way to guarantee the automatic refresh that dynamic chips require.

Putting a character 7 bits wide into an 8 bit field means that characters are separated by one bit of space. In practice we have found that one bit of space does not give the most visually pleasing text so the bits for a character are shifted into the eight bit field slightly faster than the bits of a graph. In essence, seven bits of a character are squeezed into a six bit field so that two bits are left between characters. Our experiments indicate that this gives the best visual effect. For the writable character generator, either the shifting rate of the read only character generator or the shifting rate of graphics can be used. Shifting the bits into the 8 bit field slightly faster than the graphic rate provides an extra bit of space for characters that should be well separated, and shifting the bits into the field at the graphic rate allows characters that are supposed to merge at their boundaries to do so. The control processor can set which of the bit clocks will be used for the writable characters (for the entire screen).

The read-only character generator puts dots on as many as twelve different raster lines because some of the 9-bit high characters are descended 3 raster lines. Character lines are displayed in thirteen raster lines to insure that there is always at least one completely blank raster line between them. Although this would be too-little separation if all text characters were 12 bits high, it is visually pleasing since the average separation is four raster lines for pper case and six raster lines for lower case. The appearance is not one of double spacing as in many video terminals, and it allows 37 lines of text to be on the screen. Since the writable character generators can provide information on as many as 16 raster lines, the control processor can change the number of raster lines per text line from 13 to 16. The result is more space for a text line and fewer (30) text lines per screen. This is desirable for character sets containing mathematical or drawing symbols, or for normal characters with diacritic marks.

The character row address counter starts at an initial value supplied by the control processor during the vertical retrace. Thus the first raster line of the screen may be the nth row of a text line where n is greater than one. This shifts the entire screen up by n-l raster lines, and allows the text to be scrolled up (or down) one raster line at a time. The rate at which this smooth scrolling is done is controlled by the microprocessor, and at a well chosen rate the text can be read comfortably as it moves.

Figures 5 and 6 are photographs of our prototype video graphics terminal. A single lightweight unit (19 lbs) contains the keyboard, power supplies, and all electronics; the separate standard TV monitor is a commercially available unit. The three small printed circuit boards contain only the 48K byte display memory, and the larger wire wrapped board contains the microprocessor, the program and character set memory, the serial interface, and all control logic.

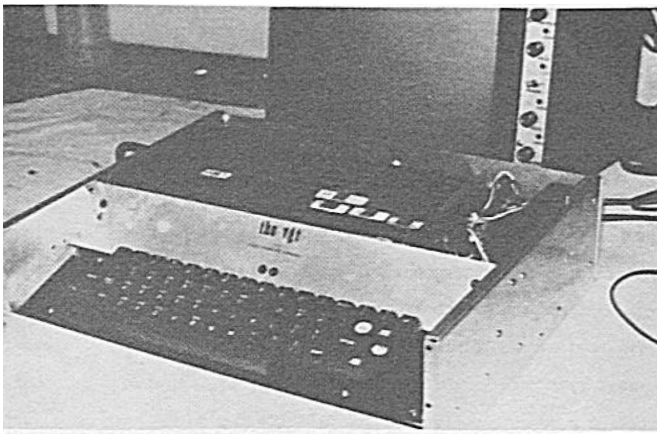


FIGURE 5.

The Video Graphics Terminal prototype with the top cover removed

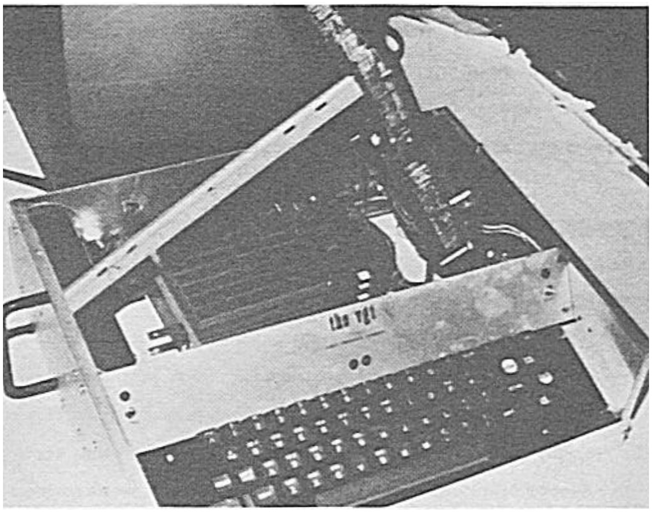


FIGURE 6.

The Video Graphics Terminal with the control electronics up and the memory boards

5. SOFTWARE ORGANIZATION

The overall design philosophy required the control processor software to be responsible for as many functions of the terminal as possible. The display address, the display format, the keyboard, and the communications interface are all controlled by the microprocessor. The processor accepts a single interrupt generated by either the communications interface or the video generator. The communications interface generates an interrupt when a new character arrives or when a character has completed transmission. The video generator causes an interrupt at the bottom of a frame, indicating that vertical retrace is occuring.

For interrupts caused by the video generator, the processor must send a new display address and an initial row number for the first line of text to the video generator for the next video frame. The display address or the initial row number can be adjusted from their previous values if the video image is to be scrolled. In addition to sending the display address to the video generator, the processor polls the keyboard to see if a new key has been struck or to see if the previous key is still depressed; polling the keyboard at 60 hertz is fast enough for even the fastest typists. Timing is done by counting vertical retrace interrupts, which gives the processor a 60 hertz line frequency clock. The clock is used for timing such things as the scrolling rate, the cursor blink rate, and the keyboard repeat delay and rate. If a key is held down for two fifths of a second, the processor starts repeating that key at a 20 hertz rate. This seems to be as fast as a key can be repeated and still allow the typist to stop at a predetermined place on the line. The character repeat rate and typing rate can be faster than the line (baud) rate of the communications interface because the microprocessor buffers characters for transmission.

Since the software of the microprocessor controls the display format and the communications interface, many combinations of local and remote editing are possible. Business oriented features such as protected fields and block transmission could be handled in a straightforward manner by the local software.

Local software is stored in 1024x8-bit erasable programmable read-only memory chips (Intel 2708 EPROMs). These chips are so easily programmed that we have considered building the programmer into the terminal. The terminal could then be instructed to accept coded binary text from the remote computer to rewrite the PROM plugged into the programming slot.

The software is written in assembly language. The assembly language we use is a more elegant and powerful one than that provided by the microcomputer manufacturer, and was easily implemented using Assembler language mapping macros on our large computer. Software in the terminal for local text editing is still under development, but the software that handles simple character mode transmission, scrolling, and graphics (a 4013 simulator) is complete and requires only 2000 bytes of read-only memory (two PROMs). Local text editing is a nontrivial problem, and we expect to use another 2000 bytes for a line editor and more sophisticated typescript management. We have allowed space for 8192 bytes of read-only memory. If we implement features, such as those described by Gerhart and Parnas [3], that take advantage of the high display speeds that are possible and the essentially random addressability of the display screen, we could use most of that program storage.

The display memory is logically divided into 600 sequential lines of 80 bytes each. Our current system does not use a linked list structure. The linked list structure such as that used by the Hewlett-Packard video terminals [4] has advantages such as minimizing storage usage and manipulating the typescript with simple changes to a few link fields. With a large amount of storage, however, its economical use is not an overriding concern. With the simple linear storage layout, the local software is very straightforward. Some operations can be time consuming but our experience has shown that these operations are infrequent so that some inefficiency can be tolerated. Linked structures are disadvantageous because it becomes difficult to quantify the time required for certain common operations such as inserting a character in a line. For our memory organization, it would not be a simple matter to insure memory refresh with a linked list organization. One desirable feature we could add if we were to use a linked list structure would be an ability to display bands of the screen in either graphics mode or in character mode.

6. LOCAL PROCESSING SPEED

We have run our graphics software at a serial interface speed of 2400 baud (240 characters per second) and have had no trouble keeping up with incoming graphic commands at that rate, but it is possible that we could not keep up with a higher line speed in graphics mode because of a memory accessing limitation we have placed on the microprocessor. We currently do not allow the microprocessor to access the graphic image memory while a scan line is being generated by the video generator. The memory is slow enough and simple enough so that if the microprocessor steals a memory cycle during the generation of a scan line, the interference results in annoying "snow" on the screen. With the limitation, the microprocessor is able to access the graphic image memory only during the horizontal retrace (one or two accesses) and during the vertical retrace (hundreds of accesses). Vector drawing commands from the communication line at a rate greater than 240 per second could require more graphic image accesses than we can deliver with the "no snow" limitation. However, it is easy to remove this restriction and we have made it subject to control by the microprocessor. For example, in order to erase the screen as rapidly as possible, the microprocessor first enables accesses during scan line generation, erases all the memory byte by byte, and then disables such cycle stealing. Thus the screen erase is snowy but fast.

For the storage of local variables and the subroutine stack, the microprocessor has immediate access to a small 128-byte random access memory. This small memory is not part of the bit map memory accessed by the video generator and is thus always available to the microprocessor.

7. COSTS

The most expensive component of the video graphics terminal is the random access memory used for the graphic image. Buying 100 chips of the type we use (according to the September 1975 list price) will cost $1250. Large customer discounts would bring the price down to $800. Price reductions anticipated for 1976 will bring the cost down further to $400. We presume that the 16K bit memory chips will eventually make the memory cost even lower. At that point the cost of the memory balances nicely with the cost of the other components of the terminal, since keyboards cost between $100 and $300 and TV monitors cost between $100 and $300. The most expensive single chip we use is the microprocessor, which can now be purchased for $40. There are five other LSI chips used that cost approximately $15 each. The PROM memory chips for program storage are new devices and currently sell for $96, but the cost is expected to drop when there are multiple sources early in 1976. Nevertheless, using current list prices, the parts cost for the terminal is approximately $2000. Since most of the cost is in the electronics where price reductions are expected rather than in components like storage tubes where price increases are more likely, we expect that future low cost graphic systems will use this approach.

8. ALTERNATIVE APPROACHES

With existing technology, the principal alternative approach that seems feasible is the use of charge-coupled devices (CCD's) rather than a random-access memory to store the bit map of the graphic image. The CCD's seem to be ideally suited to the needs of the video generator, which requires only sequential access to the bit map image. However, they are far from ideally suited to the needs of the graphic image generator in the microprocessor, which accepts commands from the communications interface and must draw vectors between arbitrary points on the screen. The bit map of the vector must be created quickly in the graphic image memory so that the buffer holding incoming commands will not overflow. Methods for simulating random access to sequential memory devices can be devised, but they seem either complicated or slow. Thus while CCD's are excellent video output devices, their organization is not appropriate for a video input device of this type. Furthermore, the current and projected cost advantage of CCD's over RAM's does not seem to justify the effort necessary to use them for this application.

9. FUTURE EXTENSIONS

The next obvious step in the development of a terminal of this type is the use of a 16 bit microprocessor that addresses 16 bit words (not bytes) together with a memory 16 bits wide. This would double the number of bits that could be addressed easily, it would double the effective memory bandwidth, and it would substantially increase the computational power of the local processor. With such a change, we could perhaps provide higher speed and higher resolution graphics, multiple graphic images, more text storage, and more sophisticated local processing. However, note that using color or gray scale would each multiply the memory size and bandwidth requirements by at least a factor of two.

It is tempting to move in the direction of the smaller minicomputers and to add a variety of peripheral devices controlled by the local processor. A very useful and easy addition would be a mechanism for locating a point on the screen, such as a lightpen or hand-held "mouse". The addition of a floppy disk or small tape drive would encourage the development of a more sophisticated local screen-oriented text editor, of a local file system, and of a more general and flexible local operating system.

ACKNOWLEDGEMENTS

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