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A New Light Pen With Subpixel Accuracy

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A new light pen system using a real-time algorithm for computing the centroid of the intensity pattern seen by a photosensor is described. This new light pen achieves an accuracy of better than one-quarter of a pixel on a cathode-ray-tube screen with 1K × 1K resolution. This corresponds to a capability of resolving 0.004 inch on a 15-inch screen, which is an improvement by a factor of at least 50 over the conventional light pens available today. The transistor-transistor logic hardware implementation of the algorithm is described in detail. The central part of the hardware is a real-time, moment-generating circuit that implements an efficient moment calculation algorithm reported earlier. Issues such as complexity of the hardware compared with the conventional techniques, and the possibility of implementing the algorithm in a single complementary metal-oxide semiconductor chip are addressed. Some line and curve drawing results sketched by the new light pen are presented and compared to similar drawings obtained by a conventional light pen.

I. INTRODUCTION

The light pen, an input device for graphics displays and work stations, has been around for quite some time. Among the many input devices for graphics systems, the light pen is probably the most natural one to use and, other than the touch-sensitive screen, the only one that directly interacts with the screen. In the world of interactive computer graphics, the light pen has been used mostly as a selection device for pointing to objects and characters on a Cathode-Ray-Tube

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(CRT) screen. Although very simple and inexpensive, the light pen has not been very popular among the users of graphics systems. Some have called it a clumsy, fragile device and predicted that it will become less and less popular as raster graphics grows.[1] One of the main reasons for the light pen's poor popularity is its limited resolution, which makes it unsuitable for accurate pointing, or writing and sketching on a CRT screen. Provided with improved resolution capability, the light pen is useful in a variety of applications, such as telewriting, accurate pointing and selecting, facsimile, brushing, and graphics generation. An example of the light pen used in a telewriting system is described in Ref. 2.

The poor resolution of the light pen is a combined result of its relatively large field of view, the signal-to-noise ratio performance of the pen's photosensor, limited image sharpness,[3] and, most important, the simple thresholding technique used to detect the position of the pen. We recently proposed a new approach to estimating the position of the pen by processing the analog signal generated by the light pen's photosensor and computing the centroid of the two-dimensional image received by the sensor. Using this new technique we can achieve subpixel accuracies on a 1K × 1K screen. The algorithm is extensively treated in Ref. 4.

This paper describes the real-time hardware implementation of the algorithm. First, we briefly describe the operation of the currently used light pen devices. In Section III we describe the new algorithm. Section IV discusses the hardware implementation and Section V presents some results.

II. CONVENTIONAL APPROACH

Conventional light pens used in today's computer graphics systems employ a very simple circuit for detecting the position of the pen on the display screen. This is illustrated in Fig. 1. A photosensor is placed in the tip of a penlike housing. Whenever the scanning electron beam falls in the photosensor's field of view, it generates an analog signal whose amplitude is a function of the light intensity received by the sensor. This analog signal is compared with a predefined threshold, and a pulse is generated indicating a hit. This pulse latches the values of two counters (the X-Y counters in Fig. 1) that track the horizontal and vertical positions of the beam. The two counters are reset at the beginning of each scan, namely, when the beam is at the top-most left corner of the screen. The X counter tracks the position of the beam on each line and is reset at the end of the line; the Y counter indicates the number of the line currently being scanned by the beam.

Obviously, when the hit pulse is generated, the values of the X and Y counters indicate the coordinates of the hit point. These coordinates

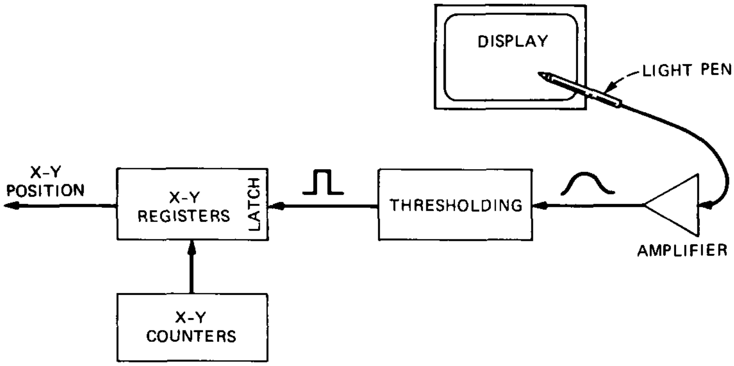

Fig. 1—Conventional light pen system.

are latched into two registers to be used by a host processor (e.g., the graphics station's display processor). Using this simple thresholding technique, the accuracy in estimating the position of the light pen is a function of the photosensor's signal-to-noise ratio and the aperture of the photosensor (size of the field of view). The latter is more important. Many attempts have been made to improve the accuracy of the light pen by controlling the field of view of the pen and using photosensors with high sensitivity.

Designers have employed various mechanical and optical arrangements in the tip of the light pen to improve the accuracy. All of these attempts, although successful in improving the performance, have not achieved the ultimate desired accuracy. To the best of our knowledge, the best of today's available light pens do not have a repeatable accuracy of better than ±5 pixels (in both directions) on a screen with a resolution of 500 × 500 pixels. Besides, even this poor accuracy is only achievable when the pen is held perpendicular to the screen and not at an angle.

Such poor accuracy in estimating the position of the light pen is mainly due to the simple thresholding technique used in detecting the hit point. In our approach, a different technique is used. Rather than thresholding the analog signal generated by the photosensor, we take advantage of the information contained in that signal to achieve an accurate and highly robust estimate of the position of the light pen on the display screen. As we will see in the following sections, using the right kind of processing can convert an ordinary light pen into one with an accuracy of one-quarter of a pixel on a display with 1024 × 1024 resolution.

III. MOMENT COMPUTATION APPROACH

If the analog signal generated by the light pen's photosensor is displayed on a monitor, one sees a cometlike pattern similar to what is shown in Fig. 2. The tail of the pattern is caused by the persistence of the phosphor used in the CRT display at which the light pen is pointed. A long persistence phosphor will cause a longer tail. In our new light pen, the centroid of this intensity pattern is used as the estimate of the position of the light pen. As shown in Ref. 4, this approach produces a highly accurate and robust estimate of the position.

The x and y coordinates of the centroid are calculated in real time (60 fields/s) by computing various moments of the intensity pattern. The scheme is illustrated in Fig. 3. After proper amplification, the

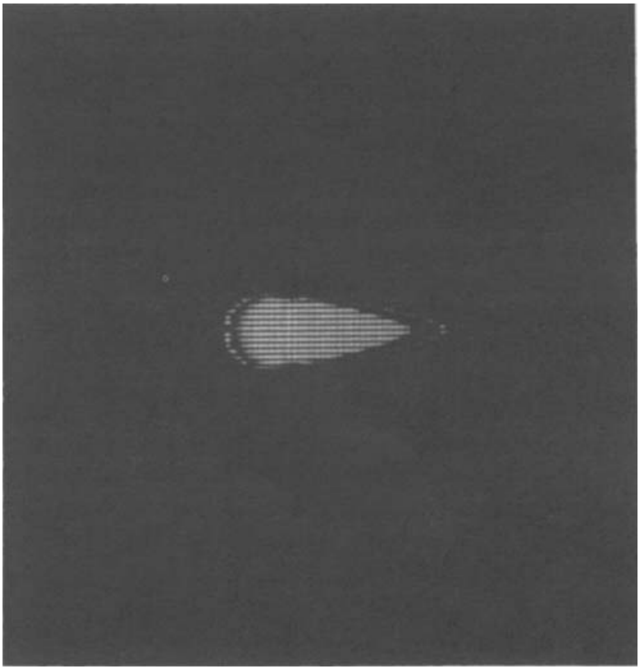

Fig. 2—Intensity pattern generated by the light pen's photosensor.

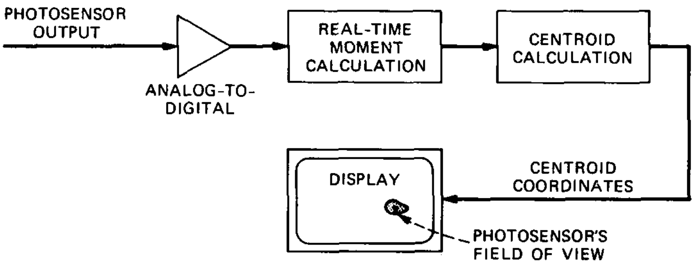

Fig. 3—Light pen system using the moment computation approach.

photosensor's output is digitized and fed to a two-dimensional digital filter, which can compute the intensity moments of the two-dimensional signal represented by the photosensor's output. The moments m^{pq} about the point (N, M) are defined as

$$m^{pq} = \sum_{i=0}^{N} \sum_{j=0}^{M} x(i, j)(i - N)^{p}(j - M)^{q}, \tag{1}$$

where $x(i, j)$ represent the digitized samples of the sensor's output, and N and M are the horizontal and vertical resolution of the display system. We recently proposed a very efficient algorithm for real-time computation of (1). This algorithm is described and analyzed in Ref. 5. It uses a set of identical single-pole digital filters and has a highly regular and expandable structure. In Ref. 5 we also present a Very Large-Scale-Integrated (VLSI) design for single-chip implementation of this algorithm in Complementary Metal-Oxide Semiconductor (CMOS) technology. The chip is capable of simultaneously computing 16 moments $m^{p,q}$ ($p = 0, 1, 2, 3$; $q = 0, 1, 2, 3$) of a 512 × 512, 8 b/pixel image in real time (i.e., at conventional video rate).

In this application for estimating the position of the light pen, only the three moments $m^{0,0}$, $m^{0,1}$, and $m^{1,0}$ are used to compute the centroid coordinates as

$$x_c = \frac{m^{1,0}}{m^{0,0}}$$

$$y_c = \frac{m^{0,1}}{m^{0,0}}. \tag{2}$$

The subpixel accuracy in our estimation stems from the fact that the above division operations can be carried out in floating point mode. This generates results accurate to almost one digit after the decimal point, as we will see in Section V.

IV. HARDWARE IMPLEMENTATION

The light pen algorithm described above has been implemented as part of a larger graphics test bed described in Ref. 6. Figure 4 shows the light pen system used in the test bed. Except for the moment generator circuit, the rest of the blocks in this figure are part of the graphics test bed. As described earlier, the signal generated by the light pen's photosensor is digitized and fed to the moment generator circuit, which generates a set of raw moments at the rate of 60 times a second (video field rate). These moments are read by the test bed's control processor (a 68000 microprocessor), which calculates the centroid coordinates and feeds them to the display processor for proper action (e.g., writing, erasing, and brushing).

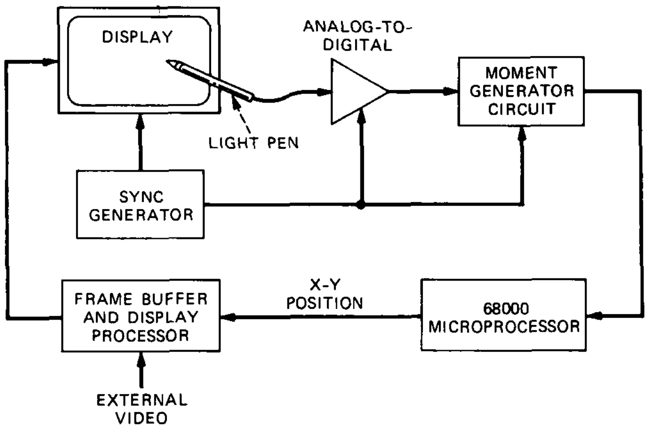

Fig. 4—Light pen system using the moment approach implemented on a graphics test bed.

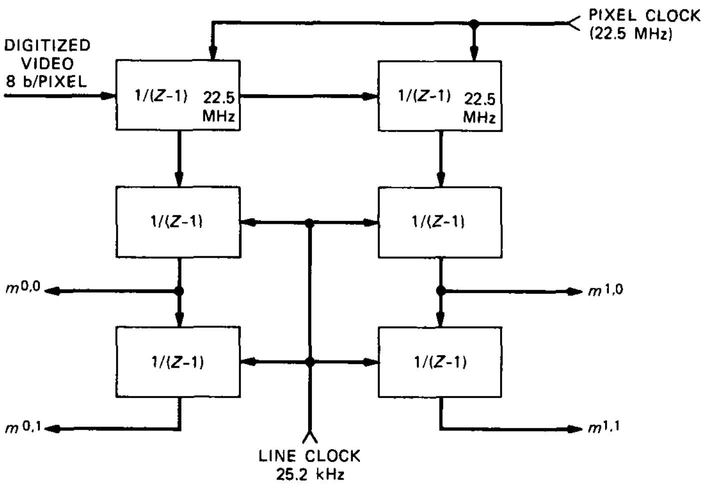

Fig. 5—Digital filter representation of the moment computation algorithm.

The moment generator circuit is basically a Transistor-Transistor Logic (TTL) implementation of the algorithm we described in Ref. 4. It consists of a number of single-pole digital filters, with transfer function $1/(Z - 1)$, interconnected as shown in Fig. 5. This is only part of a larger filter network described in Ref. 5, mainly because higher-order moments are not required in this application. Each filter block is simply implemented by an accumulator, which is basically an adder with an output register and a feedback path. This is shown in Fig. 6 for the two blocks in the first row of Fig. 5, referred to as a row filter in Ref. 5. These two blocks operate at the pixel clock rate. Figure

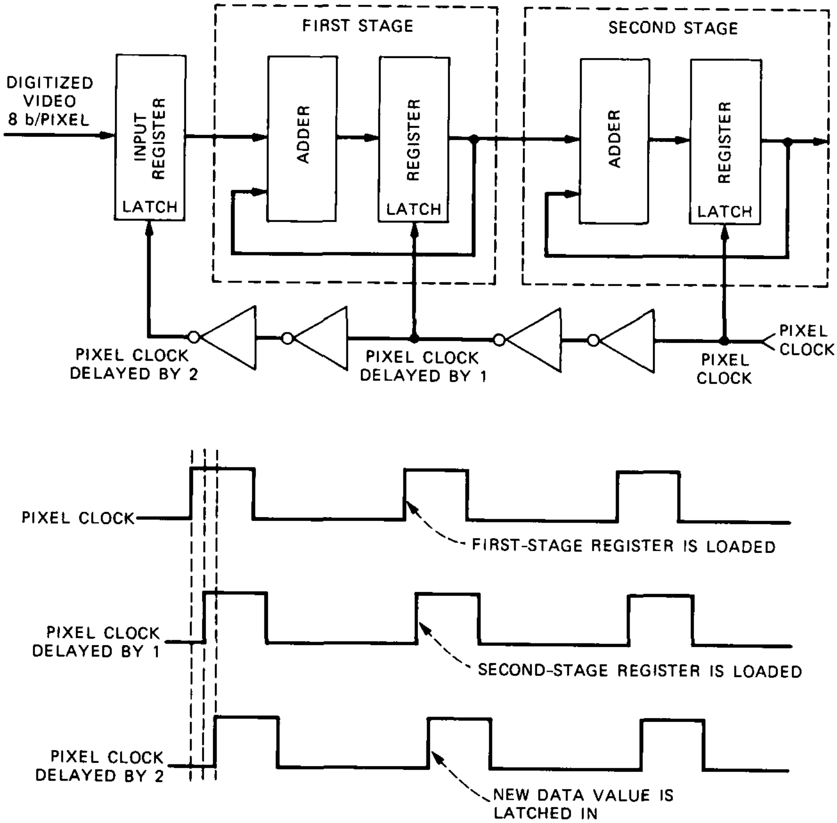

Fig. 6—Circuit and timing diagram of the row filter section of the moment generator.

6 illustrates the operation of this simple arrangement of adders and registers. The rest of the blocks in Fig. 5, referred to as column filters, are implemented in exactly the same way, except that they run at the display's scan-line clock rate rather than the much faster pixel clock rate. This feature relaxes the speed requirement on the adders in the column filter to the point where they can be implemented serially. This results in considerable savings in space and power consumption. This feature is extremely important in the VLSI implementation of the moment generator circuit, as discussed in Ref. 5.

V. RESULTS

Results obtained from the hardware implementation of our new light pen aglorithm indicate that the moment computation approach can indeed achieve subpixel accuracy in estimating the position of the light pen. All the line and curve drawings presented in this section were drawn by the light pen on a 1000-line raster scan black and white monitor that uses a short persistence phosphor (2 to 3 μs). For a display monitor with a long persistence phosphor, the output of the photosensor's amplifier should be differentiated and rectified before processing. See Ref. 4 for more details.

Figure 7 shows a number of curves and lines drawn by the light pen using the moment computation approach. Figure 8 shows similar drawings using the conventional method in determining the position

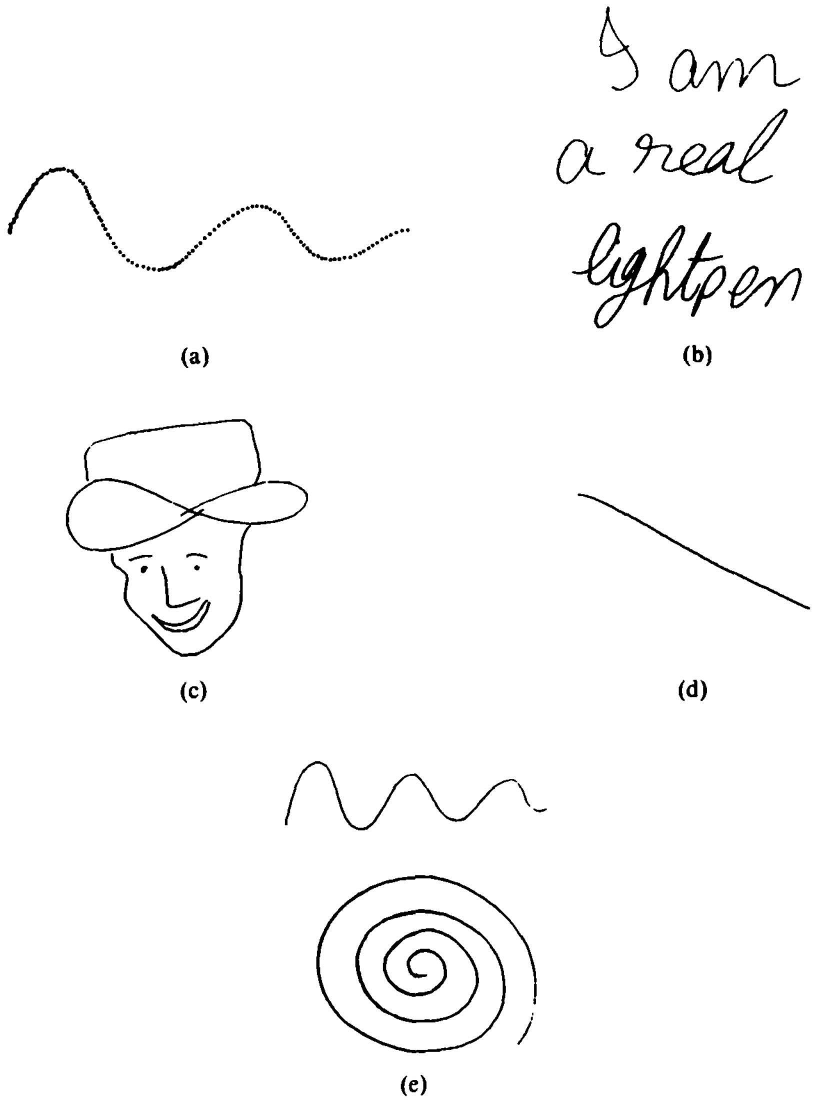

Fig. 7—Light pen drawings using the moment computation approach.

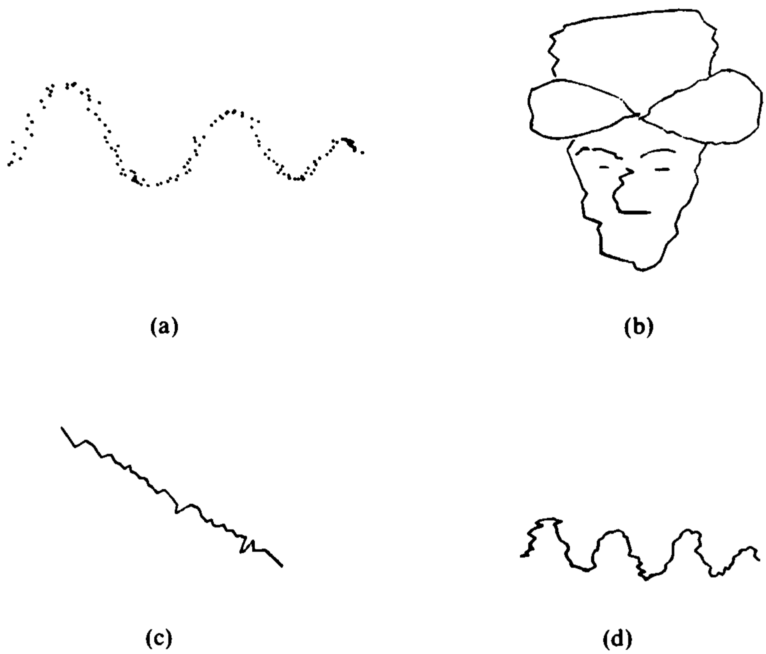

Fig. 8—Light pen drawings using the conventional technique.

of the light pen (same photosensor was used). Except for Figs. 7a and 8a, a linear interpolation has been used for connecting the points. A comparison of the drawings in Figs. 7 and 8 clearly shows the degree of improvement achieved by the moment computation approach. Figure 7b is of special interest. It shows that, even with a simple linear interpolation, light pens using this new algorithm can generate very high-quality writing on CRT displays.

To obtain some quantitative measure of the accuracy, the following experiment was performed. The light pen was attached to a micropositioning device facing the display screen. The micropositioner was moved horizontally in steps of 0.001 inch, and the floating point x and y coordinates generated by the moment processor were recorded. The results are plotted in Fig. 9. From these results we can observe an accuracy of one-quarter of a pixel on a 1K × 1K resolution monitor. The pen can resolve 0.004 of an inch on a 15-inch screen. It should be noted that, although the resolution of our display system is 1K × 1K, the signal fed to the moment generator circuit is subsampled by a factor of 2, resulting in an effective input resolution of about 500 × 500. It should also be noted that part of the error in the recorded data for the x and y coordinates is due to the jitter in the mechanical setup in the above experiment.

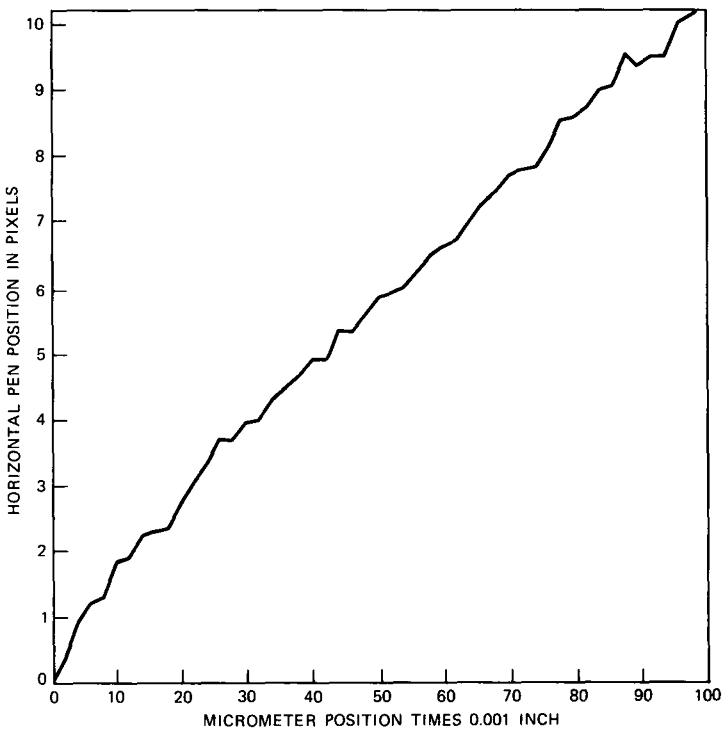

Fig. 9—Position computed by the moment algorithm in pixels as a function of the movement of the pen by a micropositioner.

To be of practical use in today's graphics systems, the cost of this new light pen must be drastically reduced. We are currently studying the possibility of implementing the algorithm in a single-hybrid CMOS chip. This would include the Analog-to-Digital (A/D), moment generator circuit, and postprocessing. A VLSI design for the moment generator part of this chip has already been prepared.[5] In applications where an accuracy of one pixel is sufficient, the requirement on the size of the A/D and the adder circuits in the moment generator can be considerably relaxed. Preliminary investigations indicate that the moments of the area of the pattern in Fig. 2, rather than the intensity moments, are sufficient for one-pixel accuracy. Using the area moment, if possible, reduces the A/D to a simple comparator (1 b/pixel), and the moment generator requires much less silicon area. All these options are being investigated and will be reported in the future.

VI. CONCLUSION

A new light pen system based on computing the centroid of an intensity pattern generated by a photosensor was presented. The hardware implementation of this system was described in detail. The central part of the hardware is a TTL implementation of an efficient, real-time, moment-generating algorithm reported earlier. The moments are used to compute the x and y coordinates of the centroid as an estimate of the position of the light pen on the screen. It was shown that this new technique can achieve an accuracy of at least one-quarter of a pixel on a display screen with a resolution of 1K × 1K. The pen can thus resolve 0.004 inch on a 15-inch screen. This is an improvement by a factor of at least 50 over the conventional techniques used in today's light pens. Such an improvement is gained at the cost of increasing the complexity of the hardware by a considerable factor. However, due to the simplicity of our moment-generating algorithm and the regularity of its structure, the required hardware can be implemented in a single CMOS chip. Such a chip can have many potential applications in the field of computer graphics. Work on this single-chip implementation of the algorithm is in progress.

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