Experimenter's Corner

By Forrest M. Mims

Experimenting with a Light Pen—I

AMONG the most interesting data-entry devices for computers and remote terminals are those that are sensitive to light. The most sophisticated optical data-entry devices are solid-state television cameras. When such a camera is used with a computer having a large complement of RAM storage capacity, complex operations such as pattern recognition, equipment monitoring, and area surveillance can be performed easily.

Television cameras provide perhaps the ultimate in optical data entry, but their cost (as well as that of the necessary interface circuit) varies from high to exorbitant. Two much more common—and cheaper—optical data-entry devices are *light wands* and *pens*. Television cameras contain many hundreds or thousands of resolution elements, but most light wands and pens incorporate a single-element light detector such as a photodiode or a phototransistor.

It's important at the outset to understand the differences between light wands and pens. Light wands are designed to detect the presence or absence of contrasting marks such as bars of ink printed on paper or plastic. Therefore, light wands usually include built-in light sources to illuminate the marks. They also include precisely focused optics that assist the detector and the light source in their work.

Light pens, on the other hand, are designed to detect a point of light on the screen of a video display such as a cathode ray tube. Simple light pens do not include an internal light source because most video displays are light emitters.

Fig. 1. Hewlett-Packard's bar code-reading Optical Wand plug into an HP-41C calculator.

However, some pens designed for use with high-resolution displays include a pinpoint light source so that the operator will know precisely where the pen is pointed.

Applications. The light wand is a one-way data entry device. You've probably seen sleek-looking wands attached by flexible cables to some late-model cash registers. A sales clerk can record a purchase merely by sweeping the wand past the bar code printed on the label or package of many different products. Some wands can even read the printed information on a price tag!

Because light wands can be used by unskilled operators and provide faster and more reliable data entry than keyboards, their use is rapidly expanding. They are currently being used in portable inventory monitoring systems in some department stores and supermarkets. They are also used in some libraries to read information from bar-coded identity cards and books.

Figure 1 is a photograph of a light wand made by Hewlett-Packard. The wand's cable plugs into the company's HP-41C programmable calculator and allows bar-coded programs to be quickly loaded into the calculator. If you've ever spent ten or more tedious minutes loading a long program into a calculator, you can readily appreciate the convenience and speed provided by such a wand.

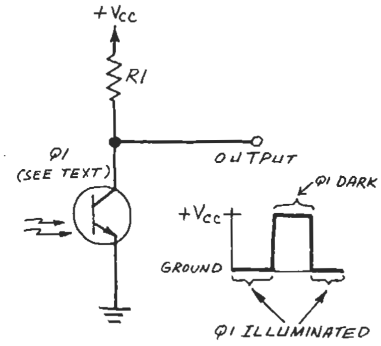


Fig. 2. A basic phototransistor light-detection circuit. Any standard npn phototransistor can be used.

Light-Pen Applications. Light pens are simpler and therefore physically slimmer than light wands.

How the light pen allows information to be "drawn" on the screen of a CRT is not immediately obvious—at least it wasn't to me when, as a high school student, I viewed a film which showed computer operators using light pens!

Actually, the light pen's principle of operation is remarkably simple. In a typical CRT/light-pen system, for example, the entire screen is repeatedly scanned by a tightly focused electron beam. This produces a fast-moving dot of light too dim to be seen by the human eye but easily detectable by a phototransistor or photodiode.

The computer knows the precise location of the moving dot at any given instant. Therefore, if a light pen is connected to an input port, the computer knows exactly where the light pen is pointed. Depending upon the computer's software, this permits the operator to select specific data to be displayed on a CRT for any desired purpose, and to "write" information, including complex graphics, onto the screen and into the computer's memory.

A Homemade Light Pen. A light pen is very easy to make. Both photodiodes and phototransistors make suitable sensors. The former are faster but the latter are more sensitive.

The basic phototransistor light-detection circuit in Fig. 2 illustrates how a straightforward detector responds to a light pulse. Any standard npn phototransistor such as the FPT-100 can be used for *Q1*. When *Q1* is dark, its collector-to-emitter resistance is much higher than *R1*. The output voltage of the circuit therefore rises very close to $+V_{CC}$. When photons strike the device's light-sensitive region, *Q1* becomes forward-biased and its collector-to-emitter resistance falls far below that of *R1*. The circuit's output voltage thereupon approaches ground potential. Summing up, the output of the circuit is normally a high voltage. When light strikes phototransistor *Q1*, the output voltage is low.

This basic circuit can be used in some light-pen applications. A much better circuit, however, is shown in Fig. 3. An operational amplifier is used without a feedback resistor to provide the highest possible gain. The gain is so high that the op amp functions as a comparator whose output switches from +5 volts to ground when the voltage applied to its noninverting input falls below the reference voltage provided by *R2*. This occurs when *Q1* is illuminated.

When *Q1* is dark, the voltage at the noninverting input of the op amp rises above the reference voltage. The comparator output then swings from ground potential to +5 volts. Potentiometer *R2* can be adjusted to alter the light level at which the comparator switches. Those readers who have experience with op amps are probably wondering about the function of potentiometer *R3*. In a working version of this circuit lacking *R3*, the output voltage when *Q1* is illuminated can be greater than 1 volt. This exceeds the maximum allowable TTL logic 0 level of about 0.85 volt. Therefore, if TTL logic is to be controlled by the circuit shown in Fig. 4, it is necessary to adjust *R3* to pull the output down a few tenths of a volt.

Incidentally, the basic phototransistor circuit shown in Fig.

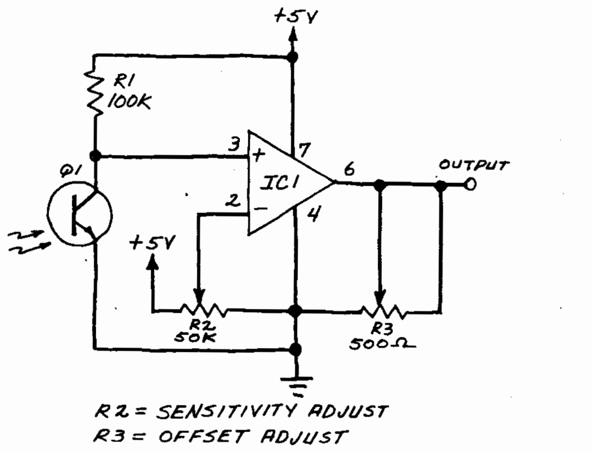


Fig. 3. An expansion of the circuit in Fig. 2. using an operational amplifier for higher gain.

2 will directly drive TTL logic without the need for a pull-down resistor. However, it is less sensitive than the circuit that appears in Fig. 3.

Light-Pen Data-Entry Circuit. It's relativitely easy to design a data-entry circuit controlled by a homemade light pen. Figure 4 is the block diagram of one such circuit I've designed.

The operation of the circuit is straightforward. The clock supplies a stream of pulses to a programmable 4-bit counter. The counter's binary output is decoded by a 1-of-16 decoder which sequentially illuminates each of sixteen LEDs.

When the light pen is dark, the LEDs are scanned at a rate determined by the clock frequency. When the light pen is brought near any of the LEDs, nothing happens until that LED glows during the scan sequence. The output from the comparator then changes state and causes the counter to be loaded with whatever data is present at its data inputs. Because these data inputs are connected to their respective outputs, the current count is loaded into the counter. This freezes the counter even though the clock continues to supply pulses to it. The address of the selected LED then appears on the 4-bit bus.

Incidentally, the usual way to block clock pulses is to insert a gate between the clock output and the counter input. The method employed here eliminates the need for such a gate.

Figure 5 is the schematic diagram of my prototype data-entry circuit. A 555 timer operating in the astable mode (*IC3*) serves as the circuit's clock. The clock frequency, and hence the LED scan rate, can be adjusted by means of potentiometer *R5*. You can also increase the value of *C1* to slow the scan rate.

Counter *IC4* is a 74193 programmable up-down counter. Note how the programming data inputs are tied to their respective outputs. The 1-of-16 decoder (*IC2*) is a 74154. The anodes of the 16 LEDs connected to the decoder outputs are all tied to a single current-limiting resistor because only one LED is illuminated at any given instant.

The light pen circuit appears above the LED array. Note that the output of operational amplifier *IC1* is connected to the LOAD input of counter *IC4*.

You can assemble a working version of this circuit on a solderless breadboard in less than an hour. The selection of devices for use as *IC1* and *Q1* is not critical. Any general-purpose op amp such as a μA741 is suitable, and any standard npn phototransistor such as the FPT-100 can be used. The phototransistor should be connected to the circuit by means of clip leads. Power can be provided by a +5-volt supply or you can use a 6-volt battery if you first connect the cathode of a 1N4001 diode to those points in the circuit marked +5 volts and the anode to the battery's positive terminal.

When you apply power to the circuit, the LEDs will either flash off and on in rapid sequence or all the LEDs will appear to glow dimly. If the latter occurs, the clock frequency is so great that the LEDs switch on and off faster than your eyes can respond. For initial tests, adjust *R5* to achieve this latter condition.

Before attempting to use the circuit, you must trim the light-pen circuit. A trial-and-error approach will eventually produce useful results, but a much better approach is to temporarily disconnect the grounded lug of potentiometer *R3* from ground and connect a voltmeter between the output of the op amp and ground. Illuminate *Q1* with a flashlight and adjust *R2* until the output voltage of the op amp falls to its lowest value, which was approximately 1.2 volts in the prototype circuit. Don't turn the rotor of *R2* beyond this point once you have found it.

When you remove light from *Q1*, the output voltage of the op amp should immediately increase several volts. (It reached 3.4 volts in the prototype.) The light pen is now adjusted for maximum sensitivity. Indeed, it is probably so sensitive that ordinary room lighting will be able to switch the comparator. Therefore, you should wrap a cylinder of black electrical tape one-half inch in diameter around *Q1* to block ambient light. Heat-shrinkable tubing can also be used for this purpose.

Next, reconnect the lug of potentiometer *R3* to ground and again illuminate *Q1* with a flashlight. Adjust the rotor of *R3* until the LEDs stop scanning and only a single LED remains on. The light-pen circuit is now trimmed and ready for use.

Test the circuit by bringing the aperture of *Q1* close to any of the LEDs in the array. Depending upon the scan frequency, the selected LED should immediately or very quickly glow brightly and all the remaining LEDs will darken. The binary

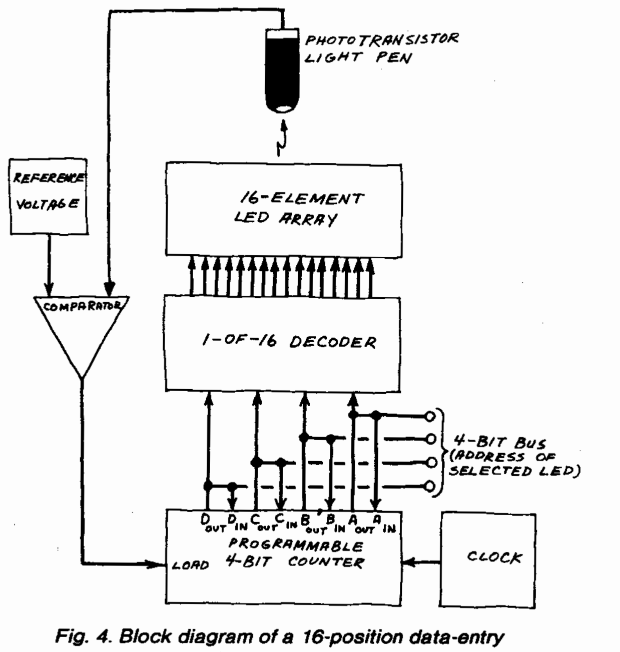


Fig. 4. Block diagram of a 16-position data-entry circuit controlled by a homemade light pen.

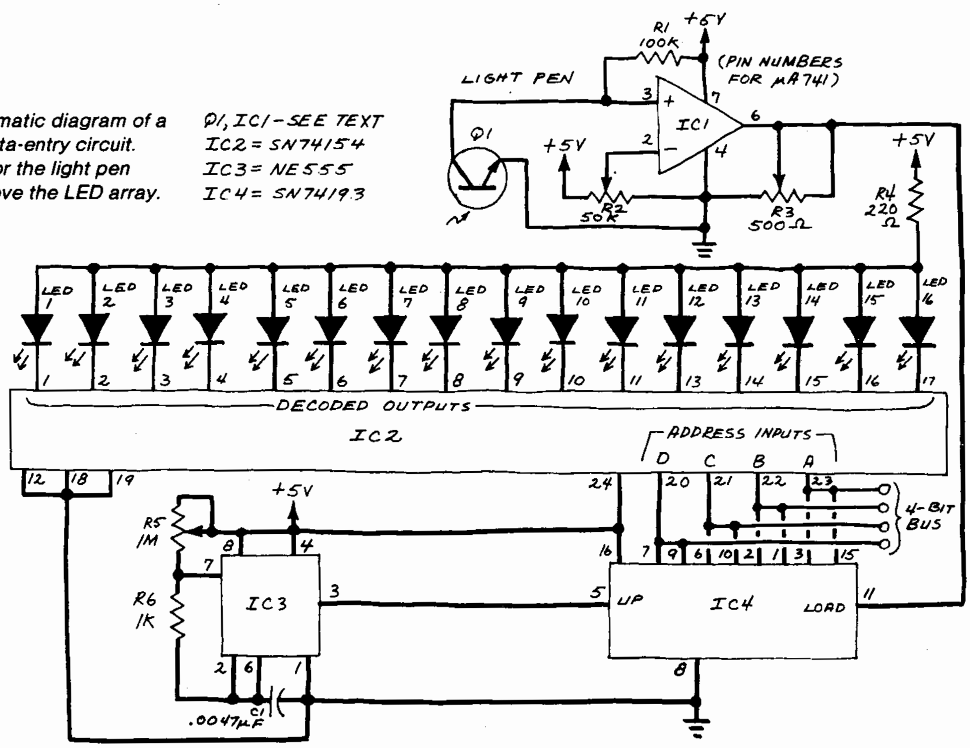


Fig. 5. Schematic diagram of a complete data-entry circuit. The circuit for the light pen appears above the LED array.

address of the selected LED will then appear on the 4-bit bus between *IC2* and *IC4*.

It's interesting to move *Q1* back and forth along the row of LEDs and watch them appear to track its movements. For best results, the scan rate should be adjusted so that all the LEDs glow dimly when none has been selected. ◇

EXPERIMENTER'S CORNER

By Forrest M. Mims

Experimenting with a Light Pen—II

IN part one of this two-part series, we discussed the chief differences between light wands and pens. We then designed a basic phototransistor light pen and experimented with a 16-position, light-pen-controlled data-input terminal.

Adding a Bus Register. The data terminal which was described in Part I can be made more compatible with external circuits by adding a register to its 4-bit bus. The register will ignore any logic signals on the bus until a WRITE switch issues a command to load the register with whatever is on the bus.

Figure 1 shows one simple way to add such a register. The register, a 74175 quad D flip-flop, follows the bus data when its LOAD input is brought to logic one by means of the WRITE switch. The data remains in the register until the WRITE switch is again toggled from HOLD. The contents of the register can be cleared to 0000 by toggling the RESET switch from HOLD to CLEAR.

You'll need to insert three-state transmission gates between the register outputs and the bus. Alternatively, you can use a 74173 4-bit D register with self-contained three-state outputs. This approach is shown schematically in Fig. 2. Note that the 74173 has more control inputs than the 74175. The system clock loads into the 74173 the data present at its inputs when both DATA ENABLE inputs (pins 9 and 10) are grounded by

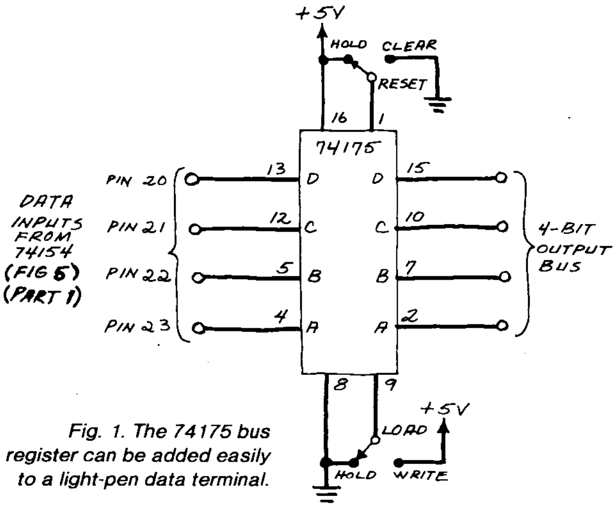


Fig. 1. The 74175 bus register can be added easily to a light-pen data terminal.

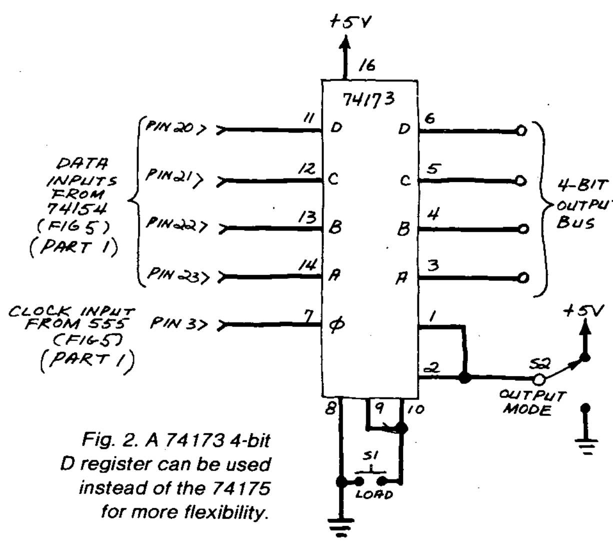


Fig. 2. A 74173 4-bit D register can be used instead of the 74175 for more flexibility.

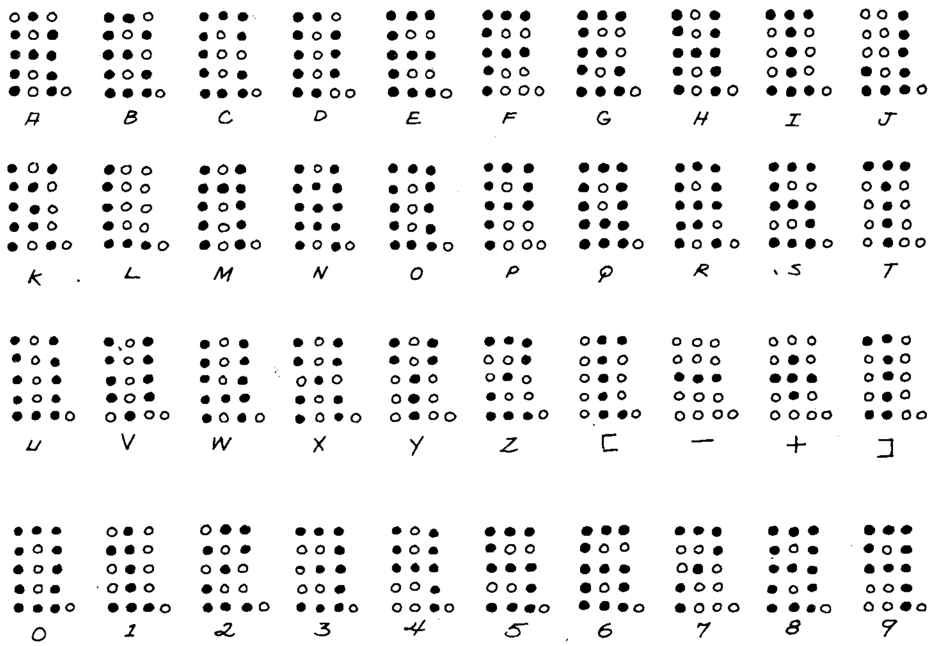


Fig. 3. Letters, symbols, and digits created by 5-by-3 dot matrix.

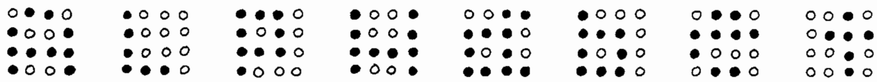


Fig. 4. Upper- and lower-case letters of the alphabet on a 4-by-4 array.

means of *S1*. This means that you must be sure to depress *S1* for at least one clock cycle—which can be a significant interval when the clock rate is very slow.

The outputs of the 74173 and therefore the output bus reflect the data stored in the chip when both OUTPUT CONTROL inputs (pins 1 and 2) are grounded. Should either OUTPUT CONTROL input go to $+V_{cc}$, the outputs enter the high-impedance state and, for practical purposes, the 74173 disconnects itself from the output bus.

A Light-Pen-Controlled LED Display. The basic light-pen data-entry terminal forms the nucleus of a 16-element LED display that can be illuminated in a pattern selected by the light pen.

If, for example, the LEDs are arranged in five rows, four having three LEDs and one having four, then each of the ten decimal numerals plus a decimal point can be formed. Figure 3 shows one possible way to form each decimal numeral or any of the letters of the limited number of display elements, the legibility and appearance of the characters generated are surprisingly good. Arranging the LEDs in a 4 x 4 array makes possible the display of many graphic symbols and some upper- and some lower-case letters. Figure 4 shows some examples.

Hopefully, you are by now as interested as I've long been in experimenting with a circuit having such capabilities. Assuming that you are already familiar with the basic light-pen data-entry terminal described in Part I, we can now begin modifying that circuit for video-graphics applications.

Two principal requirements must be satisfied. First, the circuit must be able to remember each LED location selected by the light pen. Second, the selected LEDs must be substantially brighter than the unselected LEDs.

The solution to the first problem is simply to add a RAM. The second requirement is trickier. Ideally, only the selected LEDs should glow. That's impossible, however, because all of the LEDs must be sequentially strobed to make them eligible for future selection by the light pen. There are several solutions to this apparent contradiction. You can better understand the one that I chose by referring to the block diagram of the complete light-pen-controlled display in Fig. 5.

If you compare Fig. 5 of this part with the block diagram of the light-pen data-entry terminal (Fig. 5 of Part I), you'll immediately notice several important similarities. For example, the configurations of the clock, counter, decoder, bus and light pen are identical in both circuits.

You will also notice some important additions to the circuit. One major addition is a 1 x 16-bit RAM whose address lines are connected to the 4-bit output bus. Also, a LOAD switch connected to the RAM has been incorporated into the light pen.

When a particular LED has been selected by the light pen, closing the LOAD switch records its new status in the RAM. The RAM is able to keep track of the selected LED because the count supplied to the decoder is equivalent to the address furnished to the RAM.

Notice the AND gate that has been connected to the OR array between the decoder and the LEDs. This gate network permits the LED array to be strobed and therefore to display

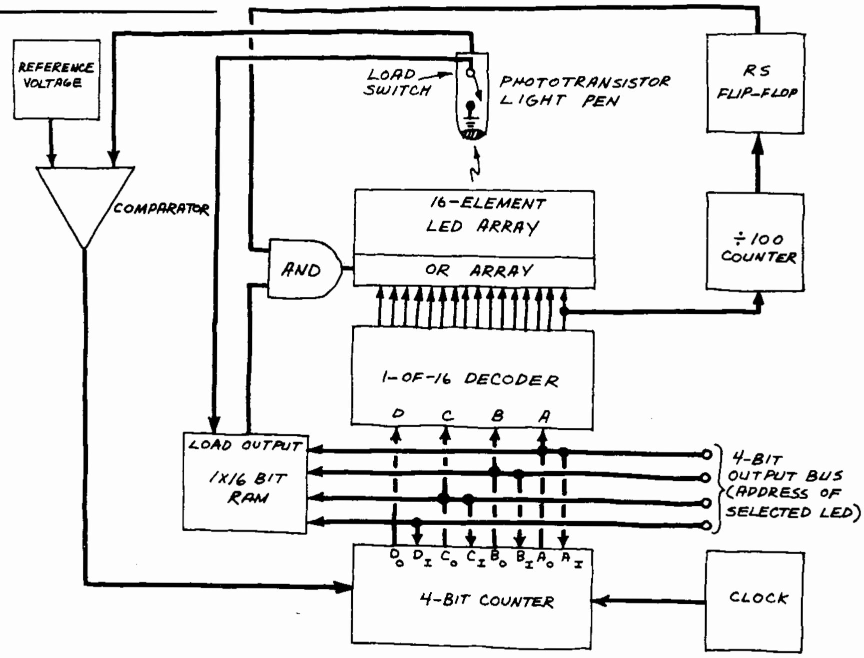


Fig. 5. Block diagram of a light pen controlling a 16-bit LED display.

selected LEDs. Without the assistance of the additional logic, the multiplexing action would be divided equally betweeen the LEDs being sequentially strobed by the scanning circuit and the LEDs selected by the light pen. This means that both the scanned and the selected LEDs would appear equally bright.

This problem is solved by means of a divide-by-100 counter and a set-reset flip-flop. Connecting the flip-flop to the counter results in a combined circuit that is a modified divide-by-10 counter. The output of the modified counter is at logic 0 for ten clock pulses. It then goes to logic 1 for 90 clock pulses. The cycle then repeats.

The outputs of the RAM and the counter are ANDed and the result ORed with the decoder outputs. This is done so that the LEDs selected by the light pen are strobed 90 times during an interval of 100 clock pulses. All of the LEDs are then strobed 10 times during the remainder of the 100-pulse clock interval. The net effect is that the LEDs selected by the light pen are substantially brighter than the remaining LEDs.

(continued on page 92)

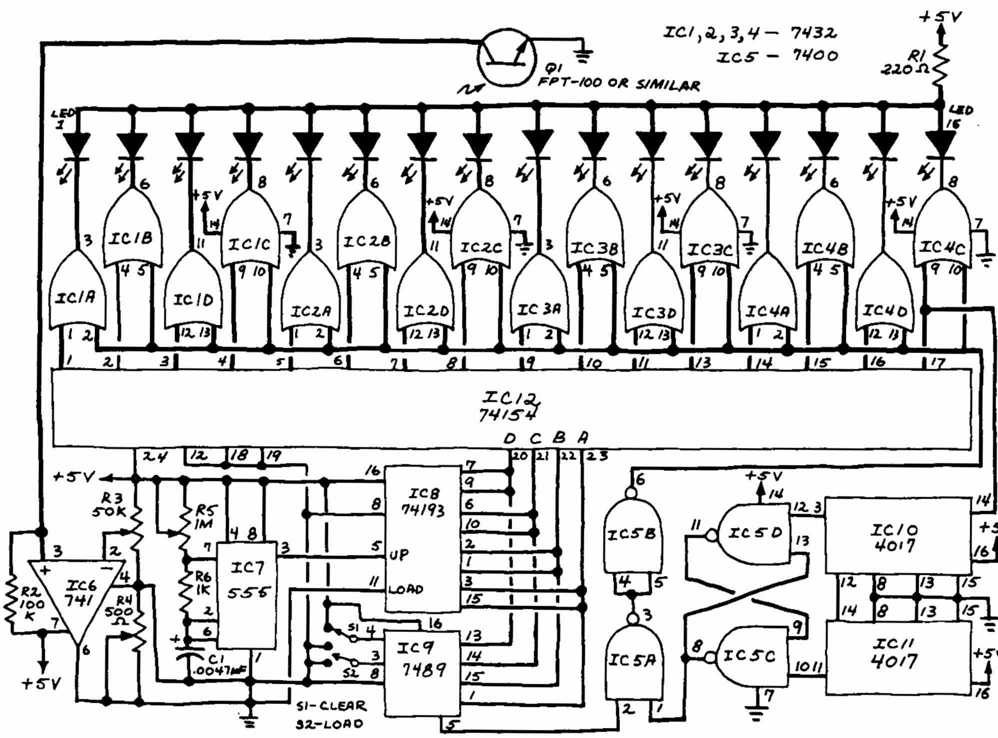


Fig. 6. Complete circuit of a 4-by-4 LED display controlled by a light pen.

It's even possible to extinguish the unselected LEDs for intervals of one second or more by slowing down the clock. The selected LEDs will appear to glow continuously and the other LEDs will blink on every second or so during the scan period.

Figure 6 is the schematic of a practical circuit that corresponds to the block diagram of Fig. 5. Although the circuit appears much more complex than the relatively simple light-pen data-input terminal described in Part I, that circuit forms the core of this one. You can verify this for yourself by noting the almost identical connections of the 555 timer, 74193 counter, 74154 decoder and the light pen comprising *Q1* and operational amplifier *IC6*.

The lowest-order bits in each nibble of a 7489 4-by-16-bit RAM (*IC9*) provide a 1-by-16-bit RAM for the circuit. Although three-fourths of this RAM is not utilized, it's always available should you wish to expand the display.

Two series-connected 4017 CMOS decade counters (*IC10* and *IC11*) and an RS flip-flop made from two gates in a 7400 (*IC5C* and *IC5D*) comprise the circuit's modified divide-by-10 counter. The remaining two gates are configured as a gate that ANDs the outputs of the RAM and the divide-by-10 counter. The AND output is ORed with each of the 16 outputs of the 74154. The LEDs are illuminated sequentially.

Modifying the Circuit. There are several modifications that can be made to the circuit that was just presented. You can eliminate counter *IC11* by connecting pin 10 of *IC5* to pin 11 of *IC10*. This will provide divide-by-10 operation, but the unselected LEDs will be strobed once for every nine times that the selected LEDs are strobed.

There are several ways to substitute other memories in place of the 7489 (*IC9*). You can, for instance, use a MOS or CMOS 256-by-1-bit RAM if you prefer. While only the first 16 bits will be used, the remaining 240 will be available for future expansion of the circuit. You can eliminate RAMs entirely by using an array of flip-flops. The resulting circuit, however, will employ more ICs than the RAM version.

A Long-Range Light Pen. During my experiments with the light-pen circuits that have been described in this two-part series, it often occurred to me how convenient it would be to have a long-range light pen. This would not be possible with red LEDs, however, because the optical power typically radiated by red emitters is measured in tens of microwatts. Also, their spectral emission peaks at approximately 670 nm, halfway down the response curve of most phototransistors.

An infrared LED made from gallium arsenide is much more powerful than a red LED. When, for example, a forward current of 20 mA is flowing, an infrared LED might emit more than one milliwatt of optical power. Also, its near-infrared emission corresponds closely to the wavelengths at which a silicon phototransistor exhibits peak response.

On the assumption that an infrared LED should increase the detection range of the light pen, I connected a General Electric 1N6266 near-infrared emitter in series with one of the red LEDs in the display in Fig. 6. The detection range increased from a fraction of an inch to several inches. I then removed the red LED and connected the infrared emitter in its place. This increased the current through the infrared emitter and resulted in a further increase in the detection range.

Of course, visible emitters must be used in light-pen-controlled displays. Therefore, I tried a GE SSL-3 LED which emits both near-infrared *and* visible green light. This LED, which is no longer manufactured, consists of a gallium arsenide chip coated with an infrared-sensitive phosphor. When forward biased, the chip emits infrared light. This stimulates the phosphor into emitting green light. The result is a visible green beam superimposed upon an invisible infrared beam.

Using the SSL-3 resulted in a light-pen detection range of several inches. But it proved impractical to use an array of such LEDs in the display because the low duty cycle resulted in a barely visible green glow.

My final attempt to extend the light pen's detection range used a simple pnp driver delivering several hundred milliamperes to the LED during each strobe pulse. This resulted in the radiation of enough infrared power to trigger the light pen at a distance of up to ten inches.

The range resulting from the use of infrared LEDs can be further extended by adding a collection lens to the light pen. Theoretically, the detection range will be doubled each time the collection area is doubled. Adding lenses to the infrared emitters is not advisable. This would restrict the detection region of the light pen to sixteen narrow cones of invisible light. The use of only the self-contained lenses of typical infrared LEDs results in a much broader detection region. ◇

Light pen generates plotter signals

by E. Chandan and Agarwal Anant, *Department of Electrical Engineering, Indian Institute of Technology, Madras, India*

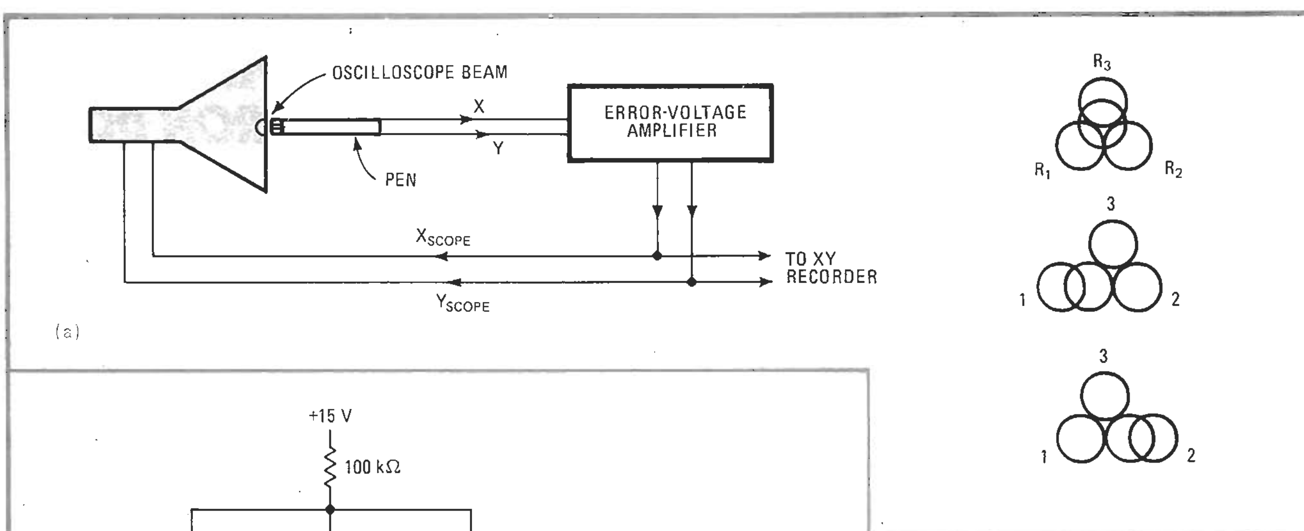
By tracing out the shape of any waveform and sending it to an X-Y plotter or other recording instrument, this photoresistive sensor, in conjunction with an oscilloscope, provides a convenient and inexpensive way to translate hand-drawn data and similar information to a remote location in real time. The sensor requires only three light-dependent resistors (LDRs) and two operational amplifiers. The scope supplies a pinpoint light source that follows the movement of the sensor and thereby generates the required X and Y signals to the plotter or recorder.

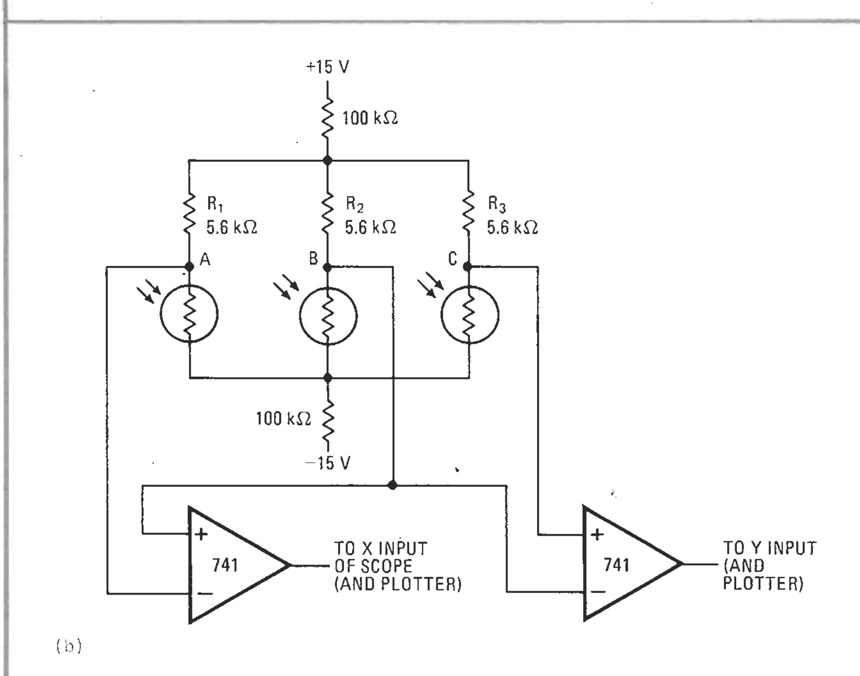
As shown in (a), the faces of three LDRs, each having a diameter of about 4 millimeters, are mounted on the tip of an ordinary pen so that their centers lie on the vertices of an equilateral triangle and in the same plane. The LDRs are then wired into the circuit whose schematic is shown in (b).

The pen is brought within a few millimeters of the scope and thus in proximity to the initially unswept scope trace, which is a spot of light on the screen when the scope is in the X-Y mode. The position of the LDRs with respect to the screen (R_3 at the top, R_1 and R_2 at the bottom) must remain fixed.

When the scope beam (shaded area) is in the center of the LDRs, their corresponding resistances are virtually equal, because approximately the same amount of light hits each device. Consequently, no error voltage (no X_{scope} or Y_{scope} signal) is generated, and the spot will not move with respect to the light pen.

If the pen is moved to the right or left or up or down, as shown, the resistances of the LDRs become unequal, an error voltage is generated, and the scope beam moves in a direction that minimizes the feedback voltage—toward the center of the LDRs. The spot thus follows the





Light pen. An oscilloscope beam will track the movement of three pen-mounted photoresistors, generating a hand-drawn waveform to drive X-Y plotters and recorders (a). The feedback circuitry (b) uses photoresistors to adjust the scope beam to follow the pen's path of motion.

pen and in so doing creates the X_{scope} and Y_{scope} signals used to drive the remote recorder or plotter. Should the pen be removed from the proximity of the screen, the beam spot returns to its original setting.

As the schematic shows, when the spot hits the center of the sensor, $R_1 \approx R_2 \approx R_3$, and so $V_A \approx V_B \approx V_C$. Thus, neither 741 op amp generates any appreciable X_{scope} or Y_{scope} signal and the spot remains fixed. For the second condition, $V_C > V_B > V_A$, and a large positive voltage is generated at X_{scope} to push the beam to the right, while a small Y_{scope} voltage pushes the beam slightly upward. For the last condition, $V_C > V_A > V_B$, and the beam is pushed left and slightly upward. □

Engineer's notebook is a regular feature in *Electronics*. We invite readers to submit original design shortcuts, calculation aids, measurement and test techniques, and other ideas for saving engineering time or cost. We'll pay $75 for each item published.

Computer notes