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The *Self-Tracker*: A Smart Optical Sensor on Silicon

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Abstract

We describe a new method for real-time, three-dimensional computer input that uses a cluster of identical custom integrated circuits as an optical sensing device. The system determines the position and orientation in a room-sized environment of the sensor as it is held or worn by a human user. The sensor is a baseball-sized cluster of outward looking lenses (like a fly's eye). Behind each lens is a custom integrated circuit with circuitry for imaging and image registration. The tracking method detects three-dimensional motion of the cluster from shifts reported by each chip in its one-dimensional image of the stationary environment. The expected advantages of this new approach are unrestricted user motion, large operating environments, capability for simultaneous tracking of several users, passive tracking with no moving parts, and freedom from electromagnetic interference.

We have designed and implemented a prototype chip that includes a one-dimensional camera and circuitry for image registration that we expect to operate at 1000 images per second. As part of this research we have designed and tested photosensors that have been fabricated on standard digital nMOS lines* and that operate in 1 millisecond in ordinary room light with modest lenses. These photosensors may be useful for designers of other integrated optical sensors.

Introduction

In the last 20 years much progress has been made toward realistic computer display of three-dimensional objects. It is now common to display pictures with hidden surfaces, smooth shading, and realistic lighting. Yet when we try to interact with these realistic three-dimensional images we are forced to use devices similar in effect to the remote manipulators used while handling highly radioactive materials. Ivan Sutherland, in 1965, suggested that a solution to this problem was to have a room within which the computer could control the existence of matter[15]; then users could experience and interact with computer generated objects just as they do with physical objects. Later, in 1968, he described the head-mounted display[16], an approximation to the ideal display that generated realistic images in the user's space. The fundamental idea of a head-mounted display[16, 19, 3] is to present the user with a perspective image that changes as he moves. The image is presented using small CRT's mounted on a helmet and it is updated in real time based on the position and orientation of the user's head so the computer generated objects appear to be in the room with the user.

The two major components of a head-mounted display are image generation and tracking. The image generation system of Sutherland's head-mounted display was successful; its descendants are in wide use today as real-time line drawing systems from Evans and Sutherland Computer Corporation. The three-dimensional tracking problem, however, was never satisfactorily solved. Although numerous methods were tried and have been developed since (see Background section), the dominant computer input devices are still two-dimensional and no three-dimensional input system has gained wide acceptance.

Three-dimensional tracking for a system like a head-mounted display is difficult because it must be fast and accurate over a large volume, with little restriction of the user or the environment and must determine both position and orientation. As evidenced by previous work on this problem, this combination of characteristics is difficult to achieve in a single system.

Although the motivating application for a system of this kind is in a head-mounted display, it could also find application in conventional graphics systems as an unconstrained three-dimensional input device, in interactive surface design, in generation of descriptions of objects for computer display, and in human and animal gait studies.

Background

This section is a brief overview of the current state of the art in areas of three-dimensional computer input, and optical applications of digital VLSI.

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Three-dimensional Computer Input

Commercial and experimental three-dimensional computer input systems have been based on acoustic, magnetic, mechanical, and optical sensing. Commercial and commonly used systems are listed here before experimental systems.

Acoustic systems, such as the commercial Spacepen[14], track three-dimensional position using a movable spark gap source and fixed ultrasonic microphones. They suffer accuracy problems from variations in air density and air motion and are limited in working volume to about two cubic meters. They cannot sense orientation and cannot track multiple targets.

Magnetic systems, such as the commercial Polhemus cube[13], track three-dimensional position and orientation using orthogonal magnetic fields and a small magnetic pickup. It provides a limited working volume, about three cubic meters, and is affected by proximity to ferrous materials but is accurate and the part of the system that is attached to the user is small and lightweight. It is currently quite expensive but there are some indications that the price may be dropping.

Mechanical linkage systems such as the custom system used at the University of Utah[19], the remote-manipulator arm at UNC[7], and the Noll box[11], have limited range, about 1.5 meters in any direction, and are restrictive due to the mechanical connection to the user and to friction and inertia in the mechanical system. Also, they make it very difficult to track multiple targets (for example the head and the hand).

All the remaining systems are optical and are listed with commercial systems first followed by experimental systems in order of their publication.

SELSPOT[22] is a commercial system marketed from Sweden by Selective Electric Corporation. It uses camera-like fixed sensors that rely on the sensitivity of a lateral-effect photodiode[21] to the position of a light spot on its surface to determine X-Y location. It can track 30 LED's at 315 samples per second, but is limited to a one cubic meter working volume with two cameras. The working volume can be extended by using three or more cameras but the cameras are expensive. It cannot directly determine orientation but can infer it if the target lights have a known and fixed spatial relationship.

OP-EYE[18], another commercial lateral-effect photodiode system marketed by United Detector Technology, is similar to SELSPOT. It can track a single light source with an advertised resolution of 1 part in 4000 at 5000 samples per second. Like SELSPOT, it provides limited working volume and cannot directly determine orientation.

Twinkle Box, an experimental system developed by Burton at the University of Utah[2], used four fixed sensors to detect light from sequentially blinked LED's that were attached to the user. Each sensor consisted of a slotted disk rotating in front of a pair of photomultiplier tubes. With a sensor at each corner of the room, Twinkle Box provided a working volume of 112 cubic meters with accuracy of 7.3 mm but it required a special flat-black room and generated considerable noise because of its rapidly rotating slotted disks. It could track up to 61 lights per second in a real-time mode or 925 per second in an off-line (record then calculate) mode, but like the systems described above it could determine orientation only from multiple lights with fixed spatial relationship.

The experimental CCD based system developed by Fuchs, Duran, and Johnson[4] used fixed sensors that consisted of a knife edge placed in front of a linear CCD array. The shadow edge caused by a light attached to the user was used to determine one degree of freedom. For sensors of 256 elements the working volume was about one cubic meter with accuracy of 6 mm. This method could be used to track multiple lights by time multiplexing but had to trade off the number of lights against the sensitivity of the CCD array, the brightness of the lights, and the speed that the lights could be blinked. Like the above systems, this method cannot directly determine orientation.

A new lateral-effect photodiode based system developed by the Microelectronics Systems Laboratory of UNC Computer Science allows a working volume of about 6 cubic meters with accuracy of about 1 part in 1000. It determines position in the same manner as the SELSPOT system but uses a new polarization method developed by the Microelectronic Systems Laboratory to directly sense orientation. The target is a light source placed under a cone of polarizing material made so that the angle of polarization of a ray of light can be used to determine the orientation of the assembly. A rotating disk of polarizing material placed in front of the fixed lateral-effect photodiode assembly modulates the incoming ray with a phase shift that is measured by additional circuitry. The major problem is that a very bright light surrounded by a cone of polarizing material must be attached to a target that is to be tracked. This causes problems of power delivery and heat removal and also of user distraction when the light enters his field of view. Another problem is that it is limited to tracking single targets.

Optical Applications of VLSI

Richard Lyon's Optical Mouse[8] was the original inspiration for this research. The optical mouse is a pointing device for positioning the cursor on a display; the mouse is moved around on a pad to move the cursor on the display. Unlike earlier electro-mechanical mice, his circuit detects motion optically using a single downward looking integrated circuit, light source, lens, and a piece of paper with a special dot pattern. It uses the light sensitive properties of nMOS integrated circuits and a "mostly digital" circuit to produce binary snapshots of the dot pattern. It tracks the features in these binary images using an inhibition network matched to the pattern. The entire system, optical sensor, memory, processing, and computer interface is realized an a 3.5 mm by 4.5 mm nMOS circuit with 5 micron features.

Howard Landman, while at the University of California at Berkeley, worked on an optical guitar string tracker that is based on Lyon's ideas. It is a 256 element linear array of nMOS photodiodes with a circuit that detects the first cell to switch. He plans to light the guitar string from below and detect its motion by tracking the light it reflects onto the array.

A group at Siemens AG[6] has developed a chip for focusing cameras that uses two one-dimensional arrays of photosensors to measure range by stereo disparity. Their photosensor is nearly identical to ours, except that they change the bias voltage while ours stays fixed. They were able to use simpler image registration methods than in our processor because their time constraints were much less severe and their images are only 24 pixels.

John Tanner of the California Institute of Technology is working on a *paperless* version of the optical mouse that uses a simple image registration system. He uses a circuit that measures image shifts of plus or minus one pixel to detect shifts in an image of the table top.

New Tracking Method

Overview

Vernon Chi, of UNC's Microelectronic Systems Laboratory, provided the initial inspiration for this research by suggesting that we could track in three-dimensions using something like an Optical Mouse[8] imaging the room instead of special paper. Our new system, which we call the *Self-Tracker*, is an expansion of that idea.

The *Self-Tracker* uses an outward view; instead of looking *in* toward the user from fixed places in the environment (figure 1), the individual chips look *out*, through lenses, at the environment from the user's position (figure 2). Each chip has a small field of view of a different part of the environment. Tracking with an outward view offers the possibility of operating in many different environments, ordinary rooms with ordinary room lights, with little or no overhead for setup. One of us, HF, recalls that this notion was discussed in the computer graphics group at the University of Utah in the early 70's but was not pursued because available imaging systems were neither small enough to be user mounted nor fast enough to follow user motions. This approach is attractive now because of the unique opportunity afforded by custom VLSI circuits to combine, in a small package, the function of a camera with image processing algorithms. This combination allows extremely fast operation resulting in small changes between successive images which in turn allows images to be matched by simple image comparison methods.

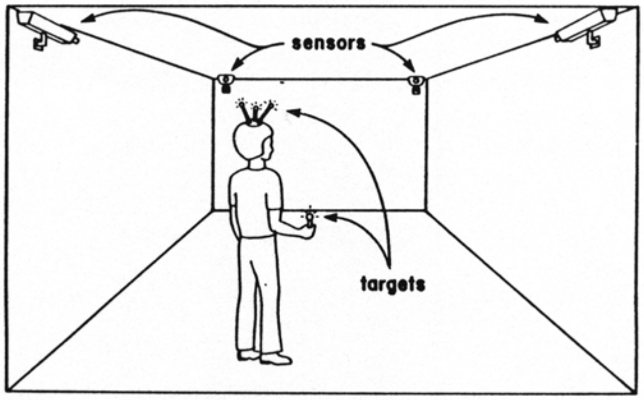

Figure 1 Conventional inward-view tracking

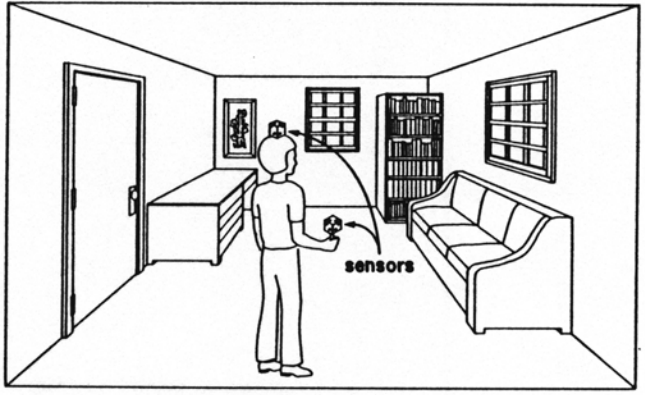

Figure 2 *Self-Tracker*'s outward-view tracking

The device will be constructed as a baseball sized cluster of identical custom integrated circuits arranged with lenses looking outward, in different directions, like a fly's eye (figure 3). Each chip contains a one-dimensional array of photosensors that acquires an image of a small field of view, and circuitry that tracks image shifts, caused by motion of the cluster, by registering pairs of images*. The integrated imaging and parallel image processing circuitry operate at millisecond rates.

To extract the three-dimensional motion of the cluster from the shifts reported by the sensor chips, distance to the scene must be known. We will measure this distance by stereo ranging with pairs of identical sensor chips separated by the width of the cluster. One chip of the pair will be designated, via an input signal, as the master and the other as the slave. Both chips will calculate and report image-to-image shifts and the master

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*Determining the similarities between images is called the correspondence problem in computer vision and cross-correlation in image processing. We use the term, registration, because correspondence implies much more complicated processing and cross-correlation refers to a function that measures similarity everywhere in the image rather than the single point of maximum similarity.

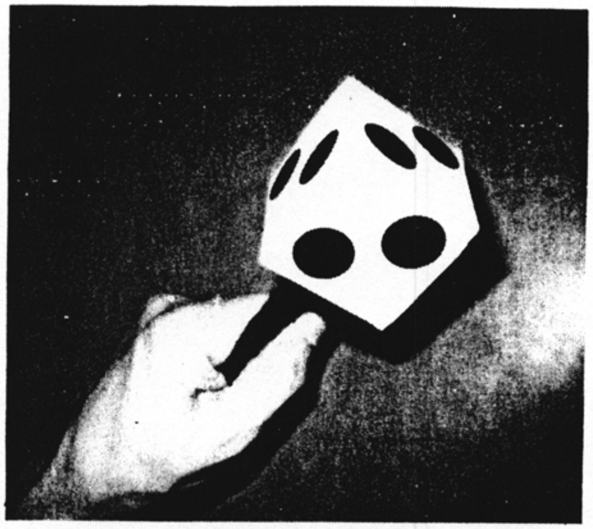


Figure 3 Mockup of a Self-Tracker Sensor Cluster

chip will also report the shift between its image and one that it obtains from the slave. The image registration circuitry will be time-shared between measuring image-to-image shift and stereo shift.

Three-dimensional motions of the cluster will be determined by a connected general-purpose computer from the multiple one-dimensional motions, and distances reported by the chips. The general solution for three translations and three rotations of the cluster of sensors requires solution of a system of simultaneous nonlinear equations in six unknowns with one equation for each sensor. We have developed a linear approximation to the solution that is based on the assumption that all rotation angles will be extremely small because of the high speed of operation. The trigonometric sines of these small angles are approximated by the angle and the cosines by constant one. Simulations of this method show that its error is much smaller than the expected error in the image registration. If improvement in the accuracy of this method is necessary we have developed methods for iteratively improving the accuracy of the result provided by the linear approximation. In the presence of noise (caused, for example, by images that are devoid of features, moving objects in the room and by correspondence errors) the redundant information, available from having many more than the minimum of six sensors, can be combined using optimal estimation (e.g. reference 5).

The *Self-Tracker* senses relative motions and must maintain its position and orientation by integration. Inevitable errors in its measurements of the relative motions will accumulate causing drift. To eliminate this drift we plan, in a later implementation, to use a small number of easily distinguished targets (perhaps blinking infrared LED's) at fixed places in the environment to reduce uncertainty whenever they come into view.

<u>Sensor Chip Design Issues</u>

The function of the sensor chips is to determine correspondence between successive images, a difficult problem in general (e.g. references 17, 1). We have greatly simplied the problem by operating much faster than the 30 images per second commonly used in video systems. Because of our high frame rate in comparison to the speed of human motions, there is very little change from image to image. Photosensors we have designed allow operation at 1000 images per second with a 10 degree field of view. If we assume a maximum rate of rotation of three times that given in industrial time-motion literature[12] for worker head motions, 45 degrees in 240 milliseconds, the maximum shift between successive images is about six percent.

$$maximum\ image\ shift = \frac{3 \times 45 degrees \times 1 ms}{240 ms \times 10 degrees} \approx 6\%$$

Image shifts this small are easy to measure with circuitry that simply registers the images by finding the point of minimum image disparity.

<u>Prototype Sensor Chip Design</u>

Our initial prototype chip is in fabrication at MOSIS and should be available for testing before this report appears. It includes circuitry for imaging and measuring shift between successive images at an expected rate of 1000 frames per second. The chip does not include circuitry for communication with another chip for stereo measurements or for communication with a host processor. It does include circuitry for testing and for reporting the measured shift and confidence, the number of identical bits in the two images. We are fabricating

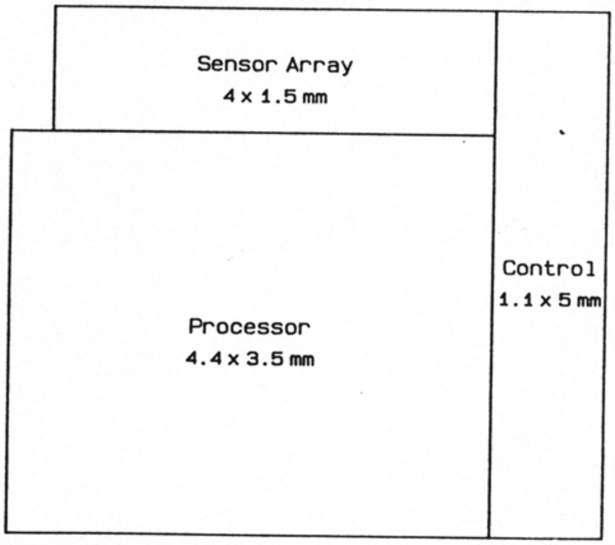


Figure 4 Floorplan of prototype sensor chip
20k transistors with $\lambda = 2\mu$

this simpler design first so that we can verify operation of the basic circuitry and algorithms in a simpler environment and because the complete chip, because of its size, can only be fabricated on the relatively infrequent 3 micron feature runs, while the simplified chip fits on a 4 micron run. The floorplan of this chip is shown in figure 4. Our design goals were one millisecond per image, less than one watt power dissipation, and a chip no bigger than 6 millimeters by 6 millimeters with 3 or 4 micron features.

Photosensor Circuit. Operation at millisecond rates in ordinary room light with lenses of reasonable size requires a sensitive imaging system. Experiments we have done with the photosensor, figure 5, used by Lyon in the Optical Mouse[8] showed that although it is adequate with the large illumination available in that application it was not sensitive enough for use with ordinary room lighting. Increasing the size of the photodiode in this design will not improve the sensitivity because the sensitivity is governed by the threshold of the inverter, not by the photodiode area. Carlo Sequin suggested a circuit, figure 6, for an improved photosensor that we have laid out, fabricated and tested. The sensitivity of this circuit is approximately proportional to the ratio of the capacitance of the photodiode to the capacitance of the amplifier input circuit. With a photodiode of 2500 square microns area and minimum capacitance on the drain side of the barrier transistor this circuit requires an energy density of about two nanoJoules per square centimeter to switch. This sensitivity allows operation in one millisecond with a modest 20 millimeter diameter lens.

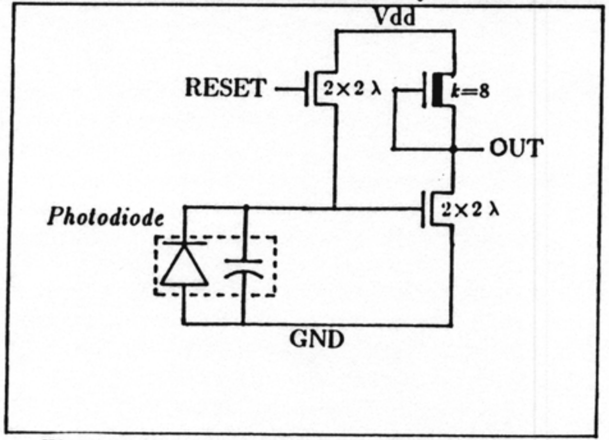


Figure 5 Photosensor from Lyon's Optical Mouse

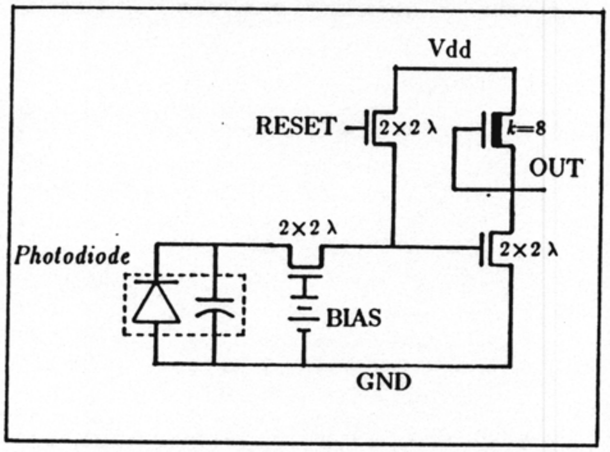
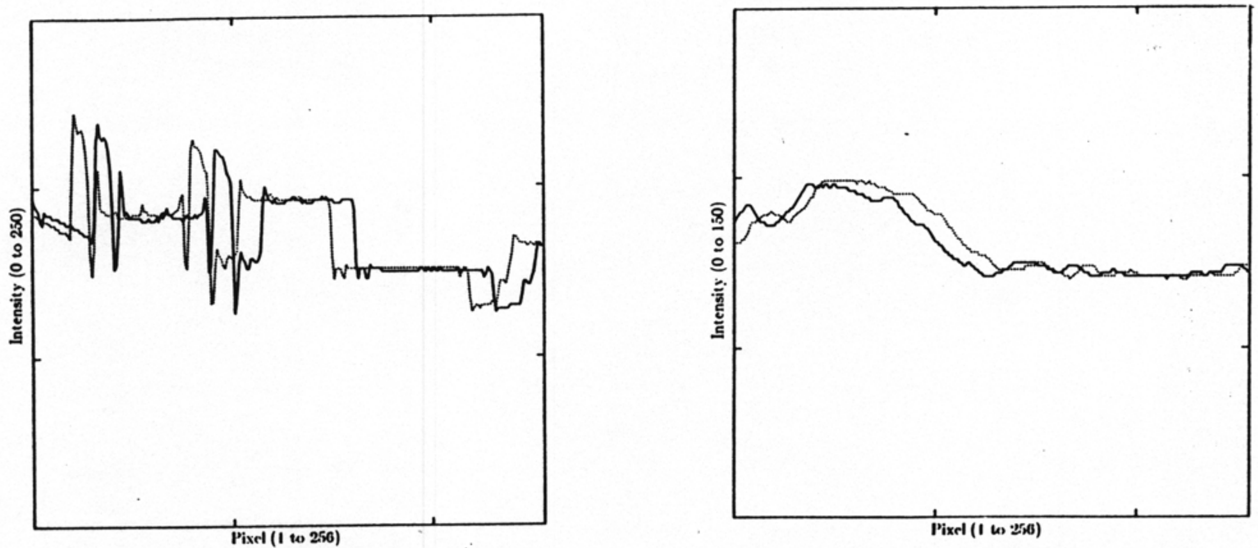


Figure 6 Photosensor suggested by Sequin

Photosensor Array. The photosensors can be arranged as arrays of either one or two dimensions. Our original plan was to use a two-dimensional array because of the naturalness of two-dimensional images. We have chosen, instead, to use a one-dimensional array because it allows better sensor resolution. Sensor resolution, the ability to detect small translations and rotations, depends on the spacing between pixel centers in the array and on the focal length of the lens. One-dimensional arrays allow much closer spacing than two-dimensional arrays because we can design one-dimensional array elements as tall thin cells but two-dimensional array elements must be square to achieve constant spacing in both dimensions. The smaller pixel spacing of the one-dimensional arrays allow use of a lens with smaller focal length for the same sensor resolution, yielding faster operation due to increased light input with the lower f-number lens.

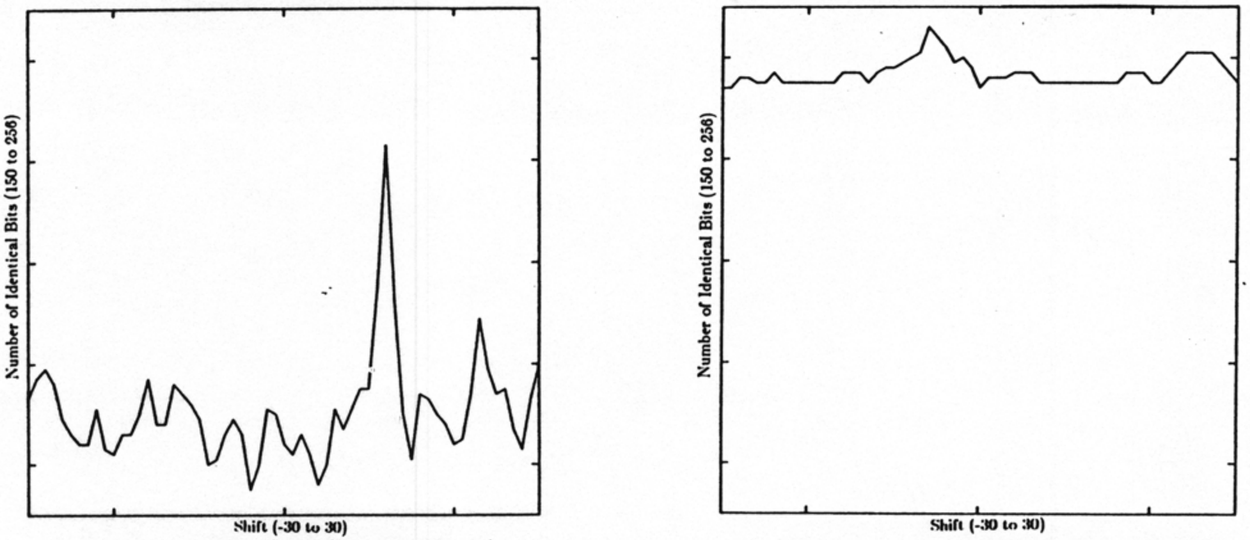
One dimensional images work well for measuring image shifts as shown by experiments done with digitized video images of our graphics laboratory. Figure 7 shows one-dimensional images of our laboratory that were made by processing a digitized video image to simulate a field of view of 10 degrees along the array and 0.5 degrees perpendicular to the array. The two curves in figure 7A and C simulate images taken one millisecond apart at the highest expected rate of head rotation. Graphs B and D are the cross-correlation of the two curves in A and C respectively. Graphs A and B represent the ideal case in which all motion is along the array. Graphs C and D represent the case in which motion is at a 45 degree angle to the array. The definite maximum in the cross-correlation curves are an indication that simple methods may be used to extract image shift from pairs of one-dimensional images.

Forming an Image. The array of photosensors does not provide an image directly; the individual photosensors merely switch from off to on after a delay determined by the incident light. We have experimented with several methods for forming an image including fixed thresholds, variable thresholds, and mutual inhibition[8, 20]. Mutual inhibition is superior to either of the thresholding methods because it responds to local changes in image intensity thus providing information about image features even when the average intensity in the scene varies greatly. We have designed mutual inhibition circuitry that determines the sign of the slope of the intensity function and that produces a signal when the image is complete. The cross-correlations in figure 7 were done on



A. Rotation along the array

C. Rotation at 45 degree angle to the array



B. Cross correlation of images in A after processing by mutual inhibition circuitry

D. Cross correlation of images in B after processing by mutual inhibition circuitry

Figure 7 1D images of our graphics laboratory simulating maximum expected image shift

images that had been processed to simulate the operation of our mutual inhibition circuitry.

<u>Processor.</u> The image from the photosensors and mutual inhibition circuitry is compared to the previous image to determine the amount of image shift. Figure 8 is a simplified floorplan of this processor; the actual processor is folded to fit in a square area. All the registers allow reading and writing to a bus that runs vertically, and those marked S also allow shifting to the right. The IO register is used to serially shift in the image from the sensor array. The two images to be compared are loaded into the **SHIFT** and **FIXED** registers. These two registers are dual ported with the second port directly feeding exclusive-or gates in **XOR**. As the image in **SHIFT** is shifted in relation to the image in **FIXED**, the number of ones in the output of the exclusive-or gates reflects the amount of disparity between the images; the function of the processor is to register the images by determining the shift that minimizes this disparity. The **PACKER** and **DONE/COMPARE** circuits compare the contents of the current minimum register, **MINIMUM** to the output of **XOR**. If the current output of **XOR** has fewer ones than in **MINIMUM**, the new value is loaded into **MINIMUM** and the current shift is recorded by a latch in the **CONTROL** section.

Registering the images requires that we compare the current output of the exclusive-or gates, **XOR** to a previous output, **MINIMUM**, to determine which has fewer ones. This comparison must occur quickly since in one millisecond we want to try 50 different shifts for the motion measurement, 10% in either direction, and, in the complete chip, up to 150 different positions for the stereo measurement, 50% in one direction; we have about 5 microseconds per comparison. An algorithm for a conventional computer might count the number of ones in the output and compare the number with the previous minimum. The silicon algorithm is much different because the tradeoffs on silicon are different than in conventional computers. In silicon we have available massive parallelism but are restricted to local communication and small area. Serial addition of up to 300 bits in the output would require too much time, and parallel addition would require too much area. The approach we have chosen uses a self-timed circuit, **PACKER**, to convert the sequence of ones and zeros from the exclusive-or gates into a unary representation with zeros on the left and ones on the right. We chose to use a self-timed circuit for maximum speed at this critical point in the processing without having to optimize the entire system for high speed operation. The circuit, figure 9, is modeled after the control for the FIFO described by Seitz in chapter 7 of reference 9; it is self-timed but not speed independent. Simulations of this circuit done with Spice 2G.5[10] using specifications from our layout predict 16 nanoseconds delay per stage with four micron features. The worst case for this design is propagating a single one from the far left which takes 16 nanoseconds/stage × 300 stages = 4.8 μs, within the design goal of 5 microseconds. The output of **PACKER** drives **DONE/COMPARE** which detects completion of **PACKER** shifting and compares the result to **MINIMUM**. The **DONE/COMPARE** circuit is made simple by the unary representation of the disparity.

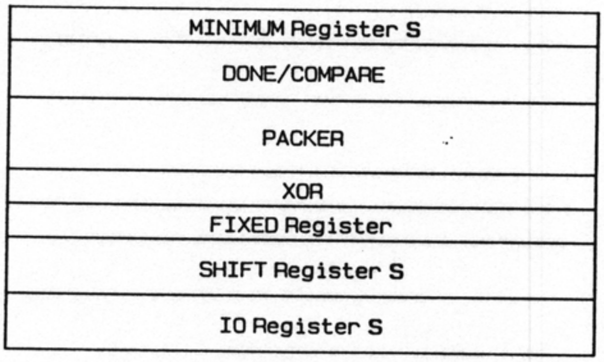


Figure 8 Simplified floorplan of processor

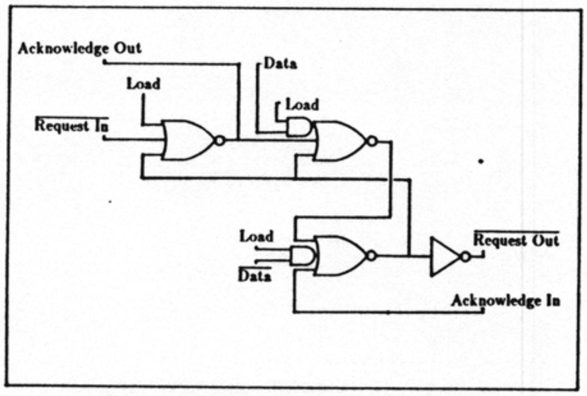


Figure 9 Self-timed packer circuit

Control. The floor plan of the control section is shown in figure 10. The clock circuit generates a two-phase non-overlapping clock signal that can be stopped between phases. Stopping the clock is necessary to allow synchronization with the asynchronous completion signals from the photosensor array and the **PACKER**.

The **DECODE** block generates buffered control signals on the 21 processor control lines from four encoded control signals originating in **MAIN**. The **DECODE** block also provides for processor testing by allowing complete control of the processor from five input pads. Signals on the five test inputs override signals from **MAIN**. The control signals are buffered using bootstrapped drivers suggested to us by Charles Seitz.

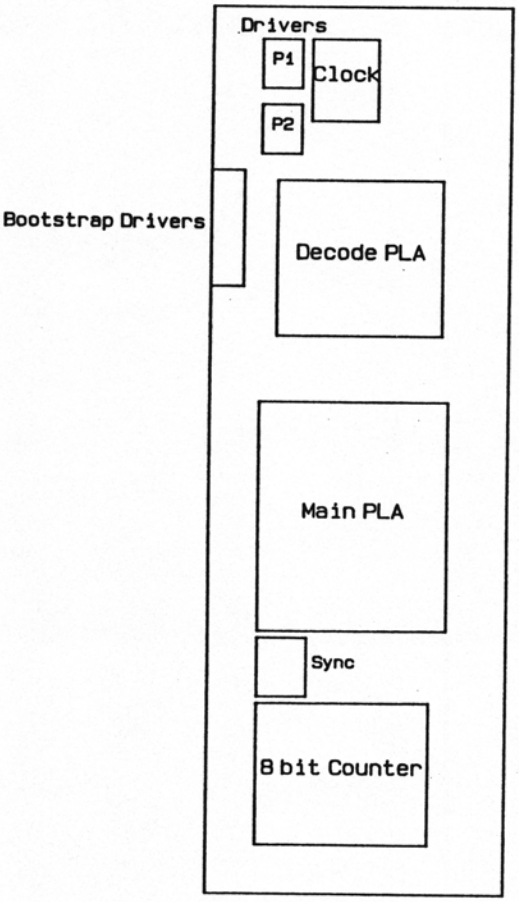


Figure 10 Floorplan of control section

MAIN implements the finite state control of the chip with a PLA and an eight bit counter. The counter is used with a latch to measure and report the image shift required for best registration and the number of disparity bits in the best match. This count of disparity bits is a measure of confidence in the registration.

Additions for a Complete Chip. For use in a tracking system, the prototype chip will have to be modified to include circuitry for stereo ranging and for simplified communication with the host processor. For stereo ranging, one non-shifting register must be added to the processor as a temporary working register. Also the control program has to be changed to include code for measuring the stereo shift. No other changes to the processor are necessary because stereo shift is measured using the same methods as shift due to motion. For communication with the host computer asynchronous bit serial communication can be implemented with little additional circuitry.

Prototype system

For the first fully functional prototype system we have chosen to use a cluster of 10 lenses, each with two chips in leadless chip carriers. Each chip will have an array of 200 to 300 pixels, the processor described above with the extra register for stereo ranging, and circuitry for communication with the control computer. We will use lenses with 20 millimeter diameter and 25 millimeter focal length yielding a field of view for each chip of about 8 by 0.5 degrees. The photosensor arrays will have different orientations to maximize information available about motions. In one millisecond at the expected maximum speed of rotation the maximum change between images will be 16 pixels. If shift measurement is done to one-pixel accuracy, the resolution of a single sensor chip for translations is 1.4 millimeter at two meters and for rotations is 0.04 degrees. We expect to further improve this resolution by combining results of the 20 independent sensor array observations.

Summary

The *Self-Tracker* is a new approach to three-dimensional computer input that determines three-dimensional motion by observing the fixed environment from the position of the target rather than by observing the target from fixed positions in the environment. It uses custom intergrated circuits arranged with outward looking lenses in a cluster like a fly's eye. In the planned prototype, each circuit will compare the position of features in successive 200 to 300 pixel one-dimensional images from a small field of view (8 degrees) at millisecond rates. The small interval between successive images insures that very little change occurs allowing simple image correspondence algorithms. Image changes reported by the chips are interpreted by a separate general purpose computer to determine the three-dimensional motion of the cluster.

Photosensors we have designed and tested are sensitive and small. They have been fabricated with standard digital nMOS processes and operate in one millisecond with normal room light and small lenses. Use of these designs may allow others to easily develop other "smart" optical sensors.

The processor that we have designed, simulated, and are having fabricated uses simple circuitry to determine best image registration quickly. The integration of sensing and processing on the same silicon chip should allow production of an inexpensive system that provides true three-dimensional computer input and that consists of 20 or so identical chips, some small lenses, and a single board control computer.

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