

CHARGE COUPLED DEVICE IMAGE PROCESSORS FOR ELECTRO-OPTICAL POSITION CONTROL

R.W. Armstrong* and E.S. McVey**

ABSTRACT

This paper reports on the development of Charge-Coupled Device (CCD) architectures capable of performing the video image processing required to determine the position of an object subject to translation within a three-dimensional coordinate system. Dimensionality of input data is reduced by using scene "signatures," thus enhancing processing speed. A description of a modified CCD image sensor capable of producing these signatures is presented. All processing is performed using analog data. A new performance index is introduced which, when minimized, establishes object position in complex scenes. CCD architectures are proposed for determining horizontal and vertical position of the image. This research is among the first to consider the use of CCD's for image processing and addresses the important conceptual problem of generating an input-output relationship for a real-time image processor which can be used for control purposes such as pointing and guidance. Potential applications cited include spacecraft navigation and precision celestial image tracking systems under development at the Jet Propulsion Laboratory and automation research at the University of Virginia.

INTRODUCTION

Recent advances in Charge-Coupled Device (CCD) fabrication provide a technological base for the development of devices capable of performing image processing using only a few integrated circuits. This represents a significant advantage in size, weight, power consumption, and speed over current signal-processing systems. Adaptive transversal filters based on CCD technology combine the advantages of hardware speed and low power consumption while retaining the versatility of software and thus can be used as general-purpose building blocks in a signal-processing system.

This paper reports on the development of CCD system architectures. The system performs the image processing required to determine the position of an object subject to translation within a three-dimensional coordinate system. Image acquisition is not considered here, and it is assumed that prior to processing to determine position, some form of pattern recognition is used to ensure that the object of interest is in the scene.

General theoretical models for analyzing scenes to determine image position are not yet available. Techniques described here were developed experimentally and are based on existing signal-processing techniques such as correlation. Moment techniques are used to process "simple" scenes. Image location in "complex" scenes is accomplished via a new performance index based on the Weiner-Hopf equation.¹

*Guidance and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

**Department of Electrical Engineering, University of Virginia, Charlottesville, Virginia.

Image locators intended for use in control systems must operate in real time. Dimensionality of input data is reduced by using "signatures" to represent the scene. This reduces the total number of data points which must be analyzed and so reduces processing time.

This research is among the first to consider the use of CCD's for video pattern analysis to determine object location and addresses the important conceptual problem of generating an input-output relationship for an image processor which can be used for control purposes such as pointing and guidance.

IMAGE PROCESSING

Processing of image data to determine object position is considered in two operations. The video data from the imaging device is operated on to reduce the amount of data to be processed, thereby improving processing speed as previously noted. This is necessary to prevent "catastrophes," which are sudden large-scale changes in position resulting in loss of the image. These initial operations are considered signal processing or feature extraction, e.g. edge detection and spatial frequency filtering. The features output by the signal processor are then operated on by the data processor to determine object position. These two major divisions of the image processor will be considered separately.

Image data has been classified here according to scene type. A simple scene contains only a single object and has pixel intensity values governed by two probability distributions with different mean values - one for the object in the scene and one for the background. Complex scenes may contain more than one object and have pixel intensities governed by more than two distributions. In addition, pixel intensities within an object's boundary may be governed by more than one distribution, allowing interpretation of shadows and varying gray levels on the object's surface for a more realistic representation.

SIGNAL PROCESSING

Mersereau and Oppenheim² have shown that any object can be represented exactly by an infinite number of projections defined as follows. The projection of a two-dimensional array of data along the axis x_2 is given by

$$P_{x_1}(x_2) = \int f(x_1, x_2) dx_1 \quad (1)$$

Using only a finite number of projections, certain information about the image may be derived. Object location may be determined from the projections along the two principal axes of the scene. These signatures are defined for the spatially discrete case as

$$S_H(j) = \sum_i f(i, j) \quad (2)$$

for the horizontal signature and similarly for the vertical signature, $S_V(i)$. This technique is particularly amenable to implementation using a CCD image sensor as the spatially discrete two-dimensional data array. Nondestructive taps are placed as shown in fig. 1. The normal operation of this type of array makes it possible by proper connection of the taps to form both horizontal and vertical signatures in only two shift operations.

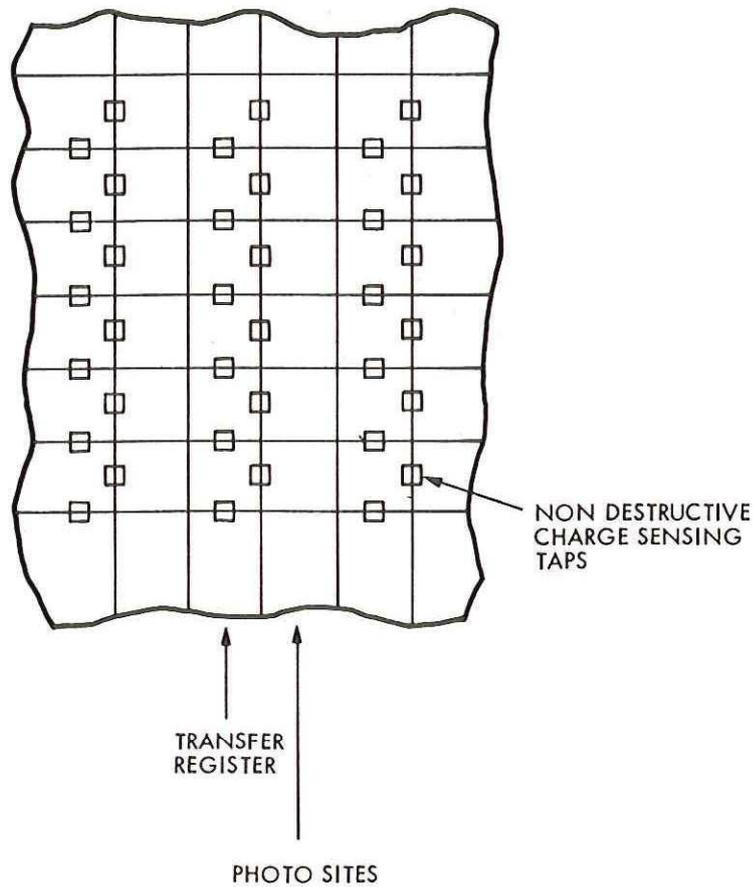


Figure 1. Imaging array with nondestructive taps for image formation
DATA PROCESSING

The relative position of an image within the sensor field of view may be determined in one of several ways depending on the complexity of the scene. Image position in a simple scene may be computed using area/moment techniques. The area technique calculates absolute image position in the field of view using signatures as inputs. Image data in each quadrant of the scene is summed, and the sums are combined in the conventional manner to compute horizontal position. This is equivalent to summing all the elements in each half of the signatures. By subtracting left half sums from right half sums, horizontal position is generated. Similar processing of the vertical signature generates vertical position. This results in the input-output relationship shown in fig. 2, which was generated by moving a light square object from left to right across a dark background. The disadvantage in this technique is that if the image is smaller than a quadrant of the field of view, image position reaches a maximum asymptotic value according to image size. To avoid this problem, the moment technique is used. Signatures are formed as described above. Prior to summing, each element is weighted by its distance from the midpoint of the scene. The left half sum of the horizontal signature now becomes

$$\text{LEFT} = \sum_j w(j) S_H(j) \quad j < n/2 \quad (3)$$

The input-output relationship for the algorithm is shown in fig. 3. Again, the shape and maximum value of the input-output relationship is dependent on the image. The output may be normalized by dividing by the sum of all

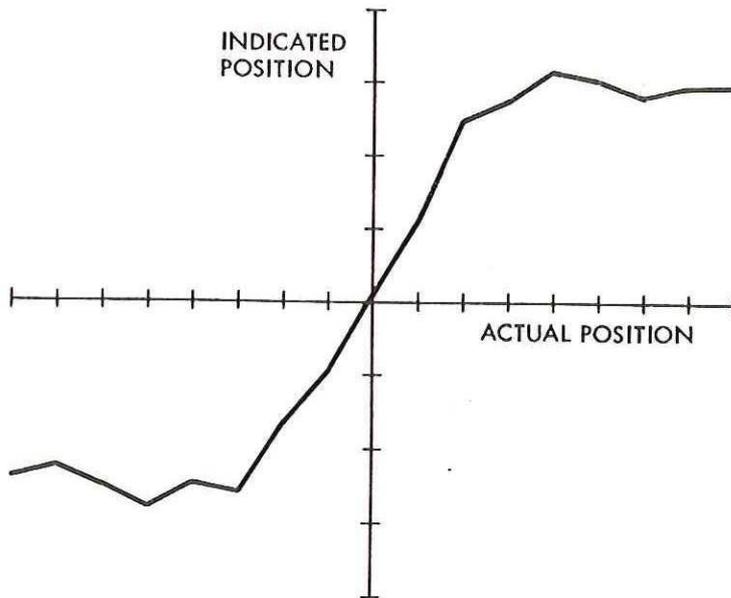


Figure 2. Result of unweighted area subtraction
Indicated position versus actual object position

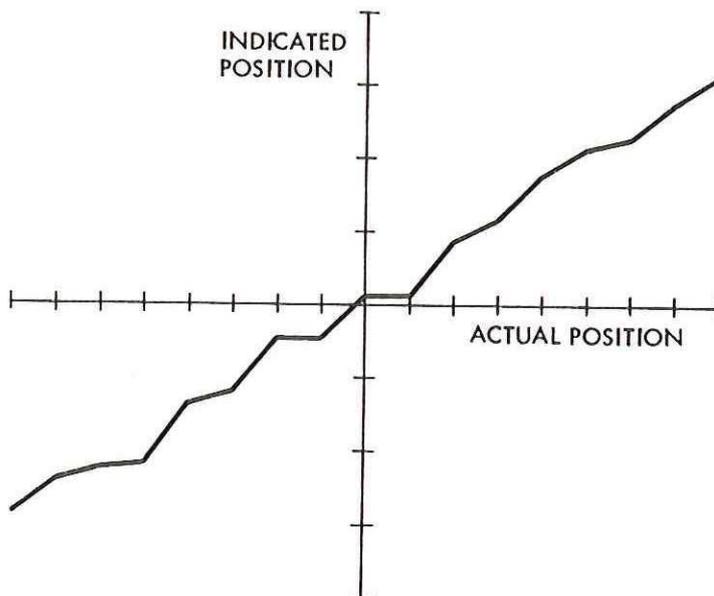


Figure 3. Result of unnormalized weighted area subtraction
Indicated position versus actual object position

pixel intensity values in the scene, i.e. by the sum of all elements of either signature. This has the added advantage that position data is now immune to changes in illumination level. A window may be placed around a given area of the scene by replacing scene signature elements outside the desired window location with zeros. Area/moment techniques may be used to analyze simple scenes containing only one object. If more than one object is present, the scene is complex and more sophisticated processing techniques must be used.

Object location in complex scenes has traditionally been accomplished by template matching via correlation techniques. Image data is correlated with template data point by point until a maximum is achieved. The cross correlation is normalized by dividing by the scene intensity at the template location. Processing all the elements in a two-dimensional array

using a microcomputer is slow enough to preclude real-time operation. Scene signatures are again used to reduce the amount of data which must be processed.

Template data is in the form of a signature and may be stored a priori or generated from the video data representing the first frame of the current tracking sequence. The template signature is correlated against the scene signature for the appropriate dimension, using a new performance based on the Wiener filter. The goal of this performance index is to minimize the difference between the template and scene signatures. Relating this signature analysis to Wiener filtering, the template signature becomes the input signal and the current scene signature is the output. Since it is desired to drive the control system such that the image position within the sensor field of view is constant, the desired output of the image location system is just the template signature.

The Wiener filter attempts to minimize the difference between the input-output cross correlation and the input-desired output cross correlation. This may be seen to be the same as minimizing the difference between the cross correlation of template and scene signatures and the autocorrelation of the template signature. Position data is expressed as

$$X = k; \min J(k) \quad (4)$$

where the performance index $J(k)$ is given by

$$J(k) = | \text{Auto}(k) - \text{Cross}(k) | \cdot \text{Auto}(k) \quad (5)$$

$\text{Auto}(k)$ is the autocorrelation of the horizontal template signature, and $\text{Cross}(k)$ is the cross correlation of the horizontal template and scene signatures. Postmultiplication by the autocorrelation is the normalizing factor equivalent to dividing by image brightness.

The input-output relationship of this performance index is shown in fig. 4 and may be seen to be linear as opposed to that of the area/moment technique, which is highly nonlinear. It must be pointed out that the correlation technique produces spatially discrete outputs corresponding to

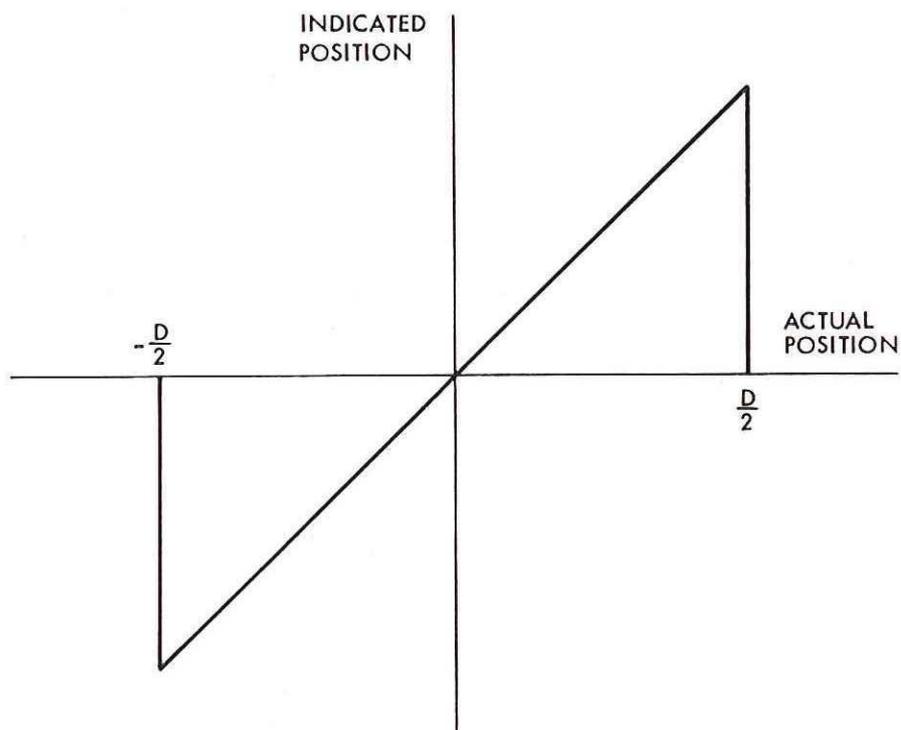


Figure 4. Input-output relationship of correlation tracker

pixel separation in the given dimension; interpolation of position data to less than $\pm 1/2$ pixel is, therefore, more difficult than in the case of the area/moment technique, which provides continuous position output. This makes the area/moment technique superior to correlation for precision tracking applications in which the image will always be within the linear range of the input-output relationship.

PROPOSED CCD ARCHITECTURES

The cross correlation of two inputs may be accomplished in hardware using a transversal filter of the form shown in fig. 5. Mavor and Denyer³ describe such an analog correlator, which uses single transistor FET tap weights to perform four quadrant multiplication. The device uses MOS capacitors to store the reference data while the input data is shifted into a serial in-parallel out (SIPO) shift register. The devices described here are similar in principle but use SIPO shift registers to hold both reference and input data. The conventional template matching process involves a template which is a subset of the input signal, i.e. the template contains fewer samples than the signal against which it is correlated. Each time a correlation is to be performed, the array to be shifted must be loaded with zeros, the data shifted in and correlation performed, and as the last element of data enters the shift register, trailing zeros must be appended. Signature processing correlates two sample strings of equal length.

Another method for performing the shifting operation is by recirculation. This may be accomplished using the multiplexed input recirculating shift register (RSR) shown in fig. 6. Data is entered into the array by turning off the recirculate gate (RG) and pulsing the input gate (IG) until N samples have been entered into the N-element register. Once filled, IG is turned off and RG pulsed to recirculate the data. Charge is transferred from cell 1 to cell 2, etc. in the normal manner, but charge enters cell 1 from cell N rather than from the input. The drain element in the center of the array was introduced by Barbe⁴ as an antiblooming device for CCD imaging sensors. It is used here to clear the array prior to entering new data. The structure is arranged in a closed ring to reduce nonlinearity and increase speed. A rectilinear architecture would require that the charge in cell N be sensed and fed back to the input for reinjection. The added reinjection and sensing of charge is slower than direct cell-to-cell transfer. Also, there is nonlinearity inherent in charge injection not present in direct transfer. It is therefore desirable to confine the charge within the CCD structure as much as possible. The disadvantage in this recirculating shift register architecture is that while data is being circulated, the register is unavailable to external inputs; this slows processing.

An alternative which allows simultaneous loading and recirculation is shown in fig. 7. Two RSR's are arranged in concentric circular arrays with

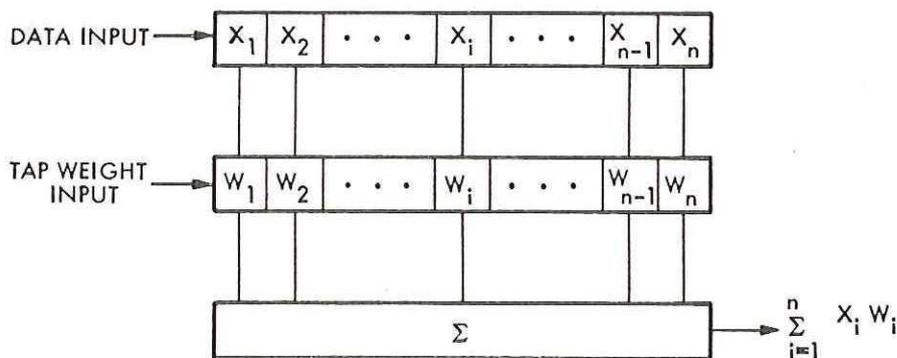


Figure 5. Adaptive CCD transversal filter

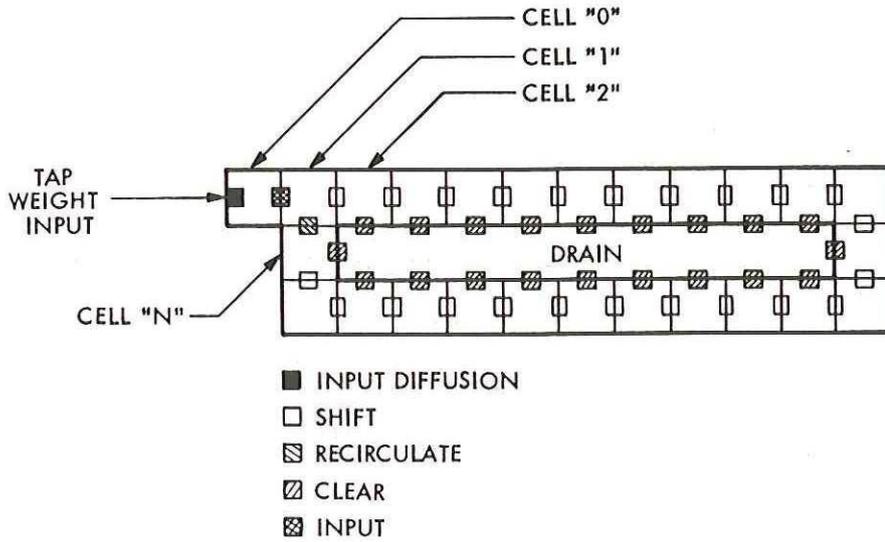


Figure 6. CCD multiplexed recirculating shift register (MRSR)

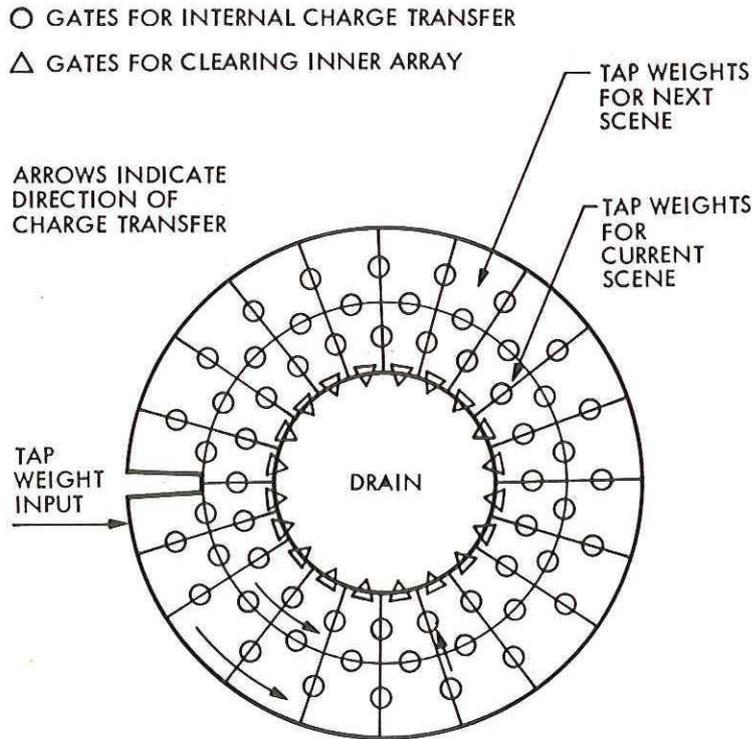


Figure 7. CCD dual array recirculating shift register (DARSR)

a drain cell at the center. The values in the inner register may be recirculated while simultaneously loading the outer array with new data. Operation of the dual-array recirculating shift register (DARSR) is summarized as follows. Prior to data entry, the device is cleared. Two successive parallel transfers move data from the outer to the inner array, then from the inner array to the drain. New data is shifted serially into the outer array, then moved by parallel transfer to the inner array. Data may now be loaded into the outer array as before while simultaneously circulating the data in the inner array. Data in the inner array is the data used in the current computation. New data is entered by first moving the data in the inner array to the drain, then transferring data from the outer

to inner array and finally serial entry of new data into the outer array and simultaneous circulation of inner array data.

The DARSR may now be used to implement the data processing algorithms described above. Entering tap weights of plus and minus one results in the area subtraction algorithm. Weights corresponding to the signature element's distance from the scene center implement the moment algorithm. Tap weights corresponding to the elements of the template signature are used to realize the performance index of equation (5) for object location in complex scenes.

The correlation is performed using the architecture of fig. 5 where the shift registers containing the data are DARSR's. In the case of complex scene analysis, the cross correlation of scene and template signatures and the autocorrelation of template signature are performed in two identical correlators. The cross and autocorrelations are then entered into the architecture of fig. 8. The comparator detects the input element with the largest value and assigns a value of +1 to the corresponding tap weight, resulting in computation of the absolute value of the difference of the cross and autocorrelations. The result is postmultiplied by the autocorrelation to ensure that the comparison of correlations is made only over the domain of definition of the object of interest within the template scene.

DEVICE DESIGN AND FABRICATION

A program is underway at the Jet Propulsion Laboratory to establish a Very Large Scale Integration (VLSI) design capability by training system engineers in device design. The goal is to improve the efficiency of the design process by allowing design of circuits directly in VLSI rather than translating from conventional breadboards. One area of interest involves the design of CCD devices. The transversal filters are being designed as 3-phase double poly devices. Tap weights are formed using the single transistor MOSFET four quadrant multiplier per Denyer.³ Tap weight values are stored in CCD shift registers as explained above rather than on chip

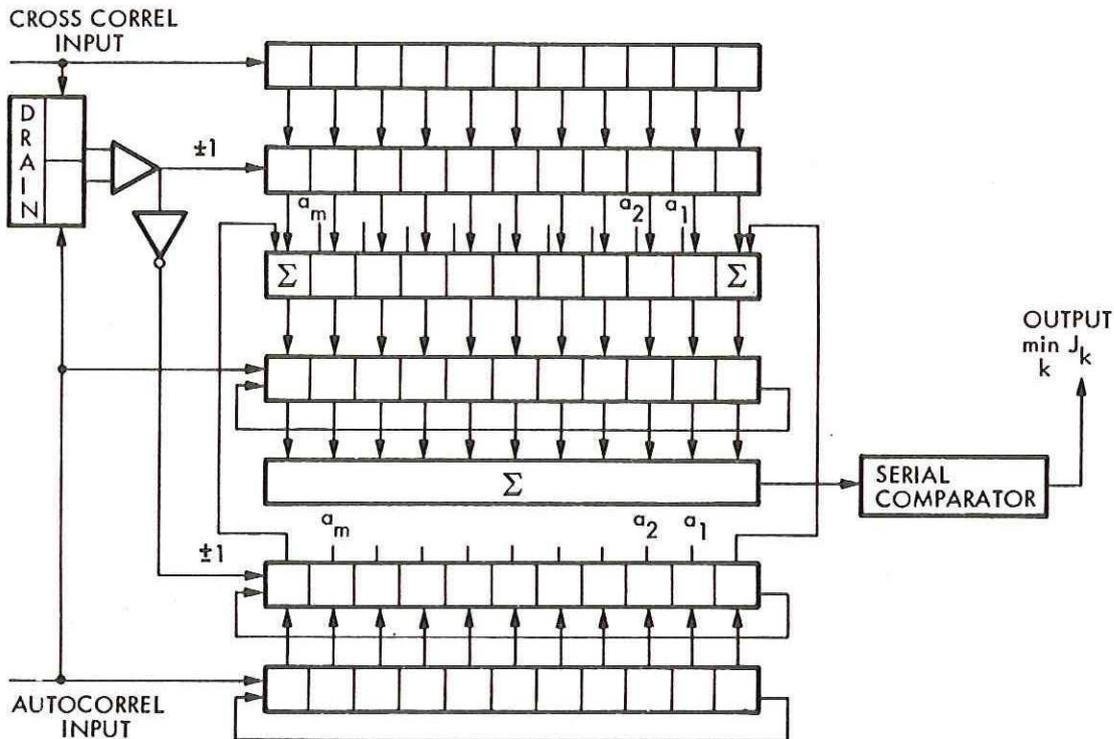


Figure 8. CCD implementation of performance index of equation (5)

capacitors. The devices will use Tompsett inputs with floating gate amplifiers.

APPLICATIONS

The Guidance and Control and Automated Systems Sections at the Jet Propulsion Laboratory are currently developing techniques for incorporating electro-optic position measurement into control systems. Image tracking has applications in robotics and teleoperator systems, spacecraft navigation, and precision pointing of science imaging cameras. It is to the latter two applications that these CCD image processing devices are particularly aimed. The precision pointing and tracking system is a control system which will employ inertial, navigation, and target-referenced video tracking inputs to precisely point science imaging cameras at specific celestial objects for science data acquisition and navigation. A system stability of 0.2 arc-second (one eighteen thousandth of one degree) for target-platform relative angular velocities of 400 arc-seconds per second is the performance objective of this system. Immediate application is intended for use on the Comet Rendezvous Mission tentatively scheduled for launch in 1985. The Precision Pointing and Tracking System (PPTS), which is responsible for pointing the science imaging cameras at the comet, contains a Target Body Tracker, which performs all image processing necessary to establish the position of the image within the sensor field of view. Mission requirements include location of the comet centroid (of brightness) to correct for gyro drift during tracking sequences and precision tracking of such surface features as may be discernible.

Spacecraft systems are designed to stringent requirements of size, weight, and power consumption and must operate unattended for long periods of time. In addition, it is desirable to maintain versatility in the design of data and signal processing to accommodate changes or extensions in mission requirements. The CCD devices described above could perform image processing in the Target Body Tracker with increased speed, lower power requirements, and smaller size and weight than a microprocessor controlled system while maintaining the programmability required to adapt to changing mission requirements during the rendezvous phase. The value of target-referenced pointing will be demonstrated by the Comet Rendezvous Mission and will provide experience for the design of more sophisticated image-tracking systems, which could incorporate pattern recognition. CCD image-processing hardware, and in particular programmable transversal filters such as those described here, are expected to become an important addition to the tools of space exploration and robotic systems. The special architectures proposed are also being used at the University of Virginia for automation research under sponsorship of the National Science Foundation.

ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract No. NAS7-100 and by the University of Virginia under National Science Foundation grant No. ENG76-23990.

REFERENCES

1. R.W. Armstrong, Charge-Coupled Device Architectures for Signal Processing, Ph.D. Diss., University of Virginia, May 1978.
2. R.M. Mersereau and A.V. Oppenheim, "Digital Reconstruction of Multidimensional Signals from Their Projections," Proc. IEEE, vol. 62m, pp. 1319-1338, October, 1974.
3. P.B. Denyer, J. Mavor, J.W. Arthur, "Miniature Programmable Transversal Filter Using CCD/MOS Technology," Proc. IEEE, January, 1979.
4. D.F. Barbe et al., "Signal Processing with Charge Coupled Devices," IEEE Trans. Elec. Dev., vol. ED-25, #2, pp. 103-125, February, 1978.