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Measurement Using Sensor Arrays

This new system may provide a substitute for film in stellar cameras, automatically yielding a real-time readout of stellar and satellite coordinates.

Introduction

Independent investigations by O'Connor[1,3] and Chen[4] provided the basis for the measuring system described in this paper. O'Connor found, as had others before him, that the superior performance of the human eye in a simple visual acuity task in photogrammetric measurement could not be simply explained in terms of the properties of light, the optical properties of the eye, and the dimensions of the retinal receptors. Experimental results showed that the standard deviation of optical settings may be of the order of 1/24 the dimensions of the finest foveal cone.

The classical, or *static*, theories of vision have proved unable to resolve this paradox, and a new set of *dynamic* theories is evolving based on image perturbation caused by the involuntary physiological nystagmus movements, and neural and central factors up to the brain. The physiological nystagmus oscillates the diffraction pattern of an object continuously across the retina for conversion into nerve fiber discharge. The nature and extent of the movements, their role in vision, and the mechanisms underlying their operation continue to be the subject of research, but with a great measure of agreement amongst investigators the following movements have been shown to be present during fixation:

- A *tremor* of mean amplitude of the order of 10 to 15 seconds of arc, and frequency ranging from 20 to 100 cycles per second, with the maximum amplitude occurring at about 50 cycles per second. The maximum angular velocity is of the order of 20 minutes of arc per second.
- A series of very rapid *flicks* or "sacades," whose amplitude ranges from 1 to 25 minutes of arc, occurring irregularly at intervals ranging from 0.03 to 5 seconds. The angular velocity is of the order of 600 minutes of arc per second.
- Slow, unidirectional *drifts* of up to 5 to 6 minutes of arc in the intervals between the flicks, of angular velocity of the order of 1 minute of arc per second.

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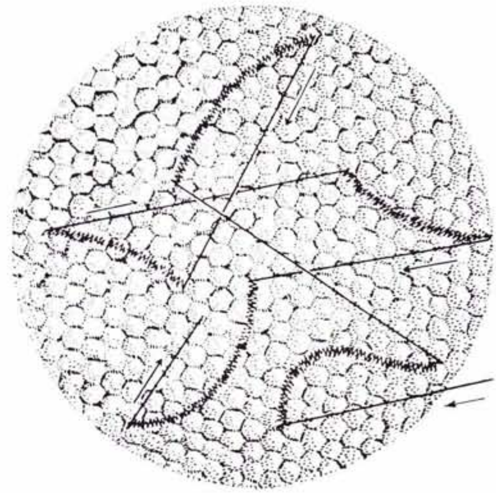

Fig. 1. An approximation showing the nature and extent of the involuntary eye movements that carry an image across the retina during fixation. The three movements are: a *drift* (curved lines) away from the center of vision, a faster *flick* (straight lines) back towards the center, and a high-frequency *tremor* superimposed on the drift. The magnitude of the movements is very small; the diameter of the patch of the fovea shown is only about 15 minutes of arc (75 μm). From Pritchard.[2]

The movements are shown approximately in Figure 1.

There seems to be little doubt that the physiological nystagmus operates to compensate for the grossness of the retinal array in minute visual tasks, and produces nerve fiber discharges. It is, however, the subtle interplay between the elements of the neural system as these discharges are processed and transmitted that provide the most startling effects. The dynamic theory of vision presents a picture of reciprocal overlap, neural recovery cycles, and multiplication of pathways at geniculate and cortex producing neural amplification, border inhibition, accentuation of gradients, and control of thresholds.

The application of some of these principles to a measurement system was developed by Chen[4], and is described in this paper. After a preliminary discussion of array techniques, two experiments are described, the first describing the use of a linear array of photodiodes to measure the distance of a slit-image from a reference axis in the array, and the second the measurement of the distance between two slit-images projected onto the array. The images were oscillated over the array in order to increase the resolution of the array over that which would be expected on the basis of receptor size alone. Two techniques are described, one a mechanical perturbation as mentioned by O'Connor[3], and the other an electronic perturbation after Chen[4].

The full neural simulation will be undertaken in following experiments as the perturbation technique is perfected. In this electronic system, "perturbation" corresponds to the involuntary eye movements. A zero sensing error is obtained by the introduction of an optimal perturbation signal[5] into the system. The effective size of the receptors used in the system, and complexity of the system, are greatly reduced by the introduction of the perturbation. A moderate size of receptor array which eliminates the lead problem is thus possible.

ABSTRACT: *The dynamic theory of vision offers a basis for explaining how a comparatively gross network of retinal receptors is capable of performing visual acuity tasks such as photogrammetric settings with a precision which is much finer than the smallest retinal receptors. The involuntary eye movements, combined with complex neural interactions, appear to be largely responsible for this. A sensing array system which makes use of these concepts has been designed and tested. The introduction of a mechanical or electronic perturbation has enabled the position of a light-point image on the array to be determined with a resolution 20 times finer than the size of an array element. Relative positions of light-point images have been determined. Possible applications of array sensing techniques in photogrammetry and metrology are considered. The system is capable of detecting position, area, shape, and velocity, and may provide a substitute for film in stellar cameras, automatically yielding a real-time readout of stellar and satellite coordinates.*

SENSING ARRAYS

If an image is projected onto an array system, the system is capable of detecting position, velocity, area, and simple shape of image and related object. A block diagram of such a system is shown in Figure 2. The system consists of a receptor array, memory (for some applications the memory may be omitted), signal processor, output indicator, and a control unit. The image in the sample space is projected onto the receptor array through an optical coupling device. The receptor array senses and converts the optical image signals into electrical signals. The array is assumed to consist of equally spaced elements, each of which has an output of *1* if

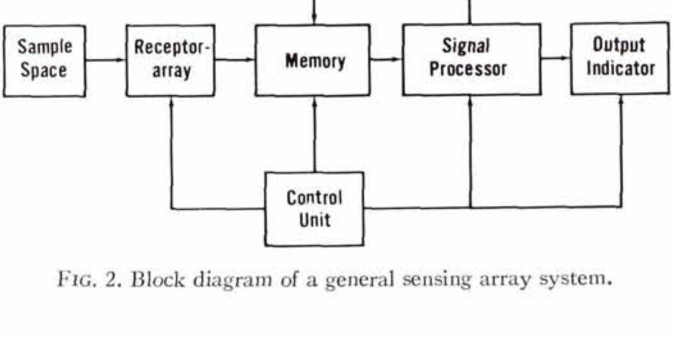

FIG. 2. Block diagram of a general sensing array system.

illuminated to a level equal to, or in excess of, its threshold value, and *0* otherwise. In the general situation, these electrical signals are then stored in the memory. The signal processor that follows the memory operates on the stored signals and produces a signal denoting the position, velocity, area, or shape of the image, depending on the type and the function of the signal processor being used. This signal is then displayed by the output indicator, and also sent to the memory. A control unit is used to control all the system functions.

If a coordinate system is defined with respect to the receptor matrix, the image position can be determined by noting which receptor elements are energized by the image. Velocity information is obtained by introducing time into the receptor array measurements. Velocity measurements require the use of a memory and logic circuits. The area of an image is obtained by summing up all the outputs from the receptors energized by the image. Some simple shapes of image are detected by using pattern recognition techniques. A relatively complicated signal processor is required in this instance.

The receptor is one of the most important parts of the system. Chen[4] has developed a theory which relates the size of the receptor array to the complexity of the input image. A receptor array having square photo-surface elements was assumed for the analysis. The elements of the receptor array were assumed to be packed closely, so that in effect no dead-space (or inactive area) existed. The theory was then extended to the situations where certain dead-spaces were assumed for the receptor array. Both one- and two-dimensional receptor arrays were considered. The size of the receptor array required depends on the complexity of the image and the desired resolution (or detecting accuracy) of the system, directly determines the memory size and the complexity of the electronic signal processor, and therefore the total cost of the entire system. For example, to detect a rotating square with an angular position-resolution of one degree, a receptor array containing 314 $\times$314 elements is required. To detect a moving cube with an angular position-resolution of one degree, two receptor arrays each having 628$\times$628 elements are needed. With this size of receptor array, a translation velocity error of approximately 0.16 percent can be obtained.[4] To achieve angular position resolutions better than one degree, a larger size of receptor array is required, and this is beyond the current state-of-the-art of sensing array technology.

Research is currently being carried out with mosaic sensing arrays[6,7,8,9]. The largest array ever tested was constructed at RCA Laboratories,[6] and consisted of a 256$\times$256 matrix of receptor elements. The primary problem with these arrays lies in connecting leads to each sensor element of the array, because the arrays are very small, (approximately 1 inch square). In order to avoid this problem, most large receptor arrays today use a time-share readout device to read the output signal either from each row or from each column of the array, one row or column at a time. In this way, only a single lead need be connected to a row (or column) of the array, instead of some hundreds of leads.

However, a proposition is presented in this paper which enables one to avoid the complex lead problem associated with a large receptor array. A method is devised which significantly increases the sensing resolution of a small-size receptor array by the introduction of a perturbation signal corresponding to the involuntary eye movements, and which has zero average value. The output of all receptor elements is then summed, and the high frequency components due to the perturbation are removed by a lowpass filter. The filtered output is significantly more nearly linear with respect to the input than in the case without perturbation. The sensing accuracy is improved by an order of magnitude or more.[4] Sine waves and ramp functions were used as the perturbation signals. The theory was then extended towards the determination of an optimal perturbation signal. It was proved that for a linear array having square sensing elements, triangular waveforms with their amplitudes equal to or larger than half the size of the receptor elements are the optimal perturbation signals.[5] A zero sensing error is obtained by the introduction of an optimal perturbation signal into the system. A mechanical scheme for producing the perturbation signal for a two-dimensional receptor array is shown in Figure 3. The moving mirrors are controlled by a servomechanism in such a way as to produce the perturbation of the image on the receptor array.

A zero sensing error was also obtained when a sweep function was applied electronically to the signal processor—an electronic perturbation. In this instance, the constraint of keeping the average value of the perturbation signal equal to zero was not required. As mechanical oscillators are not involved, the system can detect an image moving with higher velocity. The system using electronic perturbation is also relatively simple and more reliable.

Once the perturbation is introduced into the system, the array size can be conveniently determined by the largest variation of the input object position, the size of the sensing elements, and dead-space between elements. The maximum size of the sensing element allowable is governed by the uniformity of the sensing area of each element and the system resolution requirements.

Experimental System and Method

The experiments were conducted with a linear photodiode array of 31 elements, each of size 114 μm$\times$127 μm, arranged with the long dimension parallel with the axis of the array and a 12.7 μm gap between individual elements. Outputs from 8 adjacent elements only were used in these experiments.

A DC amplifier consisting of an FET and three conventional transitors was used to amplify the small output signal produced by light stimulation of each photodiode. An operational amplifier was used as a threshold gate to which an electronic perturbation signal could be applied. An adder was used to sum the weighted outputs of all the operational amplifiers. This adder produced an output voltage whose magnitude was proportional to the center position of the light-image being measured from a reference axis coinciding with the bottom edge of the array. This voltage was indicated on a digital voltmeter. A simplified diagram of the system is shown in Figure 4.

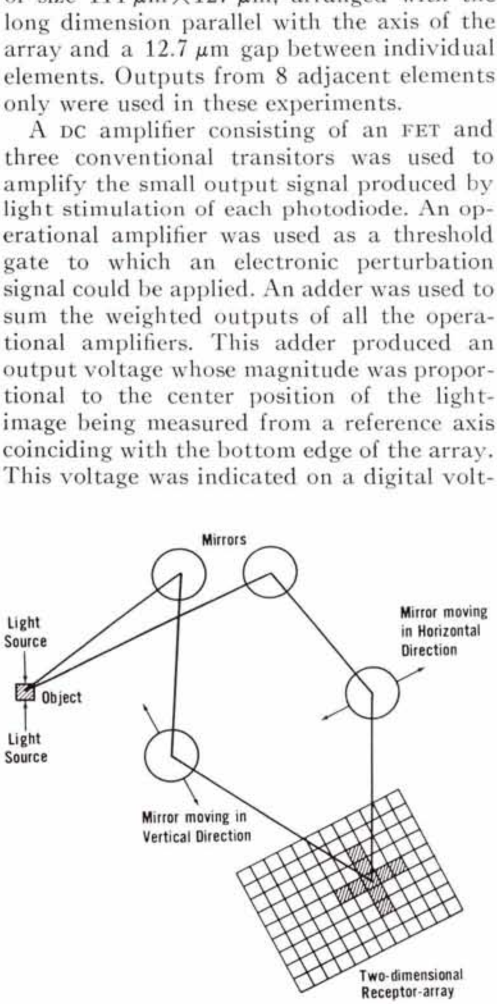

Fig. 3. Scheme for producing two-dimensional perturbation signals.

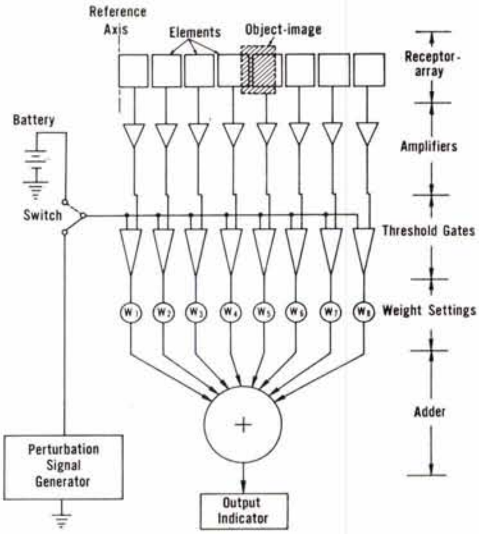

Fig. 4. Simplified diagram of the sensing array system used. The "object-image" was the image of a slit projected onto the array. The object of the experiment was the determination of the distance from the reference axis along the array to the center of the slit image.

The tasks investigated were the measurement of the distance of a single slit-image from a reference axis, and the separation of two slit-images. The slit was illuminated with a tungsten source, projected onto the array through an optical coupling device, and *perturbed* mechanically or electronically over the array.

The slit size was 127 μm$\times$254 μm, with its longer dimension across the array. Mechanical perturbation of the slit-image along the array was achieved by cam actuation of the slit. Two amplitudes (half excursions) were applied, one of 1.5 element lengths, the other of 2.5 element lengths. For the electronic perturbation, a slit-image of size 254 μm $\times$254 μm was used. A sweep waveform of amplitude 1 volt, frequency 1000 Hz, was applied to the threshold gates as a perturbation signal.

In the mechanical application the position of the center of the slit-image was measured, and in the electronic case, the edge of the image remote from the reference axis was measured.

In the single-image measurement, the slit-image was moved along the array by micrometer in increments of .001 inches (25.4 μm) with the perturbation applied. This incre-

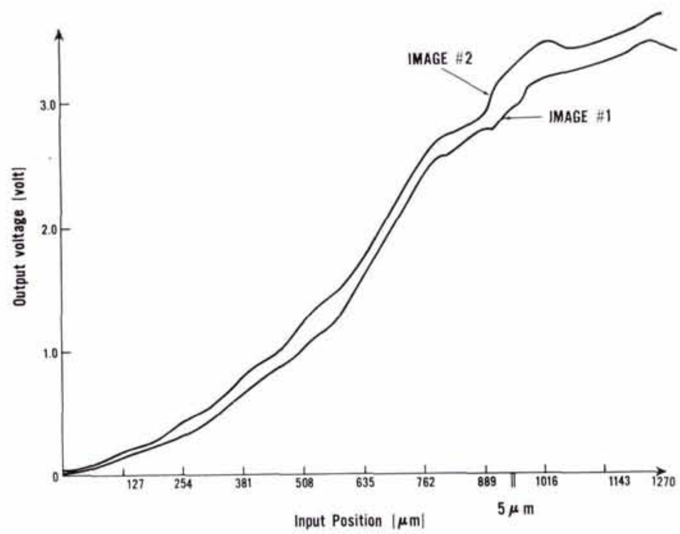

FIG. 5. Response of the system to each of the slit-images used in the difference measurement.

ment can be decreased to 6 μm without loss of accuracy in measurement. Corresponding to this the output digital voltmeter reads 40–50 millivolts.

The separation between the two slit-images was obtained in the following manner: two parallel slit images were projected onto the array from a single source via a beam splitter and micrometer-adjustable plane mirror; the other image was projected onto the array over an equal optical path via adjustable mirrors.

Before the distance difference measurement, the response characteristic of the system was obtained for each slit-image separately, and the results are shown in Figure 5. The linearity was inferior to that obtained with the single slit-image because the intensity of each image is less than half that of the full image. A relatively linear portion of the curves between 1.5 and 2.4 volts was selected for the difference measurement. Because of unequal intensities in each slit-image, the response curves are slightly separated, but this difference was removed by decreasing the intensity of the stronger beam before the measurement. Mechanical perturbation was used with amplitude equal to 2.5 element widths.

The procedure for the difference measurement was as follows:

* Two images superimposed on array with aid of microscope.
* One slit-image covered at a time, array positioned until responses fell between 1.5 and 2.4 volts (Figure 5), and beams adjusted to equal intensity (response).
* One image displaced by known amount with aid of measuring microscope. The displacement chosen had to be resolvable on the output digital voltmeter which was subject to considerable noise because of the comparatively long unstable optical paths. A displacement of 20 μm was chosen here, but in a rigid configuration, considerably smaller separations could be resolved.
* Slit-images obscured one at a time and output voltmeter read; difference in readings is function of linear separation of individual images.
* Image separation checked by measuring microscope.

The actual image separations were averaged from 6 readings of the microscope, and 33 determinations of the input-output relationship were made and included in Table I.

RESULTS

The measurement data indicating output voltage versus input-image position are shown in Figures 6 and 7. Figure 6 is based on mechanical perturbation with amplitudes, B, of 1.5 and 2.5 receptor elements. Figure 7 is based on electronic perturbation. The results of the image difference measurements are shown in Table I. Inspection of the results enables the following conclusions to be drawn:

- With mechanical perturbations of amplitudes 1.5 and 2.5 receptor elements, very close approximations to linear input-output relationships can be obtained for the middle portions of the curves, with the larger amplitude giving better results.
- The effect of receptor dead-space introduces discontinuities into the linear input-output relationship when electronic perturbation is used.
- The output indicator resolution of 40–50 millivolts corresponds to a linear resolution of

TABLE 1. THE RESULTS OF THE INPUT (μM) OUTPUT (VOLTS) RELATIONSHIP FOR THE DETERMINATION OF THE SEPARATION OF TWO SLIT-IMAGES

Actual Image Separation (center to center) (μm)	*Output Indicator Reading (volts)*		*Difference Reading of Output Indicator (volts)*
	Image No. 1	*Image No. 2*	
0	1.99	1.99	0.10
20	1.99	1.89	
0	2.00	2.00	.13
20	2.00	1.87	
0	2.01	2.01	.09
20	2.01	1.92	
0	1.99	1.99	.10
20	1.99	1.89	
0	2.02	2.02	.10
20	2.02	1.92	
0	2.02	2.02	.11
20	2.02	1.91	
0	2.02	2.02	.12
20	2.02	1.90	
0	2.04	2.04	.11
20	2.04	1.93	
0	2.04	2.04	.12
20	2.04	1.92	
0	2.05	2.05	.13
20	2.05	1.92	
0	1.97	1.97	.10
20	1.97	1.87	
0	2.00	2.00	.12
20	2.00	1.88	
0	1.90	1.90	.10
20	1.90	1.80	
0	1.90	1.90	.11
20	1.90	1.79	
0	1.90	1.90	.08
20	1.90	1.82	
0	1.96	1.96	.09
20	1.96	1.87	
0	1.95	1.95	.10
20	1.95	1.85	
0	1.94	1.94	.09
20	1.94	1.85	
0	1.92	1.92	.08
20	1.92	1.84	
0	1.92	1.92	.09
20	1.92	1.83	
0	2.21	2.21	.09
20	2.21	2.12	
0	2.05	2.05	.10
20	2.05	1.95	
0	2.09	2.09	.10
20	2.09	1.99	
0	2.11	2.11	.10
20	2.11	2.01	

TABLE 1. (*Continued*)

Actual Image Separation (center to center) (μm)	*Output Indicator Reading (volts)*		*Difference Reading of Output Indicator (volts)*
	Image No. 1	*Image No. 2*	
0	2.12	2.12	.11
20	2.12	2.01	
0	2.11	2.11	.12
20	2.11	1.99	
0	2.11	2.11	.10
20	2.11	2.01	
0	2.01	2.01	.09
20	2.01	1.92	
0	2.05	2.05	.09
20	2.05	1.96	
0	2.05	2.05	.08
20	2.05	1.97	
0	2.07	2.07	.11
20	2.07	1.96	
0	2.07	2.07	.08
20	2.07	1.99	
0	2.04	2.04	.11
20	2.04	1.93	

Average difference reading $=0.102 \pm .014$ volts, where range is the standard deviation.

the order of 6 μm in measuring the distance of a slit-image from the reference axis. This corresponds to approximately 1/21 of the receptor element size.

- On linear position of the input-output curve, 0.102 volts output corresponded to 20 μm actual separation of two slit-images. The output standard deviation was 0.014 volts, corresponding to approximately 2.7 μm.

DISCUSSION

The fact that the resolution of an array can be improved some 21 times by the introduction of a perturbation suggests that array systems for measurement can be decreased in size and complexity, and consequently in cost. Further investigation of the optimum electronic perturbation signal should improve the linearity of the response of the system, and make possible compact and portable systems without the cumbersome disadvantages of the mechanical perturbation. The reduction in array size will remove the need for the time-share readout schemes now necessary. Input information can then be read, processed, and reproduced on the output indicator in a shorter time than with conventional array systems. Because the perturbation linearizes the non-linear transfer function of the basic receptor, a more accurate output can be obtained for equivalent complexity.

The reduction in size of the array should largely eliminate the lead problem. The per-

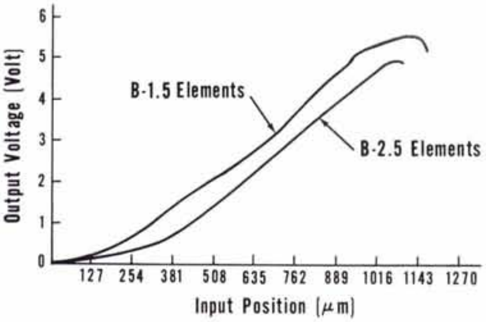

FIG. 6. Input position versus output voltage for mechanical perturbation for amplitudes (half excursions) of 1.5 and 2.5 receptor elements.

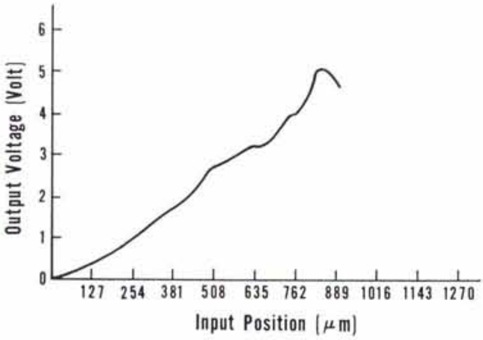

FIG. 7. Input position versus output voltage for electronic perturbation

turbation principal may also be extended to linearize many non-linearities and non-linear devices in electronics and control system theory.[10]

The experiments described in this paper open up a number of interesting possibilities for application.

Because the system can detect the relative positions of points in an object field, it should ultimately be possible to apply it to a wide range of problems in metrology, such as real-time determination of stellar and satellite coordinates by means of a two-dimensional array in the focal plane of a *camera*, or the atmospheric shimmer associated with stars. The slit-separation experiment was the first step towards the realization of this concept, but unfortunately the system instability did not permit the full resolution to be obtained. A better result should be obtained when a larger optical bench is intalled and when a circuitry is introduced to smooth noise from the last digit reading of the output digital voltmeter.

If a sufficiently large two-dimensional array is used, the system is theoretically capable of sensing photographs or maps, and storing them or reproducing them instantly. This could replace scanning techniques. The full system can detect size, shape, and velocity, and this may be used for tracking and recognition.

The array system can be used in process control to monitor dimensional properties of objects.

The perturbation concepts may be used to simplify the commercially available RATINA type optical character recognition machines by reducing the size of the sensing array. Sensor array technology is closely related to the fields of thin films, chip matrices, fiber optics, memories, and optical devices, so the perturbation technique may be expected to have widespread influence.

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