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Evaluation Of An Electro-Optic Remote Displacement Measuring System

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SUMMARY

An instrumentation system to provide a noncontact method for measurement of target positions has been evaluated. The system employs two electro-optic camera units which give stereo information for use in determining three-dimensional target locations. Specially developed, infrared sensitive photodetectors are used in the cameras to sense radiation from Light Emitting Diode (LED) targets. Up to 30 of these targets can be monitored with a sampling rate of 312 Hz per target. An important part of the system is a minicomputer which is used to collect the camera data, sort it, make corrections for distortions in the electro-optic system, and perform the necessary coordinate transformations.

If target motions are restricted to locations in a plane which is perpendicular to a camera's optical axis, the system can be used with just one camera. Calibrations performed in this mode characterize accuracies in single camera operation. This information is also useful in determination of single camera contributions to total system errors. For this reason the system was tested in both the single camera and two camera (stereo) modes of operation.

INTRODUCTION

Photogrammetric approaches are often used to determine the topology of inaccessible surfaces. This is especially true when introduction of a probe would alter the flow field as with wind tunnel testing. This paper describes the evaluation of an electro-optical ($Selspot_R$) system manufactured by the Selective Electronic Company (SELCOM) in Sweden.

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The system was evaluated in two stages. A single camera mode was used to determine two dimensional location while two cameras were used to locate targets in three dimensions. An existing minicomputer was used to collect and process the data. While the evaluation of the Selspot system was the primary objective, an important development toward this objective was the integration and modification of a 3-D transformation algorithm in the minicomputer. This algorithm, the Direct Linear Transformation (DLT), developed by Abdel-Aziz and Dr. H. M. Karara in 1971,[1] establishes a direct linear relationship between a pair of two-dimensional stereo coordinates of target points and their corresponding object space coordinates. This algorithm, along with many other programs developed for data collection, sorting and subsequent analyses combine to form a data processing technique for this application.

SYSTEM DESCRIPTION

Three separate systems were required to evaluate this noncontact displacement measurement technique:

1. An optical bench structure was needed to position targets and cameras and a calibration fixture was needed to hold an array of diodes whose relative positions could be accurately measured.

2. The Selspot cameras and associated electronics were needed to optically sense target locations and to convert the optical signals to electronic signals.

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1. Abdel-Aziz, Y. I. and Karara, H. M., "Direct Linear Transformation from Comparator Coordinates into Object Space Coordinates In Close Range Photogrammetry," Proceedings of the ASP/UI Symposium on Close-Range Photogrammetry, Urbana, Illinois, January 1971.

3. A minicomputer was needed to collect and store the Selspot data. The same minicomputer was then used to process the stereo camera data using the transformation algorithm to provide the three-dimensional target locations.

These three systems will be discussed more fully in the sections which follow.

Object Space Coordinate Reference Structures

In order to calibrate a three-dimensional displacement measuring system, a spatial reference needed to be established. The structure, shown in figure 1, consisted of various sizes of optical bench modules. The modules are extruded aluminum tubes which have been straightened and anodized with a black noncorrosive coating. Accessories can be mounted to slides on any four dovetail rails. Each of these rails has an inlaid metric scale to assist in positioning. Using this structure, and a cathetometer, absolute target positions could be defined to within 0.38 millimeters (0.015 in.).

A test fixture was constructed which held up to 52 light emitting diodes (LED's) in 5 parallel planes. Figure 2 shows the fixture with 40 of the diodes mounted. The relative spatial locations of the diodes in the fixture were established to an accuracy of plus or minus 0.0254 millimeters (0.001 in.) using a Cordax precision measurement machine.

Selspot System

The heart of this system is a specially developed camera containing a photodetector sensitive to infrared emissions. Infrared radiations from LED targets are focused on the detector surface, through a 50-mm lens system, and electrical signals are generated. Turning the LED's on and off at a high rate in such a way that only one diode is on at a time, up to 30 diodes can be located at nearly the same time. By synchronizing the signal processing circuitry, the voltage pulse location in a pulse string is related to each diode. Figure 3 illustrates this operation for five diodes where lines A-E show pulses produced by an LED control unit which turns on diodes 1-5. The synchronization is achieved through an additional time delay between diode 1 and diode 2. Line F shows the string of pulses produced from the camera signals. The pulse string is repeated each 3.2 msec providing 312 samples per second for each diode.

In the camera detector, four voltage pulses are produced (fig. 4) when a light pulse is received. The horizontal position on the sensor is proportional to (Vx-Vx') and the vertical position is proportional to (Vy-Vy'). These signals are normalized to compensate for light intensity variations and then are digitized. Additional coding is added to the digital signals to indicate if intensity levels are too high, too low, or if synchronization is lost. The time division multiplex of the two cameras' signals is output to the computer in the sequence shown in figure 5. The signals are digitized and output to the computer in a 16-bit word format. Four of these bits are information about power, synchronization, and light intensity. The remaining 12 bits comprise a count ranging from 0 to 4096. Since the data are digitized to 10 bits, there are only 1024 values, and the resolution is 4 counts. Figure 6 is a block diagram of the Selspot system.

Minicomputer and Software

A minicomputer with thirty-two thousand 16-bit words of memory was used to collect, store, and process the data. Since large amounts of data are generated from the Selspot system, the data were collected by the computer and stored on digital magnetic tape. Software routines were needed to collect, sort, test, and mask the data (to correct for distortions) and finally to transform the stereo information to three-dimensional coordinate locations. A software algorithm for transforming the stereo data from the cameras was provided with the Selspot system. Attempts to use this software proved futile. The algorithm required that the two cameras be alined such that their optical axes intersect. The legs of the triangle formed by this intersection and the two cameras then had to be measured accurately. The determination of the cameras' optical axes is not a simple task, and the technique provided with the Selspot system did not work. Since algorithms exist which do not require precise camera alinement, the Selspot transformation software was not used.

The algorithm selected (DLT) was an adaptation of a program which had been used on a large computer and was then modified for use on a minicomputer. Although the minicomputer word size is 16 bits (60-bit words were used in the large computer), comparable accuracies can be achieved by using extended precision arithmetic in some of the critical matrix operations. The DLT program requires the X, Y, Z spatial location of a minimum of six control points (targets) along with the two-dimensional sensor location of these targets from each of the cameras. From this data, "DLT parameters" (information about camera locations, orientations, and magnification factors) are determined. Once these have been determined, the three-dimensional coordinate locations of other target points can be computed from their stereo camera data. Appendix A describes the DLT program.

Calibration Procedure

Calibration could be broken into separate phases; error correction of the camera data, static and dynamic calibration of one camera, and finally static and dynamic calibration of the stereo pair.

Error Correction

The sensors in the cameras which convert the infrared optic signals to electric signals have considerable nonlinear characterisitcs and the camera's lens produces additional distortions which add to these nonlinearities. For these reasons, the cameras had to be calibrated to compensate for these effects. An error correction algorithm was provided with the Selspot system and was used for these calibrations. In this procedure, the camera field of view is arbitrarily divided into 49 squares having 64 corner points. Calibration data for the 64 points were collected by using a horizontal bar with 8 equally spaced diodes and positioning the bar on the optical structure at 8 vertical locations separated by distances equal to the diode separations. The camera was alined (also on the optical structure) so that its optical axis was perpendicular to the plane of the 64 points. While the active sensor area is spanned by 4096 counts some 256 are lost along the borders due to severe distortion. Thus, the grid point locations in both X and Y directions span locations 256 through 3840 in equal intervals of 512 as shown in figure 7. Diodes were approximately placed in the (2,4), (4,4), and (7,4) locations and their positions adjusted to give outputs of (768,1792), (1792,1792), and (3328,1792). Measured deviations from the idealized locations at each of the 64 node points are used to compute error correction values for these points. Camera to target plane distance was 159.6 cm (62.8 in.), and diode matrix separation was 10.16 cm (4.0 in.). Figure 7 (solid lines) shows a plot of the raw calibration data for one of the cameras. Figure 8 shows the same data after corrections have been applied. The dotted lines indicate the grid which would be formed if there were no distortions and the sensitivity was constant throughout the field of view. Each data point was corrected using correction values from the 4 closest points. If E_{11}, E_{12}, E_{21}, and E_{22} are the error correction values at the corners of a square, the error E of a point inside the square (fig. 9) can be expressed to terms linear in X and Y as:

$$E = E_{11}(1-X)(1-Y) + E_{12}(X)(1-Y) + E_{21}(1-X)(Y) + E_{22}XY$$

where:

X, Y are the unit normalized distances between nodes in the X and Y directions and referred to the lower left node.

The error correction data were collected and stored on digital magnetic tape for each of the cameras and used in subsequent calibrations. Once correction values are applied, a scale factor adjustment is still required.

Single Camera Static Calibration

With one of the cameras positioned as it was for collection of the linearization correction data, the horizontal bar (with 8 target diodes) was moved to 5 vertical locations in the camera's field of view. A range of approximately 71.1 cm (28 in.) in "X" and 35.6 cm (14 in.) in "Y" was utilized. Data were collected, scaled and linearized with the correction data. The actual diode locations were determined using a cathetometer. A reference was established by noting the location of diode 5 with the bar approximately centered in the field of view. All measurements were made relative to this point, and the average relative errors of the 40 diode locations were:

$$\overline{|E_x|} = 0.081 \text{ cm } (0.032 \text{ in.})$$

$$\overline{|E_y|} = 0.079 \text{ cm } (0.031 \text{ in.})$$

The maximum relative errors were:

$$\overline{|E_x|}_{max} = 0.297 \text{ cm } (0.117 \text{ in.})$$

$$\overline{|E_y|}_{max} = 0.330 \text{ cm } (0.130 \text{ in.})$$

The average errors were on the order of the system resolution as limited by the 10 bit digitizer in the Selspot electronics.

Single Camera Dynamic Calibration

Once again a camera was positioned so that its optical axis was perpendicular to a plane on the optical structure and a single diode was attached to the pen of an X-Y plotter. The plotter was mounted on the optical structure such that the plotting surface was perpendicular to and approximately centered on the camera's optical axis. The plotter pen, and thus the diode, were swept vertically at a constant rate and the pen's horizontal motion was controlled by driving the plotter with a sinusoidal signal. The 21.6 x 27.9 cm (8.5 x 11 in.) plotting range limited vertical (time) sweeps to 25.4 cm (10.0 in.) and horizontal sinusoidal amplitudes to 20.3 cm (8.0 in.) peak to peak (P/P). Twelve tests were conducted in which the signal amplitude for each frequency was varied while remaining within the slewing limits of the plotter. Data were collected, scaled, and error correction values applied for each test. The results were compared to the plots made by the plotter pen. Table 1 lists the results of these tests. The Selspot data were processed over a 1000-point range (3.2 sec). The X computations were made by comparing peak to peak displacements on the plotter with the processed camera data. The vertical (Y) motion of the plotter was measured for that same time period and compared to the corresponding Y data from the camera.

It should be noted that amplitude limitations at higher frequencies were due to the slewing limits of the plotter. The frequency response limit of the system is inherent in the system sample rate and the Nyquist theorem. The errors in the "Y" measurements tended to be greater than the peak-to-peak "X" measurements. This is due to the fact that many values were used to determine the "X" measurements, but only two values are used to measure the "Y" motion (the first and last of the 1000 samples.)

Stereo Camera Static and Dynamic Calibrations

The procedures for the two-camera (stereo) calibrations were identical to the single camera cases with the following exceptions:

1. The two cameras were positioned so that their fields of view overlapped the target field; their locations were such that the angle formed by their optical axes was approximately 90 degrees and the distance to the center of the target field was about 159.6 cm (linearization calibration range).

2. Prior to collecting the calibration data a test fixture containing 40 diodes was carefully positioned to establish a three-dimensional coordinate system. The data for these diodes were collected from the cameras and used as control points in establishing the Direct Linear Transformation (DLT) parameters. These parameters establish the cameras' locations, orientations and internal characteristics which are necessary for data transformations.

3. After applying error correction values to the calibration data the DLT was used for processing it.

The results of the stereo calibrations were not as good as those for the single camera. The static test yielded average errors:

$$\overline{|E_x|} = 0.086 \text{ cm } (0.034 \text{ in.})$$

$$\overline{|E_y|} = 0.172 \text{ cm } (0.068 \text{ in.})$$

This was the case when making all measurements relative to one of the diodes on the bar as was done in the single camera case. Absolute errors from locations in the 3-D coordinate system established by the 40 diode test fixture were found to be a little more than 2 times as large. This was due to systematic errors in the measurements. More will be said about this in the section which follows.

The measurements in the dynamic test were relative, and the results are shown in table 2. The same comments made in the single camera test apply here.

DISCUSSION

While the error correction program removed some of the system nonlinearities it did not provide for sensitivity differences at different locations in the target field of view. If the plot in figure 8 is examined closely, it is obvious that while the lines are fairly linear, the distance between the lines is not constant. This caused errors in the stereo calibration data for "Y" which were greater than those for "X." The target moved through a larger region of the grid for "Y" than the largest "X" motions. The sensitivity variation problem was also worse in "Y" than in "X." Corrections could be made in the error correction program to compensate for these sensitivity variations. It also would be desirable to use a linearization grid with better resolution. Eleven diodes could be used to provide 100 square areas in the field of view rather than 49. The single camera "Y" measurement data were processed with corrections for variable sensitivities, and results were comparable to "X" measurements.

During the calibration tests it was found that the system is sensitive to intensity variations from the diodes. Target diode orientation and location had some effect on their apparent intensity at the camera detector. The system had compensation for intensity variation, but it was found that variations on the order of ± 10 counts could be experienced in the range between intensity threshold and overload.

Another source of error which could be somewhat controlled in calibration, but may be a problem in using the system, was reflections. Objects near the target diodes can cause reflections which produce false targets. When a stainless steel bar was positioned above the bar holding the diodes used in static calibration, all the "Y" outputs changed to a higher value. The amount of change varied, but one diode change 60 counts (over 0.5 inch at that camera-target range).

The digitizer (10 bit) used in the Selspot system limits resolution to 1/1000 of the field of view. The calibrations showed that accuracies on the order of this magnitude are possible.

The DLT transformation algorithm, while better than the one supplied with the system, still imposed restrictions. It is necessary to provide a minimum of six control point targets whose three-dimensional coordinates are accurately known. In actual practice many more than six points are used for the sake of redundancy. Another transformation technique, known as the "Bundle" method, developed by Duane C. Brown,[2] requires fewer control points which need spatial definition. Future efforts to improve this system would involve the implementation of this algorithm as well as a means to reduce the computation time required to perform the computations.

CONCLUSIONS

The system can obtain dynamic stereo position data from up to 30 target diodes at a rate of 312 samples per second for each diode positioned to be visible by both cameras.

The accuracy of these measurements is limited by the system resolution which is a function of the focal length (f) of the lens, the camera-to-target distance (d), and the quantization step size of the analog-to-digital converter. The A/D converter used in this system has 10-bit resolution, or 1024 discrete levels. Hence, resolution is approximately 1/1000 of the viewing range (r) which is determined by the camera-to-target distance and the field of view (fov). The active detector area is 22 mm x 22 mm, thus the viewing range is defined by:

$$r = \frac{22d}{f}$$

For a 50-mm lens, as was used in this evaluation, the viewing range is approximately one-half the camera-to-target distance. To insure the above stated accuracy, the camera nonlinearities and sensitivity variations need to be corrected with an adequate algorithm. Also, the data can be corrupted by diode intensity variations and discrete

2. Brown, Duane C. "Application of Close-Range Photogrammetry to Measurements of Structures in Orbit," Vol. 1 and 2, GSI Technical Report No. 80-012, Sept. 15, 1980.

reflections from surrounding surfaces. The overall accuracy of the system is limited by these influences on the stereo camera data. The 3-D transformation algorithm (DLT) did not contribute to system inaccuracies.

SINGLE CAMERA

DYNAMIC CALIBRATION DATA

FREQ. (Hz)	X Plotter cm (in.)	X Sel cm (in)	Y Plotter cm (in)	Y Sel cm (in)
1	.58 (.23)	.58 (.23)	8.199 (3.228)	8.311 (3.272)
1	2.48 (.98)	2.48 (.98)	8.199 (3.228)	8.313 (3.273)
1	5.08 (2.00)	5.06 (1.99)	8.199 (3.228)	8.313 (3.273)
1	12.73 (5.01)	12.71 (5.00)	8.199 (3.228)	8.311 (3.272)
5	.56 (.22)	.56 (.22)	8.199 (3.228)	8.313 (3.273)
5	1.35 (.53)	1.35 (.53)	8.199 (3.228)	8.311 (3.272)
10	.64 (.25)	.66 (.26)	16.389 (6.452)	16.286 (6.412)
10	1.35 (.53)	1.35 (.53)	16.389 (6.452)	16.286 (6.412)
15	.56 (.22)	.56 (.22)	16.389 (6.452)	16.373 (6.446)
20	.71 (.28)	.76 (.30)	16.389 (6.452)	16.289 (6.413)
40	.20 (.08)	.25 (.10)	16.389 (6.452)	16.286 (6.412)

TABLE 1

STEREO DYNAMIC

CALIBRATION DATA

FREQ. (Hz)	X Plotter cm (in.)	X Sel cm (in)	Y Plotter cm (in)	Y Sel cm (in)
1	2.46 (.97)	2.31 (.91)	8.159 (3.212)	7.861 (3.095)
1	.38 (.15)	.38 (.15)	8.159 (3.212)	8.115 (3.195)
1	4.83 (1.90)	4.55 (1.79)	8.159 (3.212)	7.978 (3.141)
1	12.83 (5.05)	12.83 (5.05)	8.159 (3.212)	7.920 (3.118)
5	.46 (.18)	.48 (.19)	8.164 (3.214)	7.844 (3.088)
5	1.07 (.42)	1.09 (.43)	8.153 (3.210)	7.879 (3.102)
10	1.47 (.58)	1.45 (.57)	16.307 (6.420)	15.763 (6.206)
15	.46 (.18)	.43 (.17)	16.307 (6.420)	15.751 (6.201)
15	1.17 (.46)	1.17 (.46)	16.307 (6.420)	15.809 (6.224)
15	1.04 (.41)	.99 (.39)	16.307 (6.420)	15.923 (6.269)
20	.66 (.26)	.71 (.28)	16.307 (6.420)	15.768 (6.208)
40	.20 (.08)	.28 (.11)	16.307 (6.420)	15.847 (6.239)

TABLE 2

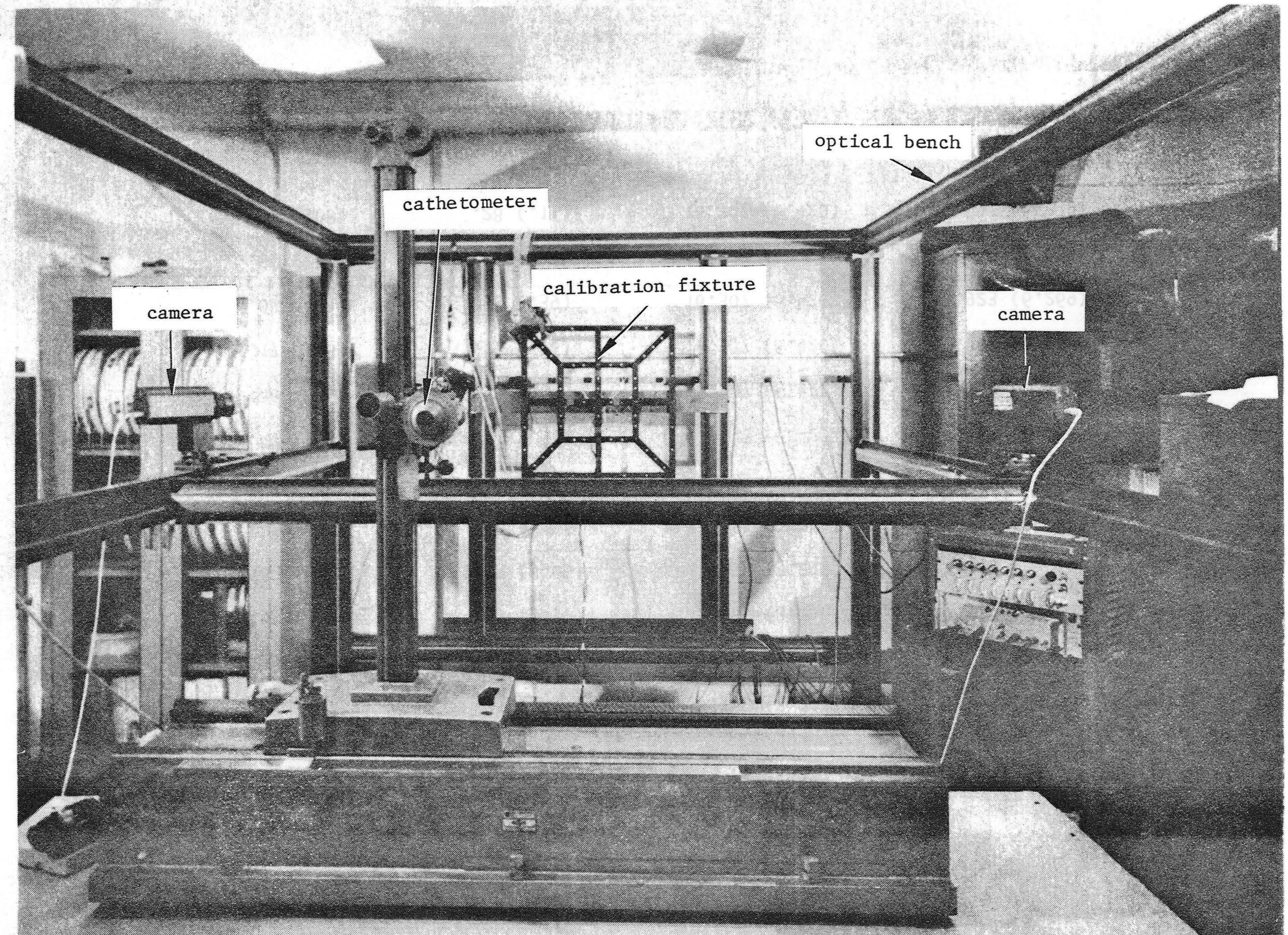


Figure 1.- Optical calibration structure.

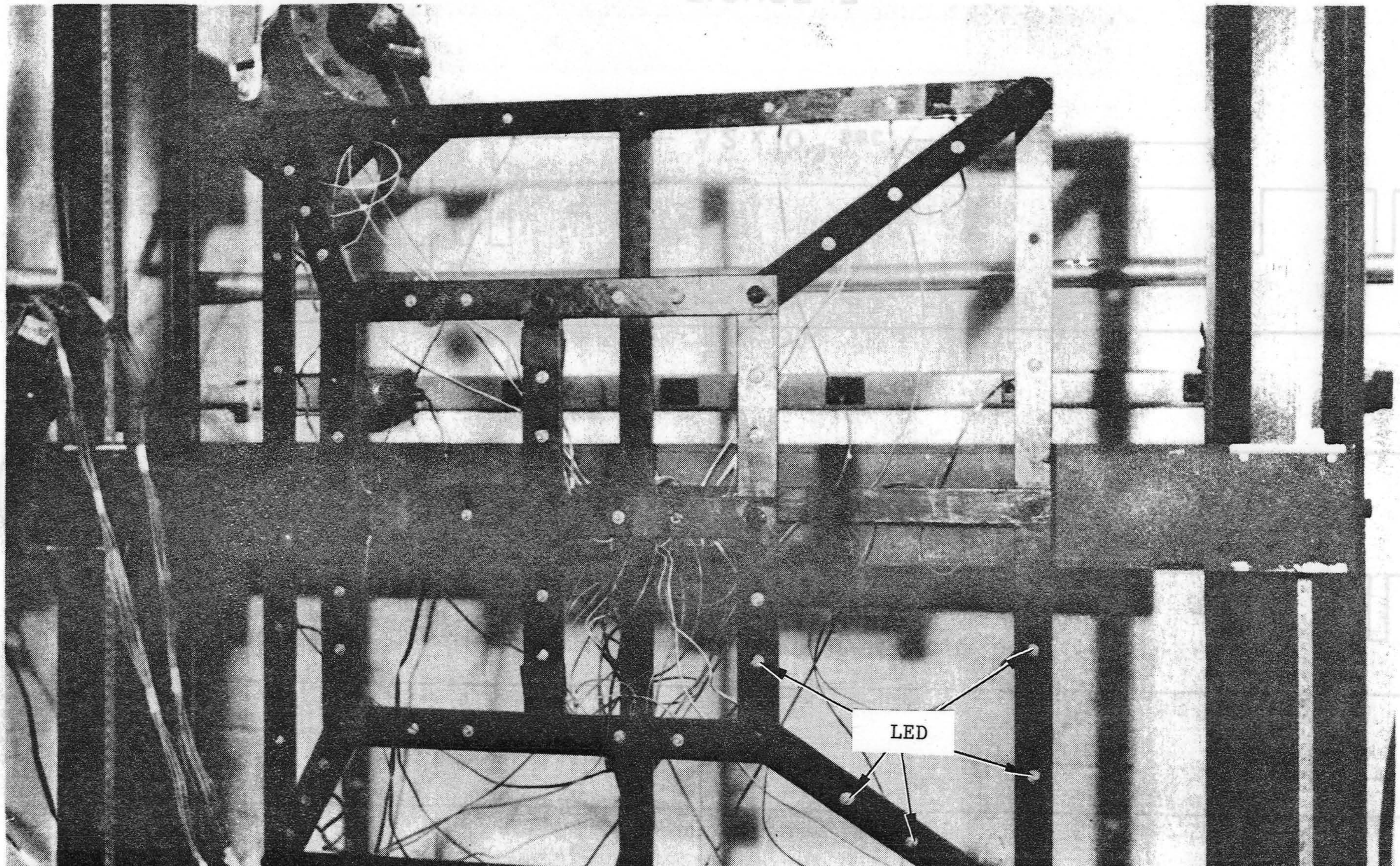


Figure 2.- Calibration fixture.

LED PULSE STRINGS

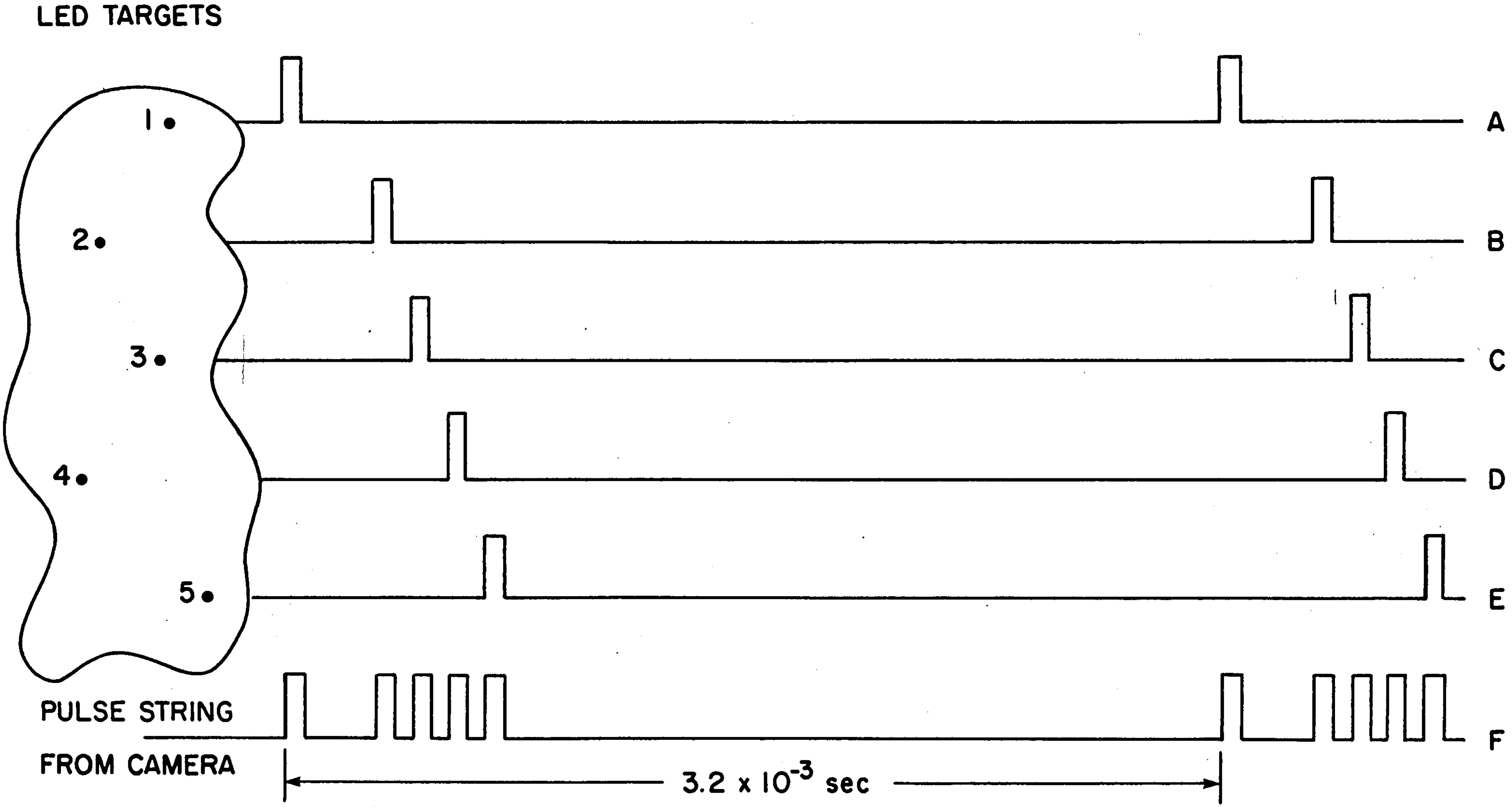
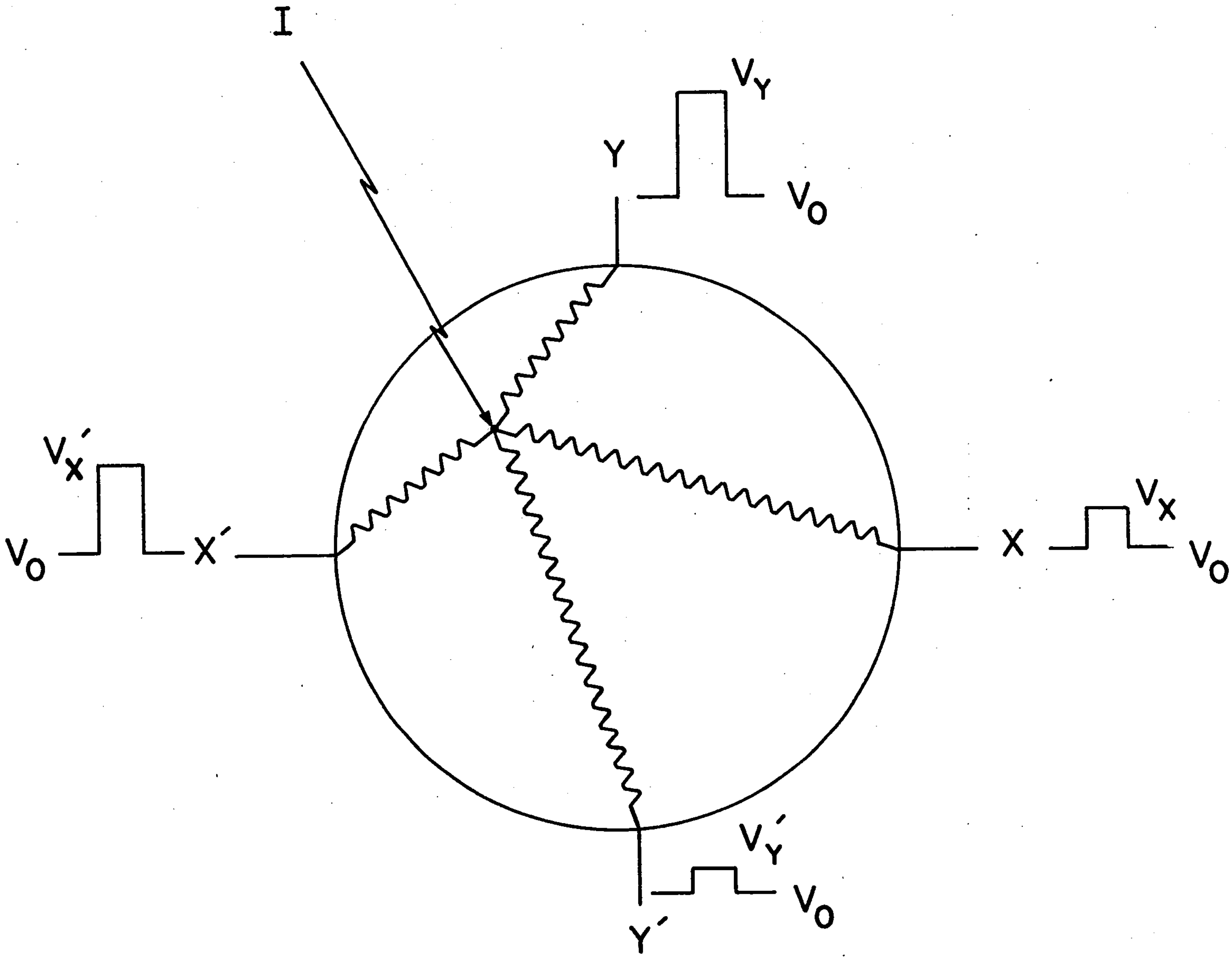


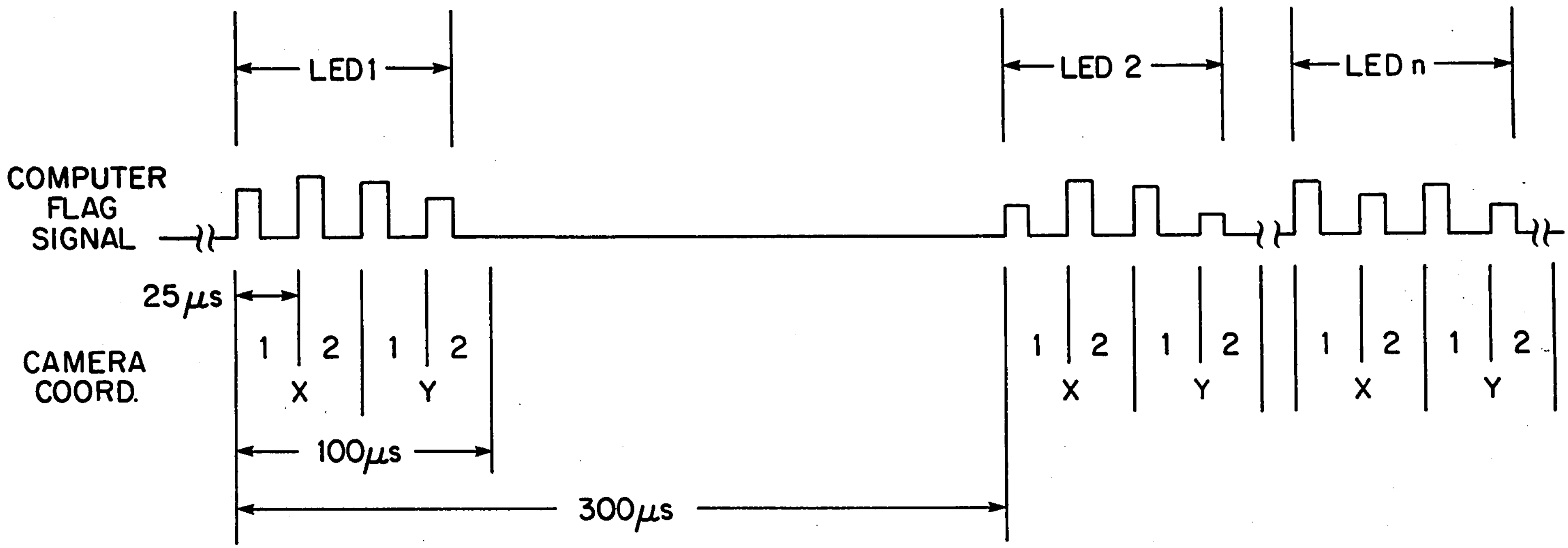
FIGURE 3

DETECTOR



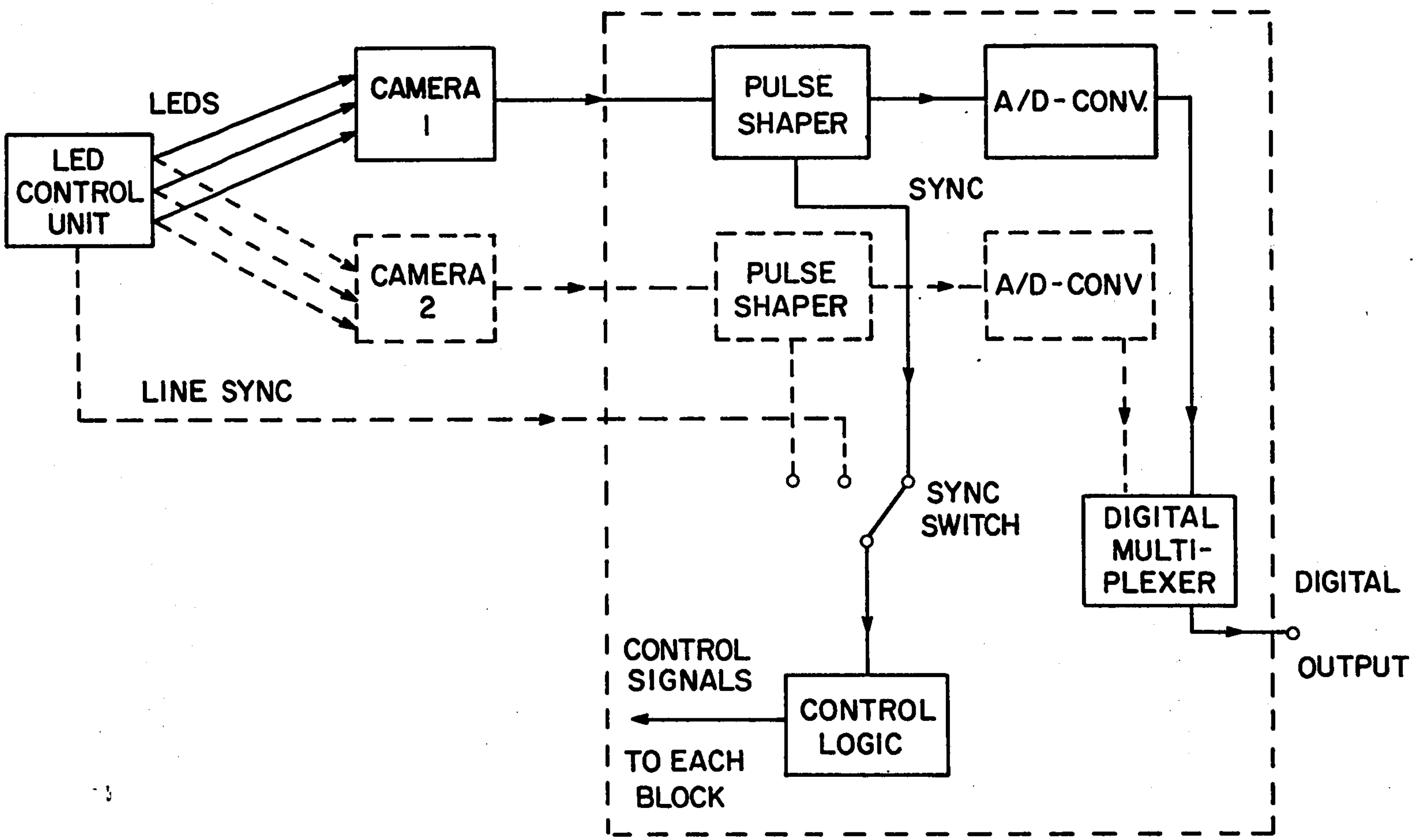
OUTPUT CURRENTS VARY WITH POSITION AND INTENSITY

FIGURE 4



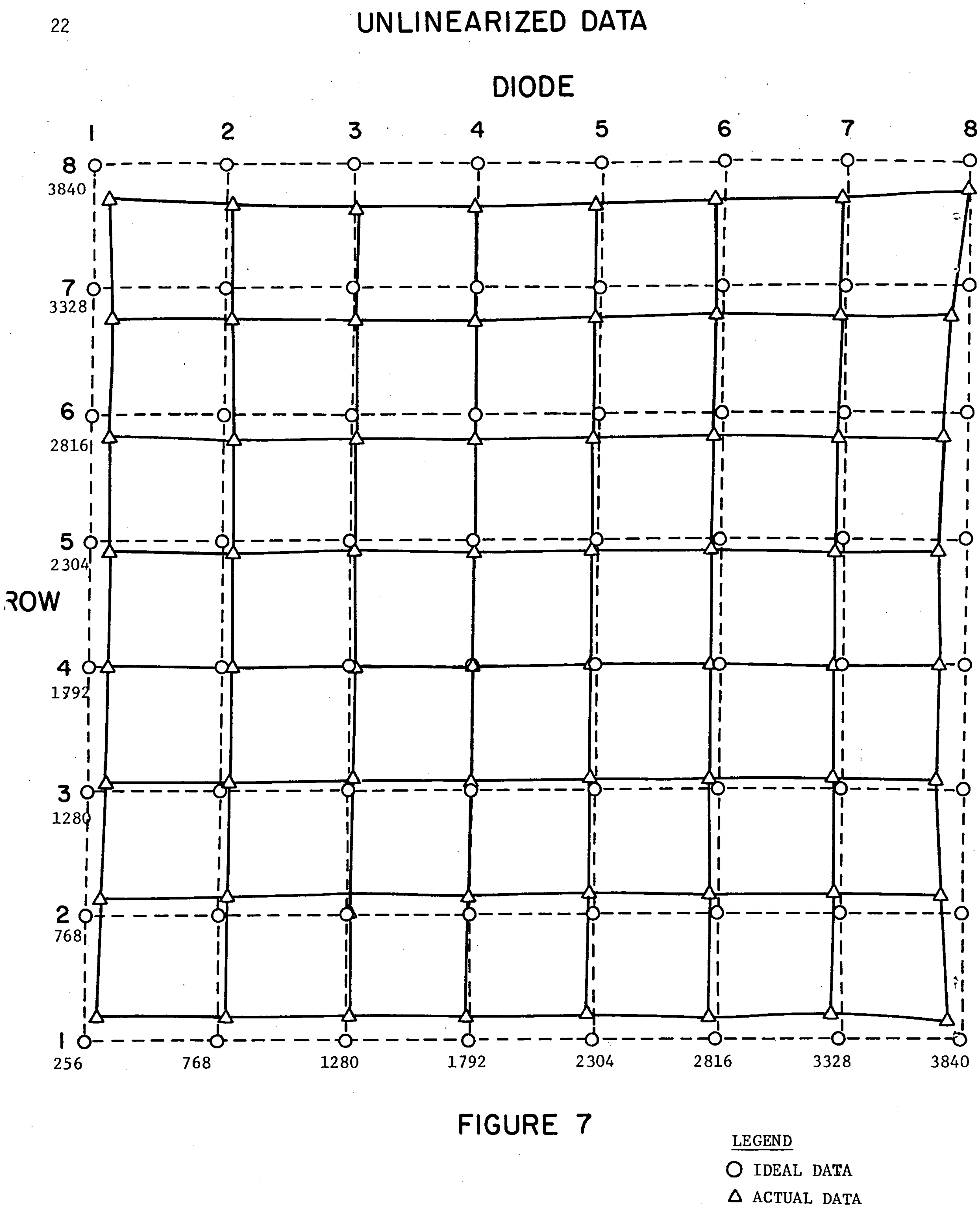
MULTIPLEXED OUTPUT

FIGURE 5



SYSTEM BLOCK DIAGRAM

FIGURE 6



UNLINEARIZED DATA
DIODE
1
2
3
4
5
6
7
8
ROW
8
3840
7
3328
6
2816
5
2304
4
1792
3
1280
2
768
1
256
768
1280
1792
2304
2816
3328
3840
LEGEND
IDEAL DATA
ACTUAL DATA

FIGURE 7

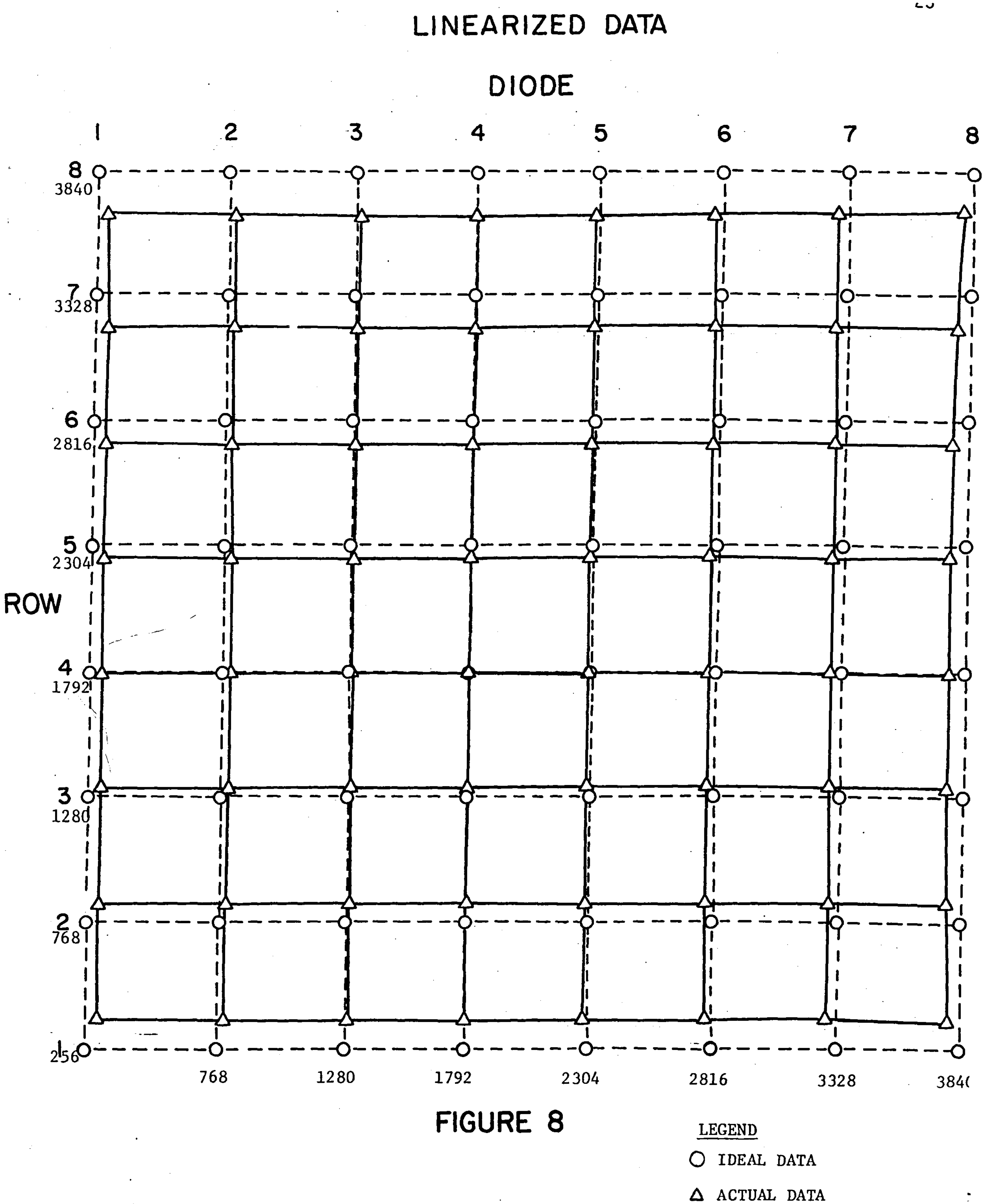
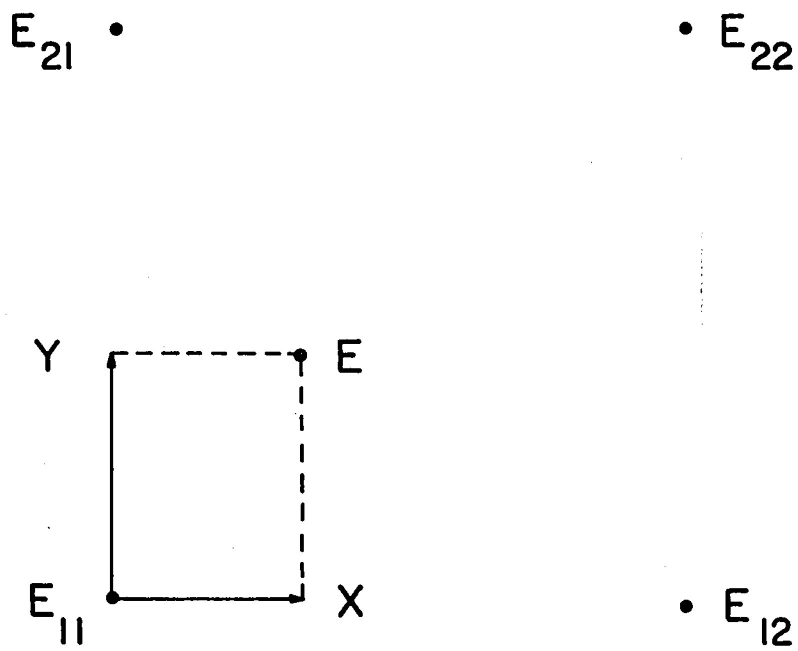

LINEARIZED DATA
DIODE
1
2
3
4
5
6
7
8
ROW
8
3840
7
3328
6
2816
5
2304
4
1792
3
1280
2
768
1
256
768
1280
1792
2304
2816
3328
384(
LEGEND
IDEAL DATA
ACTUAL DATA

FIGURE 8

LINEARIZATION TECHNIQUE



$$E = E_{11}(1-X)(1-Y) + E_{12}X(1-Y) + E_{21}(1-X)Y + E_{22}XY$$

FIGURE 9

APPENDIX

DIRECT LINEAR TRANSFORMATION

The direct linear transformation program was developed by Abdel-Aziz and Dr. H. M. Karara of the University of Illinois in 1971. The transformation is based on two assumptions, (1) colinearity--i.e., a point on the object, its image in the camera and the center of projection of the lens all lie on a common line; and (2) coplanarity--or, the image of all points photographed lie on a common plane.

The colinearity condition (eq. 1) relates image space coordinates (x, y) to object space coordinates (X,Y,Z)

$$\begin{bmatrix} x-x_p \\ y-y_p \\ -C \end{bmatrix} = \lambda \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \begin{bmatrix} X-X_o \\ Y-Y_o \\ Z-Z_o \end{bmatrix} \quad (1)$$

Elements M_{11} through M_{33} represent the rotation matrix (i.e., the orientation of the camera to the object space coordinate system). X_o, Y_o, Z_o define the distance of the center of projection of the lens (C) from the object space origin. x_p and y_p are the image space coordinates of the principal point, and λ is a scale factor.

By dividing the first and second rows in equation 1 by the third, one can express the colinearity condition, thusly:

$$x - x_p = -C_x \frac{M_{11}(X - X_0) + M_{12}(Y - Y_0) + M_{13}(Z - Z_0)}{M_{31}(X - X_0) + M_{32}(Y - Y_0) + M_{33}(Z - Z_0)} \quad (2a)$$

$$y - y_p = -C_y \frac{M_{21}(X - X_0) + M_{22}(Y - Y_0) + M_{23}(Z - Z_0)}{M_{31}(X - X_0) + M_{32}(Y - Y_0) + M_{33}(Z - Z_0)} \quad (2b)$$

Simplifying, one obtains:

$$x = \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1} \quad (3)$$

$$y = \frac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + 1} \quad (4)$$

where:

$L = -(M_{31}X_0 + M_{32}Y_0 + M_{33}Z_0)$

$L_1 = (x_pM_{31} - C_xM_{11})/L$

$L_2 = (x_pM_{32} - C_xM_{12})/L$

$L_3 = (x_pM_{33} - C_xM_{13})/L$

$L_4 = x_p + C_x(M_{11}X_0 + M_{12}Y_0 + M_{13}Z_0)/L$

$L_5 = (y_pM_{31} - C_yM_{21})/L$

$L_6 = (y_pM_{32} - C_yM_{22})/L$

$L_7 = (y_pM_{33} - C_yM_{23})/L$

$L_8 = y_p + C_y(M_{21}X_0 + M_{22}Y_0 + M_{23}Z_0)/L$

$L_9 = M_{31}/L$

$L_{10} = M_{32}/L$

$L_{11} = M_{33}/L$

From equations 3 and 4, it is obvious that for each camera, one obtains two equations and 11 unknowns. Thus, with a minimum of six control points (points whose object space coordinates are precisely known with respect to the chosen coordinate system) one can solve for the cameras' external and internal parameters. In practice more than six control points are used for redundancy, as a least squares fit of the data is done.

Once the "DLT parameters" (the 11 L's) have been determined, unknown points can be transformed using equations 3 and 4.

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7. Author(s) James H. Monteith and Marian L. Kroen		8. Performing Organization Report No.
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16. Abstract

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If target motions are restricted to locations in a plane which is perpendicular to a camera's optical axis, the system can be used with just one camera. Calibrations performed in this mdde characterize accuracies in single camera operation. This information is also useful in determination of single camera contributions to total system errors. For this reason the system was tested in both the single camera and two camera (stereo) modes of operation.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Remote displacement measuring system Close-range photogrammetry Photo-electric cameras Stereo-point tracking	Unclassified - Unlimited Subject Category 35

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