DIVERSE ELECTRONIC IMAGING APPLICATIONS FOR CCD LINE IMAGE SENSORS

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ABSTRACT

The performance and operating characteristics of a family of Fairchild CCD line image sensors provides the basis for a variety of electronic imaging applications. Multi-chip, long line, and integrating mode line image sensor configurations are well suited to such diverse applications as high resolution aerial reconnaissance, facsimile page reading, mail sack label bar-code reading and low light level periscope scanning.

CCD line image sensors used in experimental imaging configurations for these applications were 1 x 500, 1 x 1000, 1 x 1728, and 128 x 128 element devices. The 128 x 128 area device, included in this line image sensor category, is operated in a time delay and integrating mode (TDI). Results are presented of imaging performance for experimental configurations.

The real time aerial reconnaissance test configuration described consists of three 1 x 500 element devices using beamsplitting optics to achieve long line, gapless coverage of scene information. A nine-chip electronic imaging system using 1 x 1728 CCD devices and a low distortion, wide angle lens is also discussed.

The experimental page reading scanner employs a single 1 x 1728 array and lens to cover an 8-½" page width format at a limiting resolution of 200 lines per inch. An automatic hand-held reader with a single 1 x 1000 element array rapidly scans and reads mail sack labels.

Experimental results are presented for a 128 x 128 multi-row TDI charge-coupled device in a moving image system. An experimental configuration for low light level periscope scanning is described and an example of reconstructed low light level imagery is presented.

INTRODUCTION

Newer forms of CCD buried channel line image sensors, i.e., long line and multi-row integrating arrays are enhancing performance of many all-solid state electronic line image applications. Specifically, a 1 x 1728 element long line device provides a substantial number of picture elements in a single chip at a resolution density approaching 2000 elements/inch. These features are essential in applications where high resolution performance is required in single-chip configurations or in higher resolution multi-chip configurations where high density, long line sensors minimize both the number of chips and the image format size required in the sensor system.

Another interesting CCD line image sensor, a 128 x 128 element multi-row device, provides additional signal integration compared to a conventional single-row sensor when a scene is scanned across its 128 integrating rows. This mode of operation, also called time delay and integration (TDI)[1], provides the signal-to-noise performance improvement to make it useful in low light level applications. Although the size of this initial device is only 128 x 128 in its present form, it can undoubtedly increase in the near future consistent with the 380 x 488 format sizes achieved in CCD area image device technology in development[2].

Several diverse electronic imaging applications are currently being investigated which use CCD long line and multi-row line image sensors to advantage:

- a wide angle aerial reconnaissance system where a large number of picture elements, e.g., 15,000, are required across the image format for high resolution performance.
- a page scanning system where a single-chip system configuration is required for 200 line per inch performance using 8-½ inch page widths.
- a bar-code reading system where a single-chip configuration automatically reads a mail sack label code when positioned over a 2.3 inch long format.
- a submarine periscope viewing system where operation is required in both daylight and night sky environments.

This paper describes the laboratory test configurations and imaging results related to these applications. These projects were executed at the Fairchild Imaging Systems facility at Syosset, New York and were sponsored by various government agencies.

1 X 1728 LONG LINE IMAGE SENSOR

The 1728-element CCD line image array, described recently in the literature[3], is a two-phase buried channel device with read-out registers and video amplifiers included on the chip. The element-to-element pitch is 13 μm, the element width is 16 μm, and all 1728 elements form a continuous unstaggered photo-responsive line.

The 1 x 1728 element CCD line image sensor consists of five functional elements, illustrated in the block diagram of Figure 1 These elements are:

- A row of 1728 image sensor elements, separated by diffused channel stops and covered by a polysilicon photoelectrode. The photoelements are shown at the center of the diagram.
- Two aluminum transfer gate structures, one on each side of the row of 1728 photoelements.
- Two 864-element, 2 phase, analog transport registers, one on each side of the line of photosensors. The transport registers are separated from the photosensors by the transfer gate.
- A charge detector and gated preamplifier[4] which detect the charges delivered by the transport registers and convert them to a voltage output signal (video).
- A compensation amplifier which provides the capability of suppressing reset clock transients through an external differential amplifier.

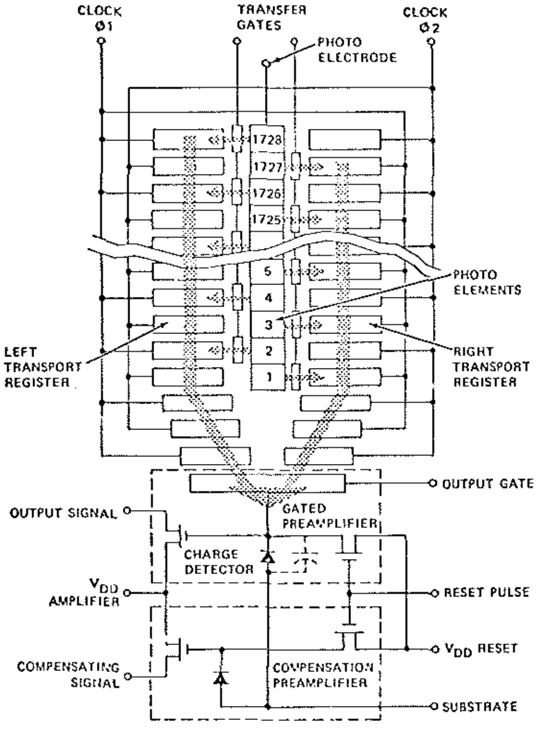


FIGURE 1. 1 x 1728 SINGLE-ROW (LINE) SENSOR

128 X 128 MULTI-ROW IMAGE SENSOR

The 128 x 128 element line image device is composed of an area-imaging array, an output register, and an amplifier section that incorporates two amplifiers. The central feature of the sensor is the area-imaging array which consists of 16,384 individual photo-sensor elements arranged in a 128 x 128 element format. The photosensor elements are also the unit cells of 128 vertical, 128-bit CCD registers as shown in Figure 2. Each 20 μm x 20 μm photosensor element is composed of two charge storage areas, two barriers, and a channel stop region.

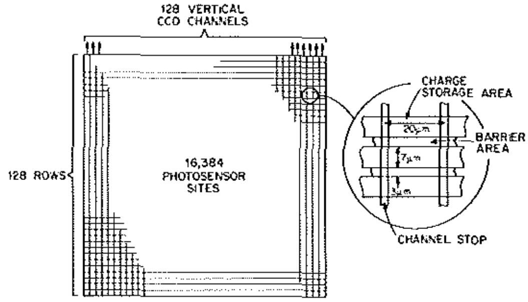


FIGURE 2. 128 x 128 MULTI-ROW SENSOR

The single-line output register receives charge from the area array via an output transfer gate. Two amplifiers, a gated charge integrator (GCI) and a low noise threshold floating gate amplifier (FGA)[5], are located at the end of an extension of the output register.

The multi-row integrating array is used in a moving image mode[6] where one direction of scan is provided by sensor or object motion. As shown in Figure 3 when the image is moved across the array (from Row A to Row B, etc.) charges developed in one row of potential wells (A_1, A_2, A_3, etc.) are transferred in synchronism with the image motion so that at the end of the array rows (Σ) a substantial signal has been accumulated. The signal is transferred to the output register and is read out in the same manner as a conventional single-row (line) imaging array. The output register readout rate is greater than 128 times the column transfer rate to clear the output register before the next input of row data.

The multi-row array is analogous to a mechanical slit in a moving film camera. The electronic "slit" of 128 rows is 128 times greater than with a conventional single-row array thereby achieving an increase in exposure time, by a factor of 128 under the same system operating conditions.

AN ELECTRONIC WIDE ANGLE CAMERA SYSTEM

A multi-chip breadboard scanner and display unit was designed and fabricated to study optical butting when using simple beamsplitter techniques to produce "seamless" pictures.

The breadboard arrangement used three CCD 1 x 500 line image sensors[4], which have 1.2 mil center-to-center spacings, and a mirror arrangement to scan a scene across the array. The eventual electronic wide angle camera system (EWACS)[7], to which the study was directed, may use nine or more 1 x 1728 line sensors operating in a pushbroom or panoramic mode to provide an approximate 15,000 line resolution performance.

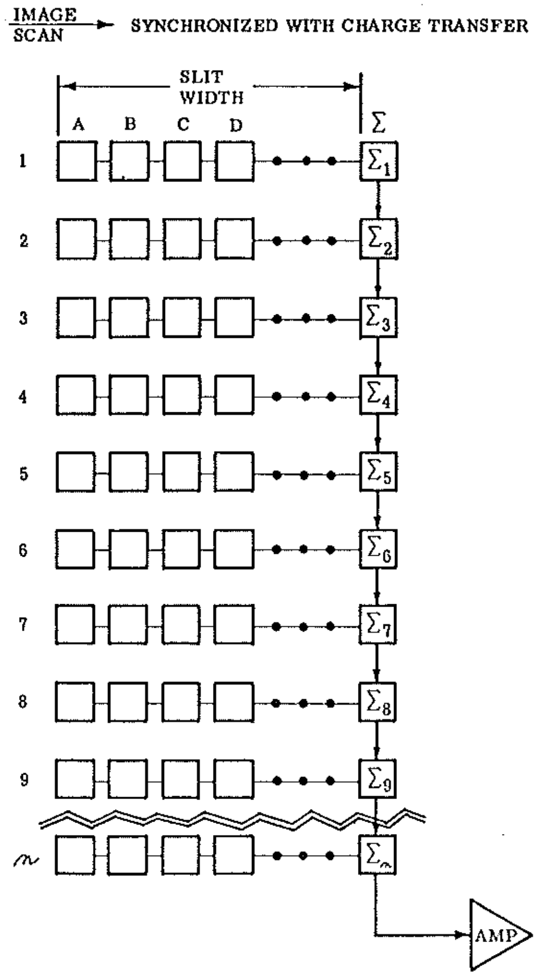


FIGURE 3. MULTI-ROW INTEGRATING LINEAR ARRAY SCHEMATIC

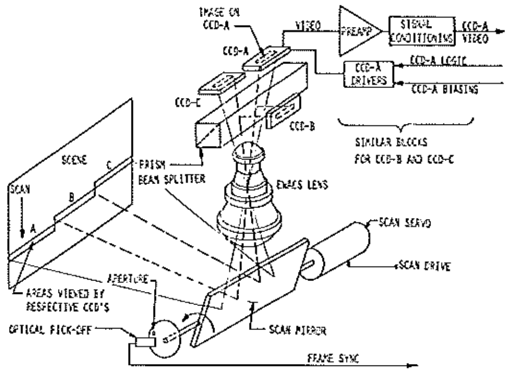


FIGURE 4. BREADBOARD SENSOR CONFIGURATION (EWACS)

SYSTEM DESCRIPTION

The EWACS laboratory demonstration sensor configuration shown in Figure 4, primarily consists of a special-design EWACS lens, a scan mirror, a beamsplitting prism, three optically butted 1 x 500 element linear CCD arrays, and associated electronics. A separate control and display unit provides logic, control functions, video processing, sweep generators and a CRT display. An additional commercial lens was also used for many of the breadboard tests.

A CCD channel selection control permits viewing imagery produced by either the 500 elements of one CCD or the beginning 250 elements and the end 250 elements of adjacent pairs of CCD's. The latter mode of operation permits viewing the optical butted sector, between the line image sensors, in the center of the CRT display.

A photograph of the optical butting section is shown in Figure 5. Major components of this unit are a beamsplitting prism, the CCD arrays, prism mount, and front end electronic components.

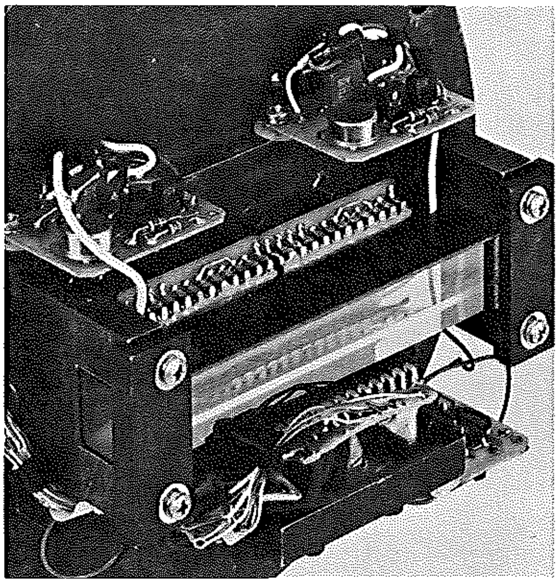


FIGURE 5. OPTICAL BUTTING ASSEMBLY (EWACS)

Multi-Chip Alignment

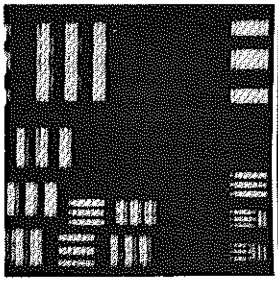
To facilitate accurate chip positioning, adjustments are incorporated into the breadboard optics. These adjustments enable focusing and butting alignments to be made while viewing the chips through the beamsplitter using a high power microscope. The three line arrays, cemented to individual base plates, form part of a six-degree-of-freedom adjustable mount. The chips are visually focused and butted to better than ¼ sensor element width. Adjusting screws for the two outboard chips are accessible from the rear so that final butting alignments can be made with the breadboard installed on the objective. The final adjustments are performed while viewing an oscilloscope and the system display monitor.

MULTI-CHIP IMAGING RESULTS

Figure 6 shows the results of combining the video signals of CCD arrays B and C on the display CRT. Photograph B represents the end 250 elements of the B array alone and photograph C shows the beginning 250 elements of the C array alone. The combined B and C photograph was taken with both arrays operating simultaneously.

The system limiting resolution, limited by the sensor geometry, corresponds to 16 line pairs per millimeter for the 1 x 500 element sensor.

The region of the displayed image where the array butt occurs is not readily detectable by viewing the polaroid photograph of the displayed image.



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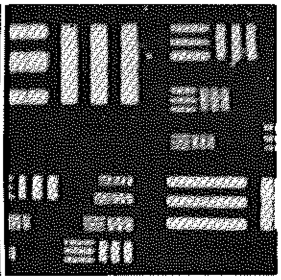

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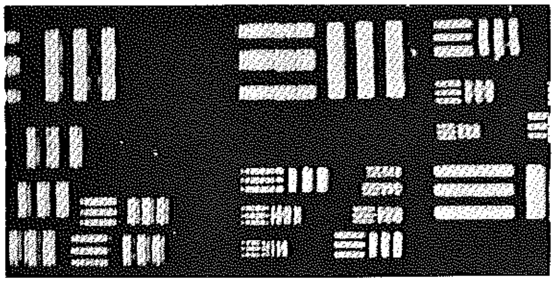

B AND C

FIGURE 6. EWACS BREADBOARD PERFORMANCE (1 x 500 MULTI-CHIP SENSORS)

An example of aerial imagery using a single 1 x 1728 line image sensor is shown in Figure 7. The imagery was scanned from a film sample and reconstructed on a CRT monitor display. The maximum of 800 lines available on the CRT monitor display limits the output recording to approximately one-half of the 1 x 1728 sensor's resolution capability.

A PAGE SCANNING SYSTEM

A page scanning breadboard was designed and fabricated to demonstrate CCD linear array performance under conditions encountered in page reading and facsimile applications[8]. The initial breadboard scanned two 1 x 1000 arrays using twin lenses to achieve high resolution performance. The 1 x 1728 was subsequently developed to achieve the 8-½ inch page width coverage and the 200 line per inch resolution in a single-chip configuration thereby eliminating the need for the multiple lens arrangement and its associated alignment requirements.

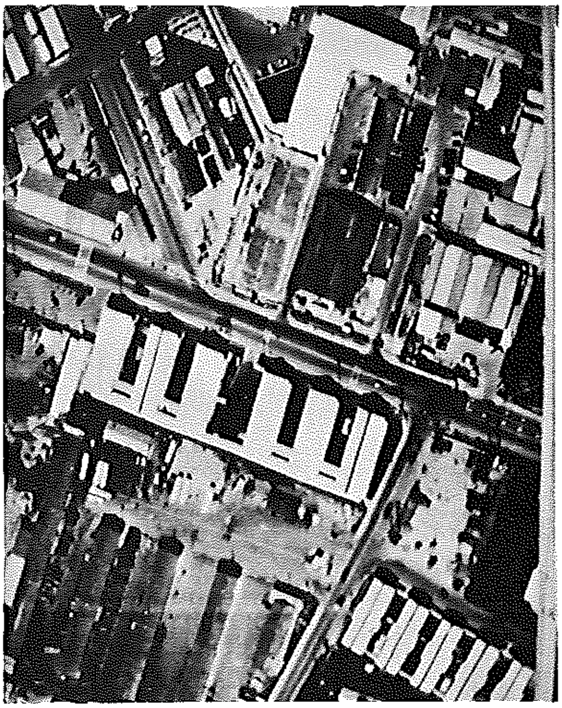

FIGURE 7. MONITOR DISPLAY OF AERIAL SCENE (1 x 1728 SENSOR)

SYSTEM DESCRIPTION

In the test arrangement the scanned 8-½ inch width page was mounted on a carriage that was transported across the field of view of the array. The page is illuminated by a row of lamps that direct a uniform light band to the field of view of the arrays. The array and its relay lens are mounted on a separate carriage above the paper carriage.

A rotating cylinder test arrangement was also used for page scanning tests. The rotating cylinder, with a standard IEEE Facsimile Test Chart wrapped around it, inputs the image across the array's field of view. The video signals developed are amplified and reconstructed on a CRT display. The video readout rate was 1 MHz.

PAGE SCANNER IMAGING RESULTS

The limiting resolution for the array in the system coverage of an 8-½ inch page was 200 lines per inch which corresponds to the results of other investigators[3, 9]. Figure 8 was taken with an expanded sweep CRT monitor.

Non-uniformity of response, largely determined in local areas by array aperture geometry control and from one end to the other (gradual variations) by non-uniformities in the polysilicon layer thickness, was approximately 5% of the mean output for the 1 x 1728 array when tested with uniform light input and without a lens. With the relay lens of the scanner included, the array response fell off gradually at the two ends of the line due to lens vignetting. The gradual variation in brightness of the recorded images, however, was found to be unobjectionable to the eye as compared to any sharp element-to-element variations.

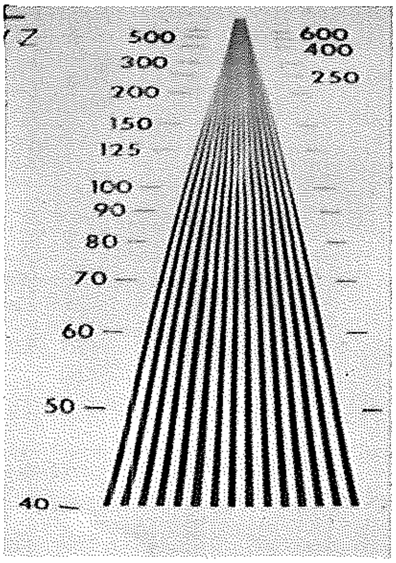

FIGURE 8. MONITOR DISPLAY OF RESOLUTION WEDGE (EXPANDED SWEEP)

Dynamic range of the 1 x 1728 page scanner sensor was measured to be 1000:1. A facsimile test chart recording from an 800 line CRT display screen is shown in Figure 9.

FIGURE 9. MONITOR DISPLAY OF IEEE FACSIMILE TEST CHART (1 x 1728 SENSOR)

A BAR-CODE READER SYSTEM

A developmental model automatic label reader was designed and fabricated to read destination bar codes on mail sack labels. The reading requires only that the operator position the hand-held scan head over the 2.3 inch long mail sack label instead of performing a manual scan as required with earlier reader equipment. The digital code read is transmitted to a computer which controls the sorting mechanism of a mail sack conveyor line.

SYSTEM DESCRIPTION

As shown in Figure 10, the developmental mail sack label reader is configured in a housing with a "pistol grip" handle. The reader system contains both a scan head assembly and an electronic interface assembly. Light source imaging optics, a 1 x 1000 CCD line array, array logic and driver circuits and video amplifier are in the hand-held scanhead assembly. The same scanhead is used for both stencil and computer code labels. The electronic interface assembly consists of an analog to digital converter, shift register memory and recognition logic. The output of the label reader connects compatibly with a decoder interface.

Indicator lamps mounted on the scanning unit are activated by logic circuits to alert the operator when the label is read successfully.

FIGURE 10. DEVELOPMENT MODEL MAIL SACK LABEL READER

SINGLE-CHIP IMAGING RESULTS

The analog output signal of the scanhead, when reading a bar-code sample, is shown in the upper trace of Figure 11. This variable space code is converted to the digital signal shown in the lower trace of the photograph. The logic "0" correspond to the wide space and the logic "1" to the narrow space reading. Different samples of labels, i.e., using colored paper stock, stencil codes, computer codes, skewed patterns and degraded patterns (voids, ink variations) were successfully tested to an engineering specification. The throughput rate, i.e., the rate at which mail sack labels are picked up from a table, successfully read by the reader, and replaced on the table was measured at greater than 20 labels per minute.

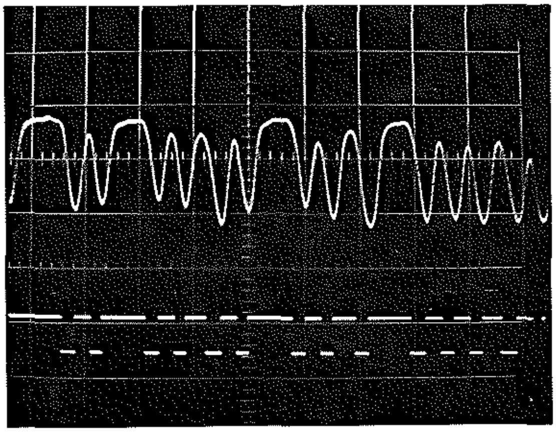

FIGURE 11. BAR-CODE VIDEO SIGNALS (1 x 1000 SENSOR)

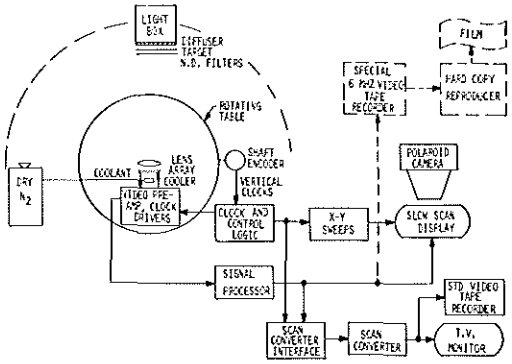

FIGURE 12. LABORATORY TEST ARRANGEMENT FOR PERISCOPE SYSTEM

AN ELECTRO-OPTICAL DAY/NIGHT PERISCOPE SYSTEM

A breadboard periscope scanner, currently being designed and fabricated uses both a long line 1 x 1728 and a 128 x 128 multi-row integrating CCD sensor to demonstrate simulated day/night periscope electronic imaging performance. Table 1 lists the test instrumentation operating parameters.

TABLE 1
TEST INSTRUMENTATION PARAMETERS
TDI/HIGH RESOLUTION ARRAYS

Array	128 x 128	1 x 1728
Number of Elements	128	1728
Element Pitch	20 μm (.00079")	13 μm (.00051")
Focal Length	1"	3"
Vertical Angle	5.86^o	16.77^o
Scan Rate	18^o/sec	37.3^o/sec
Exposure Time	325 ms	260 μs
Lines per 180^o Scan	3932	18547
Data Rate	10^6 elem/sec	6.9×10^6 elem/sec
Scene Irradiance/Brightness	3×10^{-9} W/cm^2	100 ft. lamberts

SYSTEM DESCRIPTION

The test instrumentation for demonstrating system sensor performance for the periscope application is shown in the block diagram of Figure 12. It includes a rotating table to simulate periscope scanning, controllable light source, lens, array sensors, array logic and drive circuits, signal processing amplifiers and image display equipment. The display equipment consists of both a direct CRT display with a polaroid camera recorder and a scan converter for single frame storage and TV monitor display of the image at 30 frames per second. Each sensor, with its lens and control electronics, is interchangeable on the rotating table.

Clocking voltages used to transfer signal charges from row-to-row in synchronism with the image motion at the array plane of the 128 x 128 line sensor are derived from a shaft encoder coupled to the rotating table. Temperature control of the array, required to reduce dark current under low light input conditions, is provided by cooled dry nitrogen.

A future version of the display and recording arrangements is designed to include a 6 MHz video tape recorder and a hard copy reproducer to reconstruct the images on high quality film.

MULTI-ROW SENSOR IMAGING RESULTS

Figure 13 shows a CRT polaroid recording of a high contrast tri-bar image made with a linear moving image target test configuration using a 128 x 128 multi-row image sensor. The tri-bar image easily resolved both orientations of tri-bars corresponding to the array's Nyquist limit.

The orientation and direction of the moving image as it traverses across the array to create charge summing is shown in Figure 14.

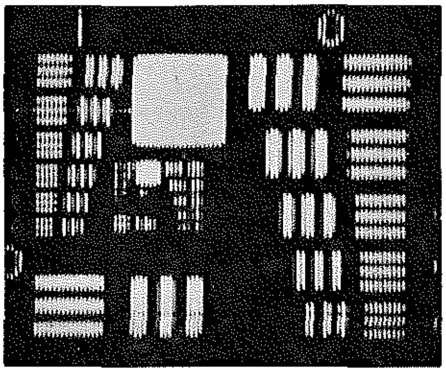

FIGURE 13. MONITOR DISPLAY OF TRI-BAR TARGET (128 x 128 SENSOR)

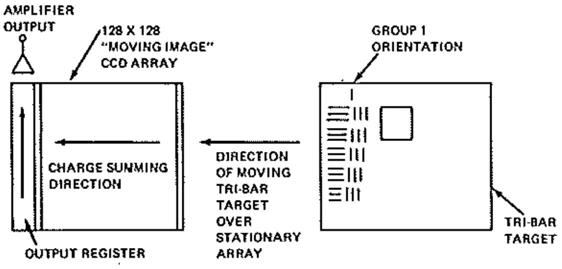

FIGURE 14. TARGET/SCENE ORIENTATION FOR MULTI-ROW SENSOR

Low Light Level Performance

The results of a low level test where the input highlight irradiance is 0.5% of the saturation irradiance is shown in Figure 15. The highlight signal level was equivalent to 1000 electrons and the noise level was 90 electrons rms. The highlight irradiance was measured as 16 x 10^{-9} W/cm^2 at a 43 millisecond integration time where the source approximated a 2854°K black body radiator.

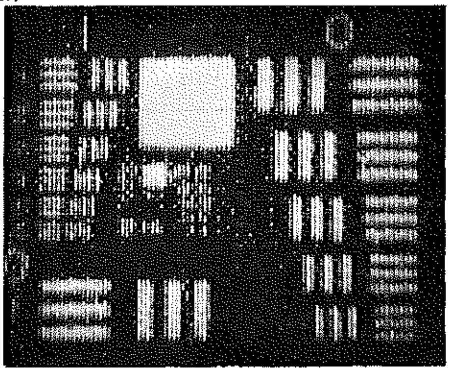

FIGURE 15. MONITOR DISPLAY OF TRI-BAR TARGET AT 0.5% OF SATURATION LEVEL

CONCLUSIONS

Although line image sensing systems have the drawback of requiring sensor or object motion to provide one direction of scan in electronic imaging configurations, they have an important role in many electronic imaging applications. Page reading and character reading [10] have long been identified as major applications for line sensors but a review of the use of line sensors in different configurations, i.e., multi-chip, multi-row and long line single-chip arrangements shows that they can also address other high performance electronic imaging applications.

The four examples discussed are believed to be only a small sample of the potential areas of use for CCD line imagers. Development, for example, of very small, lightweight (less than one pound) remote surveillance systems and high speed facsimile (7 MHz data rate) are applications made possible by recent performance improvements made in CCD long line sensor arrays. Other new features recently added to versions of the long line arrays, i.e., electrical input registers, low noise floating gate amplifiers and electronic exposure controls are expected to expand their applications to a scope limited only by the creativity of the system designer. The future expansion of the multi-row sensor to larger-sized configurations with smaller sized photosensor cells is expected to increase its suitability to newer diverse line imaging applications.

ACKNOWLEDGEMENTS

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