TELEVISION APPLICATIONS OF INTERLINE-TRANSFER CCD ARRAYS

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ABSTRACT

The design features and characteristics of interline-transfer (ILT) CCD arrays with 190 x 244 and 380 x 488 image elements are reviewed, with emphasis on optional operating modes and system application considerations. It is shown that the observed horizontal resolution for a TV system using an ILT image sensor can approach the aperture response limit determined by photosensor site width, resulting in enhanced resolution for moving images. Preferred camera configurations and read-out clocking modes for maximum resolution and low-light sensitivity are discussed, including a very low light level Intensifier-CCD concept. Several camera designs utilizing ILT-CCD arrays are described. These cameras demonstrate feasibility in applications where small size, low-power/low-voltage operation, high sensitivity and extreme ruggedness are either desired or mandatory system requirements.

I. INTRODUCTION

Charge-coupled area image sensors can be classified by the arrangement of sensing, storage and transport functions defining the flow of signal charge packets to the output detector. These functional arrangements or "readout organizations" have been selected to achieve interface compatibility with existing television system equipment requiring sequential video signals comprised of two interlaced fields at the conventional rates of 60 fields and 30 frames per second. Two readout organizations have been used to achieve interface compatibility. For the approach known as "frame-transfer" the sensor is divided horizontally to form an image sensing array and a separate light-shielded storage array. For the organization known as "interline-transfer", the image sensing, storage and transport functions are integrated within a single format region, with light-shielded vertical transport registers interleaved between columns of photosensor elements. Details of the frame-transfer organization and its application as a TV image sensor have been described elsewhere (Ref. 1); this paper is primarily concerned with the interline-transfer (ILT) device and its application as an image sensor or video signal processor component in television systems.

II. INTERLINE TRANSFER ARRAYS AS TV IMAGE SENSORS

The interline-transfer organization has been adopted for a family of charge-coupled image sensor designs with 100 x 100, 190 x 244 and 380 x 488 elements/frame (Ref.2). Features common to each of these designs are illustrated in Figure 1. The unit cell for these arrays contain one photosensor site and an adjacent light-shielded site which is one-half stage of a two-phase vertical transport register. In the normal readout mode alternate cell rows are uniquely assigned to each of the two fields comprising a TV frame, resulting in higher vertical MTF than for beam-scanned or frame-transfer type image sensors. An implanted barrier at the photosite/transfer site interface inhibits transfers to the vertical column register except when the photogate electrode potential (ϕ_p) is LOW and the adjacent transfer gate potential (ϕ_{V1} or ϕ_{V2}) is HIGH. Thus, 2/1 interlace can be achieved by pulsing ϕ_p low during each vertical blanking interval and applying complementary ϕ_{V1}, ϕ_{V2} waveforms with high states during alternate vertical blanking periods. At the start of the ODD field readout, elements corresponding to odd number rows are first shifted in unison into adjacent ϕ_{V1} sites for row transport along the column registers to the output register. The even field sequence is similar except the initial shift is into ϕ_{V2} sites. Three basic waveforms are sufficient for all charge transport functions prior to signal detection, since complementary waveforms can be used for both vertical and horizontal clock drives.

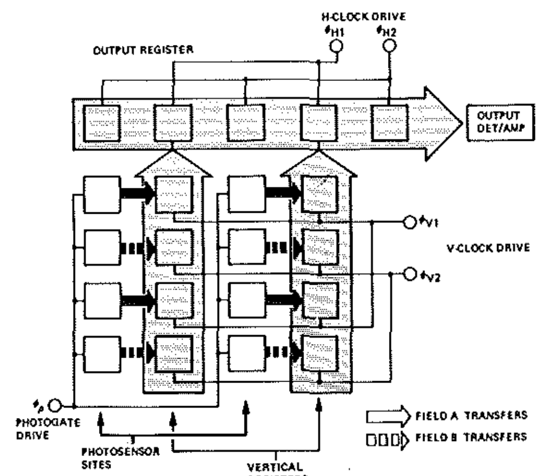


Figure 1. Interline-Transfer CCD Schematic

ILT area image sensors have characteristics which make these devices particularly useful for applications requiring high resolution display of moving image information:

1. The signal readout for each field does not contain the lag or residual signal effects from previous fields typically observed with beam-scanned image sensors.

2. All vertical transfers occur at the display line rate, thus field readout rates can be much higher than for frame-transfer type CCD sensors.

3. Since the integration period for photosensor sites is simultaneously defined for the entire field by the application of the appropriate ϕ_p and ϕ_V gate potentials, the information contained in the readout of a given field is analogous in spatial and temporal precision to the information recorded by an ideal "snapshot" camera with a fast-acting lens shutter. Thus image motion effects during a field integration period will be essentially similar for all photosensor sites, which is not the case with X-Y addressed solid-state sensors or beam-scanned image sensors where the process of sequential readout results in timing displacements of up to one field period across the vertical direction of the image format.

A unique feature of the ILT organization is its adaptability to an alternate readout mode which trades off static vertical resolution for improved moving image resolution. The normal mode for the 380 x 488 element sensor provides 2/1 field/frame interlaced readout with separate photosensor rows for addressing each active line of the displayed TV frame. Photosite integration time for the normal mode is 1/30 second and the Nyquist-limit vertical resolution is 488 TV lines. The alternate readout clocking mode is useful when it is desired to shorten the integration time to 1/60 second. In this mode charge packets from vertically adjacent sites along the even and odd field rows are added together in the vertical shift register before the start of the normal readout clocking sequence. Although the alternate mode has less vertical resolution than the normal mode, the difference can be minimized by performing the addition differently on alternate fields. For example, during the first field sensor rows 1 and 2, 3 and 4, 5 and 6, etc., are added together; during the next field sensor rows 2 and 3, 4 and 5, 6 and 7, etc., are added, with the row-addition sequence for subsequent fields alternating at field rate.

Because of the digital nature of charge transport functions, relatively simple circuit modifications can be used to change the clocking system from normal to alternate mode operation. The TV monitor test pattern photographs, (Figure 2), were obtained using a prototype 380 x 488 element CCD camera equipped with a selector switch to enable operation in either mode. Figure 2(a) shows the full screen display of a wedge-type target used for resolution tests. Figures 2(b) and 2(c) illustrate resolution effects for static imaging with normal mode 1/30 second integration and for the alternate mode with 1/60 integration, respectively. Nyquist limit resolutions for the normal mode are 488 TV lines/picture height (vertical) and 285 TV lines/picture height (horizontal). Alternate mode operation reduces the useful vertical resolution to 350-400 TV lines/picture height, i.e., comparable with the performance of frame-transfer CCD and beam-scanned image sensors in 525-line television applications.

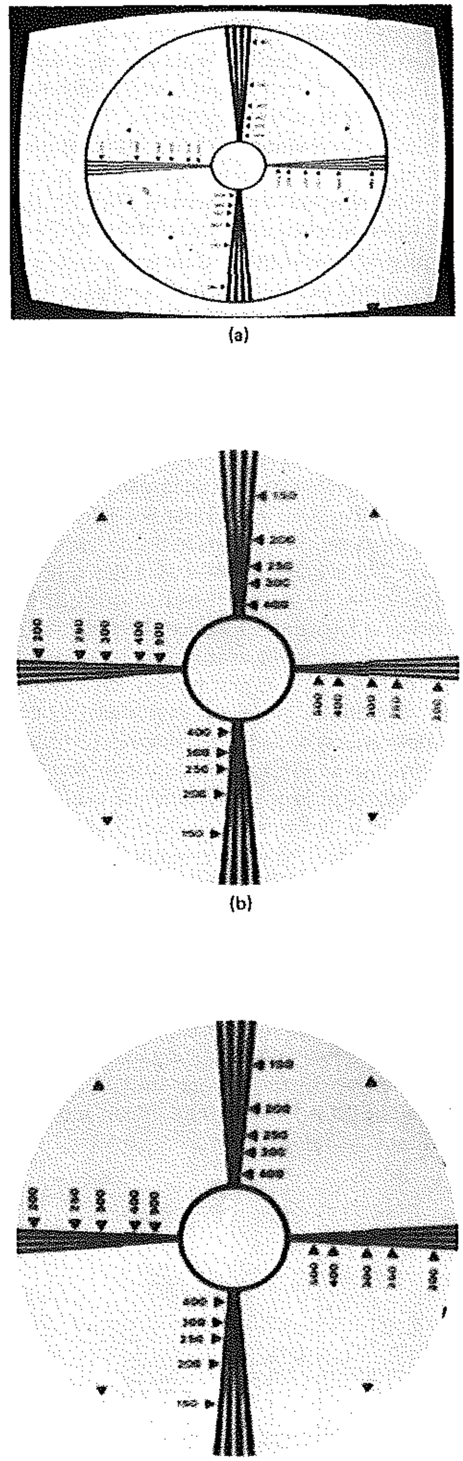


Figure 2. Resolution Test Target Imaging, 380 x 488 ILT-CCD Camera
(a) Full screen monitor display.
(b) Normal readout mode with 1/30 second integration.
(c) Alternate mode with 1/60 second integration.

One method to measure the performance of a TV camera viewing moving scene information is to expose the camera to resolution test patterns of vertical black and white bars which are moved at a uniform rate across the horizontal format direction. The observer tracks the moving information on the monitor screen and records the highest resolved spatial frequency as a function of viewfield traverse periods in the range of 5 to 20 seconds. A number of industrial and government laboratories perform tests of this type to determine the degradations in moving-image resolution caused by signal lag effects which can be particularly severe for certain types of beam-scanned image sensors (Ref. 3). Quite the opposite effect is observed with interline-transfer CCD-TV sensors. Evaluation tests of a 60 frame/second CCD camera using a 190 x 244 element array in the normal readout mode have resulted in moving image horizontal resolution observations approximately 2-1/2 times the Nyquist-limit for stationary image viewing.

The resolution enhancement observed for the moving image case is due to a combination of effects including negligible lag, precise spatial and temporal field exposure conditions, and the unique aperture response characteristics of the interline transfer organization. Figure 3 illustrates the latter characteristic. The unit cell dimensions for 190 x 244 and 380 x 488 arrays define 18 um high photosites, contiguous in the vertical direction, with 30 um center to center spacing in horizontal direction. Thus the vertical and horizontal Nyquist-limit sampling frequencies for stationary images are 27.8 lp/mm and 16.7 lp/mm respectively. The nominal photosite width dimension is 14 um , as determined by the width of aluminum stripes which opaque the adjacent vertical register sites. The output from an array pair can be optically and electrically multiplexed to double horizontal resolution as indicated in Figure 3 (b) and described in Reference (4). Figure 3(c) illustrates the sampling aperture geometry for a single-sensor camera where the effect of image motion is to displace the set of sampling apertures to new positions (with respect to the image) for each field period. In this case the observer tracking the displayed information is presented with three video frames sampling three overlapped regions of the total image space during each 0.1 second eye integration period. For preferred rates of image motion determined by (a) frame rate, (b) motion-smear effects during integration, and (c) the ability of the observer to track image motion, resolution enhancement to a limiting value fixed by MTF effects and the photosensor aperture width dimension can be achieved.

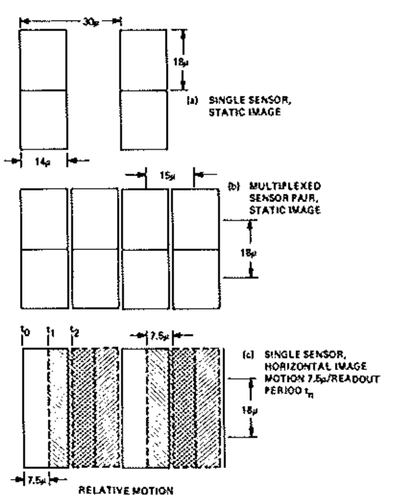
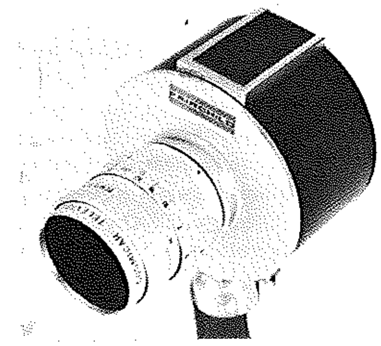


Figure 3. ILT-CCD Sampling Geometry

III. CAMERA AND TV SYSTEM APPLICATIONS

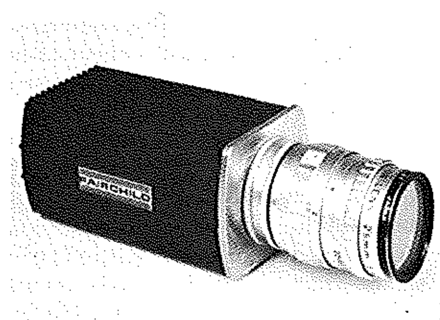
Since the development of the first CCD image sensors significant emphasis has been placed on demonstrating the advantages of these devices as replacements for conventional beam-scanned sensors in television system applications. The first commercially available device, with 100 x 100 elements, was used in the Fairchild MV-101 camera illustrated in Figure 4 (a). A subsequent design, the Fairchild MV-201 utilizing the higher resolution 190 x 244 array, is shown in Figure 4 (b). These cameras, with the exception of optics and an external power supply, are contained in small, lightweight packages of less than 17 cubic inches.

76mm OD x 48mm L



(a)

50mm H x 64 mm W x 95mm L



(b)

Figure 4. CCD Television Cameras Using Interline-Transfer Image Sensors
(a) Type MV-101 with 100 x 100 array.
(b) Type MV-201 with 190 x 244 array.

Variants of the MV-201 design have been developed for applications where the use of a beam-scanned image sensor is either undesirable or not feasible. An MV-201 camera has been incorporated in a camera system to be used for underground inspection in the event of a mine disaster. In this situation a long 2-1/2 inch diameter cylinder containing the camera, a slow-scan converter, and a battery pack is lowered into a borehole which has been drilled to reach the site. Single frame slow-scan video is then transmitted along a connecting cable to an observation site at ground level. Due to the possibility of explosive atmospheres at the mine site a standard vidicon system, with its associated high voltages, cannot be used without a large diameter explosion-proof housing. The CCD approach overcomes this limitation.

A development program, now is progress, utilizes a parachute deployed ILT-CCD camera and RF link in an artillery-launched projectile to provide real-time observation of selected areas (Ref. 5). The program makes use of the M485-A2 illuminating round for the 155 mm howitzer where the illuminant is replaced with a ballistically matched package (See Figure 5). In operation, the TV frames are simultaneously displayed in real time on a monitor and recorded on video tape. During the projectile launching, the camera system is required to endure setback accelerations of over 14,000 G's. A completely solid-state image sensor is clearly essential for operation in such an environment.

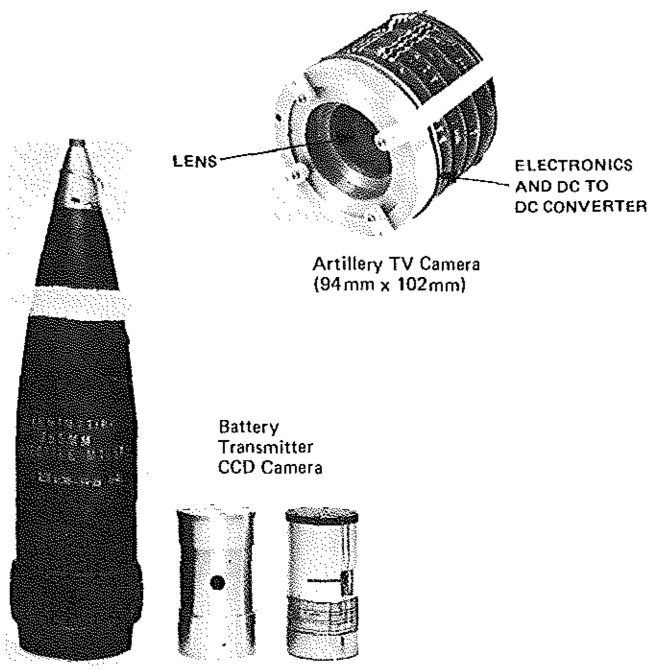


Figure 5. Artillery TV System

Recently concluded study programs have established feasibility for imaging systems consisting of a camera and video processor employing three electrically identical CCD area arrays, one of which functions as an imaging sensor supplying single-frame video on command to two opaqued area arrays operating as electrical-in/electrical-out analogue storage arrays (Ref. 6). The storage arrays are identical to the imaging array except an additional horizontal register, designed to accept analogue video signals at line rate, is used to inject charge packet information samples into column register sites on the side of the array opposite the output register. Control logic, arranged to select a particular frame of video from the imaging sensor output, is then used to load or "write-in" information into the vertical register sites of the storage arrays. Two arrays are required, each accepting one of the two fields comprising the complete frame. The frame information contained in the storage arrays can then be readout at the same rate as the input rate, or at a higher or slower rate, i.e. the two storage arrays perform a scan-rate conversion function. However, unlike other forms of electrical storage devices, the CCD array reads out the stored signal completely and therefore an erasure and priming cycle is not required. Write cycles can follow read cycles immediately with no need for dead time in between.

A major goal of CCD sensor research and development is to develop imaging devices suitable for use at very low light levels. Means for achieving this goal have been included in the 190 x 244 and 380 x 488 arrays; laboratory tests have yielded threshold imaging performance with sensor illumination levels of the order of 10^{-4} lx, 2854K (10^{-5} fc, Ref. 2, 4). The level of operating sensitivity achieved exceeds that of most beam-scanned image sensors with the exception of large-format camera tubes utilizing a form of image intensification prior to signal readout.

An approach which is conceptually similar is the subject of a current program to develop compact low-power Image Intensifier-CCD (I^2-CCD) TV cameras. In this case, the image sensor consists of a microchannel-plate image intensifier coupled by fiber optics to a buried-channel ILT-CCD array. Figure 6 illustrates preliminary test results for an assembly consisting of a 25 mm intensifier coupled through a 25/18 fiber-optic minifier to a 190 x 244 array, operating at a readout rate of 60 frames/sec. The smallest test patterns in these photographs correspond to 16.7 lp/mm resolution at the horizontal Nyquist limit. Threshold imagery was observed with sensor highlights near 10^{-5} lx, however the experimental system was gain limited at these levels. With additional gain, the threshold for the centrally located 1/2 Nyquist bars is expected to approach 10^{-6} lx, where the system would be intensifier-noise limited (Ref. 7).

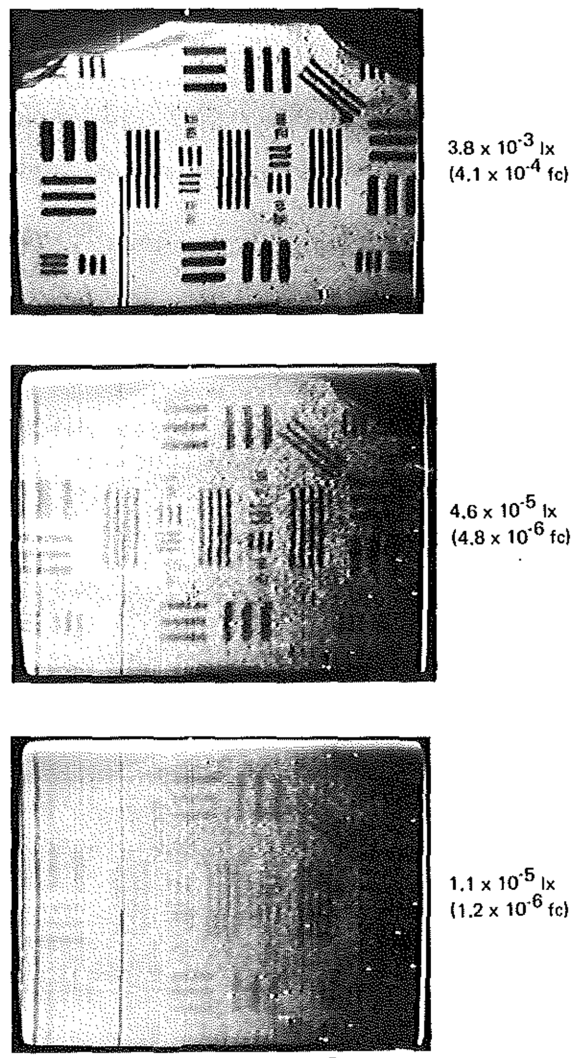


Figure 6. Image Intensifier-CCD (I^2 - CCD) TV Camera Images, 190 x 244 Array