HIGH RESOLUTION IMAGE LINE SCANNING WITH AN AREA IMAGE SENSOR

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A technique is discussed which can be used to achieve high resolution image line scanning with a low resolution area detector array. The image illuminates a metallized mask which is either fabricated as the top layer of the array or is fabricated separately and relay imaged onto the array. The mask is opaque except for small clear apertures which are located over the detector elements. These apertures are equal in size to one picture element (which is a small fraction of the size of one detector element) and have locations which are staggered sideways from one row of detectors to the next. As a two dimensional image is moved vertically past the mask, any given picture element along a horizontal line is sampled by only one row of detectors. The picture elements read out in each frame of data are thus distributed over several lines in the image. They are "destaggered" in a shift register buffer or computer memory to achieve a properly formatted image. The linear scan resolution obtainable using such a technique is equal to the total number of detector elements in the array, despite their rectilinear layout.

A breadboard document scanner was set up to demonstrate this basic concept. A commercially available area CCD detector array having 190 x 244 elements was used in conjunction with a separately fabricated metal mask and relay optics. The mask format consisted of 15 rows of apertures, with 190 elements per row, resulting in a net line scan resolution of 2850 elements. The array design was of the interline transfer type, with 190 columns of detectors and every other row interlaced. For this experiment, the top few rows of each interlaced frame were read out at an average data rate of 5 MHz, with the remaining rows rapidly dumped into the output shift register to clear dark current. This resulted in a frame rate of 250 frames per second. Data was single level thresholded, read into a high speed FIFO, and then destaggered using a NOVA computer. Results are shown which demonstrate the full resolution capability of the system, without artifacts produced by the "staggered aperture" technique.

I. Introduction

The most commonly used technique for reading high resolution imagery into an electronic data system makes use of an image line scanner. This line scanner is used in conjunction with a relative cross-scan motion between the object and the viewing system to achieve raster input scanning. Such a system is diagrammatically shown in Figure 1, where an object, which could be an original scene, a photograph, or any other two dimensional set of data, is imaged onto a linear CCD detector array. As the array is repetitively read out to detect image intensity, the object is translated perpendicular to the scanning direction to achieve raster scanning of this image data. The resolution (as measured in total number of resolvable picture elements) is limited by the number of detector elements in the linear scanner. The number of elements which can be fabricated in such a single solid state device is determined by the maximum allowable chip length divided by the minimum detector size, and is limited by the particular photolithographic process and such things as allowable yields, shift register CTE's, and minimum barrier heights.

This paper proposes an alternative way to perform line scanning which uses an area image sensor to achieve a scan resolution equal to the total number of

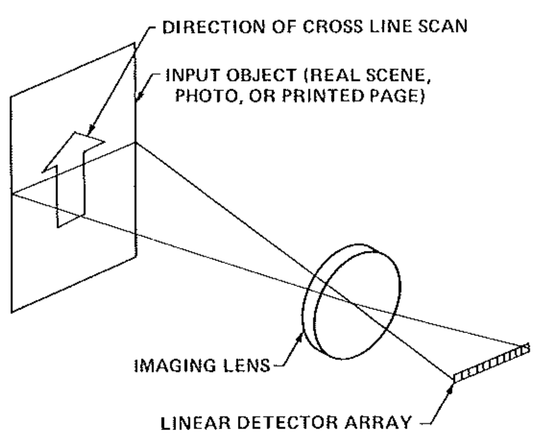

Fig. 1 Image line scanner

detector elements in the area image sensor independent of their orientation in rows and columns. A superimposed metalized mask and an auxilliary data buffer are used to achieve much higher resolution scanning than obtainable with a single linear detector chip, since the chip length/detector size limitation is no longer important.

II. Concept Description

The basic concept is explained using the diagram in Figure 2a. A two dimensional strip region of the scene to be scanned is imaged onto an area detector array consisting of a number of rows of detector elements. The magnification is such that the entire length of the region to be scanned is imaged onto the length of one row on the array. This imaged line length has the full number of desired image resolution points, but these are not fully resolved by the detector array which has a smaller number of elements per line. To enhance the resolution, an opaque mask is placed over the detector array as shown in Figure 2b, which has small clear apertures in it which allow light from only one image resolution point to fall on each detector. As shown in Figure 2b, the positions of the holes in front of each detector are staggered so that each row of detectors sees a set of image resolution elements along one line, with the element positions staggered from line to line. As seen in the figure, each time the array is read out, the number of image samples taken is equal to the total number of detector elements in the area array, but they are spread out over a number of lines in the image. By providing a translation between the imaging system and the object in the cross scan direction, all image resolution elements along an image line will be detected once the image line has moved past the entire height of the array. The resolution elements along each line are obviously not detected sequentially and must thus be rearranged using an associated buffer memory. The combination of array, mask, and associated buffer memory is called a "staggered aperture scanner". In concept, it is somewhat related to a technique suggested years ago called "spatial pulse modulation" which is here adapted to make practical hardware.[1]

In a practical system the array and mask shown in Figure 2b would not work properly because the light from some apertures would fall exactly on detector boundaries. In this situation, the photoelectrons would be collected by two photosites, resulting in poor pixel definition. To alleviate this problem, a real system would use detectors which are also staggered from row to row as shown in Figure 2c, to allow each aperture to be centered on the appropriate detector.

One possible modification of the system described above makes use of anamorphic optics. In this case, shown in Figure 3a, the optics are designed to image square picture elements on the object as tall rectangular picture elements on the array. The mask for this case has tall rectangular apertures as shown in Figure 3b. The height of these apertures could extend anywhere in the range

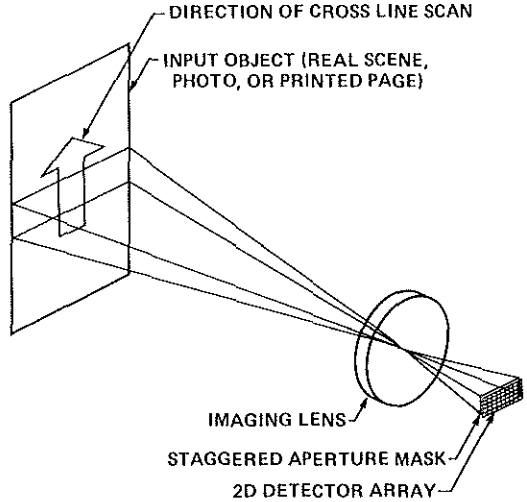

Fig. 2a. Staggered aperture scanner

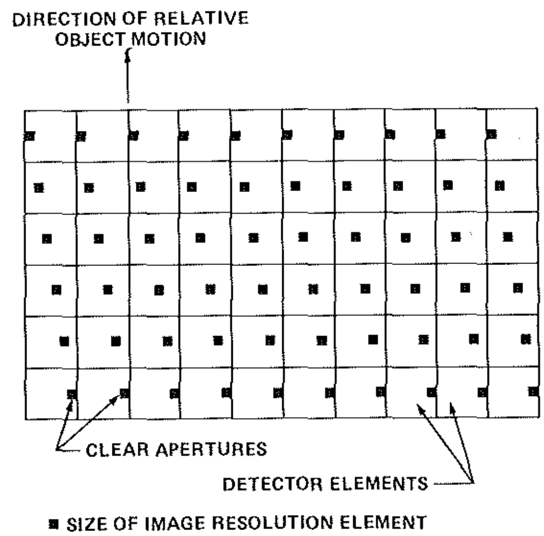

Fig. 2b. Staggered aperture mask for 6 row detector array

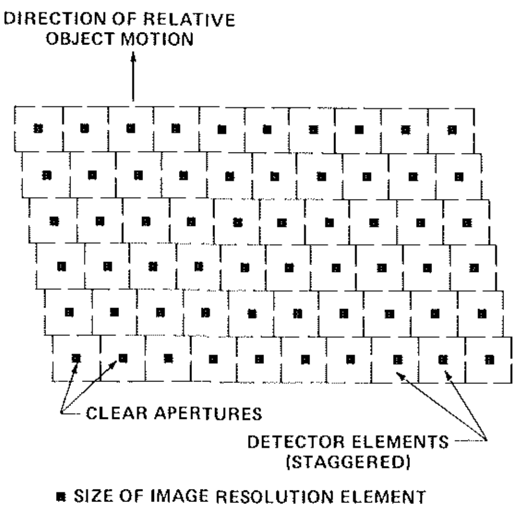

Fig. 2c. Staggered aperture mask for 6 row detector array showing optimum detector positions which are staggered sideways to line up with apertures.

from equal to the aperture width (conventional case) to equal to the height of the entire array. As the anamorphic ratio gets larger, however, the optics become difficult to build at the f/#'s required for high speed operation.

It is important to note that the total number of picture elements per line obtainable using any of these staggered aperture techniques is not affected in any way by the number of rows of detectors (which is presumed to be easily extendable to at least 32 or 64), but is instead affected only by the length of the array and the aperture spacing. If L is the length of the array and A is the aperture width (normally assumed equal to the pixel spacing), the total resolution capability of the array is given by L/A. This total number of resolution elements is thus limited by the achievable chip length L and the minimum aperture size A for a detector array with a superimposed mask. For larger numbers of picture elements per line, the minimum aperture size producable by a given photo-lithographic process may thus determine the ultimate resolution capability. (As one example, if the chip length L were 28 mm and the aperture size A were 4 microns, a single chip staggered aperture scanner would have a net resolution of 7000 elements). To extend the technology further, a relay imaging system such as shown in Figure 4 may be used, where the mask is actually larger than the detector array, but is demagnified down onto the detector array. This allows for substantially greater extension of resolution

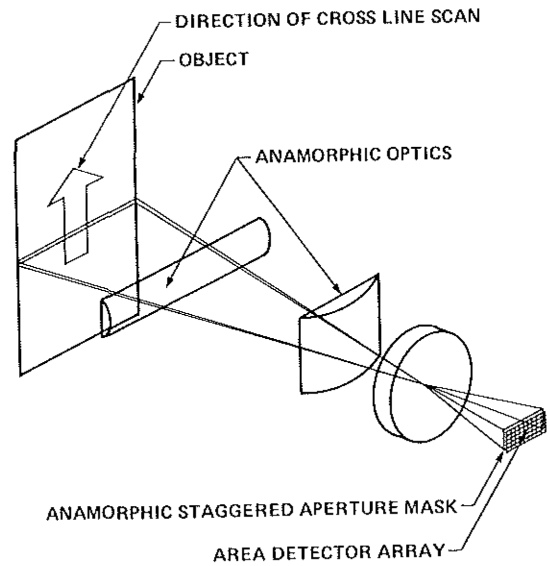

Fig. 3a. Staggered aperture scanner with anamorphic optics

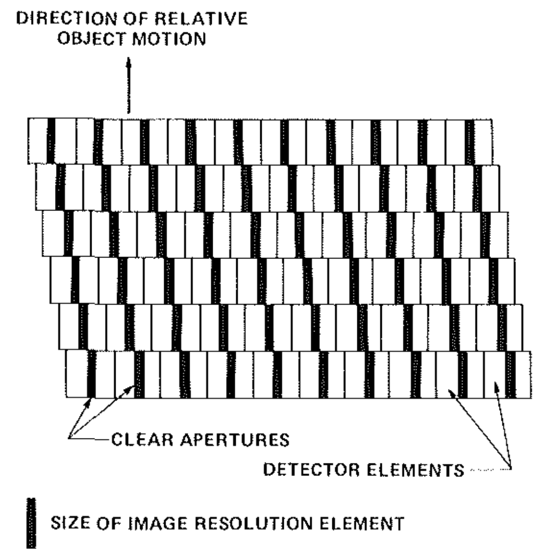

Fig. 3 b. Anamorphic staggered aperture mask (anamorphic ratio equal 6).

capability, since resolution is only limited by the mask photolithography and the resolution capability of the optics, with less concern for long detector array sizes. However, the alignment and stability tolerances on such a system are relatively tight, making it practical for only limited high performance applications.

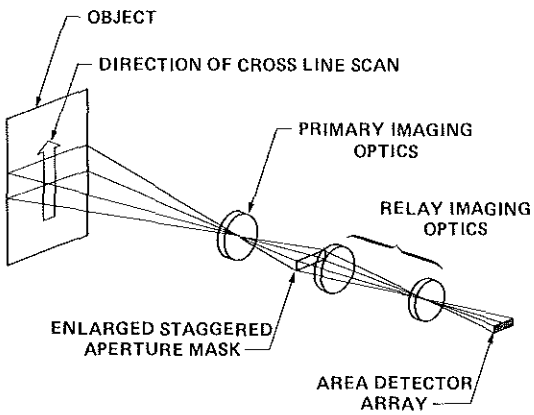

Fig. 4. Staggered aperture scanner using relay optics

Destaggering

The required "destaggering" algorithm needed to rearrange the picture elements in the buffer memory is a very simple storage operation which is understood as follows. Considering the image of a single line of data on the object, it is first translated into position under the bottom row of detectors. After readout, the image line is translated up where it is sequentially read out by each row of detectors. The destaggering algorithm is simply the following: the data read from the bottom row of detectors must be stored until the line has been translated to the top row, at which time all picture elements along the line have been read, and the line can be reconstructed. Picture elements detected with the row of detectors next to the bottom must also be stored until the line of input data is translated to the top row, but the storage time is less because the line elements read were detected by this row at a later time.

The complexity of the buffer required for this operation is determined primarily by its storage capacity, which is calculated as follows. If n is defined as the number of rows of detectors, N as the number of detectors per row, and n' as the number of picture lines between detector rows (which equals n-1 for a nonanamorphic system and equals 0 for the anamorphic optics shown in Figure 3), then the required pixel storage capacity in picture elements is given by

$$\text{buffer size} = N[n' + 1]\,[(n-1) + (n-2) + \ldots + 1].$$

This formula can be used to calculate the capacity for a system using nonanamorphic pixel elements such as that shown in Figure 2. This capacity is plotted in Figure 5a as a function of the total number of resolution elements per line, for a number of different values of n, the number of detector rows. (The total number of resolution elements is equal to Nn, the product of the number of rows and the number of columns.) Each of the solid lines represents the rising buffer capacity with increasing total picture elements for a given number of detector rows n. The rising dashed lines represent the buffer capacity required for an array having a fixed N number of detectors per row. By following these curves to their intercepts with the solid lines, any given combination of N detectors per row (from the dashed line) by n rows of detectors gives the buffer capacity on the y axis and the number of picture elements per line on the X axis. Conversely, a system designer with a given requirement for a number of picture elements per line can use this graph to determine the tradeoff of number of detectors per row, number of rows of detectors, and buffer capacity. Figure 5b shows the required buffer for an anamorphic system similar to the one used in Figure 4. These figures are based simply on number of obtainable picture elements from the detector system, without regard for other system details. For a superimposed mask imager, the combination of optics and photolithography will probably limit the maximum number of elements practically achievable to between 5000 and 10000 because of the required small aperture size. A more complicated relay setup such as shown in Figure 4 would enable extension to somewhere around 10,000 to 20,000, limited principally by the optics.

A range of other degrees of anamorphism are also possible, all the way from nonanamorphic to the extreme of optics which spread the picture elements vertically across all the detector elements and requires no buffer. The required electronics obviously decreases in complexity with decreasing number of detector rows, decreasing total number of picture elements per line, and increasing degree of anamorphism. The complexity of the optics increases with degree of anamorphism, generally resulting in lower working light levels because of system cost and complexity tradeoffs. The exact limit to which this anamorphism can be pushed without significant sacrifice of light depends upon the particular system magnification and cost constraints and is a detailed optical design problem.

Light Level Considerations

The signal level obtainable in a staggered aperture system is obviously dependent on light level, and should only be compared to a linear array system with the same resolution. If the linear array is to be implemented with a detector size equal to the aperture size in the staggered aperture system, then the light level for the two cases will be the same, since the detection areas are identical. The difference will be that due to the larger cell size, the staggered aperture system will exhibit a larger dark current and a larger charge handling capability. If the staggered aperture system is to be compared to a linear imager with the same detector size, then the staggered

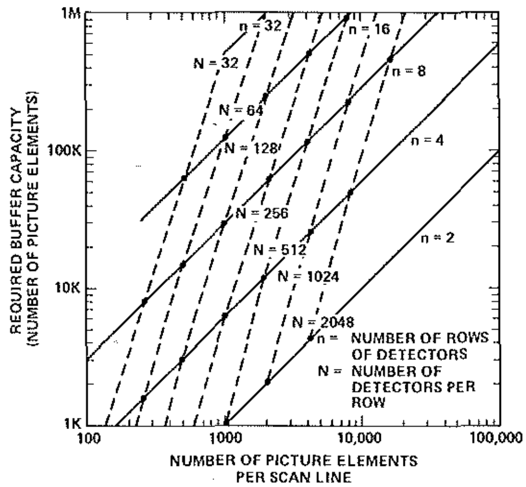

Fig. 5a. Required buffer capacity in picture elements for a nonanamorphic staggered aperture scanner.

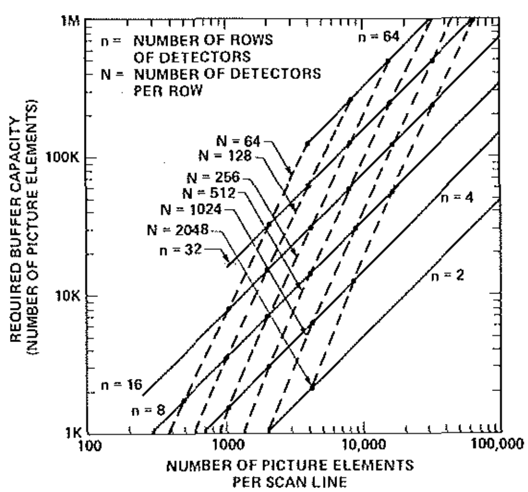

Fig. 5b. Required buffer capacity in picture elements for an anamorphic staggered aperture scanner with an anamorphic ratio of n, where n is the number of rows of detectors.

aperture system will have less light by the ratio of aperture area to detector area. However, the linear array will also be n times longer, where n is the number of rows of detectors. In addition, since the optics become easier to build for the higher demagnification required in the staggered aperture system, it may be possible to work with lower f/# optics for the smaller pixel size, recovering some of the lost light. This is a qualitative judgment however, which can only be determined through a detailed lens design for a given system application.

Sampling Aperture

One interesting feature of the staggered aperture system is the ability to almost arbitrarily chose the sampling aperture size and shape. For a conventional linear imager, square or rectangular picture elements are used which basically abut each other at the detector edges. This provides for sampling at the Nyquist limit with moderate control of image aliasing. For a staggered aperture system, other aperture shapes which over sample could be used to give much finer control of aliasing. As an example, Figure 6 shows three possible pixel sizes and shapes and the resulting system MTF. Also shown are the well known foldback aliasing terms produced by convolution of the system response with the transform of the periodic sampling function.[2] The top curve in the figure shows a conventional set of abutting pixels with the foldback aliasing image terms going through zero at the low spatial frequencies. The middle figure shows a double width pixel having a 2-1 overlap. The foldback aliasing terms are obviously much less, but so is the MTF. The bottom curve shows an overlapped diamond which is a compromise MTF between the other two but has a dramatically reduced aliasing fold back term near the origin. This type of aperture controls aliasing extremely well along the horizontal and vertical picture axes.

Filtering Considerations

One significant aspect of a staggered aperture scanning system is that neighboring detectors sample light from every nth picture element. Because of this, destaggering must be performed before any filtering operations can be applied to the readout signal. In addition, this places a higher required value on the charge transfer efficiency of the readout register than would be required for a linear scanner.

III. Experimental Breadboard

A simple laboratory experiment was set up to demonstrate the basic staggered aperture concept. A commercially available Fairchild array having 190 by 244 elements was used in a relay optics configuration similar to Figure 4. The top 15 rows of detectors in the CCD were used, resulting in a total system resolution of the 15 x 190 = 2850 elements. The magnification of the system was such that these resolution elements were spread across a 6.8 inch format resulting in an image resolution of 420 bits per inch. The input was a black and white test pattern placed on a translating stage and illuminated with light from two florescent lamps. Light

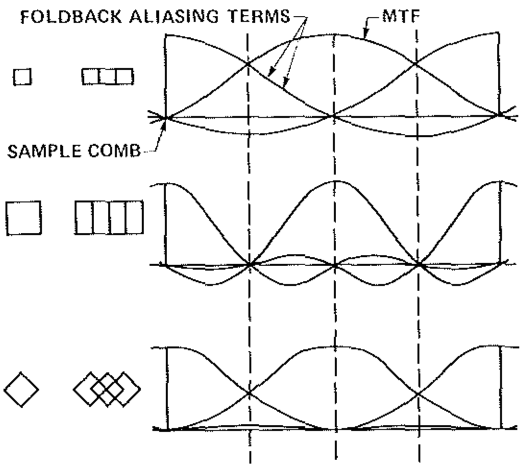

Fig. 6 System MTF and foldback aliasing response on the x-axis for three different aperture sizes and shapes.

from the illuminated region was reflected off a 45 degree mirror, traveled down an optical bench, and was imaged onto a metalized mask at 13.5 reduction. This mask was then relay imaged onto a commercially available area imager at 1: 2.25 demagnification. Figure 7a shows the basic system front end, with the metalized mask, imager, and relay optics shown in Figure 7b.

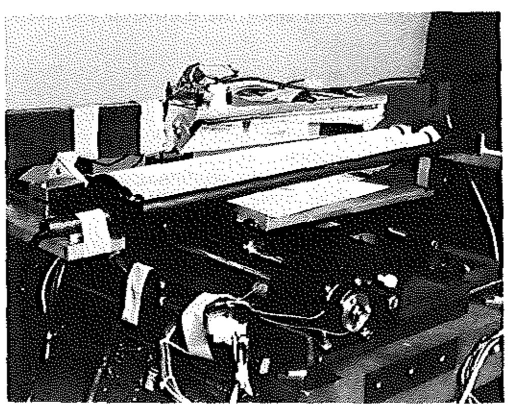

Fig. 7a. Breadboard illumination system showing transport, fluorescent lamps, 45 degree fold mirror, and test pattern.

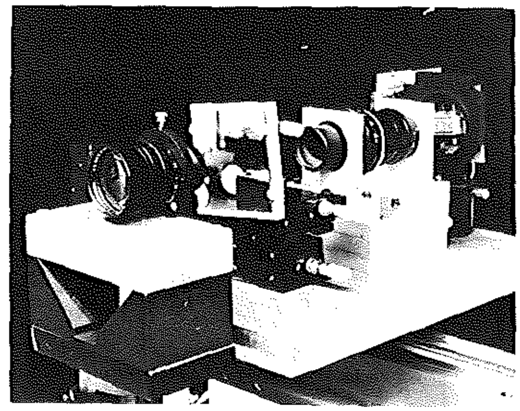

Fig. 7b. Breadboard relay optics system showing primary imaging lens, tilted mask, relay optics, and detector

Since the geometry of the array was not specifically designed for this type of application, it has detectors arranged on a rectangular format such as Figure 2b, rather than the optimum format shown in Figure 2c. To account for this, and still allow the light from each aperture in the mask to fall in the approximate center of its appropriate detector, the mask and array were tilted with respect to the direction of document transport by 6.3 degrees. The effect this has is shown in Figure 8 which shows a picture of the aperture mask, the approximate detector sensing elements, and the document picture elements. As seen in the figure, the apertures on each row of detectors were positioned to fall exactly on one picture element. Because of the tilt of the array, these picture elements were on different document rows as well as different columns. An additional complexity involves the normal use of the Fairchild array as a TV sensor, having interlaced readout of every other detector row. Compensation for this was achieved by displacing every other row of apertures vertically by one half picture element as shown in the figure. Due to the interlaced readout, these detectors were read out one half frame later than the others, allowing the transport to displace the picture elements during this time so that they fell exactly on the aperture locations. These complications involving the use of this particular array affect the complexity of the destaggering algorithm, but do not alter the basic concept.

Alignment of the mask with the array was achieved by first aligning the mask with the array using a traveling microscope. This provided a crude alignment which could be peaked up by observing moire patterns on the detector array output which were caused by interaction between mask aperture structure and the detector element structrue. With uniform illumination at the mask this moire show up as a cyclical variation of the detector output, a sample of which is shown in figure 9a.

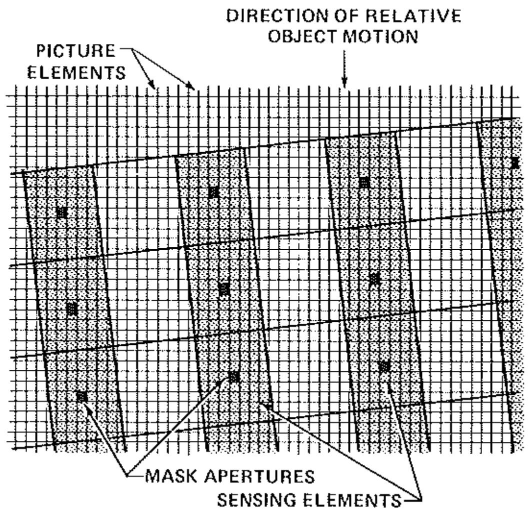

Fig. 8 Diagram of tilted mask configuration used in breadboard showing overlapping picture elements, mask apertures, and detector elements.

This cyclical variation showed maximum contrast when the mask was in focus on the array. This contrast was thus used for mean focus setting and for mask tilt (in focus) adjustments. Optimum magnification was determined by measuring the cycle length of this morie pattern as the magnification was changed and setting it to give an infinite cycle length (i.e. when one moire cycle covered the entire length of the array). Final lateral translational adjustment of the mask was achieved by peaking up the entire output signal. Vertical translational adjustment was achieved by making sure that the top row of apertures in the mask fell on the first row of detectors read out. Final alignment was achieved by illuminating one aperture at a time and checking for isolated detector output as shown in Figure 9b.

The Fairchild CCD211 array used for this experiment is organized as an interline transfer system with 190 interline transfer registers of 122 elements.[3] It is operated in the normal TV mode with two interlaced fields. For readout, charge packets from alternate sets of sensing elements are transferred horizontally to vertical interline registers, as shown in Figure 10. Each interline register accesses 244 sensing elements in two fields of 122. There are 190 interline registers for the 190 columns of the array.

The interline shift registers are clocked in parallel so that for each vertical clock cycle, one charge packet from each interline register is presented to the output or horizontal register. It can be seen that for each field the entire contents of the vertical interline registers must be shifted into the output register before the next field is accessed to avoid superimposing charge-packets from one field onto charge-packets from the next field. In our experiment 10 rows from each field are read out. (The 15 rows of data actually used are selected from these 20 read out rows by the line counter electronics.)

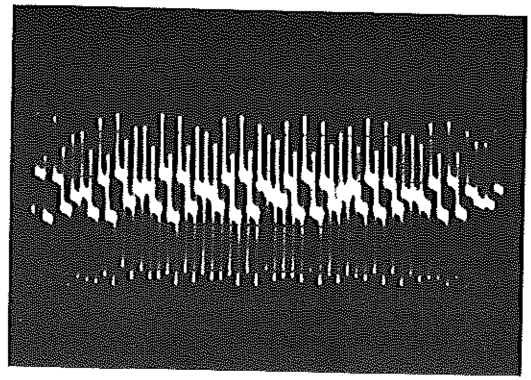

Fig. 9a Typical array output used to adjust array alignement showing moire fringes due to improper magnification.

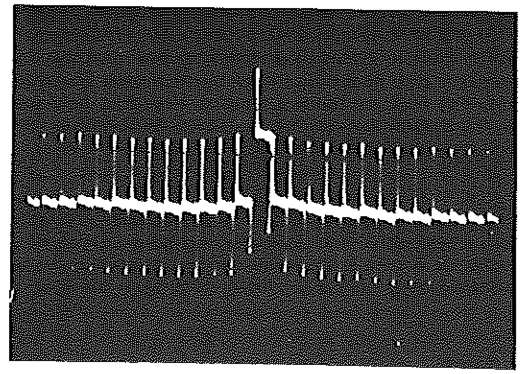

Fig. 9b Array output with single aperture illuminated.

The timing sequence used to operate the array is shown in Figure 11. The horizontal output register contains 200 elements and receives the charge-packets from the interline transfer registers at each vertical shift. Charge packets are shifted out of the horizontal register at 5 MHz. A total of 256 shift times are used for each line: 200 to empty the horizontal register and 56 to wait while the next line is shifted in from the interline transfer registers, resulting in a total line time of 51 μsec. For this experiment, 10 of the 122 rows of sensing elements in each field are read out. It is thus necessary to purge the unused accumulation of noise from the remaining registers, resulting in a total line time of 51 μsec. For this experiment, 10 of the 122 rows of sensing elements in each field are read out. It is thus necessary to purge the unused accumulation of noise from the remaining

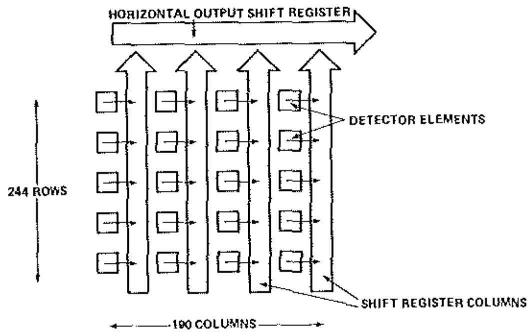

Fig. 10. Interline transfer array organization

rows of the vertical registers before a new field can be accessed. This is accomplished by increasing the shift rate of the interline transfer registers from 51.2 μsec per row to 6.4 μsec per row. This vertical shift rate of 160 KHz will empty the interline transfer registers in 717 microseconds. The total time to receive the entire frame of 20 lines is then 2.5 milliseconds. During the time that unused charge packets are being purged from the array, the horizontal output shift rate is maintained at 5 MHz even though the vertical shift rate has been increased by a factor of 8. This results in the charge-packets being superimposed on previous charge-packets at an 8 to 1 rate. Since the unused data consist only of dark current and background illumination, saturation of the output register is not reached with the 8 to 1 multiplication of the charge.

The output signal from the array is threshold detected and converted into a TTL logic signal indicating either black or white information. A sample and hold circuit has also been provided so that more accurate measurements of signal amplitude can be made.

In order to implement destaggering for this breadboard system, including the complexities of multiple lines, multiple columns, and frame interlace, an off line concept was chosen for destaggering as shown in Figure 12. The data was read from the CCD array, single level thresholded for 1 bit detection, and read in real time into a 1.5 Mbit FIFO at a data rate of 5 MHz. This data was later taken from the FIFO, destaggered with a Fortran program in a NOVA 800 mini computer, and displayed on a CRT. Although this procedure is much too time consuming for most practical systems, it was adequate for this feasibility demonstration.

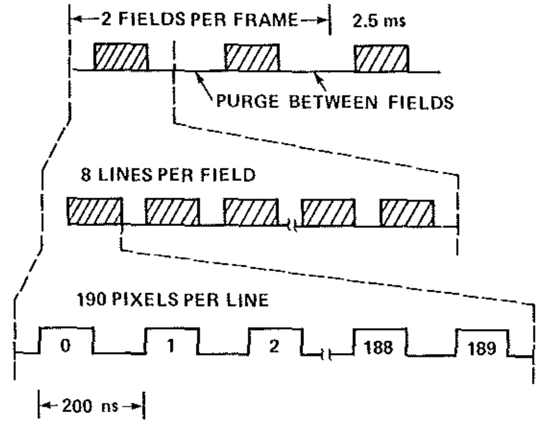

Fig. 11. Data format for staggered aperture breadboard

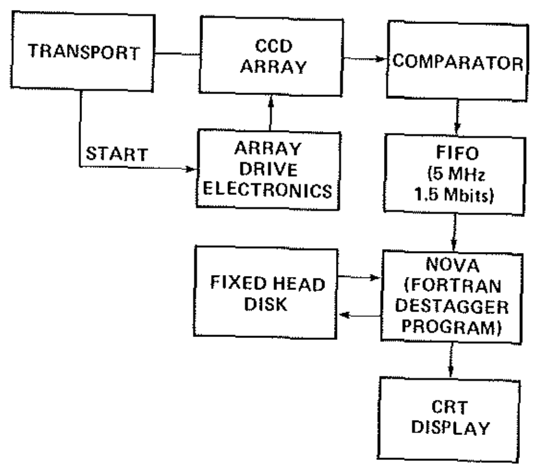

Fig. 12 Breadboard electronic system used for destaggering.

Figure 13a shows an example of data read in from a text test pattern, with output data printed on a laser printer to show the full 2850 element capability. The data file was limited in size by the FIFO to a tilted region commensurate with the tilted array. The data at the top and bottom shows incomplete data lines where the

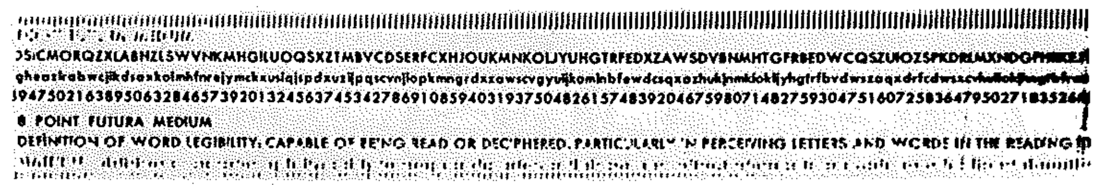

Fig. 13a Sample output of full resolution scanner showing 2850 bit resolution. Top and bottom rows of data are incomplete because data rows were imaged in middle (vertically) of detector rows when data taking started or stopped. Spacing of vertical black lines indicates spacing of detectors on array.

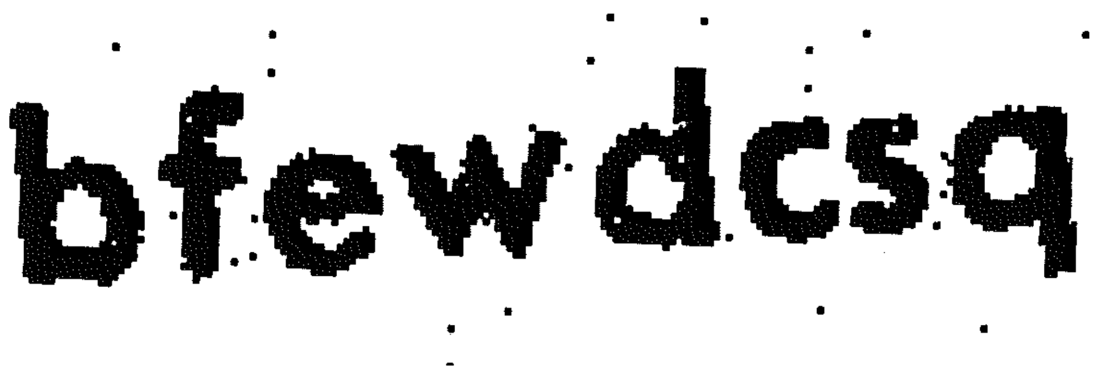

Fig. 13b. Magnified view of data in Figure 13a.

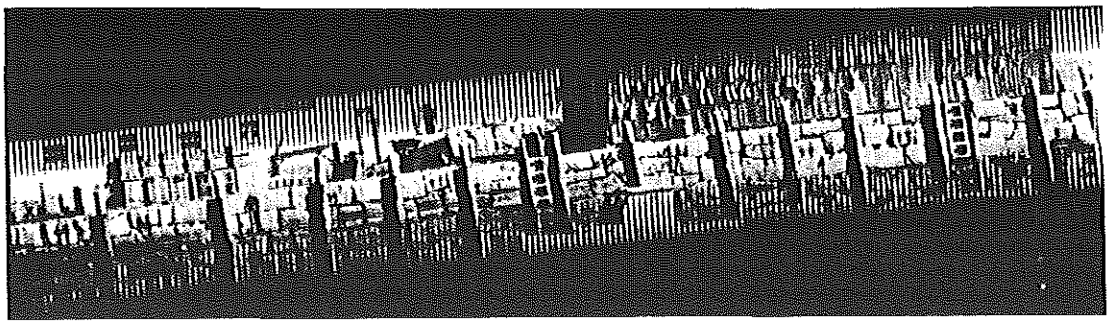

Fig. 13c. Output for input halftone pattern. Comb function at edge of picture is incomplete data. Spacing of comb function shows spacing of detectors in detector array. (Background is black for this picture because the test pattern was negative and the data has been inverted.)

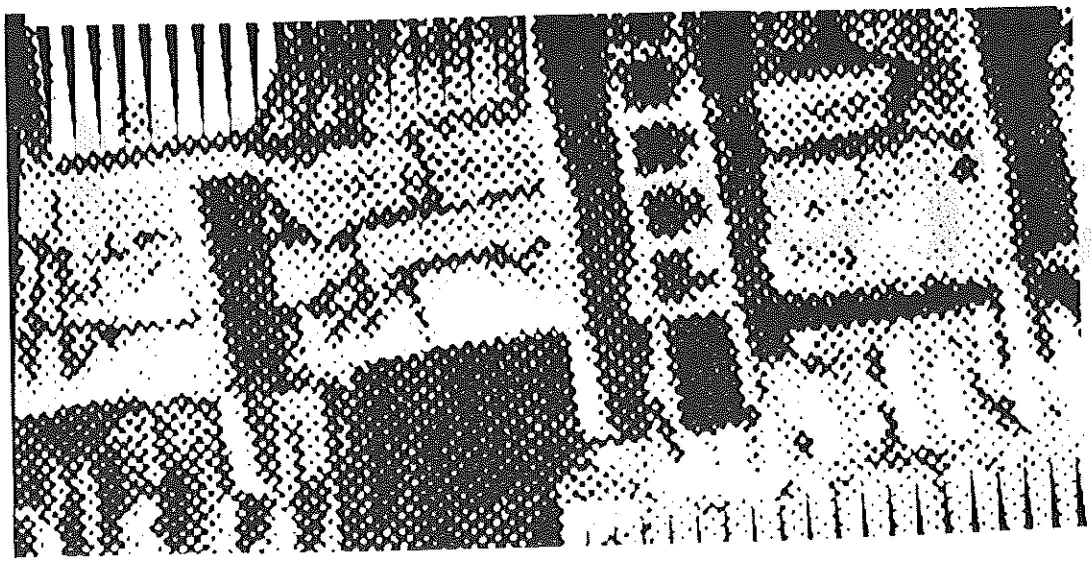

Fig. 13d. Expanded view of data in Figure 13c.

document line was imaged inside the region of the area imager when data taking commenced or when it finished. As expected, the incomplete data shows up as a triangular comb function, since data points nearer the center were sampled by more detector rows than those at the edge. Figure 13b shows an enlargement of some of the textural detail, showing no significant noticeable affect of the destaggering procedure. Some black dots are seen in the background region which were caused by noise in the electronics which were not fully optimized. Figure 13c and d show similar results for an input halftone picture with a screen frequency of 85 cells per inch. In this case, the test pattern was a negative and the picture has been inverted to clearly show the comb function at the edge of the field. The spacing of the teeth in the comb indicates the spacing of the actual detectors in the array.

Conclusion

A technique has been demonstrated for achieving high resolution line scanning of a two dimensional image by using an area detector array. This technique uses a metalized aperture mask on the optical input and a computer buffer memory on the array output to achieve higher resolution performance than possible from a single linear array. A sample breadboard system was built to demonstrate the high resolution data can be taken in this way and reconstructed without artifacts.

Acknowledgments

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References

[1] Lohmann, A. W. and Werlich, H. W., Appl. Opt. 10, 2743 (1971).

[2] B. Kazan ed., Advances In Image Pickup And Display, Vol III (Academic Press, N. Y., 1977), pp.241-255.

[3] Steffe, W., Walsh, L. and Kim, C. K., Proc. of 1975 Conf. on the Appl. of Charge Coupled Devices, pp.101-108.