CONF-9107115--44

A miniature acousto-optic image correlator

SAND--90-3161C

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1. ABSTRACT

An acousto-optic (AO) image correlator architecture will be presented that minimizes the overall system size while maintaining excellent image quality for large input scenes. The correlator can accommodate grayscale input scenes with dimensions of 512 x 244 pixels and grayscale reference templates of size 64 x 64 pixels. The size of the optical system, however, is less than ten cubic inches, 1" x 1" x 9". This design incorporates a surface emitting laser diode array that has a center-to-center spacing of the laser elements matched to the row spacing on the CCD. Furthermore, the space-bandwidth and center frequency of the AO cell are chosen to match the length of the input image information in the cell to the width of the CCD. These two design decisions allow close to one-to-one imaging through the entire optical system producing the shortest possible path length. The optics were then designed with a goal of producing nearly diffraction-limited image quality.

2. INTRODUCTION

Previous publications have shown the capabilities of the acousto-optic correlator in automatic image recognition applications.[1-4] The new design introduced in this paper provides a means for not only developing a miniature system with nearly diffraction limited image quality, but also allowing the throughput of the processor to increase from the present 60 correlations per second to 400 correlations per second.

3. CORRELATOR ARCHITECTURE

The acousto-optic correlator, shown in Figure 1, performs a 2-dimensional (2-D) correlation operation between an input scene, f(x,y), and a reference template, g(x,y).[5] The two dimensional input scene can be described as a function f(t,n) consisting of n sequentially scanned lines, such as from a raster scanned TV camera. Likewise, the template can be described by g(t,m) consisting of M discrete rows of continuous information of extent T. Each row of the reference template drives a separate element of the laser diode (LD) array. The LD array is imaged into the aperture of the AO cell which in turn is reimaged onto consecutive rows of the CCD. As each input image line propagates down the length of the AO cell, it is correlated against all of the rows of a reference template. The correlation in the direction perpendicular to the long axis of the AO cell is accomplished by operating the CCD in the shift-and-add mode. The two-dimensional correlation is performed by shifting the charge in all rows of the CCD down by one row position before each new input image line is introduced into the AO cell. The resulting charge accumulation on the CCD represents the 2-D correlation between the input image f(t,n) and the reference g(t,m).

4. ARCHITECTURE MINIATURIZATION

The objective of miniaturization is to reduce the size of the optical system for the acousto-optic image correlator to the smallest possible volume while maintaining nearly diffraction limited image quality. The system described in this paper reduces the volume of the optical system to approximately 9 cubic inches. The resultant optical system is two orders of magnitude less in volume over the previously designed AO correlator.[6]

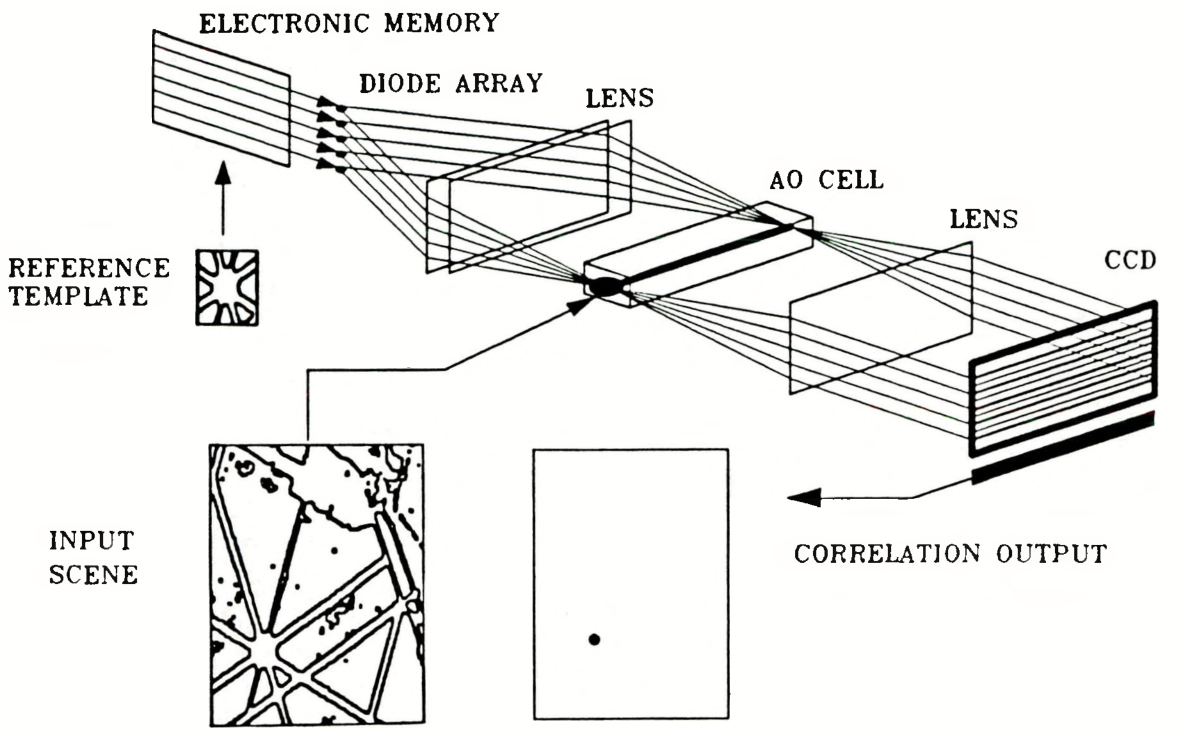

Fig. 1. Acousto-optic image correlator

Figures 2a and 2b show the top and side views respectively of a generalized AO imaging system. In order to create an optical system with the shortest possible length, it is desirable to have one-to-one imaging optics. To accomplish one-to-one imaging, the length of the information in the AO cell must equal the width of the CCD. As shown in figure 2a, the width of the CCD array is 6.28 mm. In order to match the information length in the AO cell to the CCD width, an AO cell must be chosen that has the correct bandwidth and time aperture. For our application, the width of the input scene is 512 pixels. A TeO_2 slow shear AO cell that has a bandwidth of 50 MHz and an acoustic velocity of 617 m/s was chosen as the modulator. By clocking the pixels into the AO cell at 20 ns per pixel, the 512 pixels of input scene information occupies a length of 6.31 mm in the AO cell, matching the width of the CCD. The resultant horizontal magnification required between the AO cell and the CCD is thus one-to-one.

From Figure 2b, the side view of the correlator, the row spacings on the CCD are 19.75 μm. The element-to-element spacings of the laser diode array, also being developed at Sandia National Laboratories, is 25 μm. Although 19.75 μm element-to-element spacing would be desirable, minimum bonding pad spacing and fanout requirements dictates an actual element spacing of 25 μm. This requires a magnification of 0.8 from the LD array to the AO cell in order to maintain one-to-one imaging from the AO cell to the CCD.

The throughput of the system increases by clocking the pixels into the AO cell at faster than standard video rates. The length of time it takes to load and correlate one input line of information is reduced to 10.24 μs. Therefore, the time to process a full field of 244 lines is only 2.50 ms. At this rate, 400 fields per second can be correlated, assuming the CCD array can sustain this readout rate. Therefore, this design accomplishes the goals of not only significantly reducing the volume of the system but also increasing the throughput.

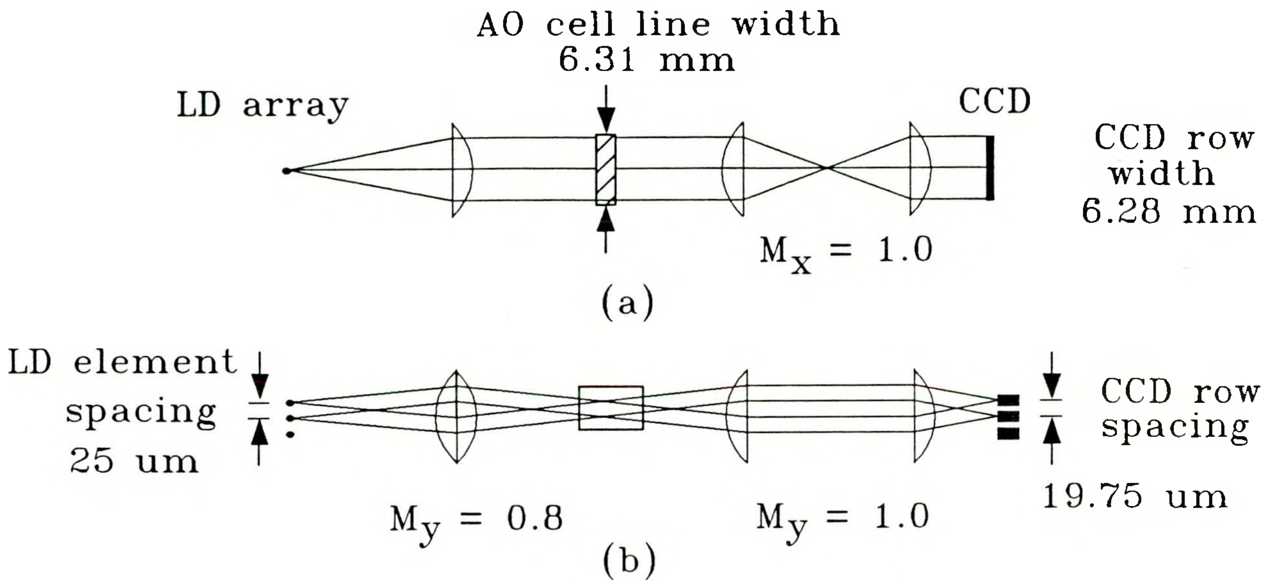

Fig. 2. (a) Top and (b) side views of a generalized acousto-optic imaging system

5. OPTICAL SYSTEM

5.1 Component characteristics

The sizes and characteristics of the diode array, the AO cell, and the CCD affect the optical design. There are 64 laser diodes in the array, which are nearly monochromatic at a wavelength of $\lambda = 0.85$ μm. The individual laser diode array elements are arranged on 25 μm centers, producing a total array height of 1.6 mm. Since the individual laser diodes are surface emitting, the light cone from each diode has a radially-symmetric intensity profile that is Gaussian. The full width, $1/e^2$ intensity of the individual elements is $\theta = 0.10$ radians which is equivalent to an F/10 beam.
The height of the 64 line foci of the LD array in the AO cell is 1.28 mm, which fits into the 2 mm wide acoustic column.

The slow shear TeO_2 AO cell has a center frequency of 75 MHz and a bandwidth of 50 MHz. The 75 MHz center frequency diffracts the input beam at a 6 degree angle. The 50 MHz bandwidth causes a ± 2 degree divergence around the center frequency angle, equivalent to an F/14 beam.

The CCD TV has a pixel spacing of 19.75 μm by 12.27 μm in the X and Y directions, respectively. We are imaging the line images from the 64 diodes onto 64 adjacent rows of pixels. The CCD has 512 columns of pixels, all of which we use. This represents an image size of 1.26 mm by 6.2 mm in X and Y, respectively. Table I summarizes the component characteristics used for the optical design.

Table I

COMPONENT CHARACTERISTICS

64-Element Laser Diode Array

monochromatic wavelength:	$\lambda = 0.85\ \mu m$
output power for each diode:	P = 1.0 mW
element spacing:	$\delta = 25\ \mu m$
array length:	$\Delta Y = 1.6$ mm
beam divergence at $1/e^2$ points:	$\theta = 0.10$ radians

Acousto-optic Cell

long axis in Y direction	
TeO_2 cell refractive index:	n = 2.6
cell thickness:	10 mm
acoustic column width:	$\Delta X > 2$ mm
shear wave velocity in cell:	$v_y = 617$ m/s
center frequency:	75 MHz
bandwidth of cell:	50 MHz

CCD

standard silicon detector response	
utilized array format:	64 x 512 pixels
pixel spacing in X and Y:	$19.75\ \mu m \times 12.27\ \mu m$
array size $\Delta X \times \Delta Y$:	1.26 mm x 6.28 mm

5.2 Optical system overview

Using the above criteria as a basis for the design, the following optical system was formulated. Figures 3a and 3b show the side and top perspectives of the miniature acousto-optic correlator. The optical system consists of three subsections; an anamorphic laser diode array collimator, the AO cell and glass wedge, and a final relay lens system. The laser diode array collimator consists of a collimating lens, two anamorphic prisms, and a cylindrical lens. The collimating lens is placed one focal length from the LD array and presents a symmetric collimated beam to the prisms. The prisms expand the beam in the Y direction to match the aperture of the AO cell. The cylindrical lens images the LD array elements to line foci in the AO cell. As the AO cell diffracts the light, the image of the diffracted information is not perpendicular to the direction of propagation. The wedge following the AO cell corrects for this tilt. The final relay lens system, composed of all spherical surfaces, images the AO cell onto the CCD with unit magnification.

5.3 Optical system design

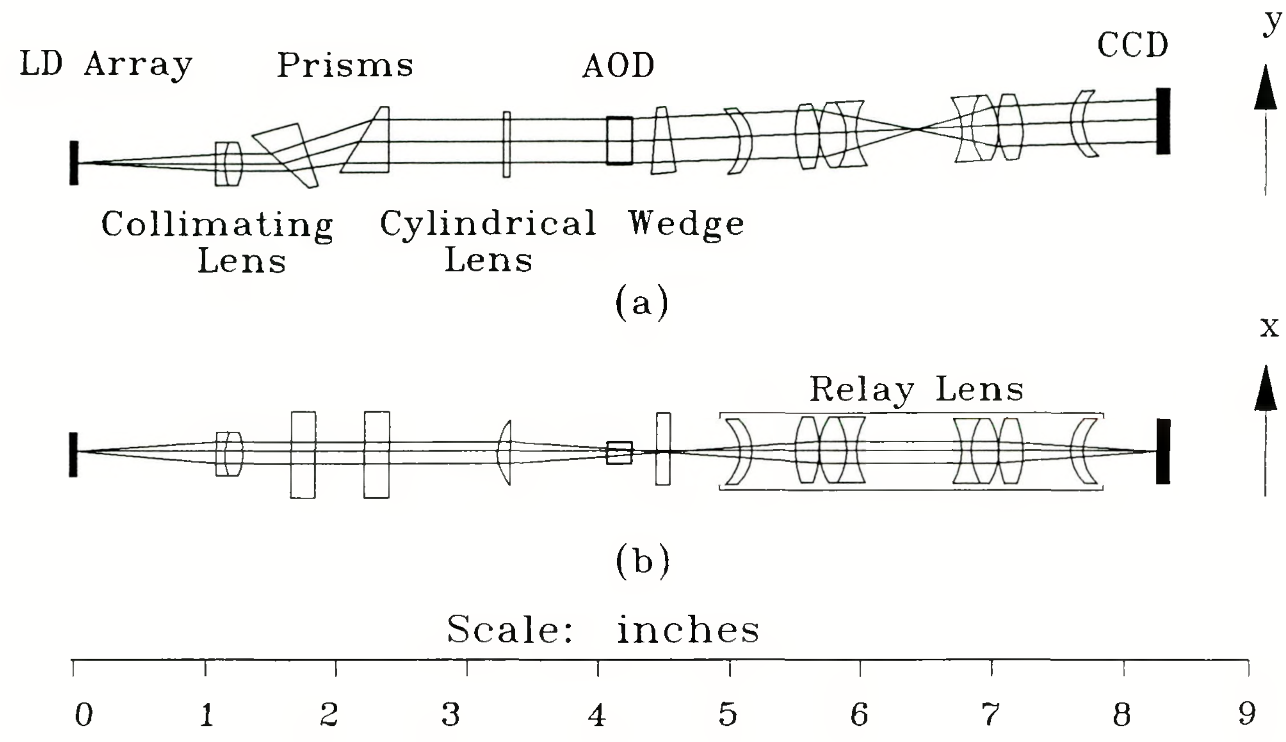

Fig. 3. (a) Top and (b) side views of the miniature AO correlator design

5.3 Optical system design

The divergence of the diode lasers sets the F/numbers of the lenses throughout the system. The divergence of the laser beams at the $1/e^2$ points is F/10. If this F/10 beam is carried through the system, the height of the image of a LD element line on a CCD row is approximately 17 μm. Since the CCD row spacings are 19.75 μm, most of the energy from each LD element is contained by its corresponding row on the CCD. To summarize the F/numbers through the system then, the front-end optical system collects an F/10 beam. Since the magnification of the front-end is $M_x=0.80$, it delivers approximately an F/8 beam to the AO cell. The relay lens has unit magnification, so it transforms the F/8 diverging beam into an F/8 converging beam.

The simplest front-end optics produce the best image quality. The light diverging from the laser diodes is collimated by an F/10 lens with spherical surfaces. At this point, the beam is about 3.2 mm in diameter. The two high-index (SF6) anamorphic prisms following the collimating lens expand the beams by a factor of 3.1 in the Y direction, thus the beam is now about 10 mm wide in the Y direction. The second lens is cylindrical (plano-convex) which focuses each beam into a line 10 mm long, parallel to the Y axis. The two lenses are separated by the sum of their focal lengths, so the line images converging toward the AO cell are also telecentric in the X direction; thus each line image passes through the AO cell in exactly the same way. There is another interesting feature of this design; the back focus of the spherical lens is a pupil plane. In order to maximize the intensity uniformity of the line foci across the AO cell, an apodizing mask can be placed in this plane. The shape of the mask can be adjusted to correct for the Gaussian beam profile and the beam ellipticity.

5.4 Optical system performance

The optical design has very little distortion and coma, since the magnification, $M_x = 0.80$, is only slightly different from one. The line foci produced by this system are also straight, there is no field curvature in the Y direction and no curvature in the plane of the image. There is a small amount of field curvature in the X direction which will defocus the lines generated by the diodes at the end of the array. The focal length of the spherical lens was chosen so the line images on the CCD would be 10 mm long between the $1/e^2$ intensity points. The CCD is only 6.2 mm long resulting in the intensity variation from center to the end of the lines of 46%.

As stated previously, the glass wedge tilts the image in the AO cell to bring it perpendicular to the direction of propagation of the diffracted order. If this were not done, the ends of the lines would be defocused by about a half of a wave resulting in serious blurring at the ends of the line images on the CCD.

The relay lens images the output of the AO cell onto the CCD. The object and image planes are both 1.26 mm by 6.2 mm and flat. The beam from the object is telecentric with an F/8 divergence in the X direction and F/14 in Y. A symmetrical design was chosen which is actually two eyepiece-like lens groups that are spaced two focal lengths apart. This means that the ray heights in the second lens group are equal and of opposite sign to what they are in the first group thus cancelling out third-order coma and distortion, though the astigmatism, field curvature, and spherical aberration must still be controlled. This is done with the steeply-curved surface in the glued lenses and the meniscus lenses near the object and image. The relay lens has a Fourier plane at its midpoint, where the light undiffracted by the AO cell can be blocked. The relay lens creates a two-dimensional image, so the Strehl ratio is a good measure of image quality. The Strehl ratio is greater than 99.9% on axis and is 98.8% at the edge, which is essentially diffraction-limited imagery. The distortion of the relay lens is about 0.1 μm at the edge of the field which is much less than a CCD pixel size. Hence, the information introduced into the AO cell will be relayed to the CCD in a nearly diffraction limited manner.

The image quality from the laser diodes to the CCD is not as good as the from the AO cell to the CCD due to the presence of the cylindrical element before the AO cell. Only one cylindrical lens was used in the design because of the difficulty in manufacturing high quality cylindrical elements and aligning them in the system. The line focus from the center diode to the CCD has a theoretical wavefront error of less than $\lambda/50$ over the center 80% of its length. Oblique spherical aberration defocuses both ends of this line to an rms error of about $\lambda/25$, which is equivalent to a Strehl ratio of 94%. The end diodes in the array create line images that have slightly more aberration. The wavefront error of the line foci drops from $\lambda/20$ rms at the center of the line to $\lambda/15$ rms at the ends; which is equivalent to a Strehl ratio of 82%. Like the relay lens, the computed distortion of the front-end optics is much less than 1 μm, and so is negligible.

6. CONCLUSION

This paper introduced an AO image correlator design that significantly reduces the volume of the system. This was done while maintaining nearly diffraction limited image quality, producing a Strehl ratio of greater than 82% throughout the system. The correlator also produces a significantly higher throughput rate by utilizing the full bandwidth of the AO cell. The result is an optical system capable of achieving 400 grayscale correlation per second yet maintains a miniature size, light weight, and low power consumption for embedded type of applications. This miniature optical design is currently being developed for integration into Sandia's hybrid electro-optic automatic target recognition system.

7. ACKNOWLEDGEMENTS

This work performed at Sandia National Laboratories and supported by the U.S. Department of Energy under contract DE-AC04-76DP00789.

8. REFERENCES

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