HOLOGRAPHIC OPTICAL ELEMENTS AND CHARGE COUPLED DEVICE TECHNOLOGY AT WORK IN LASER COMMUNICATIONS ACQUISITION AND TRACKING SYSTEMS

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In an effort to advance free space laser communication, Wright Laboratory’s Laser Communications Laboratory (LCL) personnel contracted the design and fabrication of a wide field-of-view holographic lens to image incoming laser radiation onto an electronic position sensing device. The lens was fabricated to operate at a wavelength of 850 nm and mounted on a charge injection device (CID) camera. This paper describes the lens and hardware interface that combines the lens, camera, and MicroVAX computer into a Wide Field-of-View Laser radiation angle-of-arrival sensor. It also provides a comparison of CID and charge coupled device (CCD) array technology with other position sensing devices such as quad cells for use in future laser communications systems.

Since the birth of the laser, scientists have pondered the question of using it to communicate effectively in a free space environment. Many laser communication systems have been built and tested since the early seventies and the results all reflect the same conclusion: The size of the optics must be reduced, and the gimbals used for beam steering need to be eliminated. Therefore, in an effort to advance free space laser communication by reducing the size of the optics, WL/AAAI Laser Communications Laboratory (LCL) personnel contracted with the Environmental Research Institute of Michigan (ERIM) to design and fabricate a wide field-of-view holographic lens to image incoming laser radiation onto an electronic position sensing device.

The Wide Field-of-View Laser Receiver, as delivered by ERIM, was a fine demonstration model for the use of a holographic optical element with a position sensing device to determine the angle-of-arrival of incident laser radiation. The holographic lens was designed with an f-number of .7, an operating wavelength of 850 nm, and was mounted on a government furnished CID Technologies Inc. Model CID2710 solid-state camera. The camera consists of a 776H by 512V Charge Injection Device (CID) Array, video processing electronics, and an RS-170 standard video output. The output of the camera was directly connected to the input of a standard RS-170 monitor for viewing of the focused spot and interpolation of the direction of the incident radiation over a field-of-view of 45 degrees horizontal, 32 degrees vertical, and 53.4 degrees diagonally. However, since the focused spot was the only information readily available on the monitor screen, the best one could do when viewing the image would be to make a subjective guess as to the direction from which the laser radiation was coming. Since the observer would know a priori that the field-of-view was 45 degrees horizontal by 32 degrees vertical, the angle-of-arrival could be estimated to within a few degrees. However, since the angle-of-arrival of the incident radiation can be determined to within one pixel of the detector array with a potential angular resolution of 1 milliradian, it was decided that the next logical step would be to digitize the image and program the computer to determine the angle-of-arrival.

The camera RS-170 video output and the vertical and horizontal sync inputs were interfaced to the LCL MicroVAX computer with a Univision Corporation UDC-500Q analog frame grabber which resides in a single Q-Bus slot in the com-
puter. Software to display the image on a high resolution monitor, find the laser image, and determine the angle-of-arrival of the incident radiation was written in-house. After an 850-nm narrow bandpass filter was mounted on the camera to block out extraneous light and provide a nearly black background, the Fourier Transform of the incident radiation appeared on the monitor as a nearly white spot two pixels high by two pixels wide. Upon execution of the in-house written program called ANGLE, each pixel was compared to a threshold value. If the pixel was below the threshold, then it could be concluded that the laser had not energized that pixel. Otherwise, if the pixel was above the threshold it was evident that the laser had been found.

The development of the software to determine the angle-of-arrival was fairly straightforward. Since the size of the array is known, and the location of the laser in pixel coordinates \((x,y)\) has been identified, all that needs to be done is to convert it to angles in the \(x\) and \(y\) directions. Assuming the center of the pixel screen is perpendicular to the \(z\)-axis at the origin, and the pixel plane has size \(max_x, max_y\), then the midpoint of the pixel screen is defined by:

\[
\text{half}_x = \frac{\text{max}_x}{2} \\
\text{and} \\
\text{half}_y = \frac{\text{max}_y}{2}.
\] (1)

It then follows that the \(X\) and \(Y\) of the spot are:

\[
x_{\text{adjusted}} = x_{\text{actual}} - \text{half}_x \\
\text{and} \\
y_{\text{adjusted}} = y_{\text{actual}} - \text{half}_y.
\] (2)

If the angle visible to the camera in the horizontal direction is \(\alpha\) and the vertical direction is \(\beta\), then the conversion factor from pixels to degrees is:

\[
\angle_x = (\alpha / \text{max}_x) \times x_{\text{adjusted}}
\]

and

\[
\angle_y = (\beta / \text{max}_y) \times y_{\text{adjusted}}
\] (3)

with \(\text{max}_x = 776\) and \(\text{max}_y = 512\) for the CIDTEC CID2710 camera and \(\alpha = 45\) and \(\beta = 32\) degrees for the holographic lens.

The results obtained from the angle program are then passed to another program which controls a rotatable table via the MicroVAX IEEE-488 interface. The result is a nonmechanical, acquisition system coupled with a mechanical beam steering system which points the transmit laser radiation back in the direction indicated by the acquisition system.

While working with the CID camera and holographic lens on this project, several interesting observations have been made. For example, a holographic lens is inherently capable of performing two functions: 1) focusing incoming light onto a sensor, and 2) filtering and preventing all but the design wavelength from reaching the sensor. When used in conjunction with a narrow bandpass interference filter, the holographic lens performed very well. The device was tested over an extended distance of about 1 mile using a 30-mW, 830-nm laser and an 830-nm, 10-nm bandwidth, interference filter. The background on the video screen appeared black and the focused light appeared as a small white dot. With the interference filter removed, however, the lens focused all the incoming energy into an image of the objects at which it was pointing and the small focused spot was not discernible. The fact that the holographic lens focuses the light from an 830-nm laser as well as it does an 850-nm laser leads to the conclusion that holographic lenses are fairly broad banded. A total spectral analysis of the holographic lens filtering ability was not conducted because the lens is mounted and could not be removed without possible destruction. Therefore, it was tested in the lab using 780, 830, 850 and 904 nm lasers and matching 10-nm bandwidth interference filters. The 780 and 904 nm wavelengths did not focus, but the 850 and
830-nm wavelengths focused very well. This indicates that a holographic lens will not be able to function as the only optical element in an acquisition and tracking system. Narrow band interference filters will also be required.

The CID camera used for this project has a 776 by 512 array with pixel sizes of 12.0 by 13.7 microns, and it is far more resistant to blooming than the VIDEK CCD camera being used on a different LCL project. The VIDEK camera, however, has a 1320 by 1035 CCD array with 6.8 micron square pixels which, when used with an ample amount of light filtering, can provide angular resolutions of less than one-half milliradian when outfitted with a lens having a field-of-view of 45 degrees. Even though the CCD device has almost twice the resolution of the CID device, experience shows that the best array choice for acquisition and tracking is the CID array unless antiblooming circuitry is incorporated into the image processing system. This is because it is not always possible to reduce the incident radiation on the array by filtering or by reducing the transmit output power, and the effects of blooming reduce the available resolution of the device.

The UDC-500Q with a digital and RS-170 capability was the only frame grabber used for this project. One major problem encountered, which slowed the development process and complicated the software development, was that the frame grabber would not always lock onto the beginning of the image field and a black horizontal bar approximately 100 pixels high would appear across the screen. This caused the image to be shifted down a proportional amount. Each frame after the initial acquisition would be displayed in exactly the same position giving the impression that the UDC-500Q grabbed the first frame randomly and then locked on to the video signal from there. The fact that it takes several tries to get the image to align properly, leads one to believe that there must be a better way. As mentioned previously, the UDC-500Q also has an input for a digital camera. The VIDEK camera mentioned above has a digital output and works very well with the UDC-500Q. Each frame can be captured and displayed completely. Because of this, it appears that a digital camera with antiblooming circuitry used with a digital frame grabber is the best approach.

Historically quad cells have been preferred over CCD arrays for acquisition and tracking. This was due primarily because arrays were made up of individual elements and it was theoretically possible that the focused spot of incoming light could fall between the elements and the system would not be able to determine the angle-of-arrival. Subsequently, CCD/CID array technology has evolved to the point that the elements are smaller and spaced closer together allowing for greater resolution and eliminating the possibility that the focused spot will go undetected because it lies between the elements. The size and resolution of CCD/CID arrays have expanded beyond the one mega pixel range; 2048 by 2048 CCD arrays are now available that can provide less than one-half milliradian resolution (assuming a pixel size and fill ratio comparable to the VIDEK camera mentioned above) when outfitted with a lens providing a field-of-view of 45 degrees. These devices will allow greater accuracy to be incorporated into acquisition and tracking algorithms for laser communications systems. Comparatively, manufacturers of position sensing devices such as bicells and quadrant detectors boast of angular resolutions better than 0.16 milliradians when used with an optical system having a full angular coverage of only 1.5 milliradians (.86 degrees). When used over a field-of-view of 785 milliradians (45 degrees), the angular resolution of the quad cell translates to only 5.2 milliradians. From this, it appears that CCD/CID technology can now be considered as an additional tool which can be used to solve acquisition and tracking problems.

Work has begun in the LCL to track and find a solution to compensate for atmospheric turbulence induced angle-of-arrival measurement errors using the VIDEK camera. Additional in-house work is planned to do a more in-depth comparison of CCD/CID arrays and quad cells to determine the optimum approach for acquisition and tracking. Factors to be investigated include:
1) Amount of electronic circuitry required for the acquisition, tracking and communication system. Presently CCD and CID cameras are being used in conjunction with a frame grabber and computer to determine the angle-of-arrival. Some cameras, such as the CIDTEC 2710 used on this project, process the information first and provide an RS-170 video output which must be digitized and reprocessed by a framegrabber while others send a digitized output directly to a video processing board residing in the computer. Although a system as large as a MicroVAX is not required, some form of signal processing, requiring some minimum amount of electronics will be needed for both methods.

2) Size and weight of the optical path. The use of holographic optical elements appears to be a viable approach for reducing the size and weight of the frontend optics, and can be used with either an array or quad cell; however, there are several items that need to be investigated. Quad cells do not appear to have the resolution that CCD/CID arrays have over large fields of view. It may take several quad cells coupled with holographic lenses having narrower fields of view to cover the same area as a single CCD/CID array with a single wide field-of-view holographic lens. On the other hand, CCD/CID arrays can only provide angle-of-arrival information. The communication signal has to be detected separately using a different sensor. This means splitting the optical path and adding additional internal optical elements which will contribute to the size and weight of the overall communications system. Quad cells, however, have the potential of providing angle-of-arrival information and communication signals to their respective electronic circuits.

Holographic optical elements appear to be a feasible alternative to bulkier refractive optics. Their potential for usage in laser communications equipment could be further increased if they provided greater background noise rejection. One approach would be to integrate a holographic lens with an interference filter. Interference filters are made by either depositing a material of known spectral transmittance characteristics on a glass plate or by making the filter out of a type of glass with the desired spectral characteristics. Since the emulsion used for the holographic lens is sandwiched between two glass substrates anyway, one of them could be used as the interference filter. This would delete the requirement for that particular additional optical element and mounting equipment.

The question of whether to use a CCD/CID array or quad cell in the acquisition and tracking system remains a subject open for investigation. Quad cells, while not having the resolution capability of some of the CCD/CID arrays, have the advantage of speed since they consist of only four quadrants whose outputs need to be sampled and interpreted versus the over 4 million elements in a 2048 by 2048 CCD array. The quad cell may also have the advantage that it can provide the communication signal as well as the angle-of-arrival information. Laser communications systems of the future may very well employ both technologies. A CCD/CID used with a wide field-of-view holographic lens could be used in the initial acquisition stage and then hand over control to the faster quad cell with a narrow field-of-view for tracking and communication.

Bibliography