ACOUSTO-OPTIC DELAY-DOPPLER LASER RADAR PROCESSOR WITH APPLICATIONS TO BIOMEDICAL IMAGING

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Abstract: Optical signal processing technology using acousto-optic Bragg cells provides a means of instantaneously processing large time-bandwidth product signals in a relatively small volume. Delay-doppler laser radar images can be formed directly using this technology with higher resolution than that possible using conventional electronic signal processing techniques. Biomedical imaging modalities such as MRI, CT, PET, and ultrasound share similar processing algorithms to that used in delay-Doppler imaging and thus these imaging systems may also benefit from the application of acousto-optic signal processing technology.

Keywords: Acousto-optic signal processing, Delay-doppler laser radar imaging, computed tomography

1.0 Introduction

Optical technology, using the ability of spatially extended light to carry simultaneous information, provides a powerful means for processing information. The key component in an optical processor is the device used to spatially encode the light beam with information: a spatial light modulator. In this paper we first review the operation of the acousto-optic Bragg cell - the spatial light modulator of choice for imparting information contained in a time-varying electrical signal onto an optical beam. Optical processing architectures are then described which perform the basic signal processing functions of spectrum analysis and correlation. We then describe one way in which these basic optical processing structures can be combined in a single compact matched filter architecture to form high resolution laser radar images directly on a two-dimensional photodetector array. We then discuss a common image reconstruction algorithm used in many biomedical imaging modalities, computed tomography (CT), and its interpretation as a matched filter process. Finally we suggest and describe the performance of an acousto-optic signal processor for CT image reconstruction.

2.0 Acousto-Optic Bragg Cell Technology

A Bragg cell, shown in Fig. 1, consists of a thin piezoelectric transducer bonded to a transparent medium (either a glass or crystal) capable of supporting sound propagation.

![Fig. 1. Acousto-optic Bragg cell](image-url)

An electrical signal input to the transducer is converted into an ultrasonic wave which propagates down the axis of the optical crystal. The sound wave carries both the amplitude and phase of the electrical signal, i.e., it is an exact representation of the input electrical signal. The traveling ultrasonic wave manifests itself as a density wave, altering the local density of the crystal as it passes. Through the photo-elastic effect, the local index of refraction varies proportional to the density variation. A diffraction grating is created which carries the amplitude and phase information of the ultrasonic wave (and thus the original electrical input). When the device is illuminated at a specific angle, the Bragg angle, part of the light exiting the cell is diffracted into the first order. The diffraction angle is proportional to the periodicity of the
ultrasonic diffraction grating and hence to the frequency of the input electrical signal. The amplitude and phase of the diffracted light is proportional to the amplitude and phase of the input electrical signal delayed by time $x/v$ where $x$ is the position and $v$ is the acoustic velocity in the cell. The frequency of the diffracted light is also shifted from the undiffracted light by an amount equal to the frequency of the input electrical signal as a consequence of the doppler effect. Bragg cells are commercially available with bandwidths from 50 MHz with a 100 µs time-aperture to 2 GHz with a 1 µs time-aperture.

The Bragg cell is illuminated with an optical beam focused along the length of the cell. Additional optical processing power can be by using the full two-dimensional cross-section of the optical beam too illuminate several Bragg cell channels. Multiple electrical signals can be simultaneously imparted onto a light beam using a multichannel Bragg cell. The multichannel cell, shown in Fig. 2., has multiple independent channels defined by a multielement electrode pattern on a common transducer substrate. Its optical operation is the same as the single channel device described above.

![Fig. 2. Multichannel Bragg cell](image)

A number of different types of signals from various sensor and sensor arrays can be processed using both single- and multichannel Bragg cells in combination with lenses and photodetector arrays. Two generic acousto-optic signal processors are described next.

### 2.1 Acousto-optic spectrum analyzer

The acousto-optic spectrum analyzer [1] utilizes the spatial Fourier transforming ability of a spherical lens - spatially modulated light incident on spherical lens results in a diffraction pattern in the back focal plane of the lens which is the Fourier transform of the spatial modulation in the object plane. The acousto-optic spectrum analyzer which uses this effect is shown in Fig. 3. Here coherent light from a laser is collimated and shaped to illuminate the Bragg cell. Since the angle of the diffracted light from the Bragg cell is proportional to the input electrical signal frequency, the position of the diffracted light in the diffraction plane following the Fourier transform lens is also proportional to the input electrical signal frequency. A photodetector array in the focal plane of the lens samples the diffracted light and produces electronic charge packets whose array position and quantity are proportional to the electrical signal frequency and power, respectively.

![Fig. 3. Acousto-optic spectrum analyzer](image)

The video output from the photodetector array is a signal given by

$$|F(p)|^2 = \left| \int_0^{T=Ls} f(t) e^{i2\pi \lambda p} dt \right|^2$$  \hspace{1cm} (1)

where $p$ denotes spatial position (frequency) in the photodetector plane and the finite integration time is the acoustic propagation time $T$ through the Bragg cell of length $L$ and acoustic velocity $v$. This processor detects the power spectral density of the input signal. The signal amplitude and phase could also be detected using a modification to this architecture.

### 2.2 Acousto-optic matched filter correlator

The correlation of two continuous functions $f(t)$ and $g(t)$ is defined mathematically by the relation

$$R(\tau) = \int_{-\infty}^{\infty} f(t) g(t-\tau) dt$$  \hspace{1cm} (2)
A matched filter radar receiver is formed by correlating the received signal $s(t)$ with a reference waveform which is a time reversed replica of the transmitted signal. The matched filter has a system frequency response that maximizes the output peak signal-to-noise ratio and hence its output is maximized when the value of $\tau$ is equal to the time delay of the received signal. One optical implementation of a matched filter correlator is shown in Fig. 4 [2].

![Fig. 4. Acousto-optic matched filter correlator](image)

The unknown signal to be analyzed is input to the first Bragg cell. A reference waveform, a time-reversed replica of the transmitted waveform, is input to the second Bragg cell. Light passing through the two cells acts to multiply the two signals together in the optical domain as they counter-propagate past each other. The cells are arranged so that the doppler shift of one is opposite to the other resulting in a baseband output. The doubly diffracted optical beam exiting the second Bragg cell is brought to focus in the back focal plane of a lens (the undiffracted beams are blocked). The correlation output on the optical axis ($p=0$) is (where the undiffracted beams are blocked)

$$
|C(0,t)|^2 = \left| \int_0^T S(u) R^*(u-2t) \, du \right|^2 
$$

The above two acousto-optic signal processor architectures are well developed [3] and are used in several military signal processing applications. With these two processor architectures we can configure a single processor that forms delay-doppler laser radar images on a two-dimensional photodetector array.

### 3.0 Delay-doppler laser radar imaging

A delay-doppler imaging laser radar system forms an image of a rotating object (a distribution of rotating point scatterers, as shown in Fig. 5 by measuring the range, azimuth, and reflectivity of each scatterer. This measurement is made using Inverse Synthetic Aperture Radar (ISAR) processing techniques [4]. An image is formed by mapping the reflectivity of a scatterer with range $\rho$ and azimuth $\alpha$ into a two-dimensional image space defined by the orthogonal coordinates $(\rho, \alpha)$.

![Fig. 5. Laser radar delay-doppler imaging system](image)

The laser radar system transmits a laser pulse given by

$$
S(t) = a(t) e^{i(\omega_0 t + \phi)} 
$$

where $a(t)$ is the amplitude of the signal, $\omega_0$ is the laser radar carrier frequency, $\phi$ is the phase modulation of the signal, and $\tau$ is the transmitted pulse width. The signal reflected from the arbitrary scatterer, $R(t)$, in response to the transmitted signal is

$$
R(t) = \sigma a \left( 1 - \frac{2(\rho_0 + \rho)}{c} \right) X e^{i \left( \omega_0 t - 2(\rho_0 + \rho) \frac{t}{c} \right) + \left( \frac{\omega_0}{c} (\rho_0 + \rho) \right)}
$$

which is a time-delayed and Doppler shifted version of $S(t)$, where the Doppler shift is the time-derivative of the phase

$$
\omega_d = \frac{2 \omega_0}{c} \frac{d(\rho_0 + \rho)}{dt}
$$

The time derivative in Eq. (7) is just the velocity of the
Thus the measurement of the time-delay and the doppler shift of the return from a scatterer on the object uniquely determines the position $\theta, \alpha$ of the scatterer on the object. A two-dimensional image of the object can be constructed by measuring the time-delay and doppler shift of all of the scattered returns.

3.1 Acousto-optic laser radar image formation processor

Using an optical processor, the image of the target, a sum in range/Doppler space of the delay-doppler measurement of each target point scatterer, can be formed directly on a two-dimensional photodetector array. An acousto-optic processor which uses the matched filter correlator along with the Fourier transforming ability of a lens to form this image is shown in Fig. 6 [4]. Two multichannel Bragg cells are arranged as a matched filter correlator where the received laser radar signal is fed to one cell and the time-reversed replica of the transmitted signal is fed to the other cell. This matched filter correlator operates with any waveform as long as the reference is a time-reversed template of the transmitted pulse. Multichannel cells are used in order to increase the time-bandwidth product of the processor over that available with single-channel devices. A Fourier transform lens produces a two-dimensional diffraction pattern that in one dimension displays the coarse frequency and in the orthogonal direction the fine frequency of the input signal. The correlation is displayed in time, as indicated in Fig. 4. A filter mask selects a doppler frequency window which is input to a third Bragg cell. This cell is used as a deflector to scan the correlation signal across a two-dimensional photodetector array at a rate equal to the velocity of acoustic propagation in the first two cells. In this way both the correlation (range) and doppler output (and hence the laser radar image) is displayed on a two-dimensional photodetector array. This processor is capable of processing a 2 GHz bandwidth imaging waveform containing 30 1 µs pulses. The system yields a range resolution of 0.075 m, a range window of 150 m, a doppler resolution of 33.3 Khz and a doppler window of 1 MHz. The optical portion of the processor can be housed in a 600 in$^3$ volume using off-the-shelf optics, with a power consumption less than 3 W.

4.0 Biomedical computed tomography imaging

Computed tomography (CT) is an imaging process used widely in many biomedical imaging modalities. The technique uses one-dimensional projectional views taken at different angles to form a two-dimensional cross-sectional view of the human body. The geometry of a tomographic system is shown in Fig. 7. Projection data
Lines of integration

Fig. 7. Tomographic imaging geometry

are obtained using externally generated x-rays (transmission CT) or internally generated positrons (positron emission tomography - PET) or photons (single photon emission computed tomography - SPECT) or magnetic resonances (magnetic resonance imaging - MRI).

The integrated transmission, or projection, is given by

\[ p(t) = \int \sigma(x,y) \delta(x \cos \theta + y \sin \theta - t) \, dx \, dy \]  

(9)

where \( \sigma(x,y) \) is the attenuation coefficient of the material. A number of algorithms have been developed to reconstruct the image of the two-dimensional cross section \( \sigma(x,y) \) from the projections \( p_\theta(t) \). Here we describe the reconstruction in radar signal processing terms to show the connection to laser radar image formation \[ 5 \]. The laser radar delay-doppler image is obtained by constructing a matched filter processor where the reference signal is the response due to a single scatterer on the object. In the CT geometry a projection of a single point scatterer (or source) (in polar coordinates) is:

\[ \sigma(r,\phi) = \int_0^\infty p_\theta(t) \delta(t - r \cos(\theta - \phi), \theta) \, d\theta \]

(12)

which is recognized as the backprojection operation for image formation where each projection is evaluated in image space and the image is formed by summing at each image point all of the projections over the projection angles. The backprojection reconstruction operation is shown in Fig. 8.

This procedure does not reconstruct the image exactly. The correction factor can be found by considering the backprojection produced by a point source in the image:

\[ h(r,\phi) = \frac{1}{\pi} \int_0^\infty \delta(r \cos(\theta - \phi)) \, d\theta \]

(13)

Fig. 8. Backprojection image reconstruction

Thus the reference signal needed is not the delta function of Eq. (11) but instead the filter function \( h(r,\phi) \) of Eq. (13). The signal processing required to reconstruct an image from its projections is thus: 1) process the projections in a matched filter correlator where the reference signal is given by Eq. (13) and 2) backproject the cross correlated signals as described in Eq. (12) in order to obtain the image.
Fig. 9. Acousto-optic CT image formation processor

4.1 Acousto-optic computed tomographic image reconstruction processor

An acousto-optic processor for reconstructing images from computed tomographic projections is shown in Fig. 9. It is related to other optical processors (most closely to that of Gmitro and Gindi) suggested for tomographic reconstruction but provides higher resolution with fewer components than other approaches [6]. The processor consists of a matched filter correlator followed by a scanner and image rotator. The projections are fed sequentially to the first Bragg cell while the reference filter function signal is repeatedly fed to the second Bragg cell. Each filtered projection is then backprojected by sweeping the filtering projections across a two-dimensional photodetector array at the same angle as the original projection data was obtained. As each projection is fed sequentially into the first Bragg cell the sweep angle is incremented to match the projection angle using an image rotator (or, equivalently, rotating the photodetector array). The two-dimensional photodetector array produces the integrated result which is the reconstructed image.

The processor shown in Fig. 9 is capable of generating high resolution CT images in real-time. Suppose that an image with a resolution of 1000 X 1000 is desired. This requires 1000 projections where each projection contains 1000 pixels. For real-time video operation, a single projection must be backprojected in 1/30 sec/1000 = 33 μs. A 1000 point cross-correlation must therefore be performed in 33 μs which requires Bragg cells with bandwidths of 33 MHz. Slow shear tellurium dioxide Bragg cells easily support these requirements. The scanning Bragg cell must also have a time-bandwidth product of 1000. It must sweep the projection across the photodetector array in 33 μs. The dynamic range of the system is limited by the photodetector array. At room temperature these arrays typically have a dynamic range of 30 dB. Cooling reduces the dark current noise by a factor of 2 per each eight degrees so that 40 dB of dynamic range is possible at -10 degrees C.

5.0 Discussion and conclusion

Acousto-optics provides the processing power necessary to form laser radar images using large time-bandwidth imaging waveforms. Acousto-optic technology can be housed in a small volume with low power consumption - both of which make the technology attractive for avionic and satellite applications. An acousto-optic processor similar to that used for laser radar imaging can be configured to reconstruct 1000 X 1000 CT images in real-time with a dynamic range of 40 dB when the photodetector array is cooled. Additional consideration must be given to the exploration of other biomedical imaging applications of acousto-optics. Also, to what degree the attributes of acousto-optics that are attractive for military signal processing applications are also beneficial for biomedical imaging must be explored.

6.0 Acknowledgements

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7.0 References