Acousto-optic processing of two-dimensional signals

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A new method is presented that offers the potential for the realization of image-processing systems using one-dimensional acousto-optic spatial-light modulators.

INTRODUCTION

The inherent capability of optical signal processors (OSP's) to perform parallel computations on two-dimensional data (images) is one of the most attractive features of these systems. In order to perform image processing in real time, the OSP requires a two-dimensional spatial-light modulator (SLM) on which the images to be processed can be recorded and erased at high speed. Several devices have been developed for this purpose[1]; however, at the present time, their performance characteristics are inadequate for most applications of interest. In fact, the most successful optical image-processing systems that are operational today use photographic film as the input SLM (e.g., synthetic-aperture radar) even though film is not compatible with real-time processing. Acousto-optic (AO) devices[2] are widely used as SLM's in the processing of one-dimensional signals. In general, the performance characteristics of AO devices are superior to those of existing two-dimensional SLM's. Their relative disadvantage, at least within the context of image processing, is that they are one dimensional. Consequently, AO devices have not been considered suitable for image processing in the past. Recently, Rhodes[3] proposed an AO image-processing system, and Kellman[4] mentioned the possibility of performing image processing with AO devices. In this Letter, a new method to realize such systems is described. The purpose of this Letter is to present the basic concepts that lead to the implementation of an AO image processor.

SYSTEM DESCRIPTION

It will be shown that the proposed system will perform a two-dimensional linear-filtering operation on the input function $f(\alpha,\beta)$, described by

$$g(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(\alpha,\beta)h_1(\alpha;y)h_2(\beta+x)\mathrm{d}\alpha\mathrm{d}\beta, \quad (1)$$

where (α,β) and (x,y) are the input and output variables, respectively, $g(x,y)$ is the filtered image, and $h_1(\alpha;y)h_2(\beta+x) = h(\alpha,\beta;x,y)$ is the two-dimensional impulse response of the filter. There are two restrictions on h that are imposed by the system: (1) it must be separable in α and β, and (2) it must be shift invariant in β. The significance of this limitation will be discussed later.

A schematic diagram of the system is shown in Fig. 1. The image $f(\alpha,\beta)$ is entered into the system as a temporal raster signal $s(t)$, and $s(t)$ is related to $f(\alpha,\beta)$ by

$$s(t) = \sum_{n=0}^{N-1} \mathrm{rect}\left[\frac{t-\left(n+\frac{1}{2}\right)t_0}{t_0}\right] f\left[t - nt_0, \frac{n}{N}t_0\right], \quad (2)$$

where

$0 < \alpha, \beta < t_0$, $0 < t < Nt_0$,
N is the number of raster lines,
t_0 is the duration of each raster line,
n is an integer, and

$$\mathrm{rect}\left(\frac{z}{t_0}\right) = \begin{cases} 1 & \text{for } -\frac{t_0}{2} < z < \frac{t_0}{2}, \\ 0 & \text{otherwise.} \end{cases}$$

The signal $s(t)$ is applied to the AO cell labeled AO1 in Fig. 1. The intensity modulation that is due to AO1 is a function of time t and space x_1, which is the direction of propagation of the acoustic wave in AO1; it is described by

$$s(t-x_1) = \sum_{n=0}^{N-1} \mathrm{rect}\left[\frac{t-x_1-\left(n+\frac{1}{2}\right)t_0}{t_0}\right] \times f\left[t - x_1 - nt_0, \frac{n}{N}t_0\right], \quad (3)$$

for $0 < x_1 < t_0$; i.e., the aperture of AO1 is completely filled by one raster line. The velocity of sound in AO1 is assumed for simplicity to be one unit of space per unit of time. The processing of complex signals using this system requires appropriate biases and offset carriers. To avoid excessive complication of the analysis, all functions considered are assumed

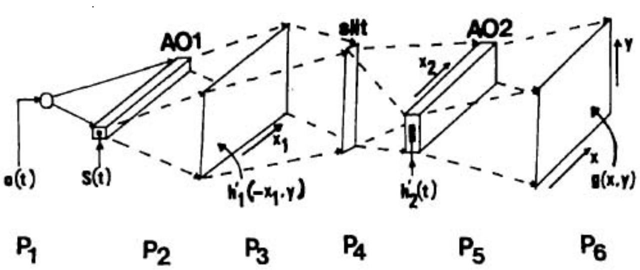

Fig. 1. Acousto-optic image-processing system. AO1 and AO2 are acousto-optic lines, P_2 is imaged onto P_3 in the horizontal direction, P_3 is imaged onto P_5, P_4 is a pupil plane, P_5 is imaged onto P_6, and P_6 is the detector plane.

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to be real and positive. The extension of the analysis to include complex signals is straightforward. The specifics of complex signal processing using incoherent light have been extensively reported.[5–7] AO1 is uniformly illuminated by an incoherent pulsed-light source. This light source can be a light-emitting diode that is pulsed by an electronic signal. The pulse-repetition frequency is set equal to $1/t_0$, and the duration of each pulse is set equal to the inverse of the bandwidth of $s(t)$. The occurrence of each pulse is synchronized to coincide with the instant that AO1 is modulated by a single raster line. Approximating the pulses from the source by delta functions, the intensity modulation on the source can be written as

$$0(t) = \sum_{n=0}^{N-1} \delta[t - (n+1)t_0]. \tag{4}$$

The intensity modulation of the light following AO1 (after schlieren filtering) is simply $0(t)s(t - x_1)$. As is shown in Fig. 1, AO1 is imaged in the x_1 direction onto plane P_3, and the light is uniformly expanded in the y direction. At P_3 a two-dimensional mask is placed with an intensity transmittance of $h'_1(-x_1,y)$. In most cases, this mask must be generated by computer. The function h'_1 can be recorded on a spatial carrier in the y direction to synthesize an effective complex intensity transmittance. Alternatively, multiple masks can be used.[7] The light-intensity distribution at plane P_3 is given by the product $0(t)s(t - x_1)h_1'(-x_1,y)$. Plane P_3 is imaged onto plane P_5 (Fig. 1) on to a second AO cell, labeled AO2. Appropriate magnification is chosen in both x and y directions to accommodate any size and aspect ratio differences between the mask at P_3 and AO2. In addition, a slit is placed on the axis in the pupil function of the imaging system (plane P_4 in Fig. 1). The slit is oriented so that it performs low-pass filtering of the image in the x direction, whereas it does not affect the y dimension. If the slit is narrow enough, the intensity of the light-illuminating plane P_5 has no variations in x, and it is given by

$$s_1(t,y) = \int_0^{t_0} 0(t)s(t - x_1)h'_1(-x_1,y)\mathrm{d}x_1. \tag{5}$$

The front part of the system is thus a one-dimensional space-integrating processor in which the image $f(\alpha,\beta)$ is filtered in the α direction. Several systems of this type were reported previously.[8,7] To realize the filtering in the β direction, the shift-invariant impulse response $h_2(\beta)$ (which is nonzero for $0 < \beta < t_0$) is time compressed by a factor of 2 and then periodically applied to AO2. The intensity modulation produced by AO2 is

$$h'_2(t - x_2) = \sum_{n=0}^{N-1} h_2\left\{2\left[t - x_2 - \left(n + \frac{1}{2}\right)t_0\right] + \frac{nt_0}{N}\right\} \tag{6}$$

for $0 < x_2 < t_0$, where x_2 is in the direction of propagation of the acoustic wave and $h'_2(t)$ is the electric signal applied to AO2. It is important to note that $h'_2(t)$ is periodic, with a period $t_0 - (t_0/N)$ that is slightly smaller than the period of the pulsed source. At times $t = (n + 1)t_0$, when the source is on, the spatial modulation in AO2 is

$$h'_2[(n+1)t_0 - x_2] = h_2\left(t_0 - 2x_2 + \frac{nt_0}{N}\right). \tag{7}$$

Thus, at successive pulses, the modulation in AO2 is shifted in x_2 by $(t_0/2N)$. A timing diagram of all the temporal signals

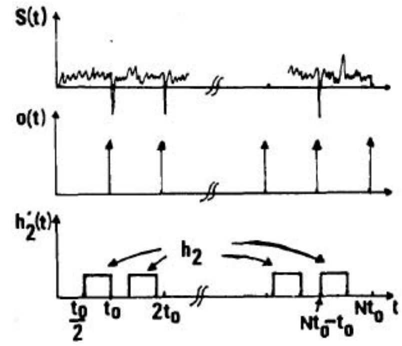

Fig. 2. Timing diagram of the signals applied to the system in Fig. 1.

applied to the system in Fig. 1 is shown in Fig. 2. Plane P_5 is schlieren imaged onto a two-dimensional time-integrating detector array at plane P_6. The integration time on the detector is Nt_0. The total light intensity integrated at each point in space on the detector plane is

$$g'(x_2,y) = \int_0^{Nt_0} s_1(t,y)h'_2(t - x_2)\mathrm{d}t. \tag{8}$$

Substituting Eqs. (3)–(6) into Eq. (8) and observing that all cross products are zero [i.e., $(\Sigma_n a_n)(\Sigma_m b_m) = \Sigma_n a_n b_n$], we obtain

$$\begin{aligned} g'(x_2,y) = \sum_{n=0}^{N-1} \int_0^{Nt_0} & \delta[t - (n+1)t_0] \\ & \times h_2\left\{2\left[t - x_2 - \left(n + \frac{1}{2}\right)t_0\right] + \frac{nt_0}{N}\right\} \\ & \times \left\{\int_0^{t_0} \mathrm{rect}\left[\frac{t - x_1 - \left(n + \frac{1}{2}\right)t_0}{t_0}\right] \right. \\ & \left. \times f\left(t - x_1 - nt_0, \frac{n}{N}t_0\right)h'_1(-x_1,y)\mathrm{d}x_1\right\}\mathrm{d}t \\ = \sum_{n=0}^{N-1} \int_0^{t_0} & f\left(t_0 - x_1, \frac{nt_0}{N}\right)h'_1(-x_1,y)h_2\left(t_0 - 2x_2 + \frac{nt_0}{N}\right)\mathrm{d}x_1. \end{aligned} \tag{9}$$

With $t_0 - x_1 = \alpha$, $(nt_0/N) = \beta$, $t_0 - 2x_2 = x$, and $h'_1(\alpha - t_0,y) = h_1(\alpha,y)$, Eq. (9) reduces to

$$g(x,y) = \sum_{\beta=0}^{t_0} \int_{t_0}^{0} f(\alpha,\beta)h_1(\alpha,y)h_2(\beta + x)\mathrm{d}x. \tag{10}$$

The only difference between Eqs. (1) and (10) is that the integration along β in Eq. (1) has been replaced by a discrete summation in Eq. (10). If the input image $f(\alpha,\beta)$ is band limited and if the sampling rate, which is determined by the pulse-repetition frequency of the light source, is appropriately chosen, then the system described above indeed performs the two-dimensional filtering described by Eq. (1).

DISCUSSION

Three basic concepts have been introduced in the above discussion: (1) use of space integration to process an image in one of its dimensions and time integration to process an image in the second dimension, (2) use of a pulsed light source to separate the two types of filtering, and (3) use of a periodic signal in the time-integrating portion of the system that is asynchronous with the pulsing of the light source to provide the necessary shift between the signal and the filter function. The system shown in Fig. 1 is only one of several possible implementations that can be realized by using these concepts. For instance, the portion of the system comprising AO1 (the mask at plane P_3 and the slit in P_4) performs the one-dimensional linear-filtering operation by space integration. There are several ways this can be done.[9] This particular system was selected because it can implement arbitrary space-variant kernel functions, and it permits the use of incoherent light. The use of incoherent light provides several advantages, such as immunity to speckle noise and tolerance to positional misalignments and vibrations.[5] Incoherent systems, however, operate on light intensity that is always positive and real. In order to encode complex data on an incoherent light beam, we must use a bias and an offset carrier. In general, this will decrease the dynamic range of the optical processor and will complicate the system. Thus, depending on the application, it may be preferable to use coherent light to implement the system. Light efficiency is another important practical consideration for the implementation of this system (particularly in the incoherent case) because of the large number of cascaded optical elements and the relatively low optical power that high-speed light-emitting diodes can deliver. The successful demonstration of a triple-product processor[3] using incoherent light breeds optimism that light efficiency will not be an insurmountable problem, since the triple-product processor consists of roughly the same number of optical elements as the system proposed in this Letter. One possible alteration in the system that would improve the light efficiency is to replace the time-integrating part of the system (AO2) with a charged-coupled-device detector–convolver array.[10]

The form of Eq. (10) dictates that the image $f(\alpha,\beta)$ must be filtered separately in each dimension or, equivalently, that the impulse response of the filter must be separable in α and β. This limitation can be overcome by modifying the system of Fig. 1. However, a sophisticated signal processor is required to generate the necessary signals. This issue will be addressed in a future publication. There are many applications in which the processing required is separable: spectral analysis of images, various types of bandpass filtering, beam forming of two-dimensional-phased arrays. multidimensional processing of long one-dimensional signals,[11] and synthetic-aperture radar. A unique feature of this system is that at least one of the kernel functions (and potentially both) is determined by temporal electronic signals and hence can be altered in real time. This would be desirable in the processing of synthetic-aperture radar signals, for instance, in which the filtering must be adjusted to eliminate range–azimuth coupling and accommodate changes in the flight path of the vehicle.[12]

SUMMARY

The concepts necessary for the realization of an image-processing system using one-dimensional acousto-optic devices have been presented. The operation of a particular implementation using these concepts has been described in detail. The advantages of this system relative to conventional image processors are the avoidance of two-dimensional SLM's and added flexibility because the system is controlled largely by external electronic signals. However, the system is substantially more complex since a sophisticated electronic-signal generator is required. Future work is directed toward the optimization of the system architecture for particular applications (most significantly synthetic-aperture radar) and the realization of systems with nonseparable kernel functions such as correlators.

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