Processing of Images and Data from Optical Sensors

William H. Carter
Chairman/Editor

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PROCESSING OF IMAGES AND DATA FROM OPTICAL SENSORS

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PROCESSING OF IMAGES AND DATA FROM OPTICAL SENSORS

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INTRODUCTION

The research employing both optics and data processing emerged chiefly from side-looking radar technology in the early 1960s and was extensively pursued during that decade. Many of the basic ideas were known and understood by 1970, but were not as yet successfully applied. The 1970s has been an exciting decade for applications. Much research has been done to reduce the results from the previous decade to practice and to develop new specialized techniques for particular applications.

For this volume I have tried to select papers which emphasize the new developments since 1970 and the wide range of interesting applications which have emerged. The papers are grouped into four general areas corresponding to the four sessions of the original SPIE meeting. The session on Optical Processing of Images is concerned with some new techniques for processing images through optical or electro-optical systems. The following session on Digital Processing of Images reviews recent progress in the U.S. and in Europe in applying the new, increasingly more powerful, digital electronics devices to processing digitized images and then presents a wide variety of practical applications. Finally the last two sessions on Smart Sensors report some of the very new and interesting military research concerned with electro-optical guidance of missiles using concepts developed from this technology.

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SESSION 1

OPTICAL PROCESSING OF IMAGES

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Partially coherent optical processing of images

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Abstract

A relationship between spatial coherence and the source intensity distribution is presented. Since the spatial coherence is dependent upon the image processing operation, a reduced spatial coherence may be used for the processing operation. The advantage of the source encoding is in the relaxation of the constraint of the coherence requirement, enabling the processing operation to be carried out using an extended incoherent source. The constraint of the temperal coherence requirement for partially coherent processing is discussed. Experimental demonstrations for image deblurring and image subtraction are also provided.

Introduction

The use of coherent light enables optical processing systems to carry out many sophisticated information processing operations.[1,2] However, the coherent optical processing systems are contaminated with coherent artifact noise, which frequently limits their processing capabilities. Recently, attempts of using incoherent source to carry out complex information processing operations were pursued by several investigators.[3-6] The basic limitations of using an incoherent source for partially coherent processing is the extended source size. To achieve a broad spatial coherent requirement at the input plane of an optical processor, a very small source size is required. However, such a small light source is difficult to obtain in practice. We have recently published papers,[7-10] showing that there are information processing operations that can be easily carried out using an incoherent source. Consequently, a strictly broad coherence requirement is not needed for some optical image processing operations.

In this paper, we will describe a linear transformation relationship between the spatial coherence requirement and the source intensity distribution. Since the spatial coherence requirement is dependent upon the image processing operation, a reduced coherence requirement may be used for a specific processing operation. By Fourier transforming the spatial coherence requirement, a source intensity distribution may be found.

The purpose of source encoding is to reduce the coherent requirement, which will allow an extended incoherent source to be used for the processing. In other words, the source encoding technique is capable of generating the appropriate spatial coherence required for a specific image processing operation and at the same time utilize the available light power more efficiently. We will illustrate examples that the complex information processing operation can actually be carried out by an encoded extended incoherent source. Experimental illustrations using this source encoding technique are included.

Source Encoding and Spatial Coherence

We will begin our discussion with the Young's experiment under extended incoherent source illumination, as depicted in Figure 1. First, we assume that a narrow slit is

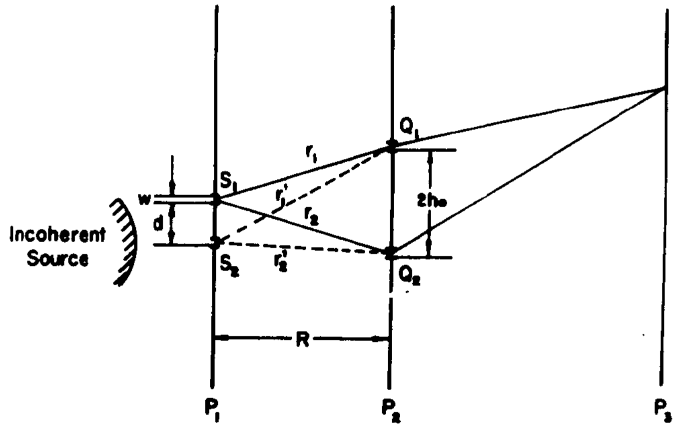


Figure 1 Young's experiment with extended source illumination.

placed at plane P_1 behind an extended source. To maintain a high degree of spatial coherence between the slits Q_1 and Q_2 at P_2, the source size should be very narrow. If the separation between Q_1 and Q_2 is large, then a narrower slit size S_1 is required. Thus, to maintain a high degree of spatial coherence between Q_1 and Q_2, the slit width should be[11]

$$w \leq \frac{\lambda R}{2h_o} \quad (1)$$

where R is the distance between planes P_1 and P_2, and $2h_o$ is the separation between Q_1 and Q_2.

Let us now consider the two narrower slits, S_1 and S_2, located at the source plane P_1. We assume that the separation between S_1 and S_2 satisfies the following path length relation:

$$r_1' - r_2' = (r_1 - r_2) + m\lambda \quad , \quad (2)$$

where the r's are the respective distances from S_1 and S_2 to Q_1 and Q_2 as shown in the figure; m is an arbitrary integer, and λ is the wavelength of the extended source. Then the interference fringes due to each of the two source silts, S_1 and S_2, would be in phase and a fringe pattern can be seen at plane P_3. To further increase the intensity of the fringe pattern, one would increase the number of source slits in the appropriate locations at the source plane P_1 with the separation between the slits satisfying the coherence or fringe condition of Eq. (2). If separation R is large, i.e., $R \gg d$ and $R \gg 2h_o$, then the spacing d between the source slits becomes,

$$d = m \frac{\lambda R}{2h_o} \quad . \quad (3)$$

Thus, by properly encoding an extended source, it is possible to maintain the spatial coherence requirement between Q_1 and Q_2, and increase the overall illumination intensity.

To encode an extended source, we first search for the spatial coherence requirement for a specific processing operation. With reference to the optical processor of Figure 2, the

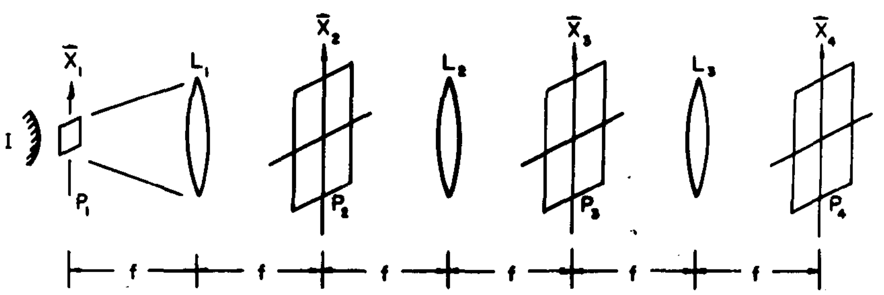


Figure 2 Partially coherent optical processing with encoder extended incoherent source. I; Extended incoherent source, L_1; Collimation lens, L_2 and L_3; Transform lenses.

spatial coherence function at input plane P_2 can be written[11]

$$\Gamma(\vec{x}_2, \vec{x}_2') = \iint S(\vec{x}_1) K_1(\vec{x}_1, \vec{x}_2) K_1(\vec{x}_1, \vec{x}_2') d\vec{x}_1 \quad , \quad (4)$$

where the integration is over the source plane P_1, $S(\vec{x}_1)$ is the intensity distribution of a source encoding mask, $K_1(\vec{x}_1, \vec{x}_2)$ is the transmittance function between source plane P_1 the input plane P_2, which can be approximated by,

$$K_1(\vec{x}_1, \vec{x}_2) \simeq \exp[i(2\pi \frac{\vec{x}_1 \vec{x}_2}{\lambda f})] . \quad (5)$$

By substituting $K_1(\vec{x}_1, \vec{x}_2)$ into Eq. (4), we have

$$\Gamma(\vec{x}_2 - \vec{x}_2') = \iint s(\vec{x}_1) \exp[i2\pi \frac{\vec{x}_1}{\lambda f} (\vec{x}_2 - \vec{x}_2')] d\vec{x}_1 \quad (6)$$

Thus, we see that the spatial coherence and source intensity distribution forms a Fourier transform pair;

$$s(\vec{x}_1) = F[\Gamma(\vec{x}_2 - \vec{x}_2')] \quad , \quad (7)$$

and

$$\Gamma(\vec{x}_2 - \vec{x}_2') = F^{-1} s(\vec{x}_1) \quad , \quad (8)$$

where F denotes the Fourier transformation. If the spatial coherence requirement for an image processing operation is known, then the source encoding transmittance can be evaluated through the Fourier transformation of Eq. (7). We note that the source encoding transmittance $S(\vec{x}_1)$ can consist of apertures or slits of any shape. We further note that in practice $S(\vec{x}_1)$ should be a positive real function which satisfies the following physically realizable condition:

$$0 \leq S(\vec{x}_1) \leq 1. \tag{9}$$

For example, if a spatial coherence function for an information processing operation is

$$\Gamma(x_2 - x_2') = \mathrm{rect}\left(\frac{|x_2 - x_2'|}{A}\right), \tag{10}$$

where A is an arbitrary positive constant, and

$$\mathrm{rect}\left[\frac{x}{A}\right] = \begin{cases} 1, & |x| \leq A, \\ 0, & \text{otherwise}, \end{cases}$$

then the source encoding intensity transmittance would be

$$S(x_1) = \mathrm{sinc}\left(\frac{\pi A x_1}{\lambda f}\right) . \tag{11}$$

Since $S(x_1)$ is a bipolar function, it is not physically realizable.

Temporal Coherence Requirement

There is, however, a temporal coherence requirement for an incoherent source. In the optical image processing operation, the scale of the Fourier spectrum varies with the wavelength of the light source. Therefore, a temporal coherence requirement should be imposed on every processing operation. If we restrict the Fourier spectra, due to the wavelength spread, within a small fraction of the fringe spacing d of a complex spatial filter (e.g., deblurring filter), then we have,

$$\frac{P_m f \Delta\lambda}{2\pi} \ll d, \tag{12}$$

where 1/d is the highest spatial frequency of the filter, P_m is the angular spatial frequency limit of the input object transparency, f is the focal length of the transform lens, and $\Delta\lambda$ is the spectral bandwidth of the light source. The spectral width or the temporal coherence requirement of the light source is, therefore,

$$\frac{\Delta\lambda}{\lambda} \ll \frac{\pi}{h_o P_m} , \tag{13}$$

where λ is the center wavelength of the light source, $2h_o$ is the size of the input object transparency, and $2h_o = (\lambda f)/d$.

In order to gain some feeling of magnitude, we provide a numerical example. Let us assume that the size of the object is $2h_o = 5$mm, the wavelength of the source is $\lambda = 5461$Å, and we take a factor 10 for Eq. (13) for consideration, that is

$$\Delta\lambda = \frac{10\pi\lambda}{h_o P_m} . \tag{14}$$

Several values of spectral width requirement $\Delta\lambda$ for various spatial frequency P_m are tabulated in Table 1.

Table 1. Source Spectral Requirement

$\frac{P_m}{2\pi}$ (lines/mm)	0.5	1	5	20	100
$\Delta\lambda$ (Å)	218.4	109.2	21.8	5.46	1.09

From Table I, we see that if the spatial frequency of the input object transparency is low, a broader spectral width of the light source can be used. In other words, if a higher spatial frequency is required for an information processing operation, then a narrower spectral width of the light source is needed.

Examples of Source Encoding

We will now illustrate examples of source encoding for partially coherent processing operations. We will first consider the correlation detection operation.[12]

In correlation detection, the spatial coherence requirement is determined by the size of the detecting object (i.e., signal). To insure a physically realizable encoded source transmittance, we assume a spatial coherence function over the input plane P_2 is

$$\Gamma(|\vec{x}_2 - \vec{x}_1|) = \frac{J_1(\frac{\pi}{h_o} |\vec{x}_2 - \vec{x}_2'|)}{\frac{\pi}{h_o} |\vec{x}_2 - \vec{x}_2|} \qquad (15)$$

where J_1 is a first-order Bessell function of the first kind, and h_o is the size of the detecting signal. A sketch of the spatial coherence as a function of $|x_2 - x_2'|$ is shown in Fig. 3a. By taking the Fourier transform of Eq. (15), we obtain the following source encoding intensity transmittance,

$$S(|x_1|) = \mathrm{cir}(\frac{|\vec{x}_1|}{w}), \qquad (16)$$

where $w = (f\lambda)/h_o$ is the diameter of a circular aperture as shown in Fig. 3a,

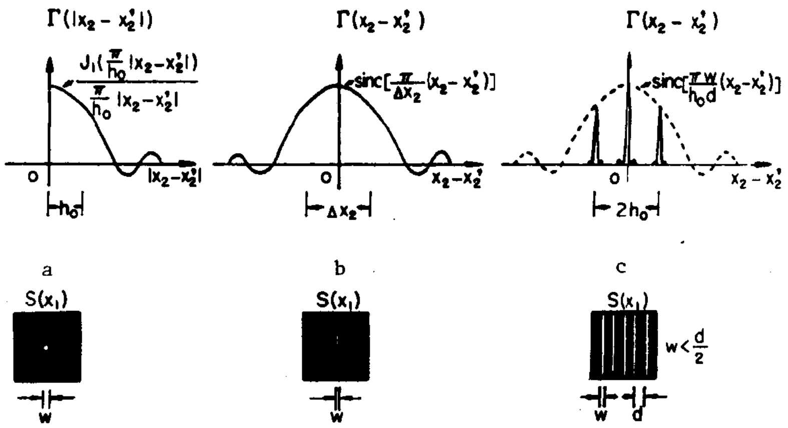


Figure 3 Examples of spatial coherence requirements and source encodings. $\Gamma(x_2 - x_2')$; Spatial coherence function, $S(x_1)$; Source encoding transmittance.

a. For correlation detection.
b. For smeared image deblurring.
c. For image subtraction.

$$\mathrm{cir}(\frac{|\vec{x}_1|}{w}) \triangleq \begin{cases} 1, & 0 \leq |\vec{x}_1| \leq w \\ 0, & \text{otherwise,} \end{cases}$$

f is the focal length of the collimating lens and λ is the wavelength of the extended source. As a numerical example, we assume that the signal size is h_o = 5mm, the wavelength is λ = 5461Å, focal length is f = 300mm, then the diameter D of the source encoding aperture should be about 32.8μm or smaller.

We will now consider a smeared image deblurring[13] operation as our second example. We note that the smeared image deblurring is a 1-D processing operation and the inverse filtering is a point-by-point processing concept such that the operation is taking place on the smearing length of the blurred image. Thus, the spatial coherence requirement is dependent upon the smearing length of the blurred image. To obtain a physically realizable source encoding function, we let the spatial coherence function at the input plane P_2 be

$$\Gamma(|x_2 - x_2'|) = \mathrm{sinc}(\frac{\pi}{\Delta x_2} |x_2 - x_2'|), \qquad (17)$$

where Δx_2 is the smearing length. A sketch of Eq. (17) is shown in Fig. 3b. By taking the Fourier transform of Eq. (17), we obtain

$$S(x_1) = \mathrm{rect}(\frac{|x_1|}{w}), \qquad (18)$$

where $w = (f\lambda)/(\Delta x_2)$ is the slit width of the source encoding aperture, as shown in Fig. 3b, and

$$\mathrm{rect}(\frac{|x_1|}{w}) = \begin{cases} 1, & 0 \leq |x_1| \leq w, \\ 0, & \text{otherwise,} \end{cases}$$

For a numerical illustration; if the smearing length is Δx_2 = 1mm, the wavelength is λ = 5461Å, and the focal length is f = 300mm, then the slit width w should be about 163.8μm or smaller.

We would now like to consider image subtraction[14] as our third illustration. Since image subtraction is a 1-D processing operation and the spatial coherence requirement is dependent upon the corresponding point-pair of the images, a strictly broad spatial coherence is not required. In other words, if one can maintain the spatial coherence between the corresponding image points to be subtracted, then the subtraction operation can take place at the output image plane. Therefore, instead of utilizing a strictly broad coherence over the input plane P_2, we would use a point-pair spatial coherence. Again, to insure a physically realizable source-encoding transmittance, we would let the point-pair spatial coherence be[10]

$$\Gamma(|x_2 - x_2'|) = \frac{\sin(\frac{N\pi}{h_o}|x_2 - x_2'|)}{N\sin(\frac{\pi}{h_o}|x_2 - x_2'|)} \; \mathrm{sinc}(\frac{\pi}{h_o} \frac{w}{d} |x_2 - x_2'|), \tag{19}$$

where $2h_o$ is the main separation of the two input object transparencies at plane P_2, N>>1 a positive integer, and we note that w<<d. Equation (19) represents a sequence of narrow pulses which occur at $|x_2 - x_2'| = nh_o$, where n is a positive integer, and their peak values are weighted by a broader sinc factor, as shown in Fig. 3c. Thus, we see that a high degree of spatial coherence has occurred at every point-pair between the two input image transparencies. By taking the Fourier Transformation of Eq. (19), we obtain the following source encoding transmittance:

$$S(|x_1|) = \sum_{n=1}^{N} \mathrm{rect}(\frac{|x_1 - nd|}{w}), \tag{20}$$

where w is the slit width, and $d = (\lambda f)/h_o$ is the separation between the slits. It is clear that Eq. (20) represents N number of narrow slits with equal spacing d, as shown in Fig. 3c. As a numerical example, we let the separation of the input objects h_o = 10mm, the wavelength λ = 5461Å, the focal length of the collimator f = 300mm, then the spacing d between the slits is 16.4μm. The slit width w should be smaller than d/2, or about 1.5μm. If the size of the encoding mask is 2mm square, then the number of slits N is about 122. Thus, we see that with the source encoding, it is possible to increase the intensity of the illumination N fold, and at the same time maintain the point-pair spatial coherence requirement for the image subtraction operation.

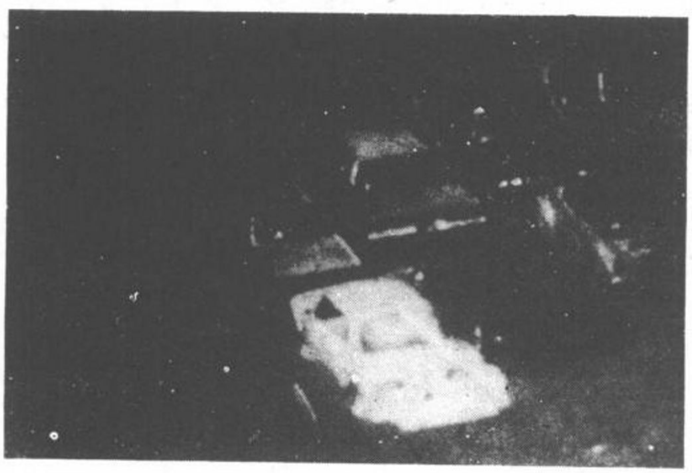
Experimental Results

In this section, we will illustrate two examples obtained from the source encoding technique. The first experimental illustration is the result obtained for a smeared photographic image deblurring with an encoded incoherent source, as shown in Fig. 4. In this experiment a Xenon arc lamp with a green interference filter was used as the extended incoherent source. A single slit mask of about 100μm was used as a source encoding mask. The smeared length of the blurred image was about 1mm.

Figure 4 Photographic image deblurring with encoded extended incoherent source.
a. Input blurred object. b. Deblurred image.

Figure 5 shows an experimental result obtained from the image subtraction operation using an encoded incoherent source. In this experiment, a mercury arc lamp with a green filter was used as an extended incoherent source. A multislit mask was used to encode the light source. The slit width w is 2.5μ and the spacing between slits was 5μm. The overall size of the source encoding mask was about 2.5 x 2.5mm^2. The mask contains about 100 slits.

Figure 5 Image subtraction with encoded extended incoherent source.
a. Input object transparencies.



b. Subtracted image.

From these experimental results, we can see that the constraint of a strictly broad spatial coherence requirement may be alleviated by using a source encoding technique to allow the optical image processing to be carried out with an extended incoherent source.

Conclusion

We have derived a Fourier transform relationship between the spatial coherence function and the source encoding intensity transmittance function. Since the coherence requirement is dependent upon the nature of a specific image processing operation, a strictly broad coherence requirement may not be needed. The basic advantage of the source encoding technique is to alleviate the constraint of a strict coherence requirement imposed upon the optical image processing system, which will allow the processing to be carried out with an encoded extended incoherent source. The use of an incoherent source to carry out the optical image processing operation also has the advantage of suppressing the coherent artifact noise.

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Optical processing of photographic images

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Abstract

Recent advances in coherent and incoherent optical information processing systems have brought into use communication and information theory to analyze their performance. An optical information processing system can be analyzed with many of the same concepts of linear system theory (e.g., spatial impulse response, spatial frequency and spatial domain synthesis, etc.), and the photographic images to be processed can be regarded in the same manner as time signals (e.g., spatial frequency content, spatial amplitude and phase modulation, space-bandwidth product, etc.). Both coherent and incoherent optical processing systems can be treated as linear systems and the processing operations can generally be carried out by communication theory concepts.

Although coherent optical information procesing operations have been used for performing complex amplitude operations, complex processing can also be performed with partially coherent or even white-light illumination. The importance of optical information processing operations, either coherent or incoherent, is due to the basic Fourier transform property of lenses. In this paper, we will discuss mostly the partially coherent systems because they are of more recent interest and possess certain advantages, we feel, over the traditional coherent optical processors. Experimental illustrations of the results are provided.

In view of the broad area of optical image processing, we will confine ourselves to a few applications that we consider of general interest.

Introduction

Communication and information theory was originated by a group of mathematically oriented electrical engineers whose interest was centered on electrical communication. Nevertheless, from the very beginning of this discovery of communication and information theory, interest in its application to optical systems has been vigorous. As a result of recent advances in optical signal processing and optical communications, the relationship between optics and communication theory has grown very rapidly.

Mention must be made of a few important early contributions to this field. It was in the early 1950's that the communication and information theory aspects of optical processing techniques first became evident. The most important impact must be due to Gabor's work on light and information[1] in 1951, Elias, Grey and Robinson's work on Fourier treatment of optical processes[2] in 1952, Elias's paper on optics and communication theory[3] in 1955, and Toraldo di Francia's work on resolving power and information[4] in 1955. However, the very first application of communication theory to modern optical information processing was probably O'Neill's work on spatial filtering in optics[5] in 1956. Because of the broad interest in this field at that time, a special symposium on communication and information theory aspects of modern optics[6] took place in 1960. Since then, the application of communication and information theory to optical signal processing has commanded great interest. The applications of optical spatial filtering were particularly evident in the field of radar signal processing, and it was in this field that Cutrona, Leith, Palermo and Porcello published a classic article on optical data processing and filtering systems[7] in 1960. This article stimulated a broad interest in optical processing of photographic images. With the invention of a strong coherent source, i.e., the laser, in the early 1960's, Leith and Upatnieks' work on reconstructed wavefront and communication theory[8] allowed for the first time the formation of high quality holographic images. Using the spatial frequency carrier concept of the Leith-Upatnieks hologram, Vander Lugt in 1964[9] introduced the subject of optical character recognition via the optical matched filter correlator. It is evident that communication and information theory have stimulated a broad range of application to modern optical information processing.

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