WAVEFRONT CODING FOR DETECTION AND ESTIMATION WITH A SINGLE-LENS INCOHERENT OPTICAL SYSTEM

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ABSTRACT

We present a unique method of designing incoherent optical systems for detection and estimation tasks. Our approach is novel in that it physically consists of a phase mask placed at the lens of a standard incoherent optical system. This phase mask provides the ability to shift the phase of the incoming light at discrete regions at the lens. The use of this phase mask allows control of the optical transfer function (OTF) and impulse response, or point spread function (PSF), of the incoherent optical system. With the combination phase mask/incoherent optical system, and digital processing of resulting intermediate image, the overall detection and estimation performance of the system can be greatly enhanced.

We describe three applications of this method. These are single-lens, single-image passive range estimation, high-resolution extended depth of field, and passive range detection.

1. INTRODUCTION

All remote sensing schemes, whether active or passive, act on a spatial and temporal wavefront reflected or radiated from a given object. Active systems induce certain desired wavefronts, while traditional passive systems merely record the intensity of the general incoherent wavefront. This intensity recording destroys or significantly degrades most phase information about the object being observed. Many views of the object are often used to replace this lost information [1, 2, 3]. We have developed a technique, termed wavefront coding, that modifies the incoherent wavefront in such a way that specific information is not destroyed by intensity recording [4].

Systems that can utilize wavefront coding are standard incoherent sensing systems modified with a spatial phase function that modifies the incoherent wavefront before intensity detection. Here we specifically consider an incoherent optical system where the spatial phase function is placed at a principal plane of the lens. This spatial phase function, or phase mask, affects only the phase profile of the incoherent wavefront; the amplitude of the wavefront is not changed. Mathematically, this phase mask acts to modify the characteristics of the incoherent optical system, such as the optical system transfer function (OTF) and impulse response, or point spread function (PSF). By optimally matching the characteristics of the incoherent optical system with a particular detection and estimation task, passive solutions to interesting sensing problems can be found.

For example, wavefront coding can be used to produce a single-lens, single-image, passive range estimation system. Wavefront coding can also be used to design systems that accurately measure the spatial intensity of objects independent of range or focus position. This type of system can also be considered as having a high-resolution extended depth of field. In addition, wavefront coding can be used to produce incoherent optical systems for passive range detection. Such systems segment the observed object volume into orthogonal range, elevation, and azimuth "bins". Each system has desirable characteristics that are possible only from modification of the incoherent wavefront.

2. WAVEFRONT CODING FOR PASSIVE RANGE ESTIMATION

Through analysis of the Cramer-Rao bound on range estimation [5, 6], given a single image from a single-lens incoherent optical system, we can determine the necessary conditions on the optical system for passive ranging [4, 7]. These conditions are on the optical system transfer function, or OTF. Specifically, the OTF must have range-dependent nulls or zeros in order for passive range estimation to be possible. Practically, these range dependent nulls should be *periodic* range-

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dependent *regions*. In other words, the OTF should be in the form of a periodic pulse train with a specifiable duty-cycle and range-dependent period. By the linear system nature of incoherent intensity detected imaging systems, these range dependent nulls of the OTF are transferred to the spatial frequency spectrum of the resulting intermediate image. The range-dependent nulls can be thought of as a "range code" applied to each object at a given range. Estimation of the period of these nulls from the image spectrum deduces object range.

By considering the incoherent optical system with Woodward's ambiguity function [8, 9], we can design the needed optical phase mask to satisfy these necessary conditions. Physically, these masks are composed of a series of tilted, or prism-like, sections where each section has a different tilt angle and width. Mathematically, the masks are composed of a series of linear phase modulated sections, with each section having a different phase modulation and total power. The optical mask is physically placed at a principal plane of the system lens [10]. See figure 1 for a general implementation of an incoherent optical system for wavefront coding.

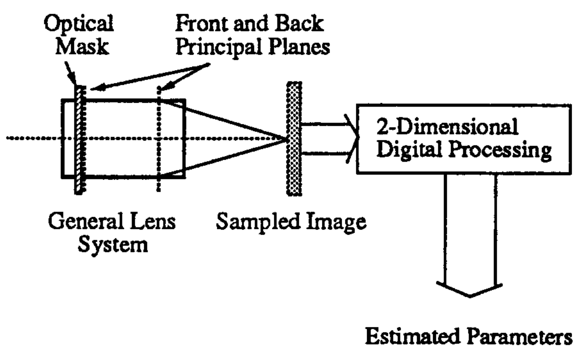

Figure 1: General Implementation of an Incoherent Optical System for Wavefront Coding

An example of the OTFs of one such system, with a comparison to the OTFs of a standard system, is given in figure 2. In general, mis-focus is monotonically related to object range.

These figures are dramatic examples of how the OTF of an optical system can be customized by the use of a phase mask. Comparing the OTFs from the wavefront coded system with the standard system we see that the wavefront coded system has a periodic sequence of nulls that is indeed a function of mis-focus or object range. These nulls are seen to have very high sidelobes, in comparison with the standard system. The standard system quickly takes the shape of a low-pass filter with increasing mis-focus while the wavefront coded system generally contains a constant

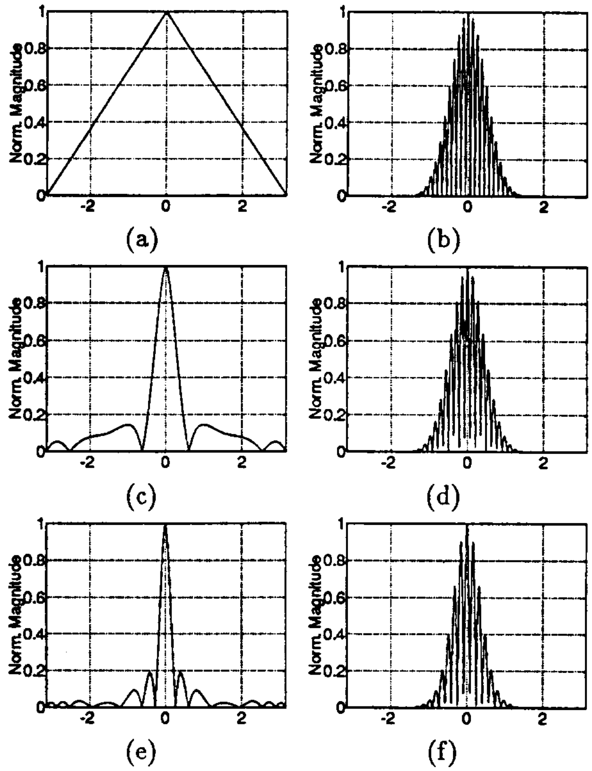

Figure 2: OTFs of Standard System (a,c,& e) and Wavefront Coded System (b,d, & f). (a,b) Geometrically in-focus, (c,d) small mis-focus, and (e,f) large mis-focus. The horizontal axes are in terms of normalized spatial frequency.

bandwidth. The period and width of the nulls shown in right half of figure 2 are but one example.

3. WAVEFRONT CODING FOR RANGE-INDEPENDENT OBJECT ESTIMATION

If an incoherent optical system can be modified by wavefront coding to "code" an image based on object range, then it should also be possible through wavefront coding to modify the system for the opposite response. In effect, with a phase mask modifying the characteristics of the incoherent optical system, it should be possible to produce an incoherent optical system that is insensitive to mis-focus or object range.

Our solution to this problem employed both the ambiguity function, and the theory of stationary phase applied to the ambiguity function [11, 12]. The needed phase mask for this problem turns out to be nothing more than a simple cubic phase profile. In other words, a one-dimensional system with a cubic phase profile modifying the incoherent wavefront will produce a PSF

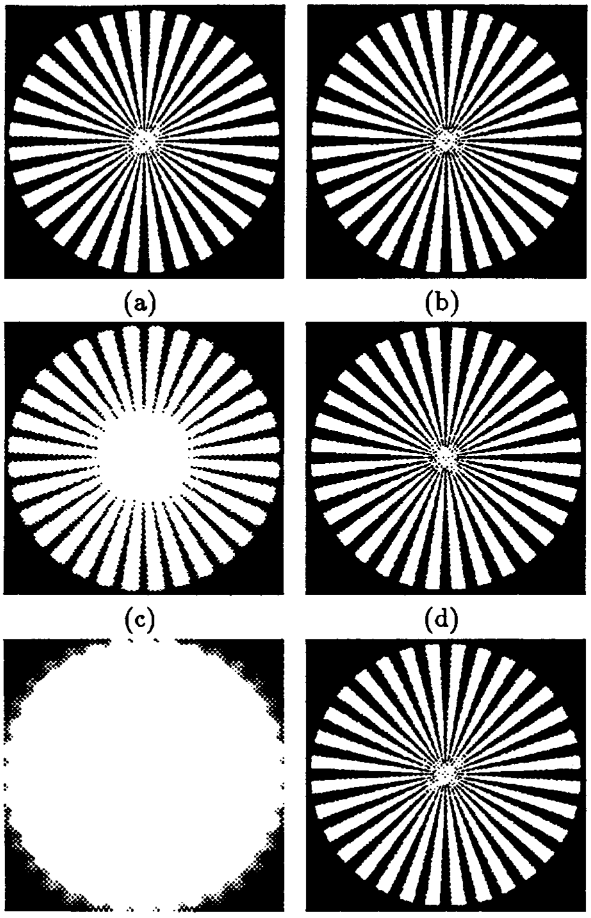

Figure 3: Image of a Spoke Target with Standard System (a, c, & e) and Wavefront Coded System (b,d, & f). (a,b) Geometrically in-focus, (c,d) mild mis-focus, and (e,f) extreme mis-focus.

that is nearly independent of mis-focus or object range. This PSF is not, however, directly a diffraction limited, or point-like, function. But, since the OTF from the wavefront coded system does not have any regions of zeros, and because it does not change with mis-focus, numerous filtering techniques can be applied to the intermediate image to "restore" the PSF. This results in an overall optical/digital system that has a very large depth of field, while also having the light gathering ability and resolution of the full aperture system.

Figure 3 graphically shows the results of wavefront coding for range independent object estimation, with comparison to imaging with a standard system. As seen from these images, the wavefront coded system far outperforms the standard incoherent optical system. In fact, at the largest mis-focus shown, the wavefront coded system differs little from the in-focus version.

4. PASSIVE RANGE DETECTION

Passive range detection differs from passive range estimation in that the object range is assumed known while the object itself is assumed unknown. In passive range estimation neither the object nor the range is assumed known. Also, the received data in passive range detection systems is assumed to be the sum of an unknown number of images of objects at known ranges. This model is similar to that used in a coherent radar processor.

Analysis of the Cramer-Rao bound for this type of system shows that the necessary condition for reliable operation is that the expected range-dependent system transfer functions form an orthogonal set. The Cramer-Rao bound also shows that system estimation variance can be independent of the unknown object, within the system pass-band. In contrast, we can show that performance of the passive range estimation system is always dependent on the characteristics of the unknown object. The independence of the range detection system performance on the unknown object leads to the possibility of employing constant false alarm rate (CFAR) detectors for reliable automatic object detection. A block diagram for the digital processing of a passive range detection system is given in figure 4. This type of processing structure is seen in general to be similar to that performed with coherent radar systems. The orthogonality of range, azimuth, and elevation "bins" leads to many direct analogies between wavefront coded incoherent optical passive range detection systems and modern coherent radar detection systems.

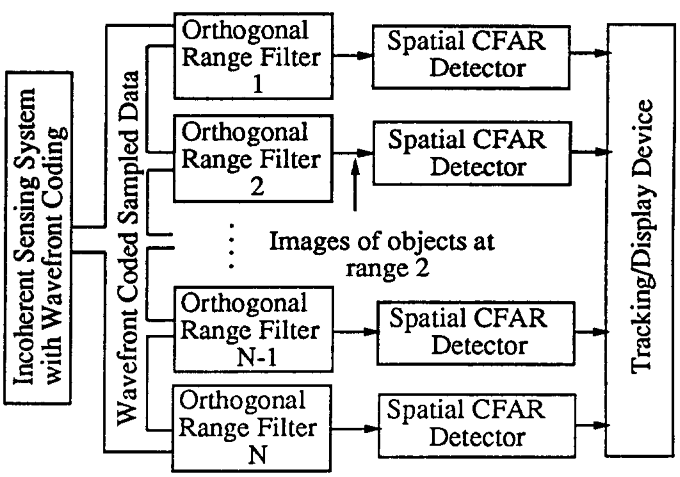

Figure 4: Generalized CFAR processing architecture for incoherent passive range detection systems

The wavefront phase function for incoherent passive range detection systems is designed so that the OTFs, over an expected range of object distances, form an orthogonal set. We have devised a statistical procedure for designing the needed wavefront phase function to approximate the necessary orthogonality of the OTFs. In this method, the spatial phase of the wavefront phase function is modelled as a random variable with a specific correlation profile. The azimuth and elevation resolution of this type of system can be comparable to that of a standard infocus incoherent system. The range resolution, through the designed orthogonality of the OTFs, can theoretically be as narrow as desired. The price paid for high range resolution is lowered effective signal power. In practice, received signal power must be balanced through the width of the orthogonal range filters.

Figure 5 is the simulated response of an orthogonal range filter. The horizontal axis describes normalized object range where half the length of this axis is the traditional depth of field of a standard incoherent imaging system. By orthogonalizing the OTFs, and with additional digital orthogonal range filters, range discrimination can be many times finer than what is normally considered the "infocus" range of an incoherent imaging system. The sidelobes of the range response is only one example of that possible.

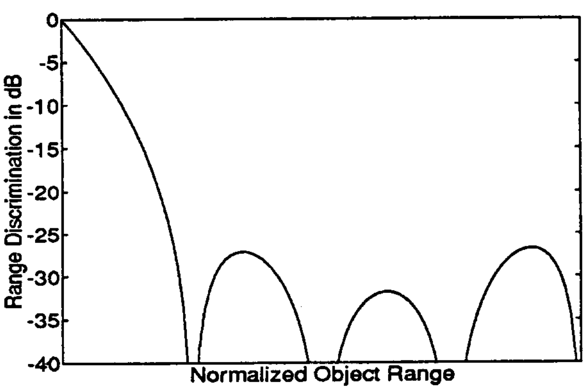

Figure 5: Simulated range discrimination of an incoherent passive range detection system. The horizontal axis describes normalized object range where half the axis length is the traditional depth of field of a standard incoherent imaging system.

5. CONCLUSION

By modifying the phase of an incoherent wavefront through wavefront coding, specific information of the unknown object can be made invariant to intensity detection and recording. Digital processing of the resulting intermediate image is used to extract this information. Many detection and estimation tasks can greatly benefit from this wavefront coding scheme. Wavefront coding for passive range estimation, range-independent object estimation, and passive range detection have been described in this work.

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