in “Computational Optical Sensing and Imaging” Topical Meeting of the Optical Society of America (June 2005), paper JMA1 (invited paper).

Lensless Coherent Imaging with Shaped Illumination and Phase-Retrieval Image Reconstruction

James R. Fienup
The Institute of Optics, University of Rochester, Rochester, NY 14627
fienup@optics.rochester.edu

Abstract: One can decrease the complexity of imaging optics by increasing the demands on the illumination system or on post-detection computations. A lens-less coherent imaging system employing a shaped illumination pattern and phase retrieval is described.

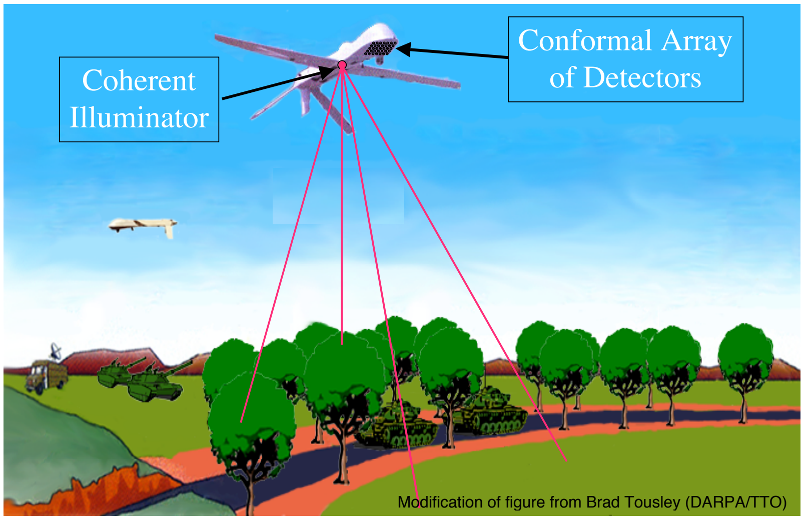
OCIS codes: (110.0110) Imaging systems; (100.5070) Phase retrieval; (100.0100) Image processing; (100.3010) Image reconstruction techniques; (100.3190) Inverse problems

1. Introduction

In an end-to-end imaging system design, one can decide whether to place tight tolerances on the optical image formation system (which is typical of conventional imaging systems) or put the burden elsewhere, such as on the illumination optics or on the post-detection processing. For example, in a focused-beam laser-scanning system, most of the burden is placed on the illumination system. For imaging through atmospheric turbulence with adaptive optics, a great burden is placed on the receiving optics, wavefront sensor, and deformable mirror. For imaging through atmospheric turbulence using phase retrieval or bispectrum processing, most of the burden is placed on post-detection processing [1]. This paper describes an approach to coherent imaging that eliminates the image-formation optics entirely, but places mild demands on the illumination system and larger computational demands on an image reconstruction algorithm [2].

2. System Concept

Figure 1 shows an example system concept. An area is flood-illuminated with a laser beam. The laser light reflected from the scene propagates (by Fresnel or Fraunhofer diffraction) to the sensor, which is just an array of detectors without any imaging optics. The detected intensity is then processed with a phase retrieval algorithm that determines the phase of the field at the sensor and at the same time reconstructs the field at the plane of the scene, the intensity of which is the desired image of the scene. For phase retrieval to be successful, one needs constraints in the image domain to limit the feasible phases at the sensor. In this scenario, this can be accomplished by illuminating the ground with a laser beam with a particular known shape. Then the constraint for phase retrieval is a support constraint: we know that the image should be zero outside the known area of illumination (the support) [3].



Modification of figure from Brad Tousley (DARPA/TTO)

Figure 1. Lensless imaging with a detector array, sensing the intensity of a backscattered laser speckle pattern.

Illumination patterns with soft edges constitute weaker support constraints and do not work as well as those with sharp edges [4]. To get an illumination pattern with very sharp edges would require projection optics with large diameter, which may not be practical. Hence we must suffer from the disadvantage of the soft-edged illumination pattern. The geometric shape of the illumination pattern on the ground plays a large role in determining the success of phase retrieval algorithms, especially for complex-valued imagery [5]. For example, asymmetric illumination patterns work much better than symmetric ones, owing to the potential for a two-fold ambiguity in the phase retrieval problem (whether one reconstructs the true image or the twin image, like the one seen in holography). Illumination patterns with separated parts are especially effective [6]. Such favorable illumination patterns will partly offset the disadvantage of the soft edges.

Such an imaging approach has several advantages over conventional approaches. The diffraction-limited resolution, which improves proportionally with the diameter of the detector array (analogous to the diameter of a telescope aperture), can be substantially better than for a conventional system, given the volume constraints of the platform. The volume of a conventional optical imaging system is roughly proportional to the cube of the aperture diameter, a fact that keeps conventional aperture diameters small compared with the width of the platform. However, with a conformal array of detectors, the effective aperture width can be the entire width of the platform. Very little depth is required in this case, making the receiver lightweight and compact. It can even be conformal to a curved surface of the platform, reducing aerodynamic drag. It does not require a large gimbal to point the sensor at a given target area.

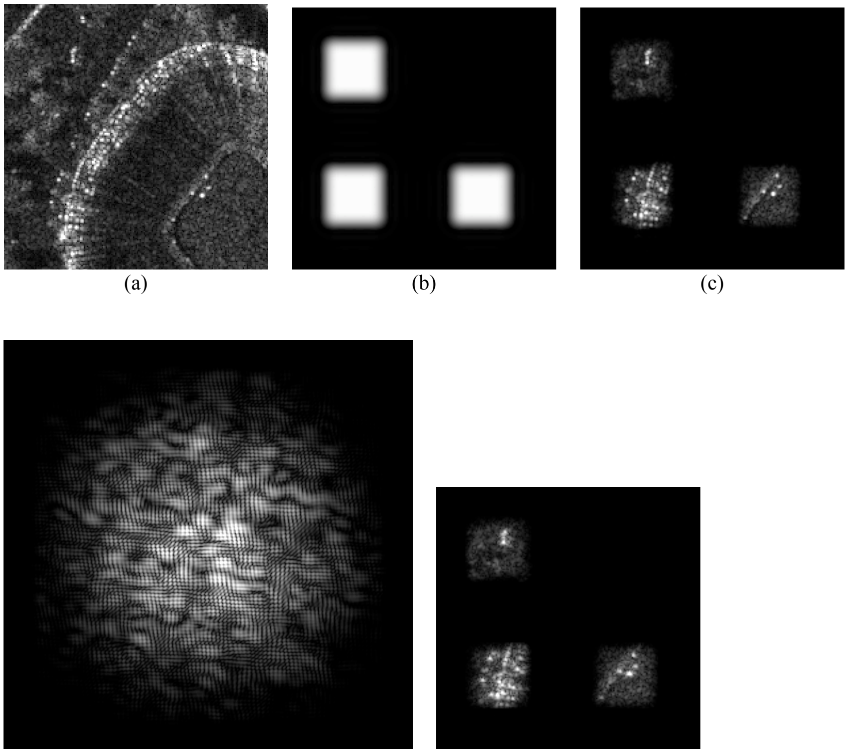
3. Phase Retrieval Algorithm

The looseness of the support constraint makes this a challenging phase retrieval problem. Additionally, this being a coherent imaging system, the lack of a nonnegativity constraint makes the problem especially challenging. For this reason we use the iterative transform algorithm [7] with some enhancements. One enhancement is to use the expanding Fourier modulus technique [8]. It involves first retrieving the phase over a small, weighted, central portion of the Fourier domain, then gradually increasing the Fourier area over which the phase is retrieved. Another enhancement is to (i) perform multiple reconstructions with different random initial starting guesses, then (ii) combining those reconstructed images, and then (iii) performing further iterations [9]. This helps to avoid stagnation problems that often occur with such weak object-domain constraints as we have here.

4. Example Result

Figure 2 shows a computer-simulation result. The intensity of the object scene, taken from a complex-valued synthetic-aperture radar image, is shown in Fig. 2(a). Figure 2(b) shows the illumination pattern consisting of three square areas each with tapered edges as would occur if being formed by a projection system having a small aperture. Such a pattern with separated parts could be formed, for example, by a diffractive optical element. Figure 2(c) shows the intensity of the illuminated scene, the product of 2(a) and 2(b). Figure 2(d) shows the intensity of the far-field diffraction pattern of (c) in the plane of the sensor. Also included in 2(d) is an apodization function applied after detection, which reduces the side-lobe energy outside the support constraint during image reconstruction. Figure 2(e) shows the intensity of the reconstructed image. It has slightly reduced resolution compared with the original object.

The image thus formed will be of a disjoint area of the scene. The entire contiguous scene can be imaged as follows. For each of several laser pulses, illuminate areas of the ground that are offset laterally from one another but overlapping. Reconstruct the images from each of these data sets, then mosaic the images together to fill in the missing areas. An added benefit is that, by incoherently averaging the intensities of the multiple images where they overlap, we can reduce the contrast of the laser speckle artifacts in the image.



(a) (b) (c)

(d) (e)

Fig. 2. Image reconstruction example. (a) Extended scene, (b) laser illumination pattern, (c) illuminated scene; (d) measured far-field speckle intensity pattern at sensor array, (e) image reconstructed from (d) and knowledge of (b).

4. Conclusion

We have described an active imaging concept that eliminates the need for an optical image formation system, but relies heavily on digital post-processing of the measured intensity data to form an image. In such a system it is important to have an integrated design of the illumination optics along with the receiver (a simple array of detectors) and the post-detection algorithms in order to be able to successfully reconstruct an image. It epitomizes one extreme of the trade-off between requirements on the image formation optics and on the digital processing of the collected data.

References

1 J.C. Dainty and J.R. Fienup, "Phase Retrieval and Image Reconstruction for Astronomy," Chapter 7 in H. Stark, ed., Image Recovery: Theory and Application (Academic Press, 1987), pp. 231-275.

2 J.R. Fienup, “Coherent Imaging with Illumination Optics Designed for the Reconstruction Algorithm,” Proceedings of the Frontiers in Optics 2004 (Annual Meeting of the OSA), October 2004, paper FTuO4.

3 J.N. Cederquist, J.R. Fienup, J.C. Marron and R.G. Paxman, "Phase Retrieval from Experimental Far-Field Data," Opt. Lett. 13, 619-621 (1988).

4 R.G. Paxman, J.R. Fienup and J.T. Clinthorne, "Effect of Tapered Illumination and Fourier Intensity Errors on Phase Retrieval," in Digital Image Recovery and Synthesis, Proc. SPIE 828-28 (1987), pp. 184-189.

5 J.R. Fienup, "Reconstruction of a Complex-Valued Object from the Modulus of Its Fourier Transform Using a Support Constraint," J. Opt. Soc. Am. A 4, 118-123 (1987).

6 T.R. Crimmins and J.R. Fienup, "Uniqueness of Phase Retrieval for Functions with Sufficiently Disconnected Support," J. Opt. Soc. Am. 73, 2l8-22l (l983).

7 J.R. Fienup, "Phase Retrieval Algorithms: A Comparison," Appl. Opt. 2l, 2758-2769 (1982).

8 J.R. Fienup and A.M. Kowalczyk, "Phase Retrieval for a Complex-Valued Object by Using a Low-Resolution Image," J. Opt. Soc. Am. A 7, 450-458 (1990).

9 J.R. Fienup and C.C. Wackerman, "Phase Retrieval Stagnation Problems and Solutions," J. Opt. Soc. Am. A 3, 1897-1907 (1986).