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### Special Issue on: Computational Imaging

Guest Editor

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# OPTICS IN INFORMATION SYSTEMS

## Power-constrained distributed transmission of sensor-network measurements

Distributed imaging using sensor arrays is gaining popularity among various research-and-development communities. A common bottleneck within the sensor-network framework is the large resulting data size. In applications where transmission power (and/or bandwidth) is constrained, this can drastically decrease the sensor-network lifetime. Nevertheless, the distributed nature of the data makes the optimal exploitation of scene redundancy challenging. One simple approach would ignore inter-sensor redundancy and simply use various available techniques to independently compress the data at each sensor. Such an approach would take advantage of the correlation inherent in a single sensor's view without acknowledging the common nature of the measurements across the array.

Here we present an algorithm that efficiently exploits (inter- and intra-) sensor correlation for the purpose of power-constrained distributed trans-

mission of sensor-network imagery. In what follows, we briefly describe a typical layout of the sensor network model.

Figure 1 illustrates such a model in which multiple sensors collaborate to image the same scene. The location of each sensor, and hence the corresponding field of view, is a random variable that obeys a probability distribution function governed by a physical law. Each sensor has a certain amount of power (battery) that it uses to send the images to a base station. As shown in the figure, the sensors do not communicate with one another but, instead, are assumed to communicate with a central base station that orchestrates the transmission strategy. Each sensor communicates two things to the base station: its location and the number of bytes (or the power) it needs in order to losslessly por-

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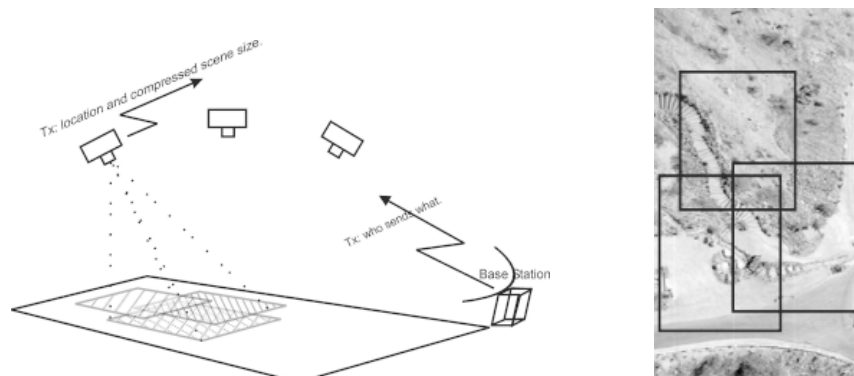


Figure 1. A typical sensor-array imaging system layout (left) and the corresponding sensors' fields of view (right).

# Moore and Maxwell work together to improve imaging

The revolution in electronics witnessed over the past few decades has had a significant impact on imaging systems. Perhaps most significant is the widespread replacement of film by solid-state detectors, especially in the consumer market, and enhancements in post-detection processing. In fact, the potential for future advances is often referenced to Moore's Law: i.e. that the number of transistors in a given area doubles every 18 months.

However, the fervor with which Moore's Law is so often cited can lead to a skewed view of the potential for further advances in imaging and imaging systems. For example, naively following Moore's Law can lead one to believe that imaging can be enhanced simply by increasing the density of detector pixels, or that all image-processing problems can be solved using digital processing in post detection. Slower progress in the design of optical systems, as compared to electronics, serves only to underscore these notions.

However, advances in imaging can be made without relying solely on electronics. Before expanding on this, consider the conventional argument. If computing is so cheap and getting cheaper, what's wrong with pointing a digital camera at a scene, detecting it, and processing the output? One answer is cost. Although computing is cheap, electronic processing may not be the best solution to a problem. To track a moving object, is it necessary to capture full-frame digital images at video rates? A second answer is capability. If an imaging system is unable to capture certain information, no amount of processing will be able to recover it. For example, due to aliasing, spatial frequencies in an image that are beyond the sampling rate of the detector cannot be recovered unambiguously through processing.

Our philosophy on imaging systems is that, for special-purpose applications, optics, optoelectronics, and signal processing should be part of an integrated design that better balances the processing load. The goal, in effect, is to balance Moore's Law with Maxwell's Equations to ensure an effective transfer of information from the physical domain into one from which decisions can be made.

We refer to a system that reflects this balance between Moore's Law and Maxwell's Equations as an integrated computational imaging system (ICIS). However, the concept is not new.<sup>1</sup> For example, Matic and Goodman provide an early example of this holistic approach in their examination of image linear filtering.<sup>2</sup> Optimal performance and resources were achieved when filtering was realized both optically and electronically and not exclusively in one domain or the other.

Two more-recent examples include extended-depth imaging using a cubic phase mask<sup>3</sup> and a snapshot hyper-spectral imager.<sup>4</sup> In neither case are the optics designed to form an image. In Reference 3, the optics introduce a cubic phase, the optical transfer function of which exhibits insensitivity to range. Although all images appear severely aberrated, the aberration is constant over an extended depth of focus, which simplifies its removal. Only a single electronic filter is required. Once removed, images from all ranges are in focus. In Reference 4, diffraction is used to highlight redundant spectral information in a multi-spectral image. The redundant information is used in the post-detection phase to create an image cube with two spatial and one spectral dimension. In both examples, the optics produce a wavefield: with those features critical to the task-at-hand being accentuated. The accentuation, or wave-front encoding,<sup>3</sup> simplifies post-detection processing and produces images that have unique properties: either extended depth of focus or spectral imaging.

Optical correlators applied to military target recognition are a good example of a failed ICIS design. The inability of Fourier optical processors to solve military pattern recognition problems does not lie in the optics but in the application. The optics was asked to aggregate information from an input that was spatially and spectrally complex, as well as spatially and temporally incoherent. The complexity of the input overwhelmed the ability of the optics to provide a quantitative output with sufficient resolution and fidelity to be useful. Fourier-optical systems have met with much greater success more recently in security applications where it is possible to control the input and the problem addressed is one of verification, not detection.

As stated, ICIS is not a new concept. So what has changed in the past two decades to make this approach likely to spread farther than before? The answer is primarily technology. This includes advances in passive optical fabrication techniques to produce aspheres, diffractive elements, and elements whose properties change arbitrarily in three dimensions. Developments in micro-electro-optical and mechanical systems are also important: as is, admittedly, the capitalization of electronics on Moore's Law which has led to new detector technology and increased processing power. New imaging metrics based on information theory have also had an impact.

However, gaps remain. Most importantly, we need to develop a mathematical framework that encompasses this integrated approach. Fast processing algorithms and smart detectors de-

signed in conjunction with optics are two relatively unexplored areas that will also have significant impact on future imaging systems. The US Army Research Office and the Defense Advanced Research Projects Agency are both working to close these gaps: so that Moore can work more closely with Maxwell.

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## References

1. W. T. Cathey, B. Roy Frieden, W. T. Rhodes, and C. K. Rushforth, *Image gathering and processing for enhanced resolution*, **J.O.S.A. A** **1**, pp. 241-250, 1984.
2. R. M. Matic and J. W. Goodman, *Comparison of optical prediction processing and postdetection linear processing for partially coherent image estimation*, **J.O.S.A. A** **6**, pp. 213-228, 1989.
3. E. R. Dowski and W. T. Cathey, *Extended depth of field through wavefront encoding*, **Appl. Opt.** **34**, pp. 1859-1866, 1995.
4. M. R. Descour and E. Dereniak, *Computed-tomography imaging spectrometer: Experimental calibration and reconstruction results*, **Appl. Opt.** **34**, pp. 48174826, 1995.

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### Deadline for the next edition, 15.1, is:

**26 September 2003:** Suggestions for special issues and guest editors.

**17 October 2003:** Ideas for articles you'd like to write (or read).

**12 December 2003:** Calendar items for the twelve months starting January 2004.

# Spatio-spectral target analysis and tracking using interferometric tracking telescopes

Systems used to observe and track objects in orbit, such as satellites, include both conventional telescopes and those with adaptive optics. Conventional telescopes have limited power to resolve small objects in orbit due to atmospheric aberrations. Adaptive optics can correct for this, but are generally very expensive to implement. A telescope with adaptive optics, however, does simplify the target-identification problem because it provides an image of the target's structure. We are constructing an alternative system based on coherence imaging for tracking and identification of objects in orbit. The system is composed of a set of rotational shear interferometers coupled to telescopes: rather than imaging the structure of the object in orbit, it measures the object's spectral signature while simultaneously providing its location information.

The rotational shear interferometer (RSI) is similar to a Michelson interferometer except that the planar mirrors on the arms are replaced by mirrors that fold at right angles.<sup>1</sup> The RSI allows us to measure the mutual coherence of the incident wavefront by interfering it with a rotated and time-delayed version of itself. One of the arms of the RSI can be rotated about the optical path, producing the shearing angle. A wavefront incident upon the RSI is initially split by the beam splitter and then traverses both of the arms. One of the arms folds the wavefront, while the other both folds and rotates it. The arm with the rotation mechanism is also translatable, allowing for a path-length difference between the two, just as in a Michelson interferometer. After traversing the arms, the wavefront is recombined and imaged on a CCD. The response of an RSI to a far-field point source is a two-dimensional sinusoidal pattern on the focal plane. The amplitude of the sinusoid is determined by the intensity of the source. For a constant shear angle, the frequency of the sinusoid—as well as its rotation angle with respect to the axes of the focal plane—is dependent on both the wavelength of the source and the angle the source makes with the optical axis. An example of the sinusoidal response to a point source is shown in Figure 1.

Attaching the RSI to a telescope allows us

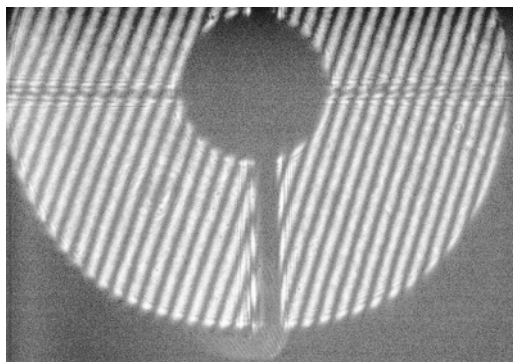


Figure 1. Picture of RSI fringes obtained by imaging a point source.

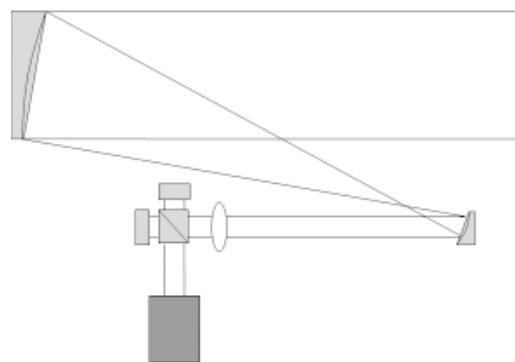


Figure 2. Optical system showing the primary and secondary telescope mirrors, RSI, and CCD camera.

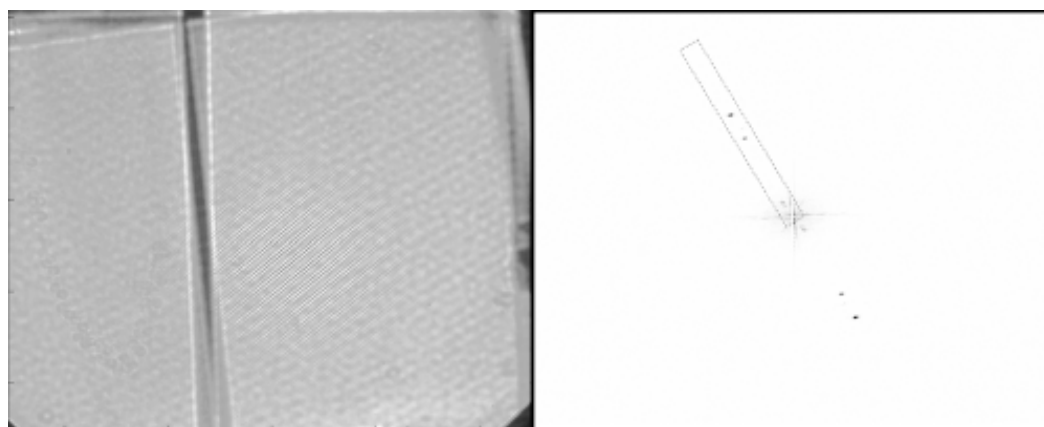


Figure 3. Fringes due to a two-wavelength point source and reconstructed spectral information.

to increase the amount of light input to system, as well as its physical aperture. The optical system is designed so that the input aperture of the telescope is imaged onto the focal plane, allowing us to use the full extent of the CCD to measure the fringe pattern created by the RSI. Figure 1 shows the experimental results when imaging a point source with a combined telescope and RSI system. In this case, a commercially-available Newtonian telescope was used. The large black circle in the center of the image is the result of the Newtonian telescope's secondary mirror, which is in the center of the optical path of the telescope. The RSI and the telescope system used for this paper are shown in Figure 2.

Our design uses an off-axis parabolic mirror, allowing the secondary mirror to be moved so that it no longer obstructs the aperture of the telescope. Removing the obstruction allows us to capture more of the fringe information

for computation of the source spectrum and location. The telescope used in our system is an f/6.7 system: since we are interested in imaging point sources, a wide field of view is more important than higher magnification.

To determine the source position and spectrum simultaneously requires multiple measurements, since both of these variables are embedded in the fringe information. For this reason, we are using an array of three telescope / RSI systems. With a monochromatic point source, it is possible to solve a simple set of equations for the source position and spectrum given at least two fringe measurements.<sup>2</sup> A target with a more complicated spectrum, like a satellite, requires multiple measurements to deconvolve the source spectrum from its position information. Figure 3 shows fringes due to a two-wavelength point source beside a fast Fou-

*Continues on page 10.*

# Restoring images with space-variant blur via pupil-phase engineering

In a seminal paper,<sup>1</sup> Dowski and Cathey proposed the use of integrated optical-digital imaging systems to extend depth of focus. Specifically, they proposed the use of a cubic phase mask in the pupil of a standard, limited-focus imaging system to encode an image of a three-dimensional object that can then be digitally restored. The surface of the cubic phase mask is given by a function of the form  $j(x,y)=a(x^3+y^3)$  where  $a$  determines the *strength* of the mask. Under suitable conditions, restored phase-encoded images exhibit excellent depth-dependent detail that, without any phase encoding, would be washed out because of the normal focus-dependent variant blur (see Figure 1). The restoration comes with no penalty

to the total light flux or the spatial bandwidth of the imaging system.

We introduce the concept of pupil-phase engineering (PPE), a procedure to optimize the design of a more general pupil-phase mask that can lead to even better performance than the cubic mask in extending the depth of focus and controlling focus-related aberrations. The fundamental basis of this procedure is to seek a phase mask that allows the greatest possible insensitivity of the phase-encoded optical image to focus variation without unacceptably compromising the digital restorability of that image. We have considered a number of classes of phase masks; here we report our optimization results for symmetric, mixed-cubic masks

of the form:  $\phi(x,y) = \alpha_1 xy + \alpha_2(x^2+y^2) + \alpha_3(x^3+y^3) + \alpha_4(x^2y+xy^2) + \dots$

We consider two different PPE approaches. The first uses the Strehl ratio (SR), while the second uses the concept of Fisher information (FI) from statistical estimation theory<sup>2</sup> as a metric of performance of an integrated optical-digital imaging system. The FI furnishes a particularly simple measure of focus independence. Furthermore, its rich theoretical framework may enable a deeper understanding of the general subject of pupil-phase encoding.

## Strehl-ratio-based design

The Strehl ratio,  $\chi(\tau)$ , is the ratio of the on-axis values of the Point Spread Function (PSF) with

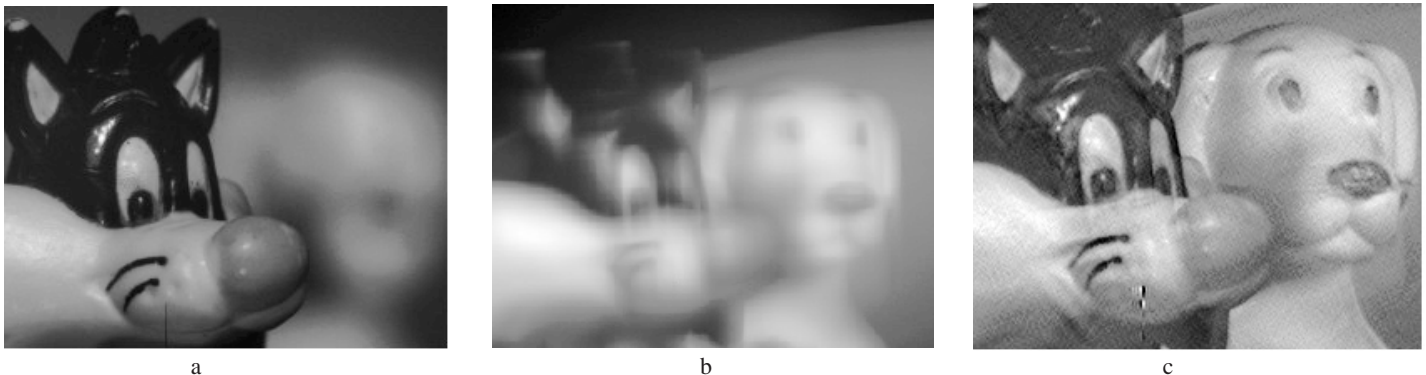


Figure 1. (a) Image captured with a standard wide aperture lens. (b) Intermediate phase-encoded image captured through a cubic phase mask. (c) Digitally-restored result from the intermediate image.

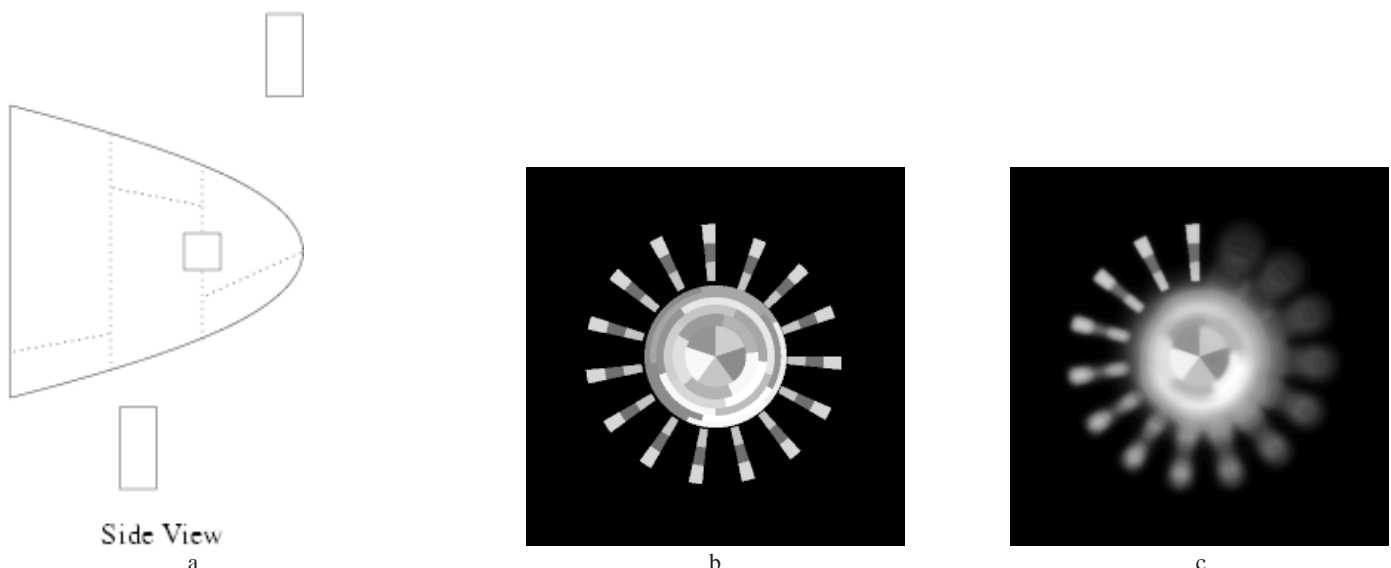


Figure 2. (a) Side view of the parabolic cone-shaped object model. (b) Theoretical blur-free perspective projection of the object. (c) Image of object when captured with a standard limited-focus system.

and without the pupil phase, where  $\tau$  is a defocus distance parameter. Very generally, the deviation  $[\chi(\tau) - \chi(0)]$  can be expressed as a Taylor series in powers of  $\tau$ . Our optimization procedure forces the coefficients of the first  $N$  terms, for some chosen  $N$ , to be small: subject to regularization constraints on the magnitude of the SR at  $\tau=0$ . By rendering the first  $N$  derivatives of the SR with respect to  $\tau$  to be small without degrading its actual value greatly, we argue for better-optimized phase masks.

### Fisher-information-based design

Our second approach employs a Fisher-information-based metric of sensitivity of the PSF to defocus. Unlike the SR, the FI metric is an integrated measure that incorporates the sensitivity to defocus of the *full* PSF, not just its on-axis value. Further, it is better suited to deducing the best phase mask under a range of imaging conditions. An optimization procedure can then be formulated to minimize the PSF defocus sensitivity subject to regularization constraints. Preliminary numerical simulations<sup>3,4</sup> have demonstrated the generally superior performance of our engineered masks when

compared to the cubic phase mask.

### Computational results

Our procedures involve the solution of global nonlinear optimization problems with numerous local minima. The objective functions require careful numerical integration of highly-oscillatory functions. A Levenberg-Marquardt method was used for finding local minima and a Monte-Carlo-type technique was used for the global optimization.

We tested our optimized phase masks using computer simulation. The software models a spatially-varying blur produced by simulated imaging of a parabolic cone-shaped object surrounded by a set of wings arranged in a spiral at equal angles and linearly-progressive distances away from a reference plane coinciding with the center point (see Figure 2). The performance of our optimized phase masks in the imaging and restoration processes is illustrated in Figure 3.

The present work illustrates the use of PPE to treat the problem of focus extension. The PPE concept is more general, however, and can

be employed for a number of other image-quality-control applications.

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### References

1. E. R. Dowski and W. T. Cathey, *Extended depth of field through wavefront coding*, **Appl. Optics** **34**, pp. 1859-1866, 1995.
2. H. Van Trees, **Detection, Estimation, and Modulation Theory**, Wiley, 1968.
3. S. Prasad, T. C. Torgersen, V. P. Pauca, and R. J. Plemmons, *Integrated Optics Systems for Image Quality Control*, **Proc. 2002 AMOS Tech. Conf.**, Maui, 2002.
4. S. Prasad, T. C. Torgersen, V. P. Pauca, R. J. Plemmons, and J. van der Gracht, *Engineering the Pupil Phase to Improve Image Quality*, **Proc. SPIE** **5108**, Orlando, 2003.

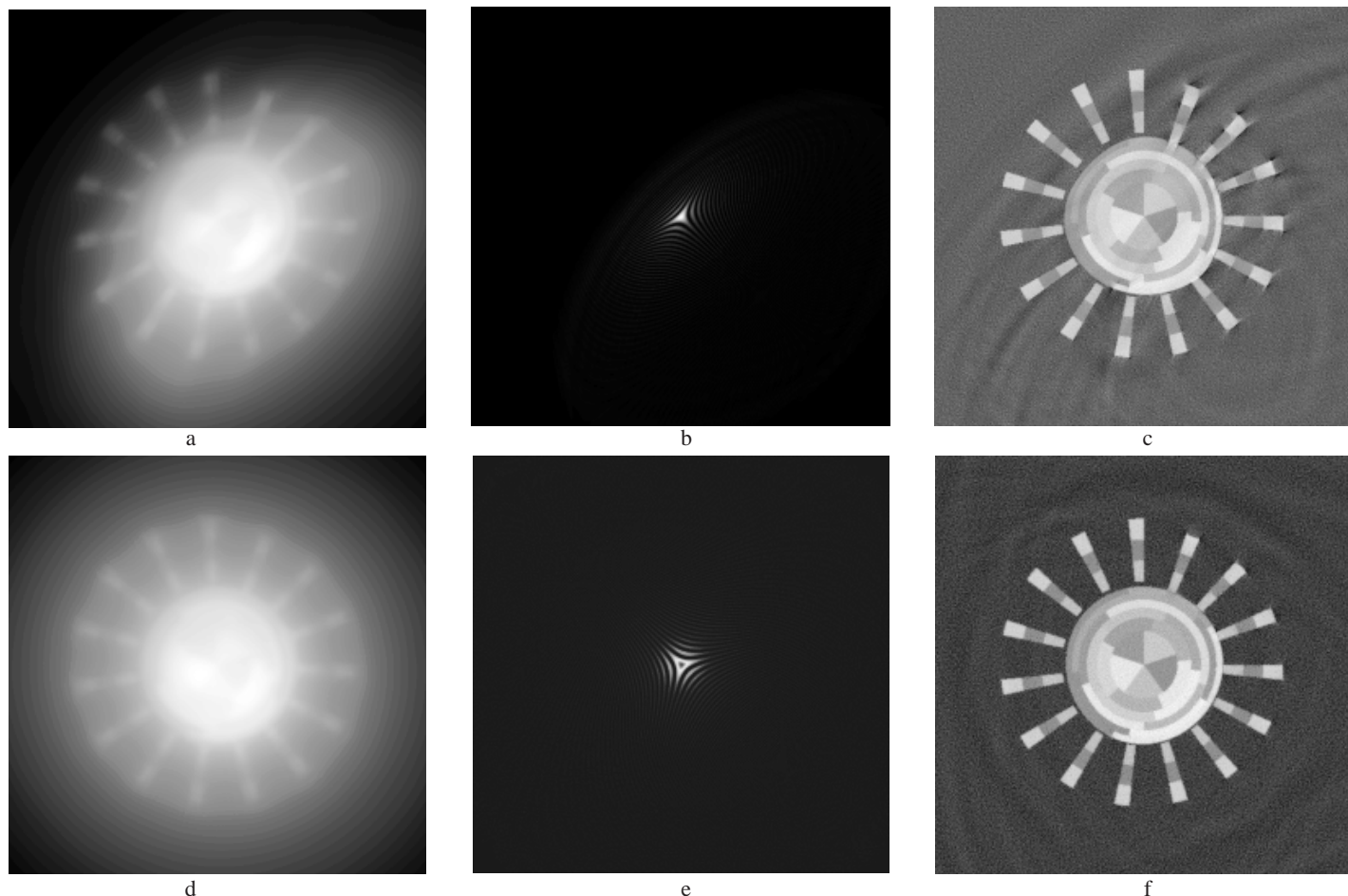


Figure 3. Simulation results (intermediate phase-encoded image, PSF image, and restored image): (a)-(c) obtained using our SR-optimized phase masks, and; (d)-(f) obtained using our FI-optimized phase masks.

# Imaging with sparse apertures

When designing imaging systems, obtaining finer resolution is an eternal quest: one can never have too much of it. Since the laws of physics dictate that the resolution of a diffraction-limited telescope improves with aperture diameter, the quest for larger and larger telescopes continues. The Hubble Space Telescope has a diameter of 2.4m. NASA is planning for its replacement, the James-Webb Space Telescope, to have a diameter of about 6m. Much farther down the road, NASA's Terrestrial Planet Finder, an infrared-imaging interferometer, might have a diameter of tens of meters.<sup>1</sup>

As the telescopes get larger, simply scaling up older designs does not work well. The Hubble has a fairly conventional design, using a monolithic primary mirror. For the James Webb, on the other hand, NASA has decided to use segmented-aperture optics.<sup>2</sup> This makes the system foldable for launch as well as keeping the weight down. A variety of approaches, including phase-retrieval algorithms, will be used to align the segments in outer space, once the telescope has been unfolded. For even larger telescopes, scientists are considering other approaches to make light-weight, affordable systems. One is to again make the primary mirror out of segments, but deploy the telescope with most of the segments missing. Another approach is to combine the light from a number of smaller telescopes, including optical delay lines for path-length equalization, and interfering the beams together in an image plane. This has the added benefits of taking up less space along the axial dimension and being faster to steer. Such an imaging interferometer was accomplished with the *Multiple Mirror Telescope* on Mount Hopkins. These two ideas are illustrated in Figure 1. In both cases, the resolution can be as fine as a conventional telescope, having a diameter equal to the entire diameter of the sparse primary aperture or the multiple-telescope array.

Raw images coming from such telescopes will have poor quality because of the sparseness of the aperture. However, given sufficient signal and using image restoration algorithms, the quality can be improved to the point of being as good as images from a filled-aperture telescope. This is illustrated in Figure 2. When the signal-to-noise ratio (SNR) is very high, an

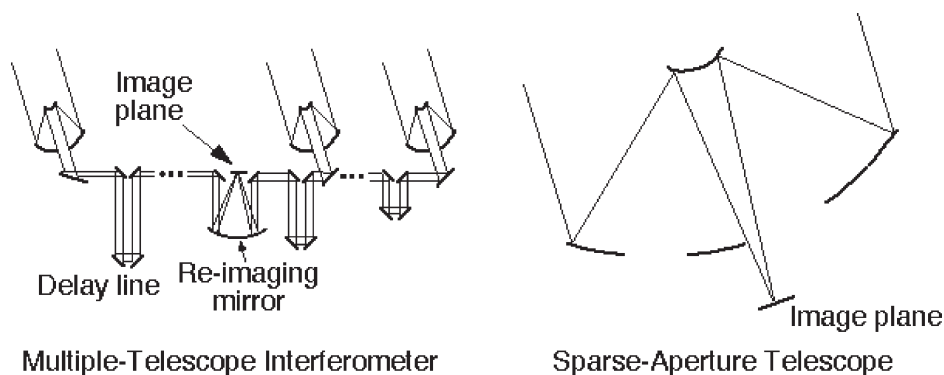


Figure 1. Sparse-aperture systems include those with multiple-telescopes linked through an interferometer (left) and telescopes with only a fraction of the primary mirror present (right).

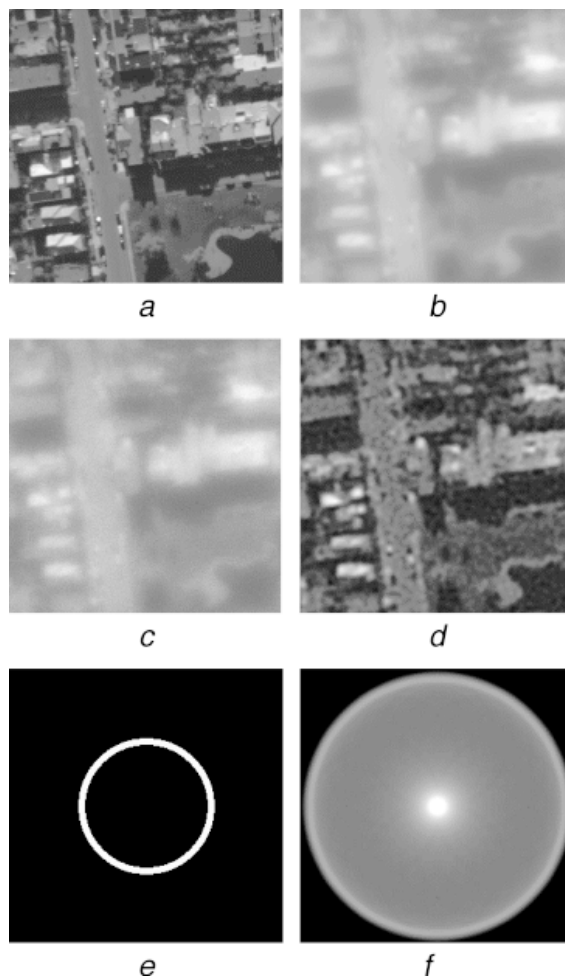


Figure 2. Images from sparse apertures: (a) original scene; (b) image through sparse aperture (no noise); (c) image with 3% average noise; (d) image restored from c (the restored image from b looks like a); (e) the sparse aperture (a thin annulus), and; (f) the MTF of e.

excellent image is restored. When the SNR is lower, restored-image quality degrades. Furthermore, as the SNR decreases, the image quality for a sparse aperture degrades faster than for a filled aperture. The reason is that the modulation transfer function (MTF) for a sparse aperture is much lower for the middle spatial frequencies than it is for a filled aperture. In the process of boosting those suppressed spatial frequencies using a restoration algorithm, one also boosts the noise.

Many different restoration algorithms can be used to improve these images. When additive Gaussian noise dominates, a Wiener-Helstrom filter<sup>3</sup> is a good choice. When Poisson noise (photon noise) dominates, a nonlinear maximum likelihood algorithm would seem to be an appropriate choice.<sup>4</sup> However, we have found that for sparse apertures looking at extended scenes—like the earth—with realistic amounts of haze and detector noise, Wiener-Helstrom filters work as well as, or better than, nonlinear maximum likelihood algorithms.<sup>5</sup> They are also more efficient computationally.

One can achieve the needed higher SNRs for sparse-aperture telescopes by taking longer exposures. Thus, one can trade off telescope sparsity (which implies lighter weight and less expense) for integration time. A measure of the sparsity is the fill factor: the ratio of the area of the telescope collecting aperture to the area of an equivalent filled circular aperture. How much longer integration time is needed depends on the type of noise that dominates. By analyzing expressions for SNR,<sup>6</sup> one can arrive at the scaling laws given in Table 1. Here, by synthetic aperture we mean that only a fraction of the spatial frequencies are measured at any

one time, but all the spatial frequencies required are measured over a period as the aperture segments move relative to one another. From Table 1 we see that, to get the same quality of imagery when read-noise dominates, a sparse aperture with a fill factor of 10% requires an exposure 100 times longer than when using a filled aperture of equivalent diameter. In a photon-rich environment, this penalty will not be felt.

In conclusion, when one must have high resolution with light weight, sparse apertures are an attractive alternative to conventional apertures. One must use longer exposure times

and restoration algorithms to get a useful image but, considering the alternatives, that may be a very affordable price to pay.

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#### References

1. [http://planetquest.jpl.nasa.gov/TPF/tpf\\_project.html](http://planetquest.jpl.nasa.gov/TPF/tpf_project.html)
2. <http://www.jwst.nasa.gov/>
3. C. W. Helstrom, *Image Restoration by the Method of Least Squares*, **J.O.S.A.** **57**, pp. 297-303, 1967.
4. E. S. Meinel, *Origins of Linear and Nonlinear Recursive Restoration Algorithms*, **J.O.S.A. A** **3**, pp. 787-799, 1986).
5. J. R. Fienup, D. Griffith, L. Harrington, A. M. Kowalczyk, J. J. Miller, and J. A. Mooney, *Comparison of Reconstruction Algorithms for Images from Sparse Aperture Systems*, **Proc. SPIE** **4792-01**, 2002.
6. J. R. Fienup, *MTF and Integration Time versus Fill Factor for Sparse-Aperture Imaging Systems*, **Proc. SPIE** **4091A-06**, pp. 43-47, 2000.

Table 1. Integration-time dependency on fill factor ( $a$ ) with various noise sources for sparse-aperture telescopes and imaging interferometers.<sup>6</sup>

	Photon & Bias Noise	Read Noise	Dark Current Noise
Fixed Aperture	$a^{-3}$	$a^{-2}$	$a^{-4}$
Synthetic Aperture	$a^{-2}$	$a^{-2}$	$a^{-3}$

## Power-constrained distributed transmission of sensor-network measurements

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tray the scene currently in its field of view.

For simplicity, we assume the following for our initial model:

- The sensor images a 2D world, so occlusion effects are neglected for now.
- The optical axes of the sensors are parallel, so that the pixel shape is the same (square) for all sensors.

- The sensors are at the same altitude, which means that the pixel spatial size is the same for all sensors.

- All sensors are identical, so the spatial resolution is the same for all sensors.

Given a random deployment of the sensors—or, equivalently, a random set of fields of view—along with the corresponding power of

each sensor, the problem is then to choose a transmission strategy that maximizes the lifetime of the sensor network. The transmission strategy consists of allocating spatial portions of the scene to various sensors while satisfying the following constraints: a sensor can only send scene elements that fall within its field of view (no inter-sensor communication is allowed); and the union of all fields of view must be sent to the base station.

Figure 2 shows a plot of the lifetime  $\alpha$  of a network of sensors versus the percentage scene coverage  $\eta$  for a fixed sensor density  $\rho$ . Here,  $\rho$  is defined as the ratio of the number of sensors used to the minimum number of sensors needed to just cover the whole scene of interest. Also, we define the lifetime  $\alpha$  as the number of transmissions before one or more sensors run out of power.

In the figure, the solid curves depict the performance of the simplistic approach, whereby every sensor sends every element in its field of view. Each of the curves corresponds to a different sensor density  $\rho$ . For example, using this basic approach, it can be seen that, for  $\eta = 45\%$  and  $\rho = 1$ , the network of sensors could transmit, on average,  $\alpha = 11$  sets of images to the base station before one or more sensors run out of battery.

Results obtained with our optimized approach are shown on the same graph with the family of dotted lines. It can be seen that gains of up to 450% are achieved with our method.

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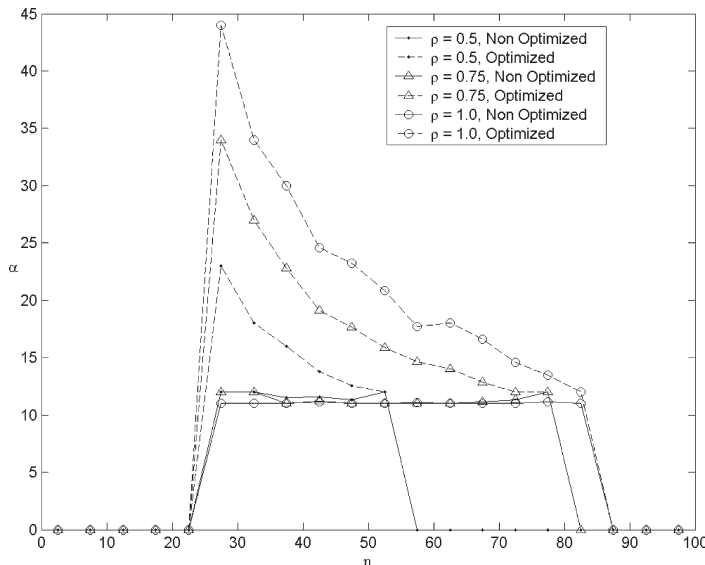


Figure 2. Expected lifetime for various sensor configurations using both simplistic and optimized techniques.

Figure 2 shows a plot of the lifetime  $\alpha$  of a network of sensors ver-

# Volume holographic real-time stereo imaging: enhancing the depth selectivity of optical profilometry with large working distances

Volume holographic imaging (VHI) systems use volume holograms as imaging elements in the same way that traditional optical systems use lenses and prisms. The image information is registered on a digital camera and post-processed for further improvement: consequently, VHI is a version of computational (or digital) imaging with the superior light-transformation properties of volume holography. In particular, the Bragg selectivity, chromatic dispersion, and holographic-multiplexing properties of volume holograms can provide depth and spectral slicing without mechanical scanning. Specific demonstrations of VHI systems from our group and collaborators have included confocal microscopes,<sup>1</sup> surface profilometers with large working distances,<sup>2</sup> and real time hyper-spectral microscopes.<sup>3</sup>

The operation of VHI systems can be thought of in terms of spatial transformations, as shown in Figure 2. The volume hologram essentially maps 3D (two spatial dimensions plus color, or three spatial dimensions) as well as 4D spaces (three spatial dimensions plus color) onto a 2D camera, where the signal is detected in real time.

This real-time, non-invasive 'slicing' operation, the first demonstration of which is described in Reference 3, is unique in VHI systems. It is appropriate for use with transparent, self-luminescent or fluorescent objects. We have also demonstrated VHI with reflective objects, in which case imaging is 'profilometric' or 2D by necessity: we have no access to the object interior.

A VHI system is constructed by first recording the volume hologram, which will later be used as a lens. Recording is accomplished in the standard way: by interfering two mutually-coherent beams inside a thick photosensitive medium such as a photorefractive crystal or photopolymer material. In all experimental results presented here, lithium niobate was used

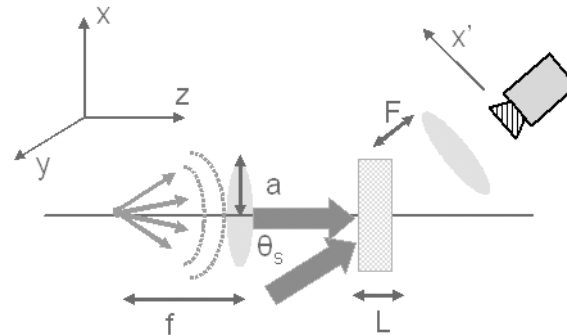


Figure 1. Schematic of the PR-VHI system. The position of the recording point source is the Bragg-matched location for the imaging system.

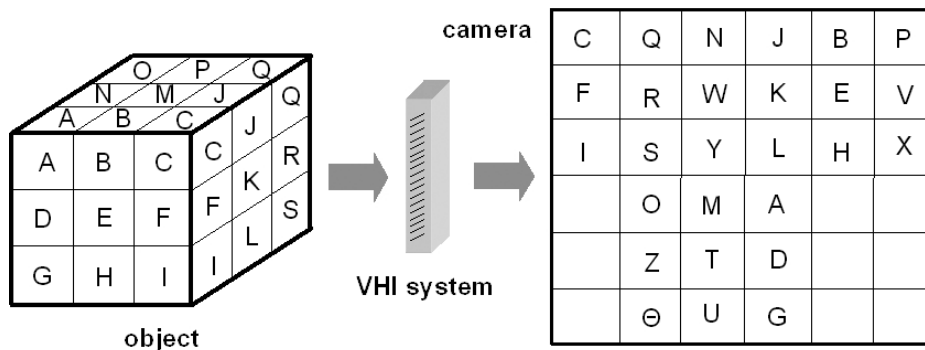


Figure 2. A VHI system captures 3D object information onto a 2D measurement plane by rearranging the information into lateral slices.

for this purpose. We describe a specific implementation, a particularly simple one, where both beams are plane waves. We refer to these holograms as planar reference (PR) holograms. PR-VHI systems are selected because they are easy to analyze and implement, and still offer rich possibilities for advanced, multi-functional optical imaging systems. As is well known from holographic storage work, PR holograms have angular Bragg selectivity. In our use for imaging, the selectivity is exploited for both depth-selective and color-selective imaging. The downside is that the monochromatic field of view of the VHI system is reduced to a 1D slit. The remainder of the field of view is reconstructed either by scanning or by multiplexing several PR holograms, each of which is tuned

to a different slit location. An example of a scanned image of a reflective artifact is shown in Figure 3. The target was illuminated using a monochromatic, doubled Nd:YAG laser beam at 532nm wavelength. In this case, the depth resolution was ~2mm at a working distance of ~5cm.

The depth resolution of VHI—like most imaging systems except those that use time-of-flight—degrades quadratically with the distance of the object from the entrance pupil of the imaging system. This degradation could be offset by increasing the size of the entrance pupil, i.e. the lateral size of the volume hologram, which would be costly and impractical. Instead, we insert appropriately-designed

objective optics, such as a tele-photo lens, in front of the volume hologram in the system. This artificially brings the effective focal plane of the optical system closer to the object. The resolution gain is quadratic in the telephoto lens lateral magnification. An image of the same reflective artifact, this time at a distance of 0.5m and using a 25×-magnification lens, is shown in Figure 4. The depth resolution was still 2mm in this case, despite the 10-fold increase in working distance.

As the working distance increases further, even the tele-photo lens cannot cope with the quadratic degradation in depth. Two methods come to our rescue for such long-haul distances: a-priori information about the object—which can be incorporated into the hardware and/or post-processing algorithms used in image inversion—and cooperative imaging, i.e. use of several VHI systems to look at the same objects from different perspectives. The combined image achieves better resolution by virtue of over-constraining methods, such as the regularized pseudo-inverse.

To see the ability of the hardware design to exploit a-priori image information, consider the case of a reflective object. Examples of such

miniature objects of interest are VLSI and MEMS structures, and larger metallic ones such as machine parts and artillery. Our method uses a telephoto PR-VHI that is inclined with respect to the mean object surface orientation to improve depth resolution. The inclined PRVHI translates the superior lateral resolution of the volume hologram to an apparent improvement in the depth resolution of the flat object. As result, it is possible to resolve  $25\mu\text{m}$  in the depth direction at a working distance of 46cm. Figure 5 shows experimental images of a MEMS micro-turbine engine whose surface features were  $\sim 225\mu\text{m}$ .

As a final example, we asked the question whether VHI can function with white light illumination as well (in all the previous experiments, the illumination was monochromatic and spatially coherent.) The broadband nature of the light presents an interesting trade-off: it increases the field of view of the VHI lens (i.e. the width of the 1D slit) but it worsens the depth selectivity. We used cooperative imaging, another method borrowed from the 'bag of tricks' of computational imaging, to offset this degradation. Several PR-VHI systems acquire different perspectives of the 3D object and then reconcile each measurement using a constrained least-squares optimization. Figure 6 shows the experimentally-obtained least-squares reconstruction for a sequence of helically-arranged fluorescent beads using three measurements.

In conclusion, VHI is a powerful way of building 3D imaging systems with high resolution. We are currently exploring means to exploit spatially-incoherent light and tomographic algorithms to achieve even better resolution.

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#### References

1. G. Barbastathis, M. Balberg, and D. J. Brady, *Confocal microscopy with a volume holographic filter*, **Opt. Lett.** **24**, pp. 811–813, 1999.
2. A. Sinha and G. Barbastathis, *Volume holographic telescope*, **Opt. Lett.** **27**, pp. 1690–1692, 2002.
3. W. Liu, D. Psaltis, and G. Barbastathis, *Real time spectral imaging in three spatial dimensions*, **Opt. Lett.** **27**, pp. 854–856, 2002.

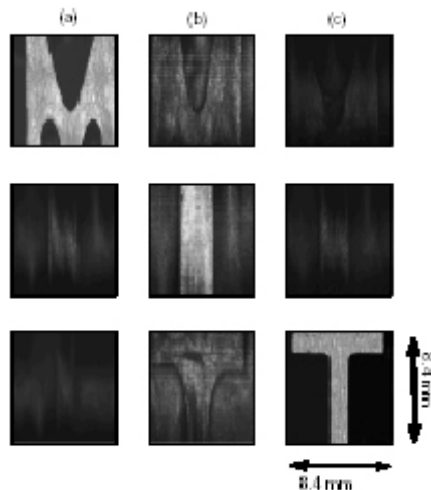


Figure 3. VHI surface reconstruction of an artifact consisting of the letters MIT<sup>o</sup> with the surface of each letter being 2mm apart.

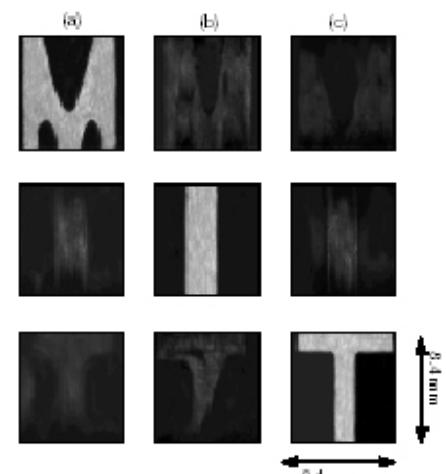
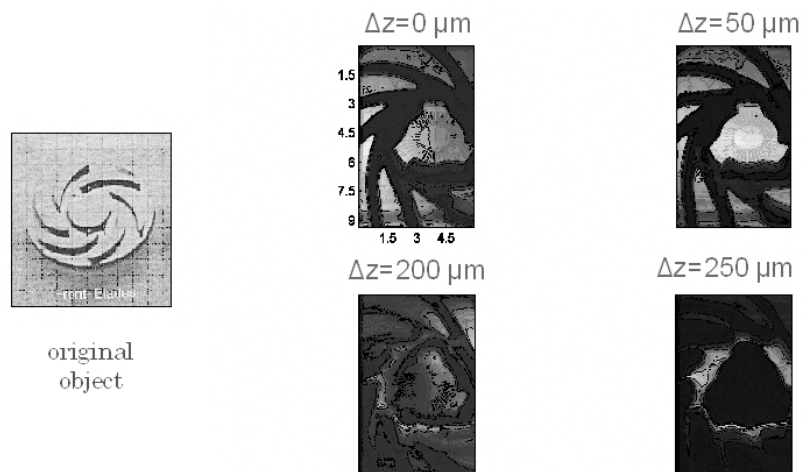
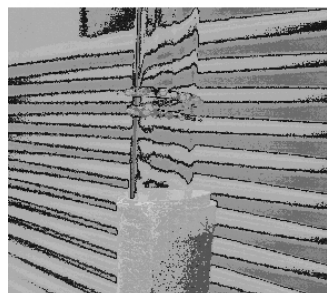


Figure 4. VHI reconstruction of the same MIT artifact but with additional objective optics to overcome quadratic degradation of depth resolution.

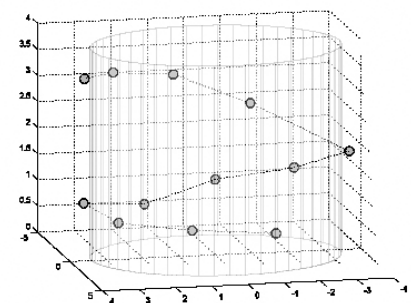


$\text{NA}=0.024$ ;  $\theta_s=12^\circ$ ;  $a=11\text{ mm}$ ;  $d=460\text{ mm}$ ;  $L=2\text{ mm}$  and  $\Phi=30^\circ$ .

Figure 5. Height map of micro-turbine fabricated by Mr. Chee Wei Wong at MIT, using a PR-VHI sensor inclined at  $30^\circ$  to the object surface. The micro-turbine has features of  $\sim 225\mu\text{m}$ .



Original object



All dimensions are in mm

Figure 6. 3D image of fluorescent beads arranged in a helical pattern, obtained using three sensors inclined at  $45^\circ$  to each other and using a least-squares optimization.

## Spatio-spectral target analysis and tracking

Continued from page 3.

rier transform (FFT) of the fringes. The FFT shows a scaled version of the source spectrum along the diagonal of the image (enclosed in the dashed box).

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### References

1. D. Marks, R. Stack, D. Brady, D. Munson, and R. Brady, *Visible cone-beam tomography with a lensless interferometric camera*, **Science** **284**, pp. 2164-2166, 1999.
2. OSA: J. Gallicchio, E. Cull, S. Kraut, and D. Brady, *Spatio-spectral triangulation using a rotational shear interferometer*, in **Proc. Integrated Computational Imaging Systems (OSATOPS 66)**, 2001.

## Design and optimization of computational imaging systems

Continued from page 12.

However, the wavefront-coding design methodology leverages these packages by using them as ray-tracing engines. Additionally, our software enables the use of arbitrary surfaces in the optical design, allows the specification and modeling of sensor characteristics, and makes possible the optimization and implementation of signal processing through modules that communicate with the system merit function and optimizer. It can also work with constraints based on the manufacturability of a surface that rely on the characteristics of the machine that will grind, diamond turn, or mold the final elements.

The wavefront coding methodology offers unique opportunities since it allows signal processing to be included in the optical design path. The software allows the designer to optimize based on application specific operation, such as feature recognition algorithms for surveillance, machine vision analysis, biomedical diagnosis or bar code reading. The desired result in many of these systems is not a high quality image, but a number or set of numbers that accurately describe a scene. Therefore, in some cases, the figure of merit is not based on creating visually-appealing images but instead, maximizing the information transfer between object space and the image processing, recognition, or identification algorithms.

Our system also gives the designer ultimate control over the system design, including the optics, detection, tolerancing, fabrication, and signal-processing implementation. It is the linking of all of the system parameters that creates the new design paradigm where innovative new systems can be designed that were not possible with traditional methodologies.

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### References

1. W. T. Cathey and E. Dowski, *A new paradigm for imaging systems*, **Applied Optics** Vol **41**, p. 6080, October 2002.
2. H. Wach and E. Dowski, *Control of chromatic aberration through wave-front coding*, **Appl. Opt.** **37**, p. 5359, 1998.
3. E. Dowski, R.H. Cormack and S.D. Sarama, *Wavefront Coding: jointly optimized optical and digital imaging systems*, **Proc. SPIE** **4041**, 2000.
4. S. C. Tucker, W. T. Cathey, and E. R. Dowski, *Extended depth of field and aberration control for inexpensive digital microscope systems*, **Opt. Exp.** **4**, pp. 467 - 474, 1999.
5. E. Dowski and K. Kubala, *Modeling of Wavefront Coded Imaging Systems*, **Proc. SPIE** **4736**, pp. 116-126, 2002.
6. M. A. Neifeld and P. Shankar, *Feature-specific imaging*, **Appl. Opt.** **42**, p. 3379, June 2003.

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#### SPIE International Symposium Optical Science and Technology SPIE's 48th Annual Meeting

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San Diego, California USA

Program • Advance Registration Ends 23 July 2003

Exhibition

URL: [spie.org/Conferences/Programs/03/am/](http://spie.org/Conferences/Programs/03/am/)

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7 - 11 September

Orlando, Florida USA

Co-located with NFOEC

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URL: [spie.org/Conferences/Programs/03/it/](http://spie.org/Conferences/Programs/03/it/)

#### Second Workshop on Extremely Large Telescopes

8 - 11 September

Backaskog Castle, Sweden

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Program

URL: [www.astro.lu.se/~torben/backaskog2/](http://www.astro.lu.se/~torben/backaskog2/)

#### Sixth International Conference on Correlation Optics

16 - 19 September

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Program

URL: [hosted.sacura.net/corropt2003/](http://hosted.sacura.net/corropt2003/)

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Exhibition

URL: [spie.org/Conferences/Programs/03/eod/](http://spie.org/Conferences/Programs/03/eod/)

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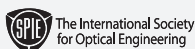
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# Design and optimization of computational imaging systems

A recent innovation in imaging is the methodology of jointly optimizing the optics, detection, and signal processing. This is in contrast with traditional systems where the optics are designed independently of the other components. This new methodology has been facilitated by the recent increases in the availability of computational power for system design, and a reduction in the cost of implementing algorithms in hardware. However, one current challenge in the design of optical/digital imaging systems is the lack of design software that allows the user to jointly optimize the optics, digital detection, and signal processing aspects of an imaging system. Commercially-available optical design software optimizes the optical portion of the system, but is not capable of modeling the detection and signal processing without significant additional software development.

At CDM Optics, we have created a methodology, called wavefront coding, that allows the designer to jointly optimize all aspects of an optical system. As a result, the system designer has access to a larger design-trade space, enabling the design of imaging systems that can image with high quality, fewer physical components, lighter weight, and less cost than traditional optics.

As an example of the joint-optimization methodology, a long-wave infrared conformal optical system, where the front-surface shape is fixed, is presented in Figure 1. Due to the limited number of variables, two optical elements are required in order to yield an image with high quality using traditional design techniques (Figure 1a). When the traditional design is optimized with a single element, there are

more aberrations present than can be controlled with the single element system (Figure 1b). In the traditional, single-element system, large amounts of spherical aberration, astigmatism, and field curvature cause the modulation transfer functions (MTFs) to decrease and the image to ultimately look blurred.

The third system, Figure 1c, shows the results using the wavefront-coding methodology: here, optics are traded for signal processing through joint optimization. The optical component of the wavefront-coded imaging system uses specialized aspheric optics that makes the detected images invariant to most of the traditional optical aberrations. In this example, the design of the second surface was used to create invariance to spherical aberration, astigmatism, and field curvature, as well as increasing the system-alignment tolerances. In the

wavefront-coded system, the detected image is not a sharp image of the object, but appears as a uniformly blurred image. Proper design of the optics ensures that the blurred image contains the maximum amount of image information. Signal processing of the captured image is applied to remove the uniform blur resulting in a high-quality final image that is comparable to an image from the traditional two-element design. Through the use of our technique, the example shown in Figure 1 was implemented with a 50% reduction in physical components, a 45% reduction in weight, and a 90% reduction in cost.

The benefits shown in Figure 1 cannot be achieved with commercially-available optical-design software because of its inability to jointly optimize all of the system components.

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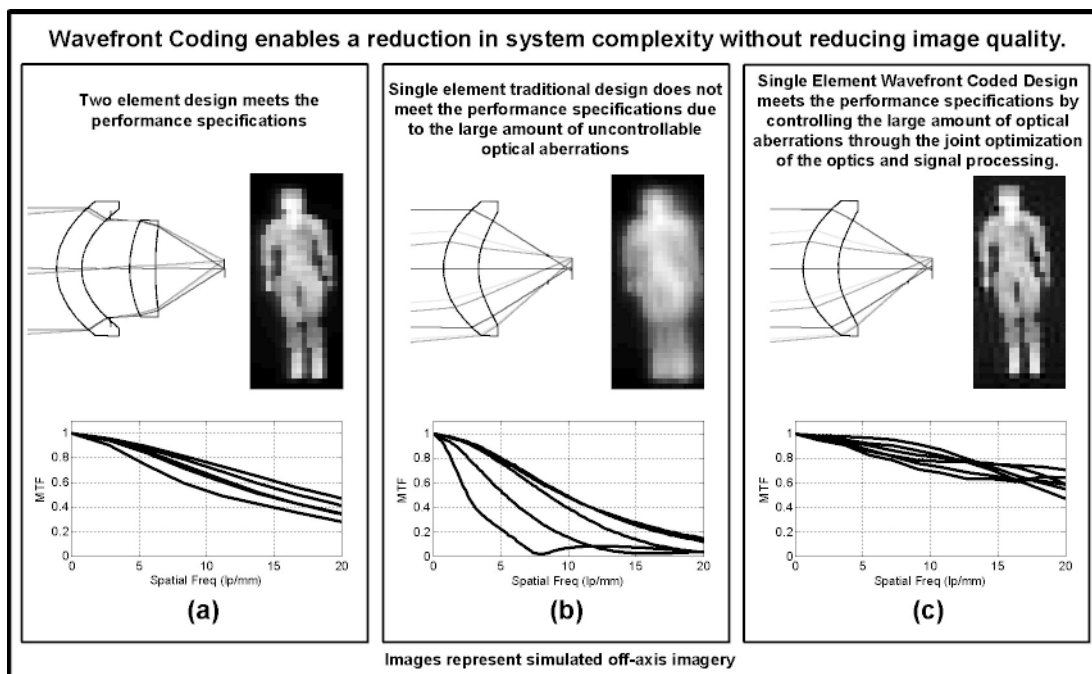


Figure 1. Wavefront coding increases the design-trade space and allows for a reduction in system complexity.