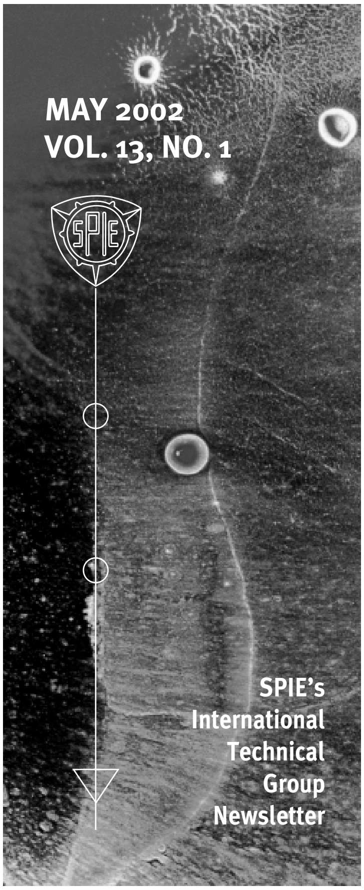

Optics in Information Systems

Special Issue:

Integrated Computational Sensors

Edited by **David Brady,**
Duke University

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Coding the wavefront to extend the depth of field

The depth of field of an imaging system can be increased if the optics are modified and some signal processing is done.[1] Figure 1(a) shows an example where the objects are diatoms viewed under 100× optical magnification with a numerical aperture of 1.3. Consequently, the depth of field of the system is very small as seen in Figure 1(a). After coding the wavefront to extend the depth of field and doing some signal processing, the image of Figure 1(b) is obtained. This shows an increase in the depth of field by about an order of magnitude. How is this possible? We use a technique that is very unlikely to have been discovered using conventional lens design techniques. It was found by using Woodward's ambiguity function and analogies with radar. However, after a means of coding the wavefront was developed, using a special optical element, it is possible to use a ray trace to see how it works.

One optical element that can extend the depth of field by coding the wavefront produces an optical path difference that varies as $x^3 + y^3$. An element such as this is placed in the aperture stop of the imaging system. After this modification, the rays of the coded wavefront do not focus. They are spread so that a cross-section of the rays changes very little with misfocus. Figure 2 shows the two-dimensional point spread functions for a normal system and one with a coded wavefront. Figure 2(a) shows an in-focus point spread function (PSF) and Figure 2(b) shows the out-of-focus PSF for a normal system. Figures 2(c) and (d) show that the PSFs for an imaging system with a coded wavefront change very little for the same misfocus. The PSFs of Figure 2(c) and (d) cause the intermediate image that is formed with the modified optics to appear blurred. This is because the object distribution is convolved with the PSF to obtain the image. After signal processing to decode the intermediate image, the PSF of the system with a coded wavefront appears as sharp as the one of Figure 2(a). Consequently, it is possible to obtain an image such as the one shown in Figure 1(a) by modifying the optics and performing signal processing.

What is the cost? In addition to the increased signal processing, there is a reduction in the signal-to-noise ratio (S/N) in the final image. From the point of view of a 3D modulation transfer function (MTF), there is a fixed amount of signal that can either be concentrated in the normal focal plane, or spread over a region about that plane.[2-4] If spread about, the level of the MTF in the focal plane must drop. Hence, there is a loss of S/N in the mid range of spatial frequencies, compared to the case of in-focus images with a conventional imaging system. Other forms of phase plates

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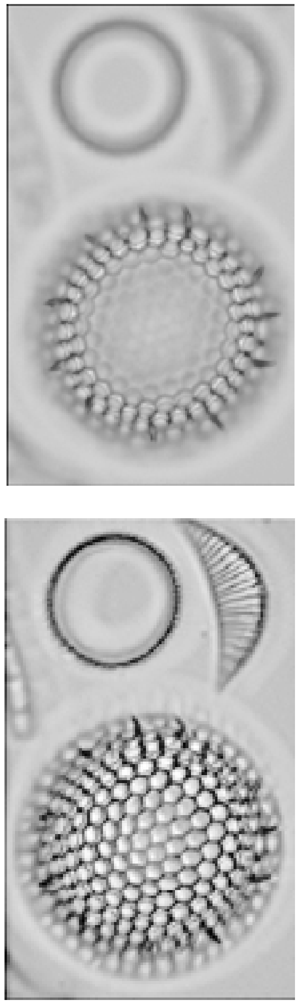

Figure 1. Diatoms imaged with 100× with a numerical aperture of 1.3. (a) with a conventional imaging system and (b) with an imaging system with a coded wavefront.

Guest Editorial

Special issue on Integrated Computational Sensors

In a pioneering 1984 paper, developed through Bob Guenther's Palantir program at the Army Research Office, Cathey, Frieden, Rhodes and Rushforth (CFRR) pointed out that imaging systems might attain better results if, "the image-gathering system is designed specifically to enhance the performance of the image-restoration algorithm." While, to my mind, CFRR does not capture the full breadth and depth of the potential revolution, the vision of integrated design that it presented has driven nearly two decades of imagination and analysis in task-specific and adaptive optical and electronic processing.

The focus on "imaging" is my primary objection to CFRR. One ought to consider the paper's distinction between image-gathering and image-restoration as a subset of more general computational sensors that integrate design of data-gathering and data analysis. Thus, this issue of the Optics and Information Systems technical group newsletter focuses on "integrated computational sensors". Given the explosion of the pixels/pupil ratio in the past 20 years and trends toward ubiquitous sensor spaces, I doubt that the authors of CFRR will object to this change. All continued to lead the integrated design community and Cathey and Frieden participated in the first OSA Topical Meeting on Integrated Computational Imaging Systems, held last fall in Albuquerque. Obviously, not every one agrees with my objection to the word "imaging."

Imaginative computational sensor system design has exploded in the past five years. This explosion is due partly to stochastic algorithm and design discoveries (such as Dowski and Cathey's work on wavefront-coding systems), partly to continuing and increasing market demand for innovative sensor systems, partly to emerging optical and optoelectronic manufacturing technologies, and partly to many other factors. The primary driving force, however, has been Moore's Law and the continuing integrated electronic processor and sensor revolution. Ubiquitous computing power, high quality electronic photodetector arrays, advanced positioning and control systems, micro-opto-electro-mechanical systems (MOEMs), computer optical design and manufacturing tools, and computer control and data acquisition tools, have converged to enable the advanced sensor system designs outlined in this issue.

In my opinion, the revolution reflected by recent designs is still only a superficial view of the possibilities. Designers and integrators of holographic and volume optics, like Barbastathis, Adibi and Descour, and of 3D optoelectronic processors, like Tanguay, provide a glimpse of the future, but the full range of sensing transformations on optical fields is amazingly unexplored. One expects recent work on photonic crystals and electronic nanostructures to eventually broaden into designs for complex 3D optoelectronic processors. Integrated with adaptive MOEMs systems and smart pixel illumination, these systems may yet make the use of analog image formation using lenses as extinct as the dinosaurs.

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Deadline for the next edition [13.2] is:

14 June 2002: Calendar items for the twelve months starting August 2002.

Deadlines for 14.1 are:

5 August 2002: Suggestions for special issues and guest editors.

19 August 2002: Ideas for articles you'd like to write (or read).

18 October 2002: Calendar items for the twelve months starting January 2003.

Volume holographic telescopes

Precision imaging, ranging, and identification become increasingly difficult as the distance from the object increases. This is a serious challenge for autonomous robotic systems operating in demanding biological, industrial and military environments. For example, industrial inspection of complex shapes is more useful if the information is returned as a three-dimensional (3D) shape rather than a planar projection. In biological specimens (cells, matrices, etc.) 3D spatial information as well as spectral information (e.g. the absorption or fluorescence spectrum) are both necessary to characterize the function of, and interactions among, biosystems. In the military context, modern autonomous scouts and smart munitions are required to inspect and identify valid targets while at the same time avoiding civilian or religious facilities and decoys. They must do this from distances ranging from a half to several miles: for instance, typical flight altitude for a reconnaissance Unmanned Air Vehicle, UAV, is 1km.

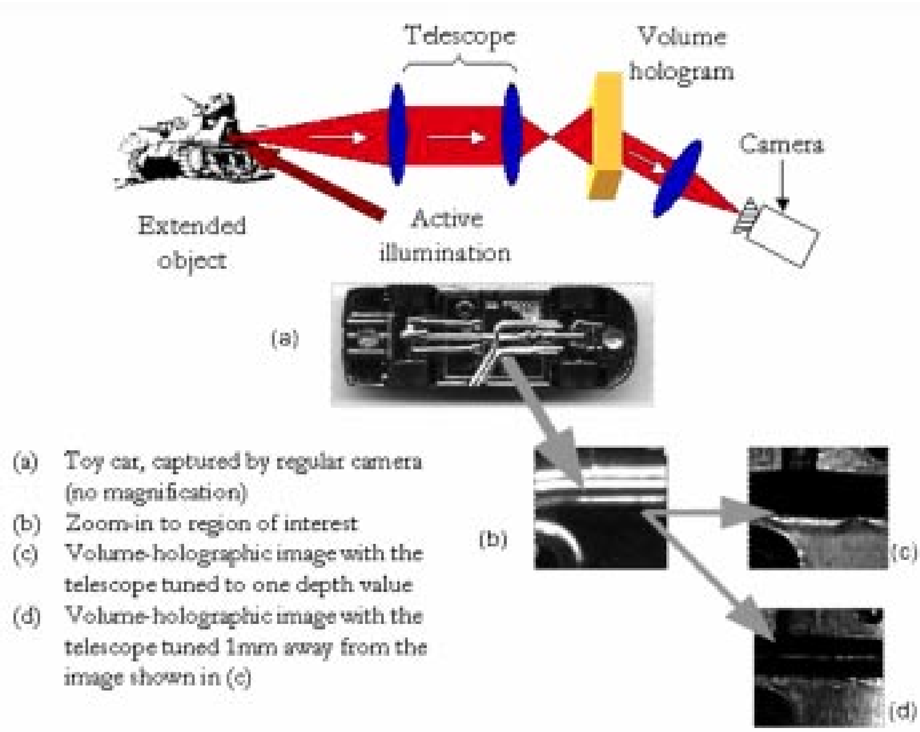

Figure 1. Volume holographic telescope schematic (top) and experimental results (bottom).

In general, as we increase the distance between the object and the aperture plane of the imaging system, the angle that the object subtends towards the imaging system (i.e., the numerical aperture, NA) decreases. As a result, lateral resolution becomes worse, as 1/NA. Longitudinal resolution depends on aperture even more strongly, as $1/(NA)^2$. We have developed a novel class of imaging elements, based on volume holography, to meet this challenge. Holographic imaging[1,2] is based on using a smart holographic lens to replace elements of an imaging system (e.g. the objective lens). The holographic lens is pre-recorded as the interference pattern of two appropriately defined simple waves (e.g. two plane waves or a plane wave and a spherical wave) in a volume holographic material (e.g. lithium niobate or photopolymer). The hologram is then fixed and aligned with the rest of the imaging system.

When light scattered from a target enters the imaging system, the hologram selectively diffracts the Bragg-matched modes of the incoming illumination, while the remaining modes propagate undiffracted. Therefore, the hologram can be thought of as a matched filter, which "sees" some selected aspects of the object and "rejects" other aspects. This property allows the real-time extraction of complex information from objects, e.g. in the three spatial dimensions and the spectral dimension combined, which in most other types of imaging systems would require scanning. Real-time spatial-spectral microscopic imaging has already been demonstrated with fluorescent microspheres by our group in collaboration with the Caltech Optics group.[3]

A volume holographic telescope is built by using a standard telescope (e.g. a 4f system) in conjunction with a volume holographic imaging element (VHIE), as shown in the schematic. The role of the telescope is to create a demagnified intermediate image of the target, which then serves as input to the VHIE. In general, the VHIE is composed of several multiplexed volume holograms, each tuned to a specific distance at the vicinity of the object. If a portion of the object surface matches one of these holograms, a strong signal is received at the detector. In general, this happens at the same time for several of the holograms contained in the VHIE (i.e., all the holograms whose tuned distances happen to lie on the object surface). The remaining holograms remain "silent." Therefore, the volume holographic telescope forms a distance-specific image. We computed and experimentally verified the longitudinal resolution of this element to $1.7l/(NA)^2$.

An additional benefit of our experimental arrangement is that the telescope determines the effective (NA) of the overall system. Therefore, by tuning the magnification appropriately, we can ensure that the desired performance is accomplished with a relatively small-area hologram. This keeps the cost and alignment sensitivity requirements of the system within reason. In our experimental system, we used a single hologram and instead scanned the object, a small toy car located approximately 0.5m away from the telescope. The results shown in Figure 1 correspond to longitudinal resolution better than 1mm with 3.5× magnification and 5mm hologram aperture.

Further improvements in imaging performance are obtained by combining two volume holographic telescopes to obtain an image of the same target simultaneously. The binocular telescope essentially over-constrains the location of the object surface. Then, the dependence of longitudinal resolution on numerical aperture becomes better than $1/(NA)^2$ (it becomes 1/NA if the two telescope axes are orthogonal to each other). We have extrapolated omni-directional resolution of ~1cm for a target located 1km away, using moderate optics (~0.5m primary mirror diameter). Experiments to verify this prediction are currently underway. This research was funded by the Air Force Research Laboratories, Munitions & Guidance division (AFRL/MNG). We are grateful to Brian Miles, Rob Murphey and Sheri Burton for discussions and support.

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Photonic multichip modules for vision applications

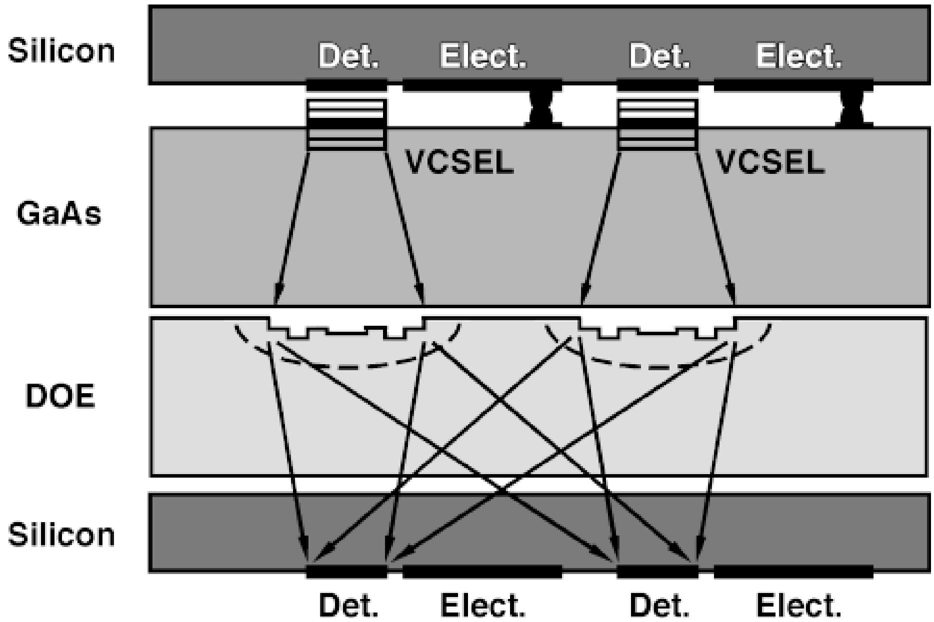

Figure 1. Schematic diagram of multilayer hybrid electronic/photonic multichip module (PMCM), showing vertical-cavity surfaceemitting laser (VCSEL) and diffractive optical element (DOE) arrays.

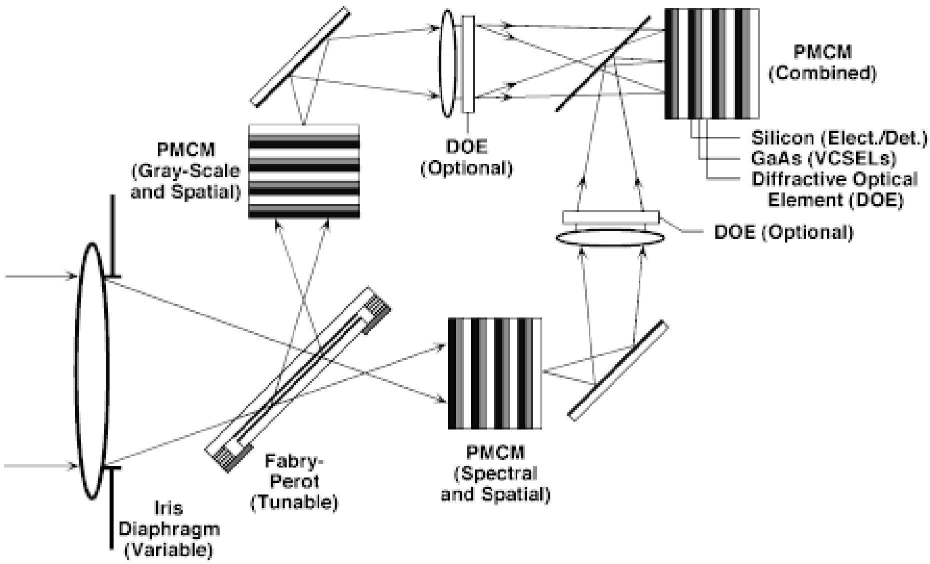

Figure 2. Schematic diagram of an optical architecture for pre- and post-processing of intimately-coupled spatial and spectral features, illustrating separate processing paths for color and gray-scale versions of the image.

The use of intelligently-designed pre-detection optics in combination with postprocessing techniques can provide a powerful paradigm for the development of sophisticated multi-dimensional sensors. The approach can extend and complement the image-formation characteristics of traditional imaging sensors such as focal plane arrays. Such integrated computational sensors achieve this unusual functionality by transforming the input wavefront, prior to intensity-based detection in a non-image or augmented-image plane, resulting in the need for complementary post-processing algorithms.

In this article, we focus on integrated computational sensor configurations in which the pre-detection optics, sensor array, and post-processor are densely integrated to form a composite, hybrid, electronic/photonic, multichip module (PMCM).[1–3] In particular, we describe efforts to develop *biologically-inspired* PMCMs that are capable of implementing a wide range of non-traditional post-processing algorithms. These have applications in both vision systems and integrated computational sensors.

Biological vision systems are characterized by high computational complexity, dense 3D integration, and relatively low power dissipation.[1–4] Several key themes are common to both mammalian and non-mammalian vision systems, including: a propensity for *layering* of the processing architecture; the employment of massive parallelism with simple processing units and little, if any, local storage; the incorporation of dense interconnections at all scales (from local to global, among multiple modules) with a high degree of fan-in and fan-out; adaptivity on multiple time scales; and distributed storage of both information and processing algorithms through interconnection weights.

One possible 3D integrated electronic/photonic PMCM structure is shown in Figure 1, pre-detection optics not shown. Multiple layers of pixellated silicon VLSI chips (chips that are divided into arrays of nearly identical devices or functional regions) are densely interconnected by a combination of electronic, optical, and photonic devices. These produce either a space-variant or -invariant degree of fan-out and fan-in to each individual pixel (neuron unit, or processing node). These weighted fan-out/fan-in interconnections are suggestive of the axonal projections, synapses, and dendritic tree structures that characterize neurobiological systems. They provide for fan-out from one terminal on a given chip to many terminals on the adjacent chip with individual weights on each connection. In particular, the use of optical and photonic devices allows for the implementation of such dense weighted fan-out/fan-in interconnection patterns *between* adjacent physical layers within the stack of chips and without significant cross-talk, thus eliminating the need for electrical connections that must penetrate through each chip.

In the implementation[2,3] shown schematically in Figure 1, 2D arrays of bottomemitting vertical-cavity surface-emitting lasers (VCSELs), fabricated on a gallium arsenide (GaAs) substrate, provide optical outputs from a given integrated layer of the structure. These VCSEL arrays are flip-chip bonded on a pixel-by-pixel basis to the silicon VLSI chips, which typically incorporate local optical detectors (for optical inputs from the previous layer), processors and memory elements (in the analog or digital domain), and VCSEL drivers. Proximity-coupled diffractive optical element (DOE) arrays are designed to incorporate both fo-

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Information-based design tools for computational imaging

Over the last twenty years, the discipline of imaging-system design has seen steady evolutionary progress in contrast to revolutionary advances in optical materials, detectors, and digital computation capabilities. Typical imagingsystem design treats the optics and detection as separate design problems. Post-detection processing is considered a last resort for the correction of imaging-system deficiencies. The impressive restored images produced during the Hubble Telescope crisis emphasized that post-detection digital computation can be a part of the image formation process. However, this digital computation merely compensated for deficiencies. Similarly, modern consumer digital cameras often employ digital dewarping to compensate for optical distortion. Image sharpening often compensates for aberrations. These examples are a first step towards an emerging integrated approach to imaging-system design that consider the optical components, the detection layer, and the computational layer, as multiple degrees of freedoms in a single design problem as illustrated in Figure 1.

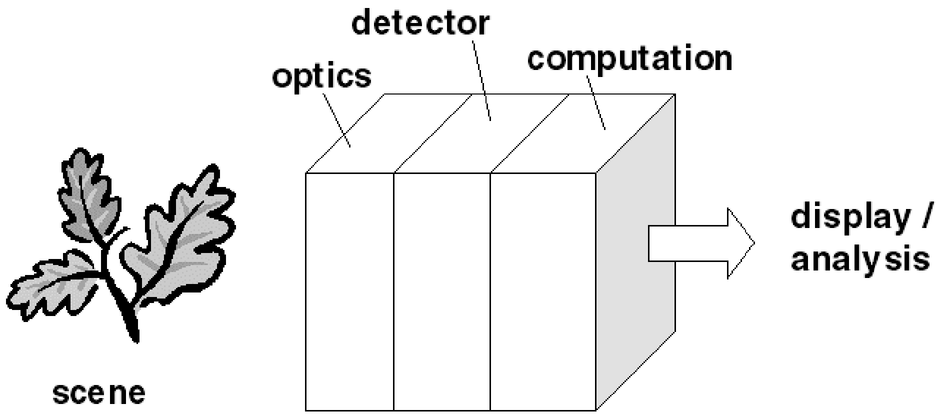

Figure 1. The parameters of the physical optics, detector and post processing are all degrees of freedom in an information-based design approach.

A major difficulty in moving toward an integrated design methodology is the choice of performance metrics. One approach is to consider the imaging-system as an information channel. The original message is the scene intensity distribution and the received signal is stored as a discrete array of numbers that may later be processed and displayed. The design problem is to maximize the mutual information between scene intensity and the image. Huck et al have applied Shannon information to analyze discrete imaging systems in this manner.[1] It is important to understand that imaging systems designed using these metrics often do not form pleasing raw images at the detector. However, the design ensures that post-detection restoration can produce faithful images.

We have applied the Shannon information approach to the problem of aliasing in discrete imaging systems.[2] This problem arises because detector sensitivity demands wide aperture settings that result in very high spatial frequencies passed by the optical system. Typical consumer cameras are under-sampled by as much as twenty times the Nyquist sampling rate. In fact, virtually all consumer cameras contain a sandwich of birefringent plates that purposely blur the image prior to detection to reduce aliasing. The design parameters for such filters have been chosen subjectively and do not take advantage of post-detection restoration. Our approach used information metrics to design the birefringent blur filter and assumes that the image will be appropriately restored.

A seemingly reasonable approach to combatting the aliasing problem is to pack in smaller detector pixels. In fact, digital cameras manufacturers continually boast of more pixels and claim superior resolution. In practice, these smaller pixels have lower light-collecting ability and suffer from signal-to-noise problems in low light. Neifeld used an information approach to address this trade-off between spatial resolution and noise for imaging discrete binary objects.[3] We are currently applying information metrics to optimal detector design for imaging continuous grey-level scenes.

Dynamic range and depth-of-field are two significant problems in digital-imaging-system design. The depth-of-field problem has been addressed in an innovative way by Dowski and Cathey.[4] Dowski's approach uses an unconventional asphere to pre-blur the image followed by post-detection processing to form a pleasing image. Information-based design allows the designer to compare the performance of the novel system to more conventional approaches and provides a means of optimizing the design parameters of the asphere.[5] Dynamic-range issues are particularly troublesome when using a video camera indoors and the subject stands in front of a window. This problem forces the user to settle for saturated areas in the image or to reduce the exposure and put up with noise problems. An integrated imaging approach driven by information metrics may be instrumental in tackling this difficult problem.[6]

The general approach discussed here attempts to maximize fidelity between the scene and the image. Maximum fidelity is not always the optimum solution. The designer should try to incorporate the specific task into the design problem. In many consumer applications, it is difficult to take advantage of such information. In scientific image analysis, many imaging-systems may be better quantified by considering more specific information about the objects of interest. The use of metrics that incorporate more specific information about the object and the task can lead to revolutionary imaging designs that take advantage of recent technological gains.

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Fast holographic recording using angle multiplexing

Fast events can be recorded using pulsed holography. In order to resolve individual holograms recorded with different pairs of pulses, spatial[1,2] or angle[3,4] multiplexing may be used. The method we describe here uses the angular selectivity of thick holograms to resolve frames that are recorded with adjacent pulses. Two specially designed cavities are used to generate the signal and reference pulse trains. The advantage of our method is that the speed is limited by the pulse width of the laser instead of a scanning mechanism. The number of frames is limited by the dynamic range of the recording material, not its spatial extent.

As shown in Figure 1(a), a sequence of signal and reference pulses are incident on the holographic medium during the recording. The signal pulses all travel in the same direction while the reference beam direction changes from pulse to pulse in order to angularly multiplex holograms. After the recording, a CW laser at the same wavelength is used to read out individual frames. Depending on the incidence angle, different frames can be read out separately thanks to the angular selectivity of the thick hologram.

In these experiments, both the signal and the reference pulse trains are generated by a single pulse from a frequency-doubled Q-switched Nd:YAG laser (wavelength 532nm, pulse width 5.9ns, energy per pulse 300 mJ, and beam diameter 9mm). The cavity used to generate the reference pulses is shown in Figure 1(b). The incident pulse is coupled into the cavity with a small mirror. The two lenses form a 4f imaging system. We break the symmetry of the cavity by slightly slanting the rear partial mirror so that, after each round trip, the pulse adjusts its direction slightly. The signal pulse train can be generated using the cavity shown in Figure 1(c). The vertically polarized (perpendicular to the paper) incident pulse is coupled into the cavity using a polarizing beamsplitter.

The Pockels' cell is timed to rotate the polarization of the pulse to the horizontal direction (in the paper) after it first enters the cavity. It is turned off afterwards while the pulse travels back towards the opposite mirror. A $\lambda/4$ wave plate is used to slightly rotate the polarization of the pulse and the induced vertically-polarized component is coupled out of the cavity from the polarizing beam splitter. In both cases, the pulse separation is controlled by the round-trip time of the cavity, which is 12ns.

We generated five pairs of pulses using the above method and used them to record five plane-wave holograms. The diffraction efficiency decays since there is less and less energy in the pulse train. The last hologram yields a diffraction efficiency of about 0.1% which is still well above the scattering noise level. Aprilis photopolymer[5] was used as the holographic recording medium.

We used this apparatus to record optical breakdown[6, 7] events. We split the pulse from the laser and focused it on a sample. This pumping pulse can optically break down the object and Figure 1(d) shows such a breakdown of a PMMA sample. Frame 1 was recorded at about 1ns before the pumping pulse vanished. Frames 1, 2, 3, 4, and 5 are the successively recorded frames and the frame interval is 12ns. Frame 6 is the final direct image of the sample after the optical breakdown. The size of the image is 1.74mm×1.09mm. The intensity of the pumping beam is about 1.6×10^{12} W/cm^2. Frame 1 shows the plasma created by the pumping pulse. The tail is likely due to the discharge in the air in front of the sample. In frame 2, a shock wave is clearly seen. The average propagating speed of the shock wave between frame 1 and 2 is about 10 km/s and that between frame 4 and 5 is about 4 km/s.

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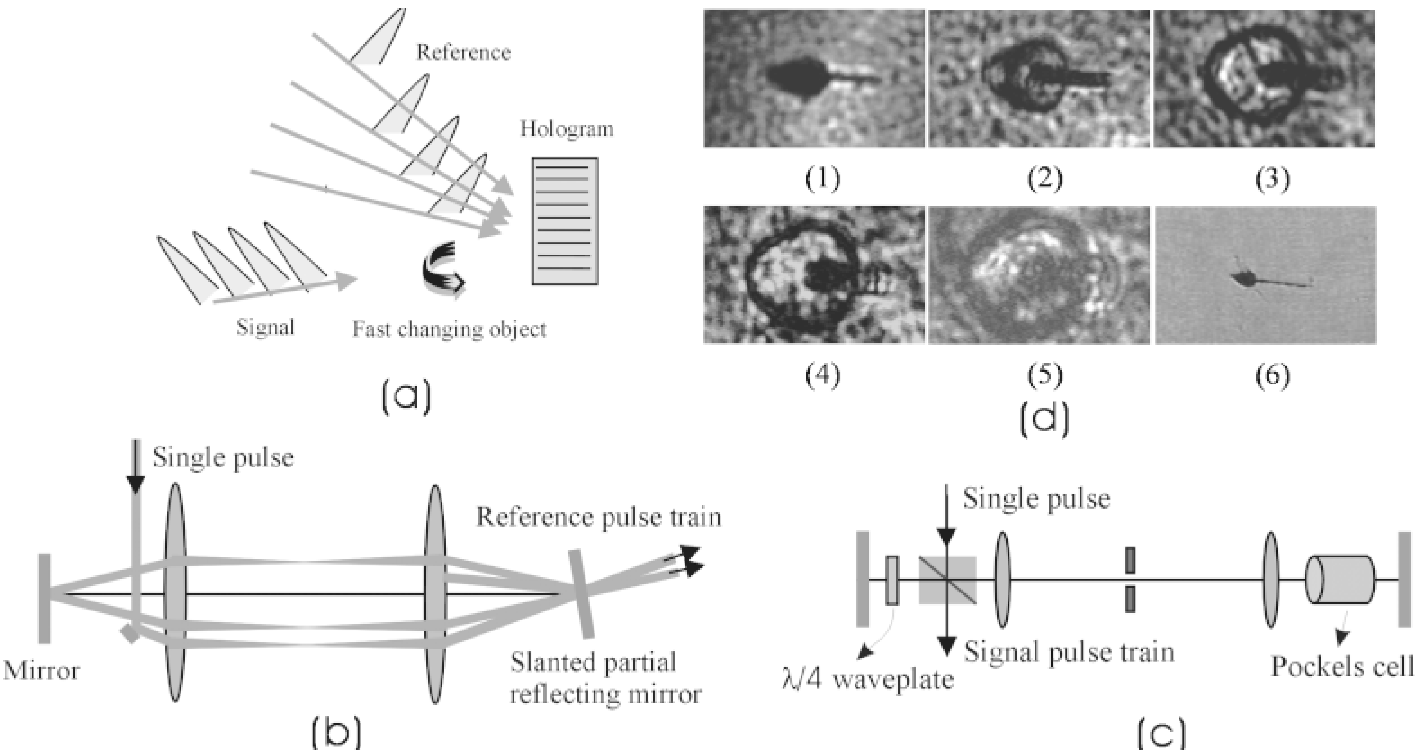

Figure 1. Holographic recording system. (a) Angularly multiplexing pulsed holograms. (b) Reference-pulse-generation cavity. (c) Signal-pulse-generation cavity. (d) Laser-induced shock-wave propagation.

Compression of digital holograms for 3D imaging

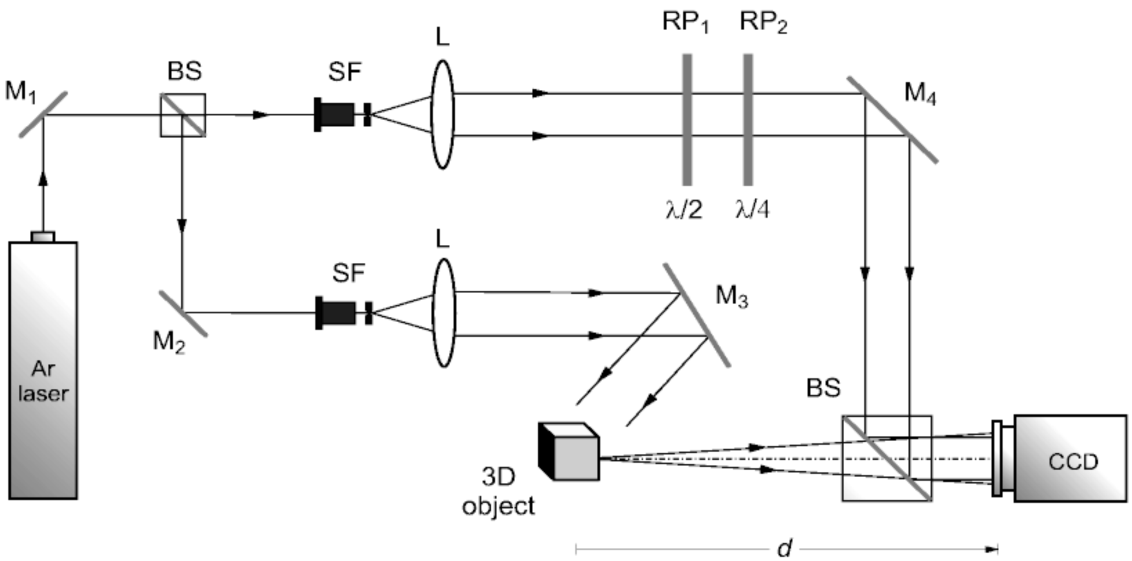

Figure 1. Experimental setup for digital holography: M, mirror; BS, beam splitter; SF, spatial filter; L, lens; RP, retardation plate.

Many existing three-dimensional (3D) imaging and processing techniques are based on the explicit combination of several 2D perspectives (or light stripes, etc.) through digital image processing. With holography, multiple 2D perspectives are optically combined in parallel. When either of the two stages in holography, recording or reconstruction, are performed digitally the process has been referred to as computer, or digital, holography. This subject that has seen renewed interest[1,2] with the recent development of megapixel digital sensors with sufficient spatial resolution and dynamic range. Synthesis of holograms by computer[3] and digital reconstruction of optically-recorded objects[4] have been demonstrated. We record digital holograms using a technique called phase-shift interferometry[5] and introduce a third step, that of digital compression and decompression.

We record digital holograms with an optical system based on a Mach-Zehnder interferometer (see Figure 1). The object beam from the linearly-polarized Argon-ion (514.5nm) laser illuminates a 3D object placed at a distance d=350mm from a 10-bit 2028×2044-pixel Kodak Megaplus CCD camera. The reference beam passes through half-wave plate RP_1 and quarter-wave plate RP_2, and can be phase-modulated by rotating the two retardation plates. Through permutation of the fast and slow axes of the plates, we can achieve phase shifts of 0, $\pi/2$, π, and $3\pi/2$. The reference beam combines with the light diffracted from the object and forms an interference pattern in the plane of the camera. At each of the four phase shifts we record interferograms, then we use these to compute the camera-plane complex-valued field by phase-shift interferometry. We call this computed field a digital hologram. Each hologram encodes multiple views of the object from a small range of angles. A particular view of the object can be reconstructed by extracting the appropriate window of pixels from the hologram and applying a numerical propagation technique.[3,4]

In advance of knowing which of the 4Mpixels are required for particular views, each hologram requires 65Mbytes of storage in its native double precision format (5s of transmission time over a 100Mbit/s network connection). This is too slow for realtime object reconstruction or recognition. We would like to compress these holograms for more efficient storage and transmission. Our digital holograms are composed of complex-valued pixels, which means they cannot be processed directly with standard image compression tools. Furthermore, digital holograms contain speckle, which gives them a white-noise appearance. It is not a straightforward procedure to remove the holographic speckle because it actually carries 3D information. The noisy appearance of digital holograms causes lossless data compression techniques such as Lempel-Ziv, Lempel-Ziv-Welch, Huffman, and Burrows-Wheeler to perform poorly.[6]

The use of lossy compression techniques seems essential. This introduces a third reason why compression of digital holograms and that of digital images differ: a change locally in a digital hologram will, in theory, affect the whole reconstructed object. Furthermore, compression losses introduced into the hologram itself might not be significant. We are interested instead in how compression losses affect subsequent object reconstruction, range of viewing angles, and so on. The lossy techniques employed here were based on subsampling, quantization, and blockwise discrete Fourier transformation. Median filtering was employed to lessen the effects of speckle in the reconstruction plane. We found that as many as 92% of the cosine and Fourier coefficients can be removed from the hologram plane, depending on the level of median filtering applied, and each complex-valued holographic pixel quantized to 8 bits of resolution, without significant reconstruction error.[6] Further work will involve combining DCT/DFT transformation, quantization, and Huffman encoding into a JPEG-style compressor for digital holograms and complex-valued inputs in general.

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Coding the wavefront

continued from cover

to do the coding cause a smaller loss in S/N, but there is always some loss, which is dependent on the amount by which the depth of field is increased. The effect of this loss is highly dependent on the dynamic range of the camera being used.

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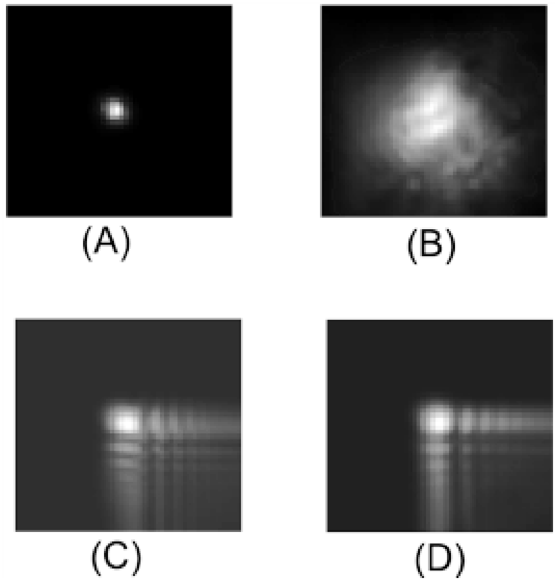

Figure 2. Point spread functions for (a) conventional imaging system in focus, (b) conventional imaging system out of focus, (c) coded imaging system in focus and (d) coded imaging system out of focus.

Fast holographic recording

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Photonic multichip modules for vision applications

continued from p. 4

cal power (lens) and establish weighted fan-out interconnections. Optical outputs broadcast over these weighted interconnections are modulated (temporally varied) in intensity by each individual VCSEL element and its associated Si driver circuit.

For adaptive vision sensors, the design of the individual Si VLSI chips and, in particular, the use of spatio-temporal multiplexing techniques for network implementation and signal processing functions, are motivated by recent advances. Specifically, several promising biologically-inspired vision algorithms have been developed that can potentially be mapped into the emerging 3D PMCM platform.

Assemblies of PMCMs can be configured for a wide variety of computational tasks, depending on the type of pre-detection optics employed. For example, in an architecture designed for the co-extraction of spatial and spectral features of an image, a tunable Fabry-Perot etalon or liquid crystal filter is used to transmit temporally-multiplexed spectral ranges. The device is oriented such that the complementary spectral information is reflected, as shown in Figure 2. This configuration provides for efficient usage of incoming photons, and at the same time provides separate processing paths for color-based and gray-scale features. The spectral range can be altered by means of a variable iris diaphragm, as shown.

To date, all of the individual components shown in Figure 1 have been successfully designed, fabricated, and tested. In particular, both fan-out and fan-in interconnections have been successfully demonstrated. Current efforts are focused on multichip-module integration and alignment in order to demonstrate full PMCM functionality.

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Single-mode photonic-crystal waveguides for all-optical circuits

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the middle slab. To reduce its thickness without breaking the periodicity of the air holes, we can increase the radii of all air holes that are adjacent to the middle slab as shown in Figure 1(b). The dispersion diagrams (normalized frequency versus normalized phase) for the even and odd modes of the new waveguide (Figure 2(b)) are shown in Figures 1(c) and 1(d), respectively, for different radii of the air holes (*r'*) next to the middle slab. As Figures 1(c) and 1(d) show, the odd mode moves out of the bandgap for $r' > 0.4a$, while the even mode exists for a range of frequencies inside the bandgap.[3] Therefore, the waveguide has only one mode in the photonic bandgap for $r' > 0.4a$.

In the design of the single-mode waveguide depicted in Figure 1, we modified the energy extent of the waveguide modes by changing the radii of the air holes. We can also change the slope of the mode dispersion diagrams by changing the periodicity of the air holes that are adjacent to the middle slab. By controlling both their sizes and locations, we can design the guided modes in photonic-crystal waveguides. The design of electromagnetic modes by changing the geometry of the defects (in cavities, waveguides, etc.) is a powerful advantage of photonic crystals that makes them very promising for the design of novel optical devices in the near future.

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Single-mode photonic-crystal waveguides for all-optical circuits

Photonic crystals have inspired a lot of interest recently due to their potential for controlling the propagation of light. Photonic crystals (also called photonic bandgap materials) are microstructured materials in which the dielectric constant is periodically modulated on a length scale comparable to the desired wavelength of light (for example, a two-dimensional lattice of air columns in a dielectric material). Multiple interference between wave structures scattered from each unit cell of the structure may open a photonic bandgap: a range of frequencies within which no propagating electromagnetic field exists. By adding point defects with sizes on the order of a wavelength, ultra-small cavities and lasers have been demonstrated.[1] Photonic-crystal waveguides can be made by adding line defects to a photonic crystal. These waveguides make the routing and interconnection of optical signals (even around sharp corners) possible. Recently, there have been enormous research activities in designing all-optical components, such as all-optical switches, for optical communications and networking. There is an urgent need for a unified platform to integrate all these components in a single substrate. Photonic crystals are the best media for such all-optical circuits. The entire circuit can be laid out on a photonic crystal by incorporating appropriately designed defects.

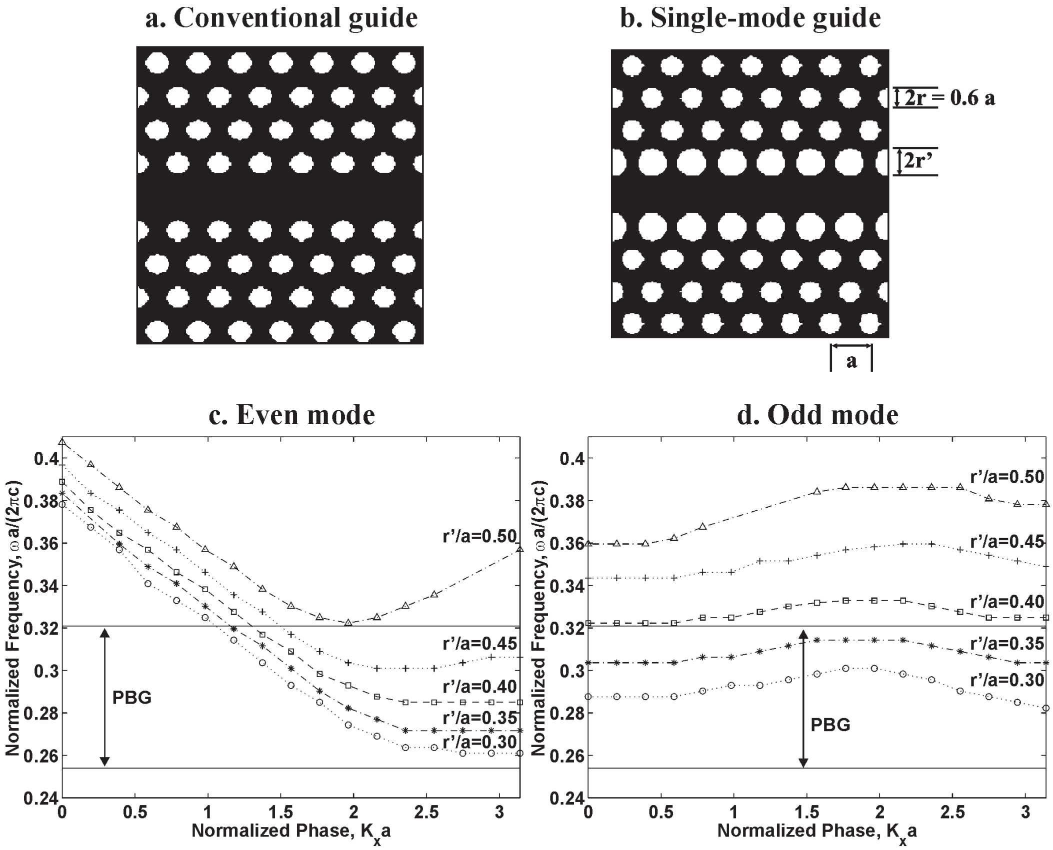

Figure 1. Design of a single-mode photonic-crystal waveguide by changing the radii of the air holes next to the guiding region.

A major requirement for using photonic crystals in all-optical circuits is the availability of single-mode waveguides. Conventional photonic-crystal waveguides are designed by removing one row of air columns from a two-dimensional photonic crystal as shown in Figure 1(a). Such waveguides usually have more than one guided mode in the photonic bandgap due to the large thickness of the middle slab of the waveguide. The waveguide shown in Figure 1(a) has two modes (one even mode and one odd mode) in the photonic bandgap when the radius of each hole is $r = 0.3a$ with a being the period of the structure in the horizontal direction. We recently demonstrated the design of single-mode waveguides by reducing the thickness of this middle slab.[2] However, the reduction of the thickness of the middle slab shifts the centers of all air holes above the slab compared to those below the slab. This added defect makes the design of multiple waveguide bends difficult. For application in an all-optical circuit, all air holes in a desired single-mode waveguide must be on the same lattice (or periodic structure).

The guided modes of a photonic-crystal waveguide are mainly confined to the middle slab and its surroundings.[2] Therefore, the properties of these modes can be considerably modified by changing the geometry of the air regions next to

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