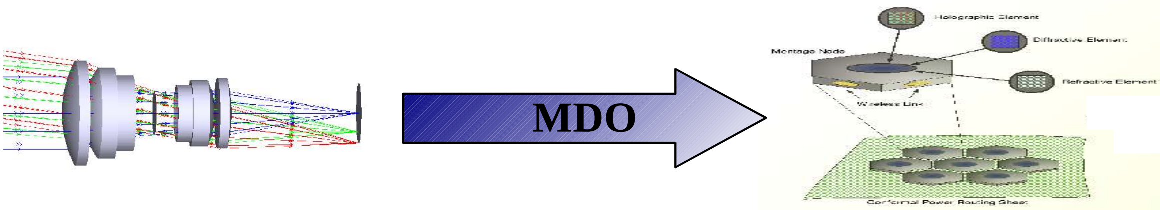

DARPA selected the MDO team to design and demonstrate their ultra-thin camera concept as part of the MONTAGE program. The challenge of the this program was to showcase novel optical architectures and revolutionary design paradigms. An important mile-stone was recently achieved with the demonstration of an instrument that realizes the superior performance of these new technologies in comparison to a conventional camera.

MDO and MONTAGE Program Background

The *MONTAGE* (Multiple Optical Non-Redundant Aperture Generalized Sensors) program is sponsored by the Defense Advanced Research Projects Agency (DARPA) under the Microsystem Technology Office (MTO) (www.darpa.mil/mto/montage). Program managers are Dr. Ravindra Athale and Dr. Dennis M. Healy, Jr. DARPA's MONTAGE web site notes, "Recent advances in technologies for optical wavefront manipulation, optical detection, and digital post-processing have opened new possibilities for imaging systems in the visible and IR regimes, suggesting the development of imagers which differ dramatically in form fit and function from time-honored camera designs. The MONTAGE program seeks to develop and demonstrate truly revolutionary imaging systems obtained by intelligent integration of the advancing capabilities of the individual optical, detection, and processing subsystems. This integration will exploit recent advances in system optimization methods, which provide an emerging capability for co-design and joint optimization of the optical, detection, and processing aspects of imagers."

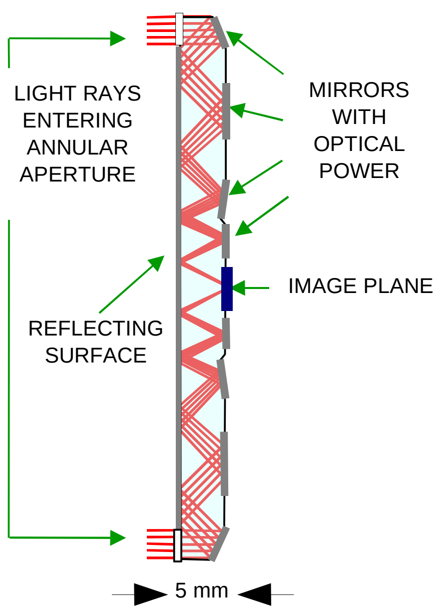

Fig. 1 Folded lens cross-section.

Fig. 2 MONTAGE demonstration camera
The folded optic is housed in the upright round disk.
Electronics for processing and communications are
housed in the platform base.

During phase 1 of the project, the team developed an integrated approach to camera design that exploits the simultaneous optimization of both optical and post-processing degrees of freedom. This multi-domain optimization (MDO) design methodology provides a powerful framework which can be used to circumvent the bottleneck of isomorphic imaging. For example, a traditional lens is designed to project the aperture field into an intensity function that can be measured. The MDO framework greatly expands the class of projections that can be realized by an imager. It is this large class of *alternate projections* and the novel optical components that derive from the associated optimization process that provides the flexibility to extract scene information much more efficiently than can be achieved using conventional methods. Phase 1 has focused on three candidate imaging architectures: conventional refractive, folded reflective/refractive, and diffractive. The demonstrator is based on one of these - the ultra-thin folded optical design.

MDO Demonstration Camera

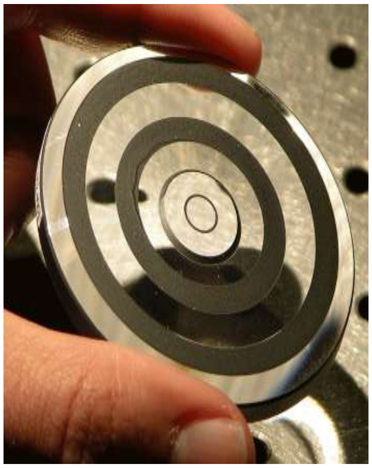

Fig 3a. Lens prior to coating

Fig 3b. Sensor side of lens

Fig 3c. Aperture side of lens

The architecture for the MDO demonstrator shown in figure 2 differs significantly from a traditional telescopic camera design. An ultra-thin telescopic lens mounts with a conventional 3 megapixel CMOS sensor integrated as a vertically aligned disk. The diagram of the innovative UCSD folded optic design in figure 1 illustrates how the 40mm focal length annular aperture lens is compacted to fit within the 5 mm thick volume. The aspheric optical element shown in figure 3 was fabricated by diamond machining the optical surface onto CaF_2 blank. Additional wavefront corrections applied to the optical surface and post-processing on the acquired image data, using MDO techniques developed by CDM-Optics, improve depth of field and tolerance to manufacturing uncertainties. Figure 4 shows how wavefront coded optics will significantly reduce optical aberrations produced via the construction process. The platform base houses a dedicated microcontroller and provides USB interconnectivity to additional computing resources. Distant Focus designed the electronic circuit boards; developed the firmware, software application interface, and several application components; designed the innovative packaging; and, together with UCSD assembled and tested the combined optical, sensor, and processing system. This demonstrator represents a rapid evolution from concept to hardware in less than 12 months.

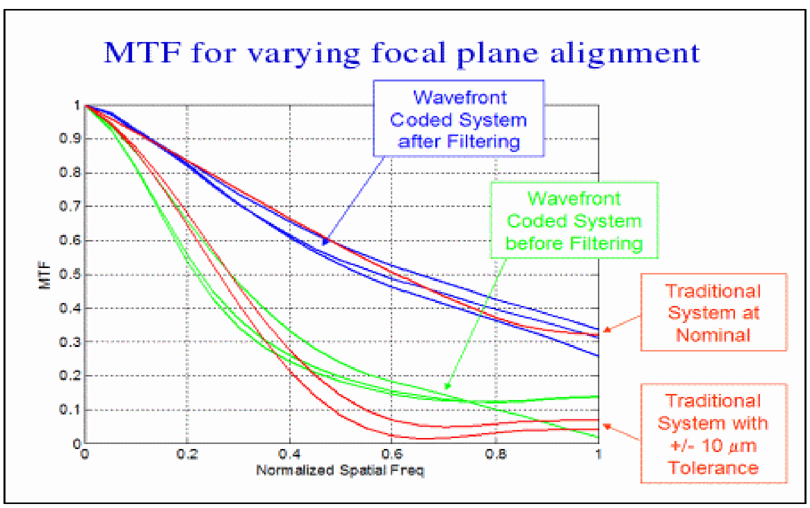

Fig. 4 MTF for traditional and wavefront coded systems.

MDO Research Activities

In addition to achieving spectacular performance with the ultra-thin folded camera demonstrator, the MDO team is aggressively pursuing fundamental research and development activities. These activities include non-traditional imager design and optimization, novel imaging device fabrication, and MDO design software development.

Several non-traditional imaging system design concepts represent extensions to the phase 1 folded-optic design and involve diffractive folding elements, adaptive pointing, active foveation, and conformal deployment. Some of these concepts will play an important role in meeting phase 2 hardware objectives. Other novel imager concepts of interest include: (1) distributed diversity imaging in which data from multiple cameras is used to obtain a super-resolved image, (2) the use of engineered point spread functions to overcome the pixel resolution limit, (3) folded polarization difference imaging, (4) volume holographic 3D and multi-spectral imaging, and (5) imaging based on 3D GRIN structures.

A number of new materials/devices have been developed in phase 1 of the program. Novel phase masks that facilitate the realization of non-traditional point spread functions are being fabricated using sub-resolution surface relief structures. These same structures can be used to create multi-layer diffractive components and have been recently been deployed on non-planar surfaces, enabling conformal imaging. Volume holographic optical components can provide enhanced depth and/or wavelength selectivity and are being fabricated using both traditional holographic as well as lithographic folding techniques.

The capabilities of the MDO software environment continue to expand. Initially, the MDO environment was capable of conducting joint optimization studies using conventional optical components and conventional design metrics. During phase 1 numerous novel optical components were added (e.g., sub-resolution surface relief structures, volume holographic optical elements, 3D GRIN devices, etc.), novel image quality metrics (e.g., image-class MSE, visually-weighted MSE, etc.), and novel post-processing algorithms. This work continues as the team expands the component library further and begin to exercise the MDO concept toward the camera revolution.

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