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Final Report to the NASA
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Rover Imaging System for the Mars Rover/Sample Return Mission

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This is the final report from Cornell University to Langley Research Center for NASA LaRC Program Code 157-04-80-28. This program was awarded to us by the NASA Planetary Instrument Definition and Development Program (PIDDP) for the study of imaging systems for future missions to the surface of Mars. At the time of our original proposal, which was submitted in 1989, the next major mission planned to the surface of Mars was the Mars Rover Sample Return (MRSR) mission. Since that time, however, the situation has changed dramatically. The next major US mission to Mars is now likely to be MESUR, and the first flight opportunity for MESUR-related hardware may come on the MESUR Pathfinder mission, to be launched as soon as 1996. Of the several types of imaging systems that we originally proposed to study for MRSR, one was a panoramic camera. With the recent shift in emphasis to MESUR and MESUR Pathfinder, we have focussed our efforts almost exclusively on this camera. In the past year we have finalized the conceptual design of a panoramic imager for MESUR Pathfinder. We have also built a prototype camera and tested its performance in the laboratory. The performance of this camera has been excellent. Based on this work, we have recently proposed a small, lightweight, rugged, and highly capable Mars Surface Imager (MSI) instrument for the MESUR Pathfinder mission. The remainder of this report is the progress report that we submitted to the NASA PIDDP program at the end of FY 1992, describing our progress to that point.

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1 Progress

Progress over the past year has taken place in four primary areas: *(1)* Specifying design requirements for the MSI flight instrument, *(2)* doing detailed design work for the MSI flight instrument, *(3)* building and testing the prototype camera, and *(4)* analyzing data from tests of the prototype camera. Summaries of our work in all four areas are given below.

1.1 Specification of design requirements

A key aspect of our approach to optimization of the MSI design is that we treat image gathering, coding, and restoration as a whole, rather than as separate and independent tasks. This approach closely combines the electro-optical design tradeoffs for the camera with the digital processing required for data compression and image restoration. All cameras that have been developed by NASA in the past have been optimized for simple image *reconstruction*, which involves just producing a continuous representation of the discrete output of the camera, rather than for true image *restoration*, which is concerned with reproducing the highest-fidelity representation of the input to this device. Because of this basic difference, one cannot expect the assessment of camera design and image coding for one representation to be valid for the other. In short, our approach leads to higher image quality, especially in the representation of fine detail with good contrast and clarity, without increasing either the complexity of the camera or the amount of data transmission.

In the past year, we resurrected and updated an end-to-end computer simulation of image gathering originally developed for the design of the Viking lander cameras and their operation on Mars. This computer simulation accounts for solar irradiance, atmospheric transmittance, surface reflectance properties, lighting and viewing geometry, camera electro-optical design and signal processing. This approach allows us to optimize design tradeoffs for imaging on Mars, to diagnose camera performance in the laboratory and on Mars, and to provide guidelines for the initial imaging on Mars.

Our work on specifying the electro-optical design of the MSI deals with angular resolution, depth of field, and sensitivity. Our goal has been to achieve an IFOV of 0.3 mrad with a depth of field that extends from 1 m to the horizon without the requirement for focus control. This goal translates into an optical design requirement that maintains a nearly constant relationship between the MTF of the optics (lens and photosensor aperture) and the sampling passband that is formed by the photosensor array and the azimuth stepping interval of the camera. Moreover, this relationship should optimize the inevitable tradeoff between aliasing and blurring in favor of image restoration. Over the past year we have applied these requirements the the process of designing the MSI optics, described below.

Another area of design specification work dealt with the MSI data system and data compression approach. Some MSI images must be of the highest possible quality, while others can be degraded significantly and must only show enough detail to, say, give the position of a microrover within a scene. We have devoted considerable effort over the past year to analysis of data compression tradeoffs for the MSI instrument. To assure the restoration of images with high visual quality, featuring fine detail with good contrast and clarity, we find that the communication channel requires an average data transmission capability of at least 3 bits per pixel. The visual quality of the restored image is very sensitive to the loss of information that occurs when the data are compressed by reducing the number of encoding levels of the high spatial-frequency signal components. Therefore, lossy coding by cosine transformation or multiresolution decomposition is not appropriate for images where high-quality restoration is intended. Instead, we prefer to combine commandable gains and offsets (similar to those of the Viking lander camera) together with DPCM and Huffman coding for such images. For images where high quality is not a concern, however, we have found that very high compression ratios can be achieved by both DCT and multiresolution decomposition approaches. The ability to do both low-loss and high-loss compression will therefore be part of the MSI design.

1.2 Detailed design work

We have made significant progress over the past year in both the overall MSI system design and in the detailed design of the MSI optics. The MSI system can be described briefly as follows: There are two sets of optics, both mounted on a single rotating mast about 1 meter in height. Each has a field of view of about 60°. The upper FOV extends to 15° above the horizon, and the lower one to 60° below it. The dual-camera approach provides redundancy, and also (importantly) provides stereo capability with a high-over-low stereo geometry that is optimal for oblique panoramic viewing of the martian surface. In the baseline MSI instrument, each set of optics images directly onto a vertically-oriented line-array silicon CCD. We are also pursuing an optional design in which imaging takes place onto an optical fiber bundle, which is then used to feed a CCD array in the body of the MESUR Pathfinder lander. The CCD's actually consist of several parallel line arrays (seven in the present design), all but one overlaid with a color filter to provide broadband or narrowband color imaging capability. We are also exploring a true imaging spectrometer mode that would operate to wavelengths of several microns, but have devoted less attention to this option since its increased complexity, cost, and weight appear to make it incompatible with MESUR Pathfinder constraints.

Design of the optical systems for the MSI has been a challenge. Our objectives include the following:

- Provide a 60° field of view with a spatially invariant MTF.
- Provide sufficient depth of field that the image will not be significantly blurred from 1 meter to infinity without any focus control.
- Provide spectral coverage comparable to that afforded by a Si CCD detector.
- Achieve 0.3 mrad resolution, with the MTF of the optics matched to the CCD pixel size in a manner that is optimized for image restoration.
- Utilize glasses certified for space flight and martian surface environmental conditions.
- Minimize weight.
- Minimize the number of elements.
- Leave room between elements for an apodizing mask if desired.
- Fit lenses to available test plates for ease of manufacturing.

In the past year we have gone through a detailed optical design process, with first-order design, second-order design utilizing ray-tracing codes at JPL, and several reviews along the way. A total of four designs have been found that meet our most important objectives, and we have converged on a 3-element, f/15 design that we plan to use as a basis for the MSI flight optics. A procurement specification for a prototype of this lens is in preparation, and procurement of the lens will be underway by the time this progress report is reviewed.

Another aspect of optical system design has been design of the optical fiber bundle that will be used in evaluating the optical fiber option. After detailed discussions with fiber vendors, we settled on a design that uses 6-micron fibers mounted in a ribbon-like configuration. These fibers will be butted against the CCD in our present prototype camera, allowing us to evaluate a design where the CCD's are mounted within the lander body rather than on the mast. Fibers made according to our design specification have recently been delivered to us by the vendor.

1.3 Prototype camera fabrication and test

In the past year we have taken a simple panoramic camera originally developed at Ball Aerospace, and have upgraded it substantially to become a prototype of the MSI flight instrument. We are presently using this camera as a testbed for MSI subsytems. The most recent version of the camera utilizes miniature wide-angle optics that image directly onto a 3-color, 2096-element CCD line array. The camera head is mounted on a stiff, lightweight mast turned by a simple drive system and motor. The CCD is clocked out in synchronization with the rotation of the mast, producing a panoramic image. There are several data-taking modes, providing resolution as high as 0.3 mrad/pixel.

After initial fabrication of the camera and laboratory checkout, we have performed a series of tests. These have included:

- Outdoor tests at Ball Aerospace to verify correct operation of the camera under field conditions.
- Calibration tests, including flat field determination, MTF determination, and geometric distortion determination.
- High-over-low stereo imaging of geometrically controlled test scenes to develop and evaluate stereo data reduction techniques.
- Imaging of Mars-like scenes at "Mars Hill" in Death Valley, CA (see frontispiece).

The data from the geometric distortion, stereo, and Mars Hill tests have been radiometrically corrected, converted to byte form for storage convenience (the original images are in 12-bit form due to the good performance characteristics of the CCD), and distributed among the co-investigator team for analysis.

1.4 Prototype camera test data analysis

Analysis tasks that have been performed or that are underway with the test data from the prototype camera include the following:

- Construction of 3-D models of imaged scenes from stereo data, first for controlled scenes and later for field scenes.
- Checks on geometric fidelity, including alignment errors, mast vibration, and oscillation in the drive system.

Preliminary stereo analysis has been very encouraging, and has confirmed that the high-over-low viewing geometry not only works well but has some important advantages over left-right pairing for oblique panoramic imaging. Analysis of geometric fidelity has been extensive. It has shown mast vibration to be minimal, and has turned up both minor CCD alignment errors and drive system oscillations that are being fixed in the latest work on the camera.

2 Work Plan

We have a number of tasks planned for FY '93, with most of them scheduled in the first half of the fiscal year in order to prepare us for submission of a flight instrument proposal for MESUR Pathfinder. Tasks planned are as follows:

- Study MESUR Pathfinder requirements and assess modifications necessary to meet these requirements.
- Investigate data compression techniques for multispectral data.
- Analyze existing test data with different compression algorithms and determine impact of high compression ratios.
- Refine the end-to-end imaging system simulation and iterate with the design effort.
- Continue work with stereo images, to develop optimal stereo data reduction techniques and to determine optimum camera head placement for stereo analysis.
- Design the mast drive system for the flight instrument and fabricate a prototype.
- Study mast designs for the flight instrument, and design and fabricate a prototype.
- Study deployment mechanisms for various mast heights.
- Incorporate optical fibers into the prototype camera and assess the potential benefits as an alternative to direct imaging onto CCD.
- Incorporate the new lens into the prototype camera and assess its performance.