The Design of Mars Lander Cameras for Mars Pathfinder, Mars Surveyor ’98 and Mars Surveyor ’01

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Abstract—The Mars Pathfinder, Mars Surveyor ’98, and Mars Surveyor ’01 lander designs all utilize charged coupled device (CCD)-based cameras to conduct scientific investigations, assist with navigation of surface rovers and/or confirm sample acquisition and delivery by robotic arms (RAs). The extreme temperature and pressure environment of the Martian surface, the vibration and shock experienced during launch and landing, and the tight volume, mass, and power budgets challenge the designer and scientist alike to develop instruments and associated electronics that will function properly to provide the desired data. This paper provides an overview of the optical and mechanical design of two of the camera configurations, as well as a detailed description of the camera electronics. The cameras described are a gimbal-mounted stereo multi-spectral imager with 1 mrad/pixel resolution, and a variable focus robotic arm camera (RAC) capable of 23-µm/pixel resolution and provided with a self-contained three-color illumination system. The electronics, housed in the cameras and in separate enclosures, utilizes such subsystems as Field Programmable Gate Arrays (FPGAs) for digital control, VME bus-mapped video memory, and multiplexed stepper motor select/phase driver circuitry.

Index Terms—Camera, charged coupled device (CCD), IMP, Mars, Mars Pathfinder, Mars Surveyor, RAC, SSI.

I. INTRODUCTION

MARs Pathfinder, the first in a series of planned Mars landers, carried the Imager for Mars Pathfinder (IMP), a stereo camera which returned over 16,000 images after landing on July 4, 1997. Fig. 1 is a mosaic assembled from 75 IMP images showing a portion of the Ares Vallis landing site, believed to be an ancient floodplain. The Mars Polar Lander of the Mars Surveyor 1998 Program (MSP ’98), launched January 3, 1999, carried the Mars Volatiles and Climate Surveyor (MVACS) science payload, which included both the Surface Stereo Imager (SSI), a close copy of the IMP, and the robotic arm camera (RAC). Mars Polar Lander was targeted to land in the South polar region where payload instruments were slated to conduct the first in-situ search for surface and sub-surface ice in an attempt to address fundamental questions about the climatological history of the planet [1]. However, studies conducted since the planned December 3, 1999 landing date show that a design flaw in the descent engine control system probably led to early engine shutoff and subsequent landing failure. The Mars Surveyor 2001 (MSP ’01) lander, originally slated to be launched in April, 2001, was to carry scientific instruments including another RAC, as well as a dust characterization experiment known as the Mars Environmental Compatibility Assessment (MECA) that incorporates an Optical Microscope. Revisions in NASA’s Mars program following the loss of both MSP ’98 spacecraft (the orbiter was lost in September 1999 during maneuvers designed to put it in Mars orbit) have led to the cancellation of the original MSP ’01 lander mission, and the instruments have been put into storage pending possible selection of an alternate platform. All of the above cameras utilize a charged coupled device (CCD) detector and associated readout electronics originally developed by the Max Planck Institut fur Aeronomie in Katlenburg-Lindau, Germany, for the Descent Imager/Spectral Radiometer (DISR) experiment aboard the Cassini Huygens probe [2]. Different science and engineering requirements led to the development of the IMP/SSI configuration for stereo and multispectral imaging.
the RAC variable focus configuration for higher resolution imaging of surface and subsurface samples, and the MECA Optical Microscope for highest resolution imaging of small samples. The IMP/SSI and RAC optical configurations will be discussed in this paper, along with the control and data readout electronics.

II. CAMERA FUNCTIONAL REQUIREMENTS AND OPTICAL AND MECHANICAL DESCRIPTION

A. The IMP and SSI Cameras

The IMP and SSI are stereo, multispectral CCD cameras designed to provide images for studies of surface morphology and mineralogy, atmospheric dust and water vapor, and aeolian processes, as well as to support operation of a micro rover, a RA, and other experiments [3], [4]. To accomplish the above tasks, the camera, shown in Fig. 2, is mounted on a collapsible mast that is extended after landing to raise the camera approximately 62 cm above the stowed position to a working position about 1.6 m above the Martian surface. A two-axis gimbal driven by stepper motors with integral gearheads provides a pointing range of 356° in azimuth and from +90° to −67° in elevation. The camera head, shown in Fig. 3, consists of a 10-cm diameter horizontal cylinder housing an optical bench that supports the optical elements and detector. Light enters through a pair of windows and is folded toward the common detector by a pair of mirrors. Filter wheels in the left and right optical paths permit interposing filters for true-color stereo imaging, characterization of surface minerals, and solar and sky imaging for atmospheric studies. A diopter lens is provided in one filter position for close-up imaging of a magnetic properties experiment target. The centrally located optics housing provides a common mounting for the lenses, fold prism, and detector. The Cooke triplet lenses, of 23-mm focal length, provide 1 mrad/pixel resolution, equivalent to a field of view of 14.4° × 14.4° in each eye. No focusing mechanism is required, since the f/18 optics provide a depth of field from about 0.5 m to infinity. An aluminized prism common to left and right paths folds the beams onto the CCD detector, a frame transfer device with the 256 × 512 pixel active area divided into identical left and right 256 × 256 pixel subarrays. Array characteristics and performance are described in a paper by Kramm et al. [5], and details of the optomechanical design are given in [6]. Mass of the camera with mast is 4.2 kg.

The 15 cm separation of the camera’s fold mirrors, together with a total toe-in of approximately 37 mrad permits stereo imaging with a complete overlap of left and right frames at a distance of about 4 m. The 62 cm difference in elevation between the camera’s “eyes” when the mast is stowed and after deployment provides additional stereo information. The inclusion of identical red and blue filters in both optical paths, along with green in the right eye, enables the creation of stereoscopic true color images. Panoramas assembled from these images permit determination of the topography, homogeneity, and photometric characteristics of surface features. Multispectral image cubes consisting of images taken in each of the 12 geological filters provide the means for discrimination of local mineral groups. Observations of the sun through the eight narrow-band solar filters, as well as observations of the daytime sky and of night-sky objects, permit determination of atmospheric properties.
B. The Robotic Arm Camera (RAC)

The MSP '98 MVACS science payload includes a 2-m long Robotic Arm (RA) designed to acquire samples of surface and subsurface materials for analysis by a Thermal and Evolved Gas Analyzer (TEGA). The RAC was designed to support RA and TEGA operations and provide science data by taking close-up images of the surface within the working range of the arm, the tip of the scoop in a digging position, the contents of the scoop, and the walls and floor of trenches excavated by the arm. It can image surface features at distances extending to the horizon, as well as a temperature probe mounted on the wrist of the arm and used to measure surface and subsurface temperatures [7]. The MSP '01 lander design also incorporates a RA to acquire samples for analysis by the MECA instruments, and to deploy a surface rover. The MSP '01 RAC provides images for use in sample selection, as well as to verify that samples have been correctly delivered to the MECA sample drawers. The MECA experiment includes sample patches of a variety of materials for exposure to the Martian environment, and images taken by the RAC are used to evaluate the interaction of atmospheric particles with the patches as evidenced by abrasion and particle adhesion. Images provided by the RAC are also used to verify several steps in the deployment of the rover by the RA.

The RAC is positioned under the wrist of the RA (Fig. 4) at an angle of 9.8° to the tube to permit optimal imaging of the required scenes. The extreme range of object distances required development of an active focus system, and the requirement to image samples inside the scoop and trenches led to the addition of illuminators [7], [8]. The camera utilizes the same 256 × 512 pixel frame transfer CCD array as the IMP and SSI cameras, but configured in landscape mode (256 pixels × 512 pixels vertical) so that the entire active area of the chip is used for each image. The RAC optical bench, shown in Fig. 5, consists of a series of three vertical bulkheads braced with left and right side frames. A rotating optics cover and entrance window are mounted on the front bulkhead. The volume between front and center bulkheads contains the focus mechanism with stepper motor, the lens and cell, and the cover drive motor. A double Gauss lens was selected for optimum performance over the wide field of view and conjugate ratios ranging from 1 : 1 to infinity. The 12.5 mm focal length and 23 μm pixel spacing give a field of view ranging from about 6 mm × 12 mm at close focus to approximately 27° × 54° at infinity. The volume between the center and rear bulkheads accommodates the detector and associated electronics and cable connectors. The upper and lower lamp assemblies are mounted on the front bulkhead, providing illumination at distances of up to 300 mm. Images are acquired separately with red, green, and blue illumination, and can be combined to generate true color images. The MSP '98 RAC utilizes incandescent bulbs with red, green, and blue glass filters, while the MSP '01 RAC uses red, green, and blue LEDs for increased light output with lower power consumption. The RAC has a mass of 0.45 kg excluding readout and drive electronics.

III. COMPARISON OF THE PATHFINDER, MSP '98, AND MSP '01 CAMERA/ELECTRONICS SYSTEMS

A. The IMP System

Fig. 6 shows a block diagram of the IMP camera/electronics system. The complete electronics package consists of three printed wiring boards (PWB), along with the Lander Remote Engineering Unit (LREU) and Power & Pyro Subsystem (PPS). All are housed in the lander’s Integrated Electronics Module (IEM). A copy of the DISR Power Converter board (IPC), developed by Lockheed Martin Astronautics in Denver, creates required voltages for the other camera boards from the lander’s 28 VDC power bus. The CCD Readout/Data Board (CRB), developed by the Max Planck Institut fur Aeronomie in Katlenburg-Lindau, Germany, sends power and clock pulses to the CCD and receives the analog pixel values from the detector for A/D conversion. The VME Frame Buffer/Motor Drive Board (FBB), also developed by Lockheed Martin Astronautics in Denver, receives and decodes lander commands and provides digital control functions. It also provides phased motor pulses for driving the camera’s three stepper motors, and reads out limit switches on the azimuth, elevation, and filter wheel drives. Finally, the FBB receives digital pixel data from the
CRB and stores them in SRAM memory before transmission to the lander computer. A 1 W heater used to maintain the temperature of the thermal tab on the CCD is powered directly from the lander’s Power and Pyro Subsystem. The detector is maintained at \(-20\) °C to hold dark current at an acceptable level and prevent variations in quantum efficiency during wide swings in Mars ambient temperatures. Temperature sensors on the CCD and camera optical bench are read out by the lander’s Remote Engineering Unit.

B. The SSI/RAC System on MSP '98

For the MSP '98 payload which includes both the SSI (stereo) and RAC (variable focus) imagers, several changes were made to the electronics package (Fig. 7). The separate Power Converter Board was eliminated and two DC/DC power converter modules were added to the CCD Readout Board to provide analog and digital power for the CRB and detectors and the Frame Buffer Board. The CRB was also modified to operate two CCDs instead of one. The Frame Buffer Board was revised to operate two stepper motors in the RAC as well as the three motors in the SSI. The FBB reads out limit switches on the filter wheel drive in the SSI and focus and cover drives in the RAC, as well as temperature sensors in both cameras. A DC/DC power converter was added to supply power to the SSI CCD heater, and FET drivers were added for the RAC lamps, supplying the same regulated voltage used for the motors. Optically-isolated discrete I/O bits are used for reporting instrument status to the lander computer and for reset commands from the lander. All command and data communication with the lander computer is routed through a 2 MHz synchronous serial port on the Payload and Attitude Control Interface (PACI). This replaces the direct connection via the VME backplane utilized on the IMP camera and allows the camera electronics to be located at an increased distance from the lander CPU.

C. MSP '01

The electronics for MSP '01 is a duplicate of the MSP '98 package with minor changes. The CCD Readout Board again operates two detectors, one in the RAC and another in the Optical Microscope, which replaces the SSI camera. The Frame Buffer Board incorporates the same motor select/drive circuitry as on MSP '98, but since the Optical Microscope does not employ motors, only the RAC motors are operated. The FBB power converter was eliminated since its only purpose on MSP '98 is to supply power for the SSI CCD heater. Finally, the lamp supply voltage and driver configuration were modified to operate LEDs instead of incandescent bulbs.

IV. ELECTRONICS DESIGN

A. The Power Converter Board (Pathfinder Only)

The Power Converter Board incorporates a pulse-width modulated controller in a transformer-isolated flyback configuration to generate multiple output voltages. Levels of \(+8\) VDC,
-10 VDC, ±15 VDC, and +24 VDC are provided for the CCD Readout Board, and +8 VDC, +12 VDC, and +15 VDC for the Frame Buffer Board. Unregulated +28 VDC is also passed through to the FBB for operating the camera motors. The IPC board incorporates both differential and common-mode L-C filtering on all inputs and outputs for noise suppression.

B. The CCD Readout Board

The IMP CCD Readout/Data Board provides the operating link to the Sensor Head Board (SHB), which includes the CCD detector and a preamp board, both mounted in the camera head. The CRB incorporates a digital control unit which generates synchronous operating sequences for standby mode, exposure timing, and pixel readout of the CCD, and for A/D conversion. Voltages from the IPC Board are regulated to +20 VDC, +5 VDC, and -9 VDC for operation of the SHB. The analog signal chain includes correlated double sampling for best noise performance, a sample and hold amplifier, and a 12-b A/D converter. As noted above, for the MSP '98 and MSP '01 missions, the CRB was modified to operate two cameras, and power converters were added to provide the necessary operating voltages for the CRB and FBB. A detailed description of the CRB and SHB is provided in [5].

C. The Frame Buffer/Motor Drive Board on Pathfinder

The Frame Buffer/Motor Drive Board serves as the link between the IMP system and the spacecraft computer through its direct connection to the VME backplane. Fig. 8 shows a block diagram of the board, which is operated by a digital control unit in the form of a Field Programmable Gate Array (FPGA). The FPGA decodes commands from the spacecraft computer for execution by FBB circuitry or transmission to the CRB digital control unit via a 16-b bi-directional bus. A 16-MHz oscillator on the FBB provides the timing reference for both the FBB and CRB. Image data from the CRB is routed by the FPGA to the 16-b static RAM frame buffer, which is mapped directly onto the VME bus using an 18-b address [9]. The +5 VDC supply from the VME backplane powers the VME interface circuitry, while +8 VDC from the IPC is regulated to provide +5 VDC to the FPGA, frame memory, clock oscillator, and limit switches, as well as to the CRB. The -15 VDC supply from the IPC board is used for the +5 VDC regulator and the power on reset circuitry, and +12 VDC supplies amplifiers for the multiplexed stepper motor select/phase driver circuits described below.

Fig. 9 shows the switching matrix used to drive the three stepper motors. The motors utilize unipolar windings, and are normally operated in single coil mode (sometimes referred to as wave drive) for increased efficiency. The coils are driven...
by four linear current regulators acting as current sinks, and comprised of opamps driving N-channel FETs. Since motor torque is proportional to current, the current sinks provide regulated torque for the motor coils over a wide range of supply voltages (+24 to +36 VDC). This torque regulation involves a reduction in efficiency since the linear current regulators require a minimum voltage drop across the outputs amounting to a power dissipation of about 0.5 W for a 1 A motor. In operation, one motor is selected by turning on the +28 VDC supply to the motor’s common connection. The current sinks are then switched on individually in sequence by software-configurable timing pulses from the FPGA, and the sequence order and duration of the pulses determine direction of rotation and motor speed. A diode–resistor snubber network is provided across each motor coil to suppress inductive voltage spikes.

One four-phase coil driver circuit is used to drive multiple motors by means of isolation/steering diodes configured such that when the supply voltage to a particular motor is shut off, that motor is isolated from the driver circuits and from the other motors. This multiplexing scheme permits driving any number of motors from a common four-phase driver circuit.

D. The Frame Buffer/Motor Drive Board on MSP ’98 and MSP ’01

For the MSP ’98 and MSP ’01 Frame Buffer Boards, shown in Fig. 10, digital control is divided between an input/output FPGA and a separate memory control FPGA. The I/O unit decodes incoming commands, generates motor drive pulses, and coordinates imaging commands to the CRB. Digitized data from the CRB is transmitted via a 16-b parallel tri-state bus. The Memory FPGA controls image data storage in the SRAM frame buffer memory, after which the I/O unit serializes the data for transmission to the lander through the PACI serial interface. The 2-MHz PACI clock signals from the spacecraft provide the digital signal timing reference for the FBB, while a 16 MHz oscillator on the FBB supplies clock signals to the CRB only. Power converters on the CRB provide the +5 VDC supply for digital circuitry and ±15 VDC for temperature sensors and other analog circuitry.

Stepper motors in both cameras are again operated in a unipolar, single coil configuration, but are supplied constant voltage from a +22 VDC linear regulator rather than constant current as in the IMP. This change was implemented because the incandescent lamps on the MSP ’98 RAC are supplied from the same source, and their light output and lifetime are dependent on the operating voltage. Each motor phase is driven by a FET switch, which improves efficiency at the expense of
torque regulation vs. temperature. Since the coil resistance is proportional to temperature, coil currents are higher when the motors are operated at low temperatures. The FBB employs the same motor select/phase driver multiplexing configuration used on IMP, but the isolation/steering diodes were moved from the FBB to the SSI and RAC camera heads, saving space on the FBB and reducing the number of wires in the lander wiring harnesses (and therefore the diameter and mass of the harnesses). For MSP '98, a 1–2 s turn-on delay or “soft start” is employed in the incandescent lamp circuits to improve bulb lifetime. The delay was eliminated on the MSP '01 board because LED lifetimes are not affected by application of full current at turn-on.

For the MSP '98 FBB, a DC/DC power converter supplies +15 VDC to the CCD heater in the SSI camera though a linear proportional control loop which replaces the on–off control utilized in the IMP camera. This approach was chosen to improve CCD temperature control since the controller runs independently of other lander electronics. Temperature sensors in the SSI and RAC cameras (RAC and Optical Microscope on MSP '01) are biased with a 5 VDC reference supply and conditioned by transimpedance amplifiers. The temperature sensor amplifiers, SSI filter wheel limit switch on MSP '98, and three DC operating voltages are monitored via an 8-channel analog multiplexer. The multiplexer feeds a 12-b A/D converter whose output is returned to the lander computer over the PACI serial link. Opto-interrupter type limit switches in the RAC are read out via a digital status command.

V. INSTRUMENT POWER CONSUMPTION

A. The IMP/SSI Camera

As noted above, power for the CCD Data Board and Frame Buffer Board on Pathfinder is supplied from the Power Converter Board, which is connected to the lander +28 VDC supply. Power for the Lander Remote Engineering Unit, CCD heater, and launch restraint and mast release mechanisms is supplied separately. For the MSP '98 and MSP '01 systems, the lander +28 VDC supply is routed directly to the FBB and passed through to the CRB, and the power converters on the FBB and CRB (CRB only on MSP '01) provide power for all functions except the SSI mast release mechanism. Since the actuators and detector used in the IMP and SSI cameras have the same nominal power requirements, the power consumption for both cameras is similar, although as noted the power dissipation in the stepper motor constant current supply on IMP differs from that in the constant voltage supply used on MSP '98. The maximum CCD heater wattage was increased from 1 W on the IMP camera to 2 W on the SSI, and the power profile is different because the IMP CCD heater is either fully on or off while the SSI CCD heater is operated by a linear controller and runs continuously. Fig. 11 shows a representative
power profile for the SSI camera and electronics at 25 °C. The duration of gimbal moves in azimuth and elevation of course depends on the relative pointing positions from image to image; full motion in azimuth takes approximately 32 s at a pulse rate of 20 PPS, and in elevation approximately 14 s. The duration of each filter wheel move likewise depends on the filter used for each image; the mechanism moves at a rate of five filter positions per second. Also, the operating temperatures of the camera, interconnect harnesses, and electronics affect power consumption since the resistance of conductors in motor windings, harnesses, and other components changes with temperature. Temperatures of the cameras and harnesses can fall below −100 °C, increasing power consumption by several watts over the values shown in the figure.

B. The RAC Camera

On the MSP ’98 and MSP ’01 systems in which two cameras are connected, only one is operated at a time, and the CCD subsystem power is similar regardless of which camera is in use. The primary additional power consumers in the RAC are the stepper motors and the lamps. The MSP ’01 RAC incorporates two changes to reduce power consumption compared to the MSP ’98 camera. First, the stepper motor wattage was reduced based on the performance of the MSP ’98 instrument. Second, LED lamps were substituted for the incandescent lamps used on the MSP ’98 camera. Fig. 12 shows a representative power profile for the MSP ’01 RAC and electronics at 25 °C. The duration of focus motor moves depends on the relative focus position between successive images, and since the lamps are powered for the duration of each exposure, the time interval for power usage at the lamps on/image level in the figure is dependent on the exposure time selected. In addition to the temperature effects discussed above for the IMP/SSI cameras, the forward voltage of the LEDs used on the MSP ’01 RAC also varies with temperature, and will affect the values shown.

VI. INSTRUMENT CALIBRATION AND IMAGE ANALYSIS

The IMP/SSI and RAC cameras underwent extensive laboratory calibration before integration with other spacecraft systems. Tests for the IMP/SSI include CCD properties (including dark current), radiometric uniformity (flat field), absolute and spectral responsivity, modulation transfer function, geometric distortion, stray light, and pointing accuracy. For the RAC, tests include CCD properties, radiometric uniformity, absolute and spectral responsivity, focus position vs. motor position, lamp spectral profile, modulation transfer function, geometric distortion, and stray light [10], [11]. During the cruise and landed operations portions of each mission, data sets are acquired and analyzed to verify that the system is operating nominally. Image calibration algorithms are used to correct instrumental sources of noise and to calibrate images relative to observations of lander-mounted radiometric targets [12]. A summary of scientific results achieved with the IMP camera is presented in [13].

ACKNOWLEDGMENT

The authors wish to thank J. B. Wellman of the Jet Propulsion Laboratory for the invitation to participate in the IMTC conference that led to the writing of this paper. J. Montgomery and T. Gallagher of Lockheed Martin Astronautics in Denver, CO, were responsible for design of the IMP Frame Buffer Board and the FPGA programming, and M. Bigler, M. Pollard, and M. Snodgrass were responsible for the original IMP mechanical design. R. Kramm of the Max Planck Institut fur Aeronomie in Katlenburg-Lindau, Germany, designed the CCD Readout Board for all systems, and H. Hartwig designed the structure and many of the components of the RAC. M. Fontanarosa of Great River Technology and R. Kingston of the University of Arizona contributed to the FPGA architecture and logic design for the MSP ’98 and MSP ’01 instruments. R. Tanner and D. Crowe of the University of Arizona were responsible for design of the RAC illumination system. Many other individuals at the University of Arizona, the Max Planck Institut fur Aeronomie, and Lockheed Martin Astronautics participated in the fabrication and testing of the cameras, and the contributions of all are necessary for the success of each of the missions.
REFERENCES


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