EMBEDDED CONTROL OF A MINIATURE SCIENCE ROVER FOR PLANETARY EXPLORATION

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ABSTRACT

Recent advances in micro-technology and mobile robotics have enabled the development of extremely small, automated vehicles for new application frontiers. One of these possible applications is the use of miniature robotic vehicles equipped with on-board science instruments for planetary surface exploration. One such vehicle is being developed as part of a technology research task at the Jet Propulsion Laboratory. A rover prototype has been integrated into a package of several hundred grams in mass. Aspects of the embedded rover control and software implementation are discussed which enable mobility and operation of science instruments for navigation and surface exploration.

KEYWORDS: rover, planetary exploration, embedded control, in-situ science, miniaturization, space robotics

INTRODUCTION

Embedded controllers have been referred to as electronic systems embedded within a given plant with the aim of influencing the plant such that certain functional requirements are met within prescribed time constraints [1]. They can also be regarded as physically embodied or purely computational processors embedded in environments whose dynamics they can influence but not completely control [2]. Each of these are suitable descriptions of rovers intended for planetary exploration. Functional requirements of such robotic explorers often include autonomous or semi-autonomous mobility, as well as science data gathering and transmission to landers or orbiting spacecraft. Rover functionality for planetary missions must be provided under severe constraints on power, weight, computation, and communications. To further increase the challenge, use of some of the popular state-of-the-art processors, instruments, and components which enable advanced capabilities of current research robots is infeasible. This is due to the fact that space flight projects require proven, radiation-hardened, or otherwise space flight-qualified components on its subsystems; rovers are no exception [3, 4].

Feasible alternatives in computers and electronics do exist however for realizing robotic vehicles with the required functionality. In particular, advances in micro-technology and mobile robotics have enabled the development of extremely compact and lightweight rovers. Such vehicles could be used, for example, to survey areas around a lander, or even to conduct long-range exploration involving surface chemical analysis. We are developing a highly integrated prototype rover system using current-generation technology including mobility,

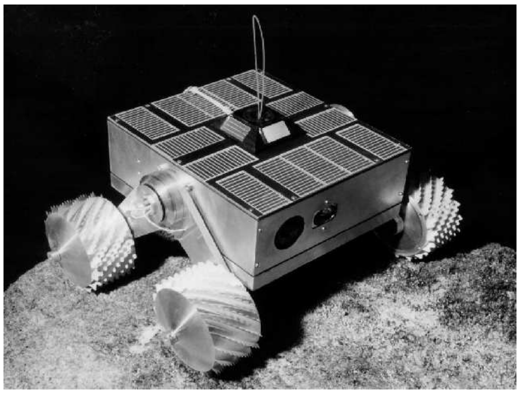

Figure 1. Miniature rover prototype.

computation, power, and communications in a package of several hundred grams in mass [5]. The product of this ongoing technology development is a miniature, but scientifically capable, rover that should easily fit within the projected mass/volume reserves of future missions to Mars as well as small planetary bodies such as asteroids and comets. In this paper, we discuss embedded control and software aspects of the current rover prototype. A general description of the rover system is provided. This is followed by the approach taken to develop a software control system that enables mobility and operation of science instruments for navigation and surface exploration. We conclude with plans for future technology development and mission applications.

ROVER DESCRIPTION

The current prototype consists of a novel four-wheel mobility chassis which incorporates posable struts (each wheel strut can be positioned independently). As shown in Figure 1, its largest dimension (length) is 20 cm which makes it 30% the size of the Mars Pathfinder microrover, *Sojourner* [3], deployed on Mars in July of 1997. Each aluminum wheel (6 cm in diameter) contains a drive motor within and helical cleats on the outside to increase performance for skid steering (turning in place). The rover is designed to be completely solar powered requiring just over one watt of power (a battery is included as an alternative power source). This includes a radio frequency telecommunication system, which allows the rover to communicate with a lander or an orbiter serving as a communications relay with Earth. The high-mobility articulated mechanism provides the rover with the capability to self-right as well as operate upside down. It includes the ability to recover from overturning and allows body pose control for pointing of science instruments. Several possible pose configurations are shown in Figure 2. Motors are only needed for the wheels; the additional degrees-of-freedom which achieve the various poses are entirely actuated using these same motors. No prior robotic vehicles are known which combine many or most of the desirable features of this design.

Science Instruments

The chassis houses two science instruments — a multi-band camera system for gathering images and a near-infrared point reflectance spectrometer to provide mineralogical information about terrain features of interest. The camera uses the Active Pixel Sensor 256x256 imaging array developed in the JPL MicroDevices Laboratory. The spectrometer uses a

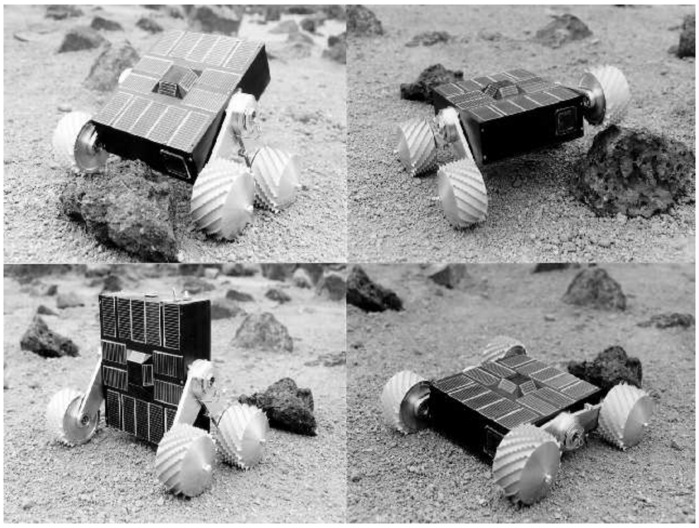

Figure 2. Posable-strut chassis configurations.

mechanically scanned holographic diffraction grating from which spectra are reflected onto a pair of IR point detectors. The lens of each instrument focuses at a common point several centimeters in front of the rover. To limit our discussion to relevant aspects of instrument control, we refer the reader to [5] for more detailed descriptions of the instruments and the internal optical arrangement. The instrument suite inside the chassis provides a *single* motor actuator for moving the camera focus tube and indexing an eight-position filter wheel, as well as for scanning the spectrometer grating (via a passive cable-pulley mechanism connected to the focus tube). We will refer to this actuator as the instrument motor.

Sensors

The miniature rover design accommodates a variety of sensors for navigation control, body pose and mobility control, and limit sensing. Hall effect sensors are used for wheel odometry. Four solar cells are mounted in a pyramid-like arrangement on the top surface of the vehicle (see Figure 1). These are used collectively as a sun sensor for estimating rover heading relative to the sun. Proximity sensors (eight infrared) are used to provide hazard detection capability. The camera can also be used for hazard detection by focus-based ranging, either alternatively or concurrently. The pivot hub assemblies on either side of the body are outfitted with potentiometers which measure strut angular position relative to the rover body. Accelerometers provide pitch and roll information which, along with knowledge of strut orientation, facilitate body pose control and mobility in rough terrain. For instrument control, an optical encoder is used to enable position and speed control of the instrument motor. Finally, limit sensing is provided for the camera focus tube travel and for all motor currents. [1]

EMBEDDED CONTROL APPROACH

In applications to planetary exploration, control algorithms for miniature rovers must be designed to operate robustly subject to the aforementioned constraints. The embedded

[1]Although some of these sensors had not been fully integrated on the rover at the time of this writing, their functionality was verified through integration on the benchtop software development setup.

control development is complicated by these and other factors. We have approached the problem by adopting a software control architecture that is similar to that used by the very successful Sojourner microrover [4]. We have leveraged actual code, particularly in the area of ground control software and its rover software interface.

The on-board computer is designed around radiation-hardened components including an Intel 80C51 microprocessor, a Field Programmable Gate Array (FPGA) and static RAMs. Early in the design phase, a survey of available space flight computing environments indicated that the 80C51 CPU was the best choice given the available power budget and based on required minimum computation rates [5]. More sophisticated space flight processors that have since become available are being considered for the remainder of the rover technology development. The computer hardware architecture for the current prototype is depicted by Figure 3. The 256K bytes of SRAM in the memory model map to four banks of 64K bytes each. Memory bank switching is controlled using one of the 80C51 I/O ports.

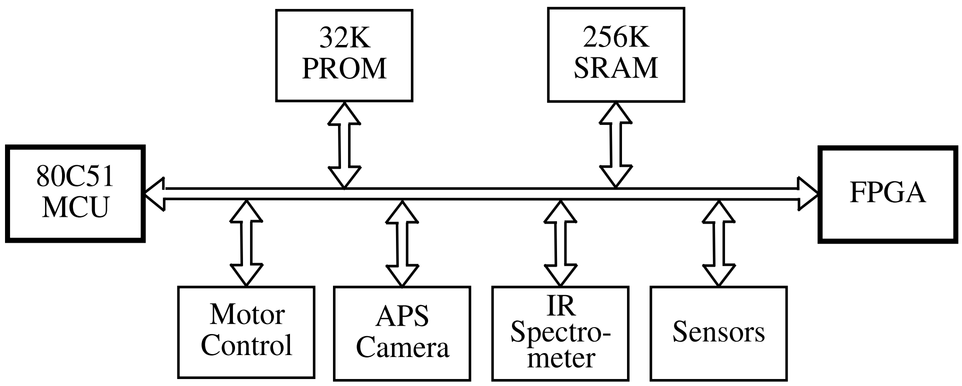

Figure 3. Computer electronics hardware architecture.

Software Control Architecture

Software for embedded control was written primarily in the C programming language. Some time-critical functions and low-level device drivers were written in 80C51 assembly language. A variety of commercially available tools including 80C51 cross-assembler, C cross-compiler, in-circuit emulator, and EPROM emulator facilitated the software development process. The software is organized as a top-level control loop with interrupt handling for exception conditions. The control loop invokes command handlers required to autonomously execute single commands or command sequences uplinked by a remote operator from a ground control station. The control station also enables uplink/downlink of data and display of downlink telemetry (engineering data, images, and spectra). The command structure is the same as that used to operate Sojourner. A variety of software modules supports these command handlers and the control loop. Here, we limit our discussion to aspects generally related to mobility, navigation, and instrument control.

Mobility and navigation. The rover's small DC gearmotors are controlled using 8-bit Pulse Width Modulation with encoder feedback and odometry provided by hall effect sensors. An evolving collection of primitive motion behaviors enables point-to-point navigation. These include moving to specified coordinate locations, turning at various radii of curvature (including turning in place), and orienting the rover in the general direction of the sun, all of which are based on simple servo control loops.

When the rover is moving nominally the drive wheels simultaneously rotate with the same direction and speed, and the struts (on either side) remain at fixed angles with respect to each other and the vehicle body. To change the angle between one of the struts and the body, the motor for that wheel is actuated alone. To change the angle between struts on a given side, both corresponding wheel motors are actuated in opposite directions. With this posable-strut capability, instrument-pointing behaviors involving body pose and articulation control are also possible. We have yet to exhaust the possibilities in this regard. Thus far, we have closed control loops around the strut potentiometers providing position control of individual struts and strut combinations. These basic capabilities allow simultaneous coordinated control of body pose and strut angle. This in turn enables more complex behaviors such as inchworm-like motions which serve to alter the body pitch, self-righting if overturned, and canting the body such that the solar panel is oriented at a preferential sun angle of incidence.

Instrument control. Closed-loop control of the instrument motor relies on the its optical encoder feedback. This actuator effectively controls all moving parts of the two science instruments — focus tube, filter wheel, and grating. The mechanism is initialized by homing the focus tube at one of its limit switches. All subsequent instrument motor position control is then referenced to this home position. The prismatic action of the focus tube serves to ratchet and index the filter wheel (which is referenced to a separate home switch corresponding to a particular filter). This same prismatic action rotates the holographic grating. Bounds of the grating full rotational range are mapped to instrument motor position in encoder counts. This arrangement permits camera focus, filter selection, and grating scan functionality with the accuracy required to capture variable-focused images and spectra. While this single-actuator instrument arrangement facilitates integration of multiple instruments within small volumes, the co-dependence of the camera and spectrometer on the instrument motor prohibits simultaneous image and spectra capture. The inability to perform more than one function at a time, however, is not unusual for planetary rovers given practical constraints on electrical and processing power [4].

To date, qualitative testing of an integrated rover prototype has verified the base functionality of the system. Rover subsystems were tested individually and incrementally on a benchtop software development setup comprised of duplicate electronics and instruments. This allowed early identification of any hardware, software, or integration problems that might have been difficult to isolate after the fully integrated rover was assembled. The capability to perform fundamental surface exploration functions was demonstrated on the rover prototype. The demonstration involved traverses of several meters, at speeds of about 4 cm/sec, in rough terrain including the capture of images and infrared spectra of rocks.

CONCLUSION AND FUTURE PLANS

The technology described in this paper lays the groundwork for evaluating the utility of very low mass, scientifically capable rovers for Mars and small body exploration. This miniature rover technology will permit mobility-based science surveys on planetary surfaces with a small fraction of the science payload expected for currently planned, and future, rover missions. The key objective is to build a rover which is sufficiently low in mass and cost that all future lander missions can include mobility. With the base functionality verified, the ongoing technology development will be aimed at improving its capabilities of autonomous navigation and science data return.

Technology Development

Important control-related technology elements of this work include: a computer/electronics design that enables control of miniature actuators in severe thermal/vacuum environments, a singly-actuated mechanism for control of two active science instruments, a mobility mechanism that enables control of twice as many degrees-of-freedom as there are drive motors, and on-board sensing and autonomous control of rover operations. In the near future, additional technology enhancements are planned including robust mobility behaviors that further exploit the flexibility of the vehicle chassis, as well as mobility and navigation control laws that are effective in low-gravity environments characteristic of small planetary bodies. Some of the interesting factors that impact the control problem with respect to the latter are discussed in [6]. Additional experimentation aimed at evaluating the performance and reliability of the integrated system will also be done in the context of typical mission scenarios. An upgrade to a commercially available radiation-hardened 32-bit processor, such as the MIPS R3000, is being actively pursued. Finally, a miniaturized version of the alpha-proton X-ray spectrometer used on the Mars Pathfinder rover is being considered as a third science instrument. The resulting science complement would give essentially complete and unambiguous mineralogic and morphologic information about target sites visited.

Planetary Exploration

A flight version of the rover has been selected as a technology experiment on a Japanese mission called MUSES-C which is scheduled for launch in January 2002. The MUSES-C mission is currently under development by Japan's Institute of Space and Astronautical Science (ISAS) and is designed for sample return of material from the near-Earth Asteroid NEREUS (4660) [7]. NASA is responsible for the portion of the mission involving asteroid surface exploration. The rover will be deployed to the surface of the asteroid to gather close-up imagery and spectral data of surface material for relay to Earth via the MUSES-C spacecraft.

Acknowledgments

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors acknowledge software development efforts provided by Jack Morrison and Michael Newell, and overall prototype engineering efforts of the rover team.

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