Lunar Rover Demonstration

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1. Objectives

Our objectives for FY95 are to build a space relevant configuration and to continue a significant testing program for perception, planning, teleoperation and mission operations with the new robot. This will culminate in a 10km outdoor traverse. This program is to demonstrate capability here on earth with an intent to eventually transfer this into a real lunar mission. Through this we will demonstrate a convincing, comprehensive mobile robot mission capability required for the Lunar Rover Flight Mission. The project will have demonstrated rover technologies suitable for lunar missions, and will provide those technologies to NASA and industrial initiatives for scientific and commercial enterprise on the Moon.

In FY95, the CMU program will provide a capable rover configuration tested over many multi-kilometer demonstrations. These tests will evaluate a range of user observation, control and interaction ranging from direct teleoperation through fully autonomous scenarios. The terrestrial mission will be compelling and attract a widespread audience through quality imagery, high-bandwidth interaction and enticing mixture of science and adventure.

2. Justification

Spacefaring nations are now re-examining the role of lunar activities in support of human exploration and utilization of space. The proximity of the Moon enables cheap access and rich telemetry; its terrain permits far-ranging mobility; and its solar insolation supplies abundant power. New lunar-focused projects are being considered in lunar science, astronomy, technology demonstration, Earth observation, video production and entertainment,. Most of these projects require or derive added value from mobility over the lunar surface.

The proposed Lunar Flight mission will supply answers to questions about lunar geology and science. For the first time, a long duration (time and distance) excursion can examine areas and features that were precluded in the missions and explorations of another era. By visiting original landing sites we can also learn more about long term effects of the lunar environment upon man-made mechanisms and materials.

The mission will be far more than an exploration of a small territory; it is envisioned to be a tour of historic sites, interesting features, and unknown areas. It will be compared to the voyages of new world explorers of centuries past and reach a large and widespread audience. It will draw comparisons to the age when explorers pushed the frontiers and knowledge of our own world, but involve and excite many rather than a select few.

The proposed program will advance the state-of-the-art in planetary surface robotics. The program will produce scientists, systems, and rover technologies that are crucial to the realization of NASA's long-term objectives in planetary exploration. Applications of the technologies developed here will impact the non-aerospace private sector in agriculture, mining, construction, and hazardous waste remediation.

The proposed research program will continue to form productive partnerships with industry. By including industrial organizations as team members early in the mission's definition, the proposed program will serve to catalyze the development and transfer of technologies, which in turn stimulate the economy.

We intend a scope beyond this program to enroll the public in the lunar missions. As part of this, these precursor lunar missions will provide an interactive, live means to enroll public awareness, participation and support into lunar and space missions. NASA's mission is to provide stepping stone to space and the planets and this program is a compelling means to do so for the space community and the public.

People will find that live 'immersion' into lunar exploration will be fascinating, educating and enchanting. Rather than dry commentary about geologic features and flickering black and white views the relatively fast moving rovers and high quality imagery will prove to be an edge-of-seat experience to the public. Tie-ins to mainstream media, education and the proliferation of Internet access will allow real-time access to this information.

3. Approach

We will provide significant developments in perception, planning and mechatronics that will greatly add to our capabilities during the FY95 demonstrations. Each of these areas is addressed in this section.

3.1 Perception

The perception effort in FY95 will concentrate on two main topics: stereo mapping of the local environment, and multi-sensor position estimation. These are required to achieve the 10 km traverse.

For stereo mapping, in FY94 we implemented a system consisting of a stereo module that computes disparities from trinocular images, and a mapping module converting disparities into elevations (or equivalent). In FY95, we will improve and extend this system in two directions. First, we will optimize it for speed by customizing the algorithms for the processors, video links, and terrain. We expect to achieve a twofold increase in speed. Second, we will relax the requirement for precise camera calibration by adopting the "fundamental matrix" formulation implemented in the FY94 Autonomous Rover Technologies task. We anticipate that this will improve the robustness of the overall stereo system.

For position estimation, in FY94 we concentrated on dead reckoning using inputs from the Ratler wheel encoders and onboard compass. In FY95 we will implement a more general position estimation system that incorporates sensor data from the Ratler turn-rate sensor, inclinometers, and differential GPS. Note that the DGPS system will be used to provide ground-truth information only since GPS is not seen as viable for the lunar mission. In addition, if it becomes available, we will incorporate a strapdown inertial measurement unit (IMU) built by Watson and used in the Unmanned Ground Vehicles program at CMU.

3.2 Planning

The planning efforts in FY95 will focus on enhancing local navigation, integrating route planning and global navigation, and providing reliability in the form of execution monitoring and exception handling. These technologies are critical for autonomous navigation and add great value to teleoperation by providing safeguards for the rover.

In FY94, we adapted local navigation software from the UGV effort to drive the Ratler in rough terrain using stereo input. For FY95, we will augment the navigation system to utilize proximity sensing (making the rover more reactive) and to handle uncertainty better (using results from the Autonomous Rover Technologies program). This will enable the rover to navigate in rougher terrain. To traverse multiple kilometers, the rover must also plan at a more global level. Even under supervised teleoperation, it will be advantageous to have the rover suggest potential routes. We will to adapt route planning software developed at CMU and integrate it with the local planners: the route planner will provide desired heading information, which the local planner will follow. The route planner will monitor overall progress and update the desired goal heading as needed to keep the rover on track.

To achieve the times and distances required, the rover will have to be extremely reliable, monitoring both internal and external sensors for any indications of trouble. The rover must react to such exceptional situations, at least by informing human operators, and at best by handling the situation itself. We will utilize expectations generated by the local planner to monitor for potential problems in navigating, will augment the real-time controller to monitor the health and safety of the underlying hardware, and will provide proximity sensors on the vehicle as an added safeguard. The methodology will be one of incrementally increasing system reliability, using the control constructs of TCA to minimize the need for code changes when adding new monitors and exception handling strategies.

3.2.1 Virtual Reality Interface and Teleoperation

An effective way to interact with the Lunar Rover is in a semi-autonomous mode. This allows a human to use a virtual reality interface to view the area surrounding the rover and to indicate preferred directions for the rover to follow. We are partnering with NASA's Ames Research Center, in this work.

Site maps are used to facilitate planning and commanding large-scale routes for the rover to follow as well as monitoring rover progress over terrain. We are utilizing existing digital maps published by the United States Geological Survey, the Defense Mapping Agency and other agencies, and have developed tools for reading, writing, and manipulating such maps. We will also implement more advanced operations such as real-time display of local information provided by the stereo and dead-reckoning systems, and also add texture mapping information from the video images to provide a very realistic view to the user.

3.3 Mechatronics

Currently, we are using the Sandia National Laboratories' Ratler vehicle as a basis for providing immediate testing for planning, perception and task control. In addition, we will have evaluated this configuration and use our past experience in mobile machines in producing a new configuration in FY94.

In FY95, we will design and build the newly configured rover. The design process will follow the guidelines successfully established for the Ambler, Dante, Tessellator, and Daedalus robots. We will employ off-the-shelf design tools, as well as innovative tools developed in the Autonomous Rover Technologies task. The construction process will include fabricating components, unit testing, assembling them as rover subsystems, and then adding on electronics, sensors, processors, and a low-level real-time control system.

At this time, we envision a capable wheeled machine that provides simplicity of mechanism while still providing high terrainability for locomotion over lunar surfaces. Communications and power are key elements that impact the configuration. The real-estate to support this will be at a premium. We are also examining solar power integration options for our current rover to extend operations.

Later, in FY96, we will study selected components for use in a real space mission. The purpose of this effort is to identify critical but vulnerable components, and to aggressively promote their flight qualification. The qualification process will include vibration, shock, radiation, and thermal tests for hardware, and validation and verification tests for software.

Critical areas of development include the communications systems for lunar to earth video and data transmission. Our Precision Pointing proposal will directly address these needs. For FY 95, we anticipate continued use of the RF and microwave links that we already have and are licensed for, but we will closely examine the options available for lunar-earth communication. Compression techniques have advanced significantly in the past several years and we will make use of the appropriate ones for our program.

3.4 Demonstration

We will perform a series of terrestrial traverses in natural terrain, progressing from 10 km in FY95 to 100 km in FY96. In FY96, the third year of the program, we will conduct the long demonstrations with a novel, lunarworthy rover configured for the terrestrial demonstrations. These will take place in the slag heaps (See Facilities Section) and White Sands, New Mexico to provide lunar-like terrains for testing.

As we build, fabricate and assemble, it is important to evaluate the rover's capability vis-a-vis an actual mission scenario. We plan to quantify and evaluate performance of each component separately — for instance, mobility, endurance and power consumption of the mechanism, accuracy and computational complexity of the perception system, reliability and generality of the planning system, etc. The quantification will also extend to issues of speed, reliability and terrainability. For operator interface work we will quantify differences in teleoperation versus semi-autonomous versus autonomous control.

3.5 Consortium.

We are forming a Lunar Rover Consortium with prominent members from the space robotics, lunar science, and commercial communities. This group, including both technology providers and technology users, will pursue a lunar rover mission scenario that fulfills both scientific and commercial objectives.

The Lunar Rover Consortium includes members from three communities: space robotics, lunar science, and commercial. The initial membership invitations will include the following:

- Robotics: NASA Centers, DOE Laboratories, and industry, including Martin Marietta.
- Lunar Science: LEXSWG.
- Commercial: Lunacorp, Shimizu, International Space Enterprises.

In FY95 the Consortium will perform a system study, addressing issues such as launch vehicles, orbital trajectories, landing technologies, deployment techniques, high-bandwidth telemetry, user interfaces for novices, mission profiles, and rover technologies. We will then determine a small number of comprehensive systems that satisfy mission and budgetary constraints.

In FY96 the Consortium will analyze in detail the mission components identified as critical during the system study. This analysis will lead to the selection of a single comprehensive system. In addition, the Consortium will seek suppliers for key products and services required for launching and operating a lunar rover flight mission.

4. Participants

— Carnegie Mellon University

- The Robotics Institute
  The Robotics Institute, part of the School of Computer Science, is the largest organization devoted to the study and application of robotics. With over 200 faculty, researchers and students the work spans a wide variety of programs, research and applications.
- Carnegie Bosch Institute. (CBI)
  CBI is a part of the highly rated business school at CMU. Each summer CBI holds a nine-week intensive development program for senior technical managers for Managing Engineering Design and Development (MEDD). MEDD teaches new process skills and in the lecture sessions and exercises separates process development from product tasks. As part of the MEDD program, a project is used so participants can apply process techniques to a real task. In summers past this has included the Erebus Project, Apex project and for FY94 we anticipate the development of lunar consortium business plans. For FY95 we plan a lunar mission focus.
- Software Engineering Institute (SEI)
  Each year a new group of experienced software personnel enter the SEI's Master's in Software Engineering Program. An extensive Studio Project brings classroom experiences plus individual talents and skills to bear upon real software development. For two years the Tessellator, the KSC Tile Robot Project, was the focus of the Studio and for this year, Task Controller Architecture components and the Lunar rover navigation system are the studio tasks.

— DOE Sandia National Laboratory

Sandia's Robotics program has produced a wide variety of mobile devices and systems. The Ratler, an articulated, four-wheeled, skid-steer machine is the cornerstone of CMU's initial development and testing program for the Lunar Rover Demonstration. Sandia is providing both the vehicle and support for the onboard controller. In return, CMU is providing key developments in simulation, TCA, and stereo vision. The partnership is both strategic and fruitful.

— NASA Ames Research Center

Ames' teleoperation and virtual immersion work has developed a set of powerful tools for interface and control development for teleoperated systems. Butler Hine's group at Ames has tested and used these developments in Antarctica and elsewhere for underwater work and are beginning to explore remote driving uses with CMU.

— LunaCorp

LunaCorp is a private for-profit enterprise, based in the Washington DC area, dedicated to the development of lunar missions. LunaCorp is attracting investors and other organizations to partner in these activities. We are partnering with LunaCorp to realize a lunar mission.

5. Deliverables

We will provide a new configuration for a rough terrain lunar roving vehicle for use on the moon. We will demonstrate the system in a 10km traverse in FY 95.

Figure 1 illustrates the three-year plan for the Lunar Rover Demonstration task. Level 1 milestones appear in bold type; the others are level 2 milestones. The task culminates in FY96 with a 100 km outdoor traverse featuring multimedia interactions permitting novice operators to participate in the traverse.

Element	FY95	FY96
Rover Navigation	**10 km Outdoor Traverse with New Rover, Flight-like Processors**	**100 km Outdoor Traverse with Multimedia Public Interactions**
Rover Configuration	Design and Build Novel Rover	Qualify Selected Components
Consortium	Detailed Mission Plan	Mission Analysis

Figure 1. Lunar Rover Demonstration schedule (level 1 milestones shown bold)

Figure 2 shows the milestones scheduled for FY95. Level 2 milestones appear in bold type; the others are level 3 milestones. The year will include a 10 km traverse over natural terrain by the new rover and milestones for the Lunar Rover Consortium which will produce a detailed mission plan of both lunar and terrestrial missions.

Element	95Q1	95Q2	95Q3	95Q4
Rover Navigation	Continued Testing and Runs With Rover	Refinements and Interface Testing	Continued Trial Runs	**10 km Traverse With New Rover**
Rover Configuration	Design and Component Analysis	Procurement and Fabrication	Fabrication and Testing Continued	**Rover Constructed**
Consortium	Mission Study	Mission Study		**Detailed Mission Plan**

Figure 2. Lunar Rover Demonstration FY95 schedule (level 2 milestones shown bold)

6. Commercialization Potential

We have already attracted commercial interests through LunaCorp, a company devoted to initiating a lunar mission. We are in process of reaching out to several large companies in the entertainment community including Disney and other large companies.

7. Funding

The overall budget to perform the work described in this proposal is at $1.15M and uses subcontracts to reduce overhead costs and utilize experts outside of CMU. Rough cost breakdown is as follows: Personnel Costs are $310K, Department Expenses are at $148K with Subcontractors and Equipment at $200K each respectively. The remaining amount is overhead.

The equipment budget includes new configuration design and fabrication, logistics and siting and field tests. It also includes communications and power systems for the new configuration.

To fit within the $900K guidelines we would reduce the scope of the proposal: while we would still design and build the new configuration, the 10K traverse would be demonstrated with the existing Ratler rover. This will be a much less convincing demonstration of space-relevance, in addition to the fact that the Ratler's power system is currently inadequate to allow an uninterrupted traverse of that length.

8. Facilities

All development and initial testing will be done in the laboratories at Carnegie Mellon. Testing in FY94 will also include the slag heaps of the Pittsburgh area. These desolate areas resemble the rough sandy terrains of the lunar surface and offer varying features including plateaus and steep climbs. This area is large enough to support multi-kilometer traverses of extended duration, yet they are closely accessible and we have used them for years for programs such as ARPA's Unmanned Ground Vehicle and the Dante tests prior to Antarctica and Alaska missions. In partnership with Sandia, we will also be using the White Sands area in New Mexico. White Sands has been offered to Sandia and our program by the Air Force.

9. Principal Investigators

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