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NASA PLANETARY ROVER PROGRAM

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ABSTRACT

The Space Exploration Initiative (SEI) announced by President Bush on July 20, 1989, the twentieth anniversary of the Apollo 11 landing, will return man to the Moon, this time to stay, and will lead to a manned mission to Mars. NASA has begun an important new technology initiative, entitled the Exploration Technology Program (ETP), which will develop the technologies needed for the SEI. Developing new technology, including a new generation of planetary rovers, is critical to the success and cost effectiveness of the President's Initiative. The Planetary Rover Project will develop the technology to enable the manned and unmanned vehicles needed for surface transportation. Surface transportation systems of many types will be required for the SEI. These include:

- o Unmanned rovers for outpost site survey and for regional exploration and science
- o Piloted rovers for transportation local to the outpost and for regional and long range manned exploration and science
- o Unmanned cargo handling, construction and mining vehicle(s)

The eventual capabilities of autonomous navigation, high mobility, low mass surface electrical power, high performance computing, high bandwidth communications with Earth, efficient thermal control, and a high level of onboard mission autonomy (eg. sample identification, acquisition and analysis, resource mining operations and outpost construction) are enabling technologies which affect the

vehicle's travel range and ultimate mission return.

The Planetary Rover Project was initiated in 1989. The emphasis of the work to date has been on autonomous navigation within the context of a high mobility wheeled vehicle at the Jet Propulsion Laboratory (JPL) and an innovative legged locomotion concept at Carnegie Mellon University (CMU). The status and accomplishments of these two efforts are discussed in the paper. First, however, this paper provides background information on the three rover types required for the SEI.

UNMANNED SCIENCE AND EXPLORATION ROVERS

The U.S. has not previously operated an unmanned roving vehicle on an extraterrestrial planetary surface. In the mid 1970's, The U.S.S.R. teleoperated (ie, using terrestrial controllers) two unmanned roving vehicles, called 'Lunakods' on the surface of the moon.

Lunakod 1 operated around 12 lunar days (almost 365 terrestrial days). The vehicle traveled a total of 10 kilometers, took many television pictures and conducted soil experiments. Lunakod 2, with twice the speed of Lunakod 1 and more experienced (and adventurous) controllers, traveled 35 kilometers in five lunar days (70 terrestrial days).

Within the SEI Program, unmanned science and exploration rovers may characterize potential outpost sites, emplace networks of science instruments, construct observatories on the far side of the Moon and perform long range exploration missions. Traverse distances of up to several kilometers per terrestrial day, through terrain containing 1 meter diameter obstacles, and a mission life of 1 to 5 years is desired for the next generation of robotic exploring vehicles.

PILOTED ROVERS

The U.S. has operated a roving vehicle on the surface of another planetary body (the Moon) with the direct involvement of a human driver. The piloted Apollo Lunar Rover Vehicle (LRV), first used in Apollo 15, provided a quantum jump in exploratory capability from the earlier Apollo missions. The LRV made it possible to travel substantial distances as well as ensuring the transportation of substantial quantities of experimental equipment and a remotely controlled television camera, which provided visual evidence of this achievement to the world. Apollo 17 (the last Apollo mission), carrying the third LRV to the moon, allowed the astronauts the longest traverse of all with a total distance of 35 km.

The next generation of piloted rovers will be satisfied by an unpressurized rover similar to the

LRV, but enhanced in range, payload and life capability. It will transport both crew and cargo about the outpost and will be used to perform human exploration and science missions up to tens of kilometers from the outpost. That rover may later be reconfigured for autonomous navigation and will perform unmanned science and exploration at distances of 1,000 kilometers from the outpost for 1 to 2 year missions.

CONSTRUCTION AND MINING VEHICLES

Technology development is required to meet the SEI needs for unmanned cargo handling, construction and mining; there is currently no technology base for extraterrestrial construction. Whereas the use of terrestrial robotics is growing in the manufacturing business, in field-oriented industries like construction, adaptation to automation technologies has been slower. Although recent progress has been made, principally, to the authors knowledge, in the United States and Japan, terrestrial cargo handling, construction and mining robotics must be considered an immature technology.

Cargo will be unloaded from a lunar excursion vehicle by a moveable gantry crane, or some other suitable device, which is teleoperated from Earth with on-site supervision by robots or a crew member. A set of interchangeable 'implements' will enable the vehicle to perform construction tasks such as excavating, relocating and smoothing regolith, and grasping and lifting objects such as boulders or structural components. The implement set will also include mining and hauling equipment for lunar soil.

NAVIGATION

Because of round trip light time, bandwidth limitation and communication channel availability delays, it is impractical to teleoperate an unmanned planetary rover from mission control on Earth. Therefore, some autonomy on the rover is needed. A highly autonomous rover capable of traveling safely over long distances for many days in unfamiliar terrain without guidance from mission control operators is beyond the present state-of-the-art. In between the extremes of teleoperation and high autonomy, various degrees of autonomy are possible. Two in particular; namely, computer aided remote driving (CARD) and semiautonomous navigation (SAN) have been identified as feasible with additional technology development

With CARD, stereo pictures from the rover are sent to mission control, where they are viewed by a human operator using a stereo display. The operator designates a safe path for the vehicle to follow as far ahead as can be seen. The plan is sent to the rover which executes the path by dead reckoning navigation aided by surface property determination sensing, maneuver level autonomous hazard detection and avoidance and expectation generation and monitoring. A new stereo pair of pictures is taken from the new position and the process repeats itself. Depending on the terrain, the rover might travel about 5 to 30 meters on each of these iterations. CARD navigation offers about a 7 km daily traverse capability on the moon and about 400 meters on Mars.

In the SAN method, local paths are planned autonomously (ie, without interaction from humans) using images obtained on the vehicle, but they are guided by global routes planned less frequently by humans in mission control. These global routes are developed from topographic map produced images obtained by an orbiting satellite or by some other means.

The sequence of operations in the portion of SAN involving mission control is as follows. As commanded from mission control, the orbiter takes a stereo pair of pictures (by taking the two pictures at different points in the orbit) of an area to be traversed. A spatial resolution equivalent to that of the rover (approximately 1 meter for a 1000 kg class unmanned rover) is desired. The pictures are sent to mission control where they are used by a human to plan an approximate route for the vehicle to follow designed to avoid large obstacles, dangerous areas and dead-ends. This route and a topographic map for the surrounding area are sent from mission control to the rover. The process repeats, as needed; perhaps once for each traverse between sites where experiments are to be done, or perhaps once per day or so on long traverses.

The sequence of operations in the portion of SAN taking place on the planetary surface is as follows. The rover views the local scene and, by using automatic stereo correlation, computes a local topographic map. This map is matched to the portion of the global map sent from mission control for purposes of position determination. The high resolution local map is analyzed by computation on the rover to determine the safe areas over which to drive. A new plan is then computed, revising the approximate route from mission control. The traverse of the revised path is simulated in order to produce sensor expectations. The expectations are used for execution monitoring and contingency planning. Using the revised path, the rover then drives, aided by surface property determination sensing, maneuver level autonomous hazard detection and avoidance and expectation generation and monitoring, a short distance (perhaps 5-10 meters), and then the process repeats. SAN navigation offers about a 24 km daily traverse capability on the moon and about 23 km on Mars.

WHEELED VEHICLE NAVIGATION DEVELOPMENT AT JPL

The major accomplishments at JPL through May, 1990 include the implementation of a wheeled rover vehicle navigation testbed, development of SAN algorithms and code, integration of SAN software onto the rover vehicle and successful feasibility demonstration.

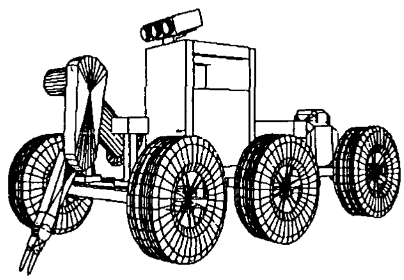

Figure 1. Robby

The construction of the wheeled rover navigation testbed, named 'Robby', was completed in December, 1989. Robby is a six-wheel, three-body articulated vehicle which offers superior mobility than conventional four-wheel, single-body vehicles. It is about 4 meters long, 1 and 1/2 meters wide and 2 and 1/2 meters high and weighs a little over 1000 kg. A commercial robot arm, for future sample acquisition experiments, is mounted on the front body. The middle body contains an electronics rack to house the onboard processors and other electronics, while serving as a mounting pedestal for the stereo camera navigation sensors. The rear body contains a commercial generator.

Over 25,000 lines of software, implementing SAN functionality, was designed, coded and integrated on Robby. In the month of May, 1990, the first continuous SAN traverse, covering a full test day, was achieved in the rough, natural terrain, arroyo test course adjacent to the JPL facility.

LEGGED VEHICLE NAVIGATION DEVELOPMENT AT CMU

The major accomplishments at CMU through May 1990 include the implementation and testing of an integrated system capable of walking with a single leg over rough terrain and the design, construction and indoor testing of the six-legged Ambler vehicle.

A prototype of an Ambler leg is suspended below a carriage that slides on rails. To walk, the system uses a laser scanner to find a clear, flat foothold, positions the leg above the foothold, contacts the terrain with the foot, and applies force enough to advance the carriage along the rails. Walking both forward and backwards, the system has traversed hundreds of meters of rugged terrain including obstacles too tall to step over, trenches too deep to step in, closely spaced rocks and sand hills.

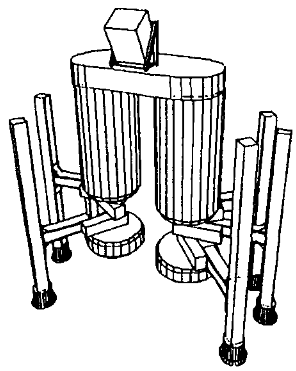

Figure 2. Ambler

The six-legged Ambler is configured to have two stacks, with six circulating legs. The actuators for body support are independent of those for propulsion. Each Ambler leg is a rotary-prismatic-prismatic orthogonal leg. The configuration enables level body motion, a circulating gait, conservatively stable gaits, high mobility and many sampling deployment options. The two shafts are connected to an arched body structure that includes four enclosures that house power generation, electronics, computing and scientific equipment. Ambler has a typical walking width of 4.5 meters, a typical walking length of 3.5 meters and a height of 4 - meters and weighs (leg and body structure) approximately 2000 kg.

SUMMARY

This paper has described the two highlights of the first year and one-half of two parts of the Planetary Rover program. Other parts of the Rover program include the development of advanced mission operations, mobility and power technology at JPL, mission operations research at Ames Research Center and piloted rover technology at the Marshall Space Flight Center. The accomplishments achieved to date represent a first step in developing the kind of machine intelligence that someday will affect how explore the universe.

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