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SPACE ROBOTICS PROGRAMS AT SANDIA NATIONAL LABORATORIES

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Abstract:

Existing robotic rover and space satellite technologies at Sandia National Laboratories (SNL), coupled with existing launch vehicles and converted military Multiple Independent Reentry Vehicle (MIRV) technologies, can be applied towards the realization of a robotic lunar rover mission in the near term. SNL's Advanced Vehicle Development Department has been designing, producing, and operating prototype rover systems at the Robotic Vehicle Range facility since 1984, and has extensive experience with teleoperated and semiautonomous mobile robotic systems. SNL's Space Systems Directorate has been designing, producing, and operating satellite systems and subsystems in Earth orbit for national security missions since the early 1960's. The facilities and robotic vehicle fleet at SNL's Robotic Vehicle Range (SNL-RVR) have been used to support technology base development in applications ranging from DoD battlefield and security missions, to multi-agency nuclear emergency response team exercises and the development of a prototype robotic rover for planetary exploration. Recent activities at the SNL-RVR include the Robotic All Terrain Lunar Exploration Rover (RATLER) prototype development program, exploratory studies on a Near Term Lunar Return Mission scenario for small robotic rovers based on existing space hardware technology, and demonstrations of the utility of existing rover technologies for performing remote field geology tasks similar to those envisioned on a robotic lunar rover mission. Specific technologies demonstrated include low data rate teleoperation, multi-vehicle control, remote site and sample inspection, and standard bandwidth stereo vision. These activities serve to support the use of robotic rovers for an early return to the lunar surface by demonstrating capabilities that are attainable with off-the-shelf technology and existing control techniques. Due to the breadth of technical activities at SNL, there are many supporting technology areas for space robotics applications development. These range from core competency areas in advanced aerodynamics, computing, and microsensor technologies, to the actual design, production, and space-qualification of flight components using existing in-house capabilities. These various capabilities have been developed over the years to serve SNL's role in missions for a variety of customers, including U.S. industry, NASA, the U.S. Departments of Defense and Energy, and other federal agencies. The paper describes Sandia National Laboratories' activities in the Space Robotics area, and highlights the laboratory's supporting technical capabilities.

Introduction

In July 1989 President George Bush announced the Space Exploration Initiative (SEI), a bold plan to revitalize America's leadership in space exploration and the associated technologies required to accomplish the goals of "...returning to the Moon, and this time to stay...", and the first manned exploration of Mars. Independent of efforts by NASA and blue ribbon panels to study missions to Mars, the Moon, and to examine the degree of commonality between them[1,2], engineers and scientists at Sandia National Laboratories began looking at currently available technologies that could be applied towards an early return mission to the lunar surface. This concept of an early return mission was based on the assumption that advanced development of new launch systems, lunar landers, habitats, and a space station are not hard requirements if the desired goal is simply to explore the Moon in finer detail and on a wider scale than has been done to date. In combination with proposed lunar orbital mapping missions[3], a set of small robotic rover vehicles could be placed on the lunar surface in a few years, using existing and available technologies, to begin the exploration and site characterization process that could eventually lead to manned missions and a lunar base[4].

Existing launch capacity in the form of either the Space Transportation System (STS) or from the military stable of vehicles, coupled to existing upper stage hardware, navigation and guidance techniques, and passive deceleration and landing hardware,

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could realistically place several small robotic rover vehicles on the lunar surface with a single launch. Robotic rovers are a proven technology for lunar exploration[5], so long as a high degree of autonomy is not required. Supporting technologies for such a mission including radiation hardened electronics, advanced microsensing, advanced communications, high performance computing, and advanced robotics techniques. These technologies currently exist in forms mature enough for spaceflight, and in many cases have already been used in missions in Earth orbit and to support NASA missions to the outer planets. .

The wealth of existing and very near term technology that is envisioned for use on an early lunar return mission are, for the most part, the result of thousands of man-years of investment by the U.S. taxpayer for the purposes of national security and defense. To turn these technological swords into plowshares for the peaceful exploration of space would be a bonus return on that investment which was never imagined in the days of the cold war. Sandia National Laboratories' unique history and capabilities provide the potential to act as a focal point for the design and implementation of a multi-agency early lunar return mission, utilizing capabilities and expertise that currently exist in DOE, DoD, NASA, and the international community. With the above discussion as a context and point of reference, Sandia's current efforts in Space Robotics, Space Satellite Technologies, and related supporting fields are discussed below.

Space Robotics

Sandia National Laboratories' Robotic Vehicle Range (RVR) in Albuquerque has been developing robotic rover technologies for use in DOE and DoD application areas since 1984. The RVR comprises over 200 acres of varied terrain, ranging from flat barren mesa to rugged mountainous country. A fleet of robotic rover vehicles has been developed or are currently under development at the RVR, ranging in size from a few pounds to over five tons, and ranging in capability from simple remote control to telerobotic and semiautonomous robotic vehicle systems. Recent additions to the fleet include an advanced wheeled mobility design for planetary exploration[6], and an integrated mobile manipulation system employing a pair of high strength Shilling TITAN manipulators mounted on a robotic military High Mobility Multi-purpose Wheeled Vehicle (HMMWV). The RVR's Space Robotics work has concentrated on three aspects of robotic planetary rover vehicle technology; vehicle mobility design, the application of telerobotics to performing a field geology task, and human factors issues.

Robotic Planetary Rover Technologies

The Robotic All-Terrain Lunar Exploration Rover (RATLER) is a four wheeled all-wheel-drive platform with twin body compartments connected by a hollow central pivot. The general configuration is shown in Figure 1, which is a three-view schematic of the dual-body central-pivot design.

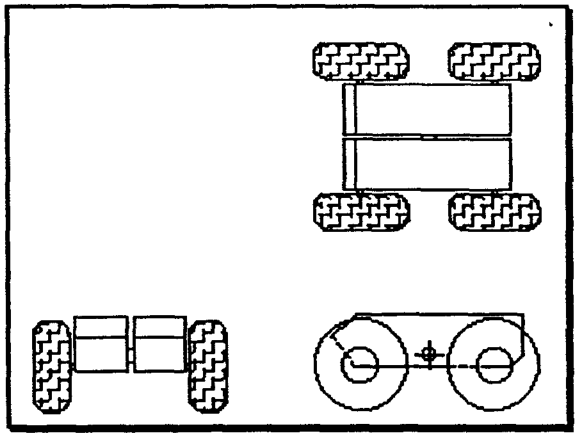

Figure 1. RATLER Schematic.

The uniquely simple method of chassis articulation by means of the hollow central pivot is employed between the bodies to allow all four wheels to remain in contact with the ground while traversing uneven terrain. This central pivot, as well as the vehicle center of mass, is located as close to the axle line and the geometric center of the vehicle as possible to ensure maximum stability while climbing over large obstacles. The articulating action of the dual-body central-pivot is illustrated in Figure 2, which is a picture of the first remotely controlled prototype being driven over some large rocks in Death Valley, California.

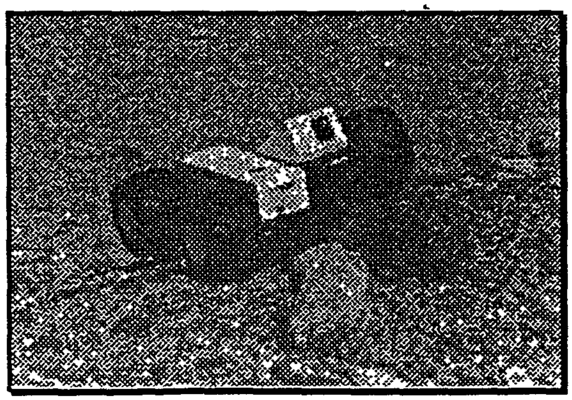

Figure 2. RATLER Prototype at Death Valley.

The RATLER proof of concept prototype has evolved into an internally funded program at Sandia to develop a one-meter scale version called RATLER II, an initial pathfinder version of which shown in Figure 3 The RATLER II is currently funded for FY93 through the DOE's Laboratory Directed Research and Development (LDRD) program, and funding is expected for FY94. The RATLER II will reach an initial teleoperational capability in late summer of 1993, and will then enter field trials and begin advanced software development during the fall and winter of 1993-1994. The integration of a manipulator and a representative science payload is planned for the spring and summer of 1994, with a simulated lunar mission scenario demonstration planned at the completion of the project in September 1994.

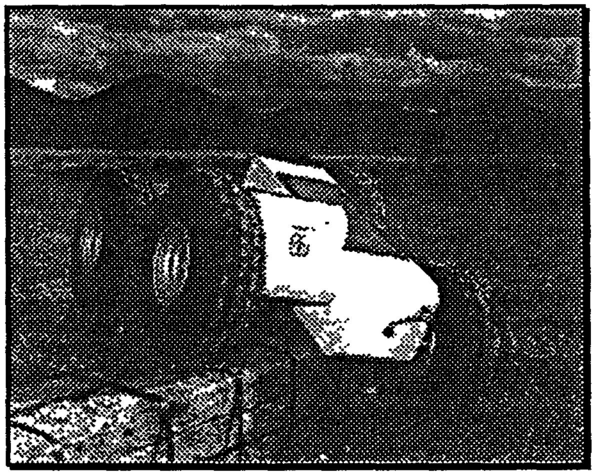

Figure 3. RATLER II pathfinder vehicle

Telerobotic Field Geology

In order to investigate the practical utility of telerobotics for performing science, a set of demonstrations of telerobotic field geology tasks were conducted using two of the existing robotic rover vehicles at the RVR. The DIXIE and RAYBOT vehicles, shown in Figure 4, were teleoperated from a common Control Driving Station (CDS) by alternating control between the two in a serial fashion. DIXIE was fitted with stereo video cameras, and was initially positioned to overlook a site that was determined to be of geological interest, as would be done on the lunar surface from orbital data. The RAYBOT vehicle, which is very similar to DIXIE but fitted with a simple manipulator arm, was then driven into close proximity to the site, and the manipulator was then used to place a video camera within a few inches of some geological formations. The arm-mounted monocular camera on RAYBOT was used to simulate a science instrument, which would be used to acquire spectral or compositional data directly from the geological site of interest The use of two robots in tandem pointed out the advantages of having more than a single perspective of the site in question, in a manner similar to that described by geologists when they perform a field investigation Results from these trials of telerobotics in field geology tasks clearly illustrated to the operators and researchers that multiple rovers can be combined with definite advantage over single rovers in the performance of such tasks.

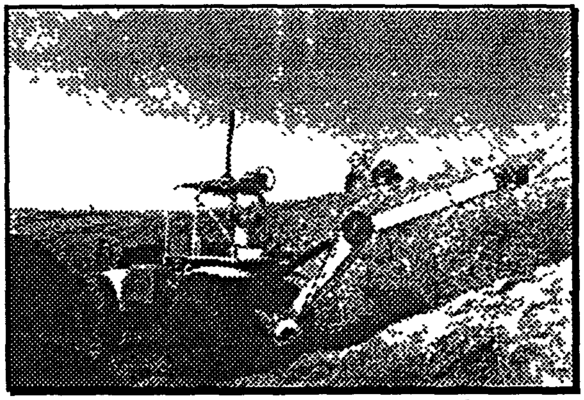

Figure 4. Telerobotic Field Geology

Human Factors

Additional work that has been ongoing relates to the human factors aspect of telerobotics, commonly called the man-machine interface. As with all of the systems developed at the RVR, practicality and affordability have been major driving factors in the technical approach taken as well as in the choice of hardware employed. A system that provides true stereo vision over a single-bandwidth RF transmission link has been under test and evaluation for several years. The benefits of stereo vision over monocular vision for teleoperation of vehicles in smooth terrain are debatable, however when used for remote manipulation or fine positioning of an end effector, stereo vision has definite advantages since depth perception plays a key role in the performance of such tasks. A major disadvantage of stereo vision is the high bandwidth requirements for sending two full motion, high resolution video images back to a teleoperator. The use of an alternating-field multiplexing scheme, coupled with a demultiplexer and special electronic viewing goggles reduces the bandwidth requirement to the equivalent of a single video link while providing the teleoperator with a satisfactory stereo effect. Bandwidth reduction has obvious advantages for a planetary rover, but was in fact developed to meet military battlefield bandwidth limitations. Although high speed teleoperation with monocular vision has been demonstrated at the RVR, the use of stereo vision has allowed the RVR to teleoperate prototype robotic battlefield vehicles at speeds up to 14 m/s in rough terrain, where the limiting factor has been terrain-induced vehicle stability effects rather than any factors associated with teleoperation itself. The introduction of time delay into the teleoperation link has been demonstrated, up to a full second, with minimal degradation in teleoperation efficiency at speeds of less than 3 m/s. When delaying the control signals over one second, considerable difficulty in maintaining smooth control and movement of the vehicle was experienced, resulting in a switch from a "continuous" driving mode to a "stop and look" mode. Proficiency in teleoperating at time delays of over one second was definitely degraded compared to operations with no time delay, but the operator quickly adapted his control technique to anticipate the vehicle's reactions, and was able to operate reasonable well at low speeds in rough terrain. As demonstrated with the Soviet LUNOKHOD lunar rovers[5,7], teleoperation of a robotic rover with a three second time delay is possible, although can be somewhat clumsy compared to teleoperation with no time delay. Further work in these areas will include the addition of intelligent 'driver's aids' to reduce the teleoperator's workload, experiments with various stereo vision configurations to examine different display technologies and effects, and extension of the time delay teleoperations experiments into the three second regime.

Near Term Lunar Return Mission

Engineers at Sandia National Laboratories have been developing a concept for a Near Term Lunar Return Mission, which makes use of existing technologies and hardware as much as possible[8]. The concept begins with the notion that a small and highly mobile wheeled rover can be built to a scale that allows six to ten of them to be launched on a single carrier bus, thus providing redundancy and a "force multiplication" factor to what might otherwise be a high risk single rover exploration mission. By using either an existing expendable launch vehicle, or by loading a commercially available rocket motor configured as a translunar injection stage system into a Space Shuttle payload bay, a converted military Multiple Independently targetable Reentry Vehicle (MIRV) carrier bus fitted with robotic rovers and associated systems could be placed into lunar orbit, and used as a platform to deploy the rovers down to the lunar surface in a manner very similar to that used for the independent targeting of military reentry vehicles. The rovers would be arranged in small garage-like canisters, and ejected from low lunar orbit using existing MIRV system bus technology.

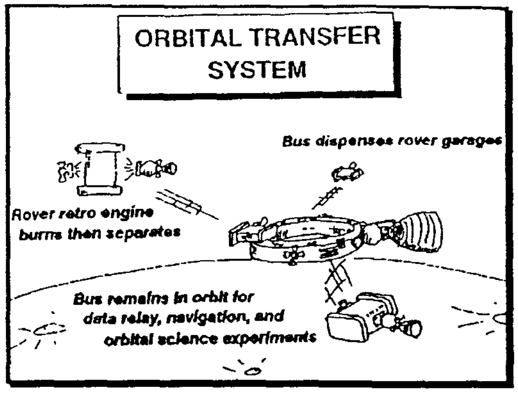

Figure 5. Canister Deployment from Lunar Orbit

The MIRV system bus technology is quite mature, and is already integrated with existing military launch and delivery systems. Following insertion of the bus into a 5 to 10 kilometer circular lunar orbit, the canisters would be ejected backwards along the bus path onto a noncircular lunar impact trajectory, while the MIRV bus remains in orbit to conduct orbital science missions and communications relay for the surface rovers. The canister uses a commercial 5 kg storable propellant retro engine to retrofire to an almost "dead-stop" one kilometer above the lunar surface. The rover canister would then free fall to an impact on the surface at approximately 50 m/s. The rover canisters would be fitted with a specialized passive soft landing system which is based on existing automotive airbag technology, to ensure their mechanical integrity through the impact sequence. A military Reentry Vehicle (RV) radar proximity fuse would be used to inflate the airbags just prior to impact. Automotive airbags have already demonstrated their ability to protect humans in crashes at decelerations similar to that envisioned here, and it is a plausible assumption that a technology that can protect a human head from fatal damage in impacts at speeds up to 54 m/s (120 mph) could protect a properly designed rover at similar speeds.

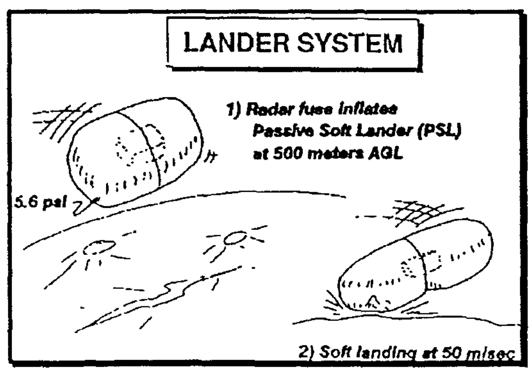

Figure 6. Rover Canister on Final Descent

Once the canister has come to a halt after impact, it will simply jettison the airbags, open, and allow the rover to drive out. The canister will be clamshell shaped to ensure that it will end up in one of two positions (upright or upside-down), and the act of opening will ensure that the rover's attitude will always be upright. The inner surface of the canister will incorporate a communications antenna and a small science package similar to those carried on the rover.

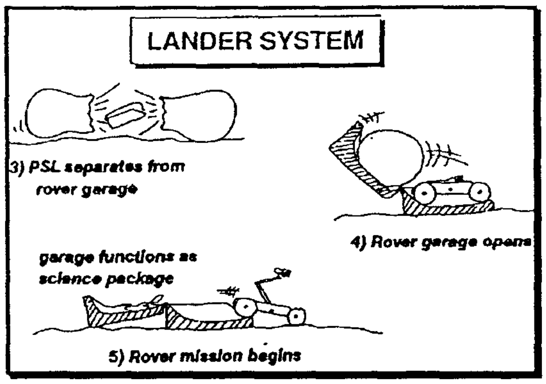

Figure 7. Rover Deploys from Canister

The concept is based on an existing rover prototype model, published launch vehicle system performance data, existing military MIRV system bus and automotive airbag technologies, and a simple rover "garage" canister design. The mission concept is simple and straightforward, requiring no new technologies and a minimum of refinement to existing ones. The elimination of a powered lander requirement allows a mission of this type to be launched before the ARTEMIS Common Lunar Lander system is ready, and can act as an inexpensive precursor to soft landed missions in later years.

Space Satellite Technologies

In programs sponsored primarily by the U.S. Department of Energy, the U.S. Air Force, and NASA, Sandia National Laboratories' Space Systems Center has been designing, building, testing, and operating satellite sensor payloads for over 30 years. Approximately 90 satellite or space probe payloads have been launched to date, of which approximately 85% are Department of Defense (DoD) missions; the remainder are NASA sponsored missions. Sandia's responsibilities for these missions run from the "cradle to the grave", that is, from designing systems to meet specific customer requirements, through system integration, space qualification, testing, and check-out of the operational hardware after deployment to their on-orbit assignments. Sandia's work in Space Satellite Technologies represents a total of over 1600 cumulative years of on-orbit operations, and approximately 3600 man-years of effort by Sandia personnel.

During this time, Sandia has established an impressive in-house capability to support Space Satellite operations. Facilities at Sandia include several thermal vacuum chambers which range in capacity up to several cubic meters, for space qualification and checkout of complete systems. In order to satisfy DoD customers' occasional requirements for very rapid development and fielding of orbital systems, Sandia has also developed an in-house capability to perform thermal-vacuum and radiation effects testing on various components, and maintains a large inventory of electronic hardware that has been tested and qualified for space flight. Concurrent with the test facilities and hardware inventory, Sandia has also has in place a program of quality assurance and operational procedures that have been developed over the lifetime of the Space Satellite Systems program. These procedures[9,10] help ensure that future spaceflight systems developed at Sandia will prove to be as successful as those deployed to date.

Additional Supporting Technologies

Additional supporting technologies at Sandia National Laboratories that have been developed primarily for defense and national security missions include advanced aerodynamics, computing, and microsensor technologies.

Sandia has developed an advanced aerodynamics capability to support various national defense missions[11]. The capability to deploy weapons at high speed and extremely low altitude required advances in the state of the art in parachute design and associated computer modeling techniques. That expertise is currently being used by NASA for parachute and airbag designs, primarily to support the planned Mars Environmental Survey (MESUR) Pathfinder mission, scheduled for launch within the next few years. NASA has also asked Sandia to evaluate a special fiber optic sensor technology developed at the Laboratory[12], potentially for use in soil reactivity experiments on the Russian MARS-94 mission. An additional technology that appears to be an attractive one for a Mars mission is the Sandia Winged Energetic Reentry Vehicle Experiment (SWERVE)[13]. The SWERVE vehicle is a specially modified reentry vehicle, that is fitted with aerodynamic surfaces and guidance technology that allow it to guide itself with very high accuracy to a specific target Although intended for defense related applications, SWERVE could enable a robotic probe mission to Mars to have essentially complete global access, with the ability to land anywhere from the equatorial to the polar regions[14].

Summary

Since its inception as the nation's primary nuclear weapons engineering laboratory, Sandia National Laboratories has developed a wide range of technical capabilities and expertise that were originally intended for national defense and security missions, but can be readily applied towards the realization a program of civilian space exploration Significant expertise and capabilities in robotics, space systems, advanced aerodynamics, computing, and microsensing are just some of the areas that the U.S. taxpayer has invested heavily in for over 40 years, and which represent a resource that is ready to be applied towards the fulfillment of national goals, both military and civilian alike. Although some of the potential is being tapped by outside agencies in support of planned space exploration missions, there remains a wealth of capabilities at the Laboratory that have not yet been recognized. Existing technologies both within and outside Sandia can be brought to bear on a concerted effort to resume exploration of the lunar surface by robotic orbiters and surface rovers, and Sandia National Laboratories stands ready to contribute to that effort should it be called upon to do so.

Acknowledgments

Virtually all of the concepts and ideas related to lunar rover vehicle design, lunar exploration missions, and Mars exploration missions are not the author's, but rather are the product of work by **Dr. James W. Purvis** of Sandia National Laboratories. Dr. Purvis has graciously allowed the author to reproduce his sketches for the purpose of disseminating those ideas, and has been a driving force behind the Space Robotics Programs development efforts at the Laboratory. **Dr. Larry S. Walker** of Sandia's Civil Space Programs Department has provided the resources to support Space Robotics Programs development, and is the Laboratory's Program Manager for all civilian space-related work.

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