N94-34023

Lunar Exploration Rover Program Developments

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Abstract

The Robotic All Terrain Lunar Exploration Rover (RATLER) design concept began at Sandia National Laboratories in late 1991 with a series of small, proof-of-principle, working scale models. The models proved the viability of the concept for high mobility through mechanical simplicity, and eventually received internal funding at Sandia National Laboratories for full scale, proof-of-concept prototype development. Whereas the proof-of-principle models demonstrated the mechanical design's capabilities for mobility, the full scale proof-of-concept design currently under development is intended to support field operations for experiments in telerobotics, autonomous robotic operations, telerobotic field geology, and advanced man-machine interface concepts. The development program's current status is described, including an outline of the program's work over the past year, recent accomplishments, and plans for follow-on development work.

Introduction

Sandia National Laboratories' Robotic Vehicle Range (SNL/RVR) has been developing mobile robotic systems for a variety of DOE and DoD applications since 1984. Beginning in 1989, the SNL/RVR began exploring civil space applications which could make use of the existing technology base, particularly in lunar exploration missions. A philosophy that stresses simplicity in the design and implementation of a rover system wherever possible has been the basic tenet of the SNL/RVR's approach to the problem of lunar exploration. In line with this philosophy and without official funding, an innovative concept for a simple, agile lunar rover vehicle was developed and evaluated in the form of several scale models [1,2]. The Soviet Union's space program successfully operated two lunar rovers in the early 1970's [3,4] using very simple technology, thereby demonstrating that teleoperation is a viable technique despite the inherent Earth-Moon communication time delay, and that relatively simple mechanisms can provide a useful level of capability to perform meaningful science through telerobotics. Figure 1 shows one of the early models of Sandia National Laboratories' Robotic All Terrain Lunar Exploration Rover (RATLER), the focus of Sandia's lunar exploration efforts, during field testing at Death Valley National Monument in late spring of 1992.

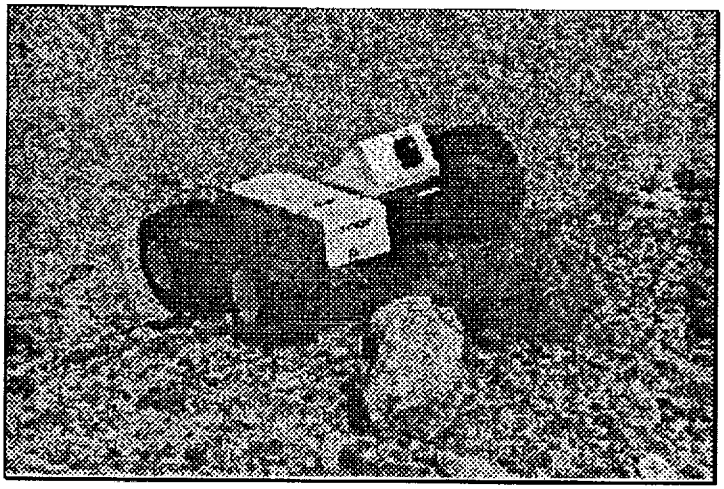

Figure 1. RATLER Testing at Death Valley

Over the summer of 1992, two summer students employed at the SNL/RVR designed, constructed, and tested a more robust version of the scale model RATLER, called RATLER-A. RATLER-A and the original models provided additional testing opportunities at the White Sands National Monument, where the RATLER design concept showed promise for very good mobility and agility characteristics in very dry, loose gypsum sand. Two additional models were built to support demonstration of the concept to NASA, DOE, and the public at the National Air and Space Museum's Planetary Rover EXPO in September 1992. Figure 2 shows the RATLER-A being operated over a simulated Mars terrain at the Planetary Rover EXPO.

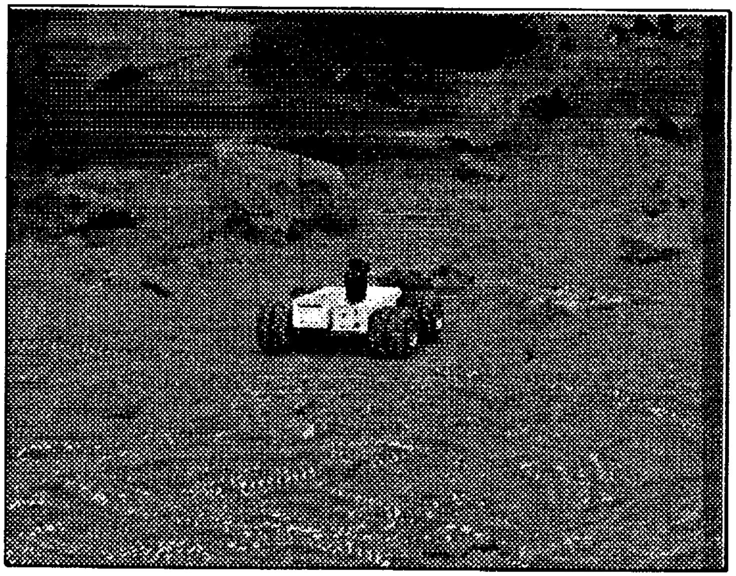

Figure 2. RATLER-A in Simulated Mars Terrain

As a result of the work with the scale models, a Laboratory Directed Research and Development (LDRD) program was initiated to develop a full scale RATLER vehicle. The LDRD project was originally proposed for a period of two years, beginning in October 1992, and was recently approved for further development in FY 1994. The remainder of this paper focuses on the LDRD program for development and testing of the full scale RATLER, called RATLER II.

RATLER II Development Program

The goals for the RATLER II development program are to develop a 1-meter scale RATLER vehicle using off the shelf technology, and to demonstrate a capability commensurate with stated or inferred requirements for a lunar exploration rover vehicle. In conjunction with the actual vehicle platform, a compact, portable Control Driving Station (CDS) is also under development to support field operations. Both the CDS and the RATLER II incorporate multiple processors on a 32 bit communication bus, and implement a real-time, event-driven multitasking software architecture.

When the RATLER II program initiated in October 1992, the first task was to determine what performance requirements or specifications existed in the literature for a lunar exploration rover. Although examples of lunar roving vehicles were found [3,4,5], a contemporary set of requirements for future missions by rovers to the Moon were not found. A trade-off study [6] was performed to attempt to derive requirements that could then be used by the project team to design and build the RATLER II. Results of that study led to a RATLER II design that could be constructed using off the shelf technology, and which was expected to meet a reasonable set of performance criteria in terms of mobility and payload capacity. The current RATLER II configuration was sized to meet the mass and volume constraints imposed by the ARTEMIS Common Lunar Lander [7], and to provide a significant science payload capacity. Figure 3 shows the current RATLER II configuration.

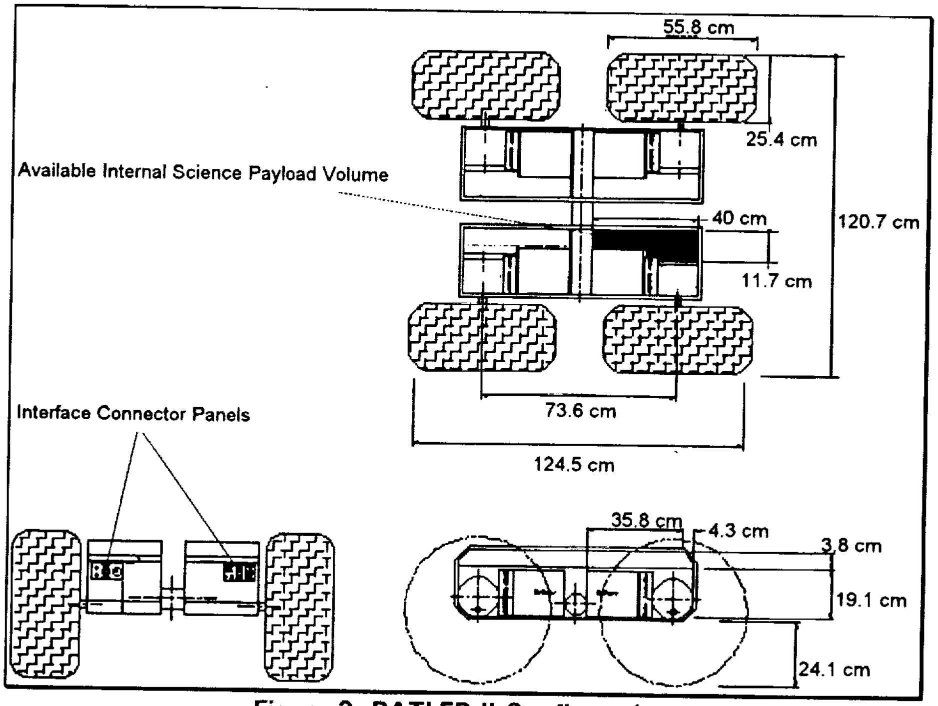

Figure 3. RATLER II Configuration

Based on the trade-off study results, a RATLER II pathfinder test article was constructed and tested at both the SNL/RVR, and at the White Sands Missile Range (WSMR) during November and December of 1992. Those field trials and additional analysis led to a few minor changes in the vehicle's configuration, which should result in improved mobility and an increase in mechanical strength of the structure. The changes included the addition of aluminum skid plates to protect the under-sides of the carbon composite chassis, larger wheels, increased drive motor torque, and a slight increase in the vehicle's lateral stance. The RATLER II prototype currently under construction is shown in Figure 4.

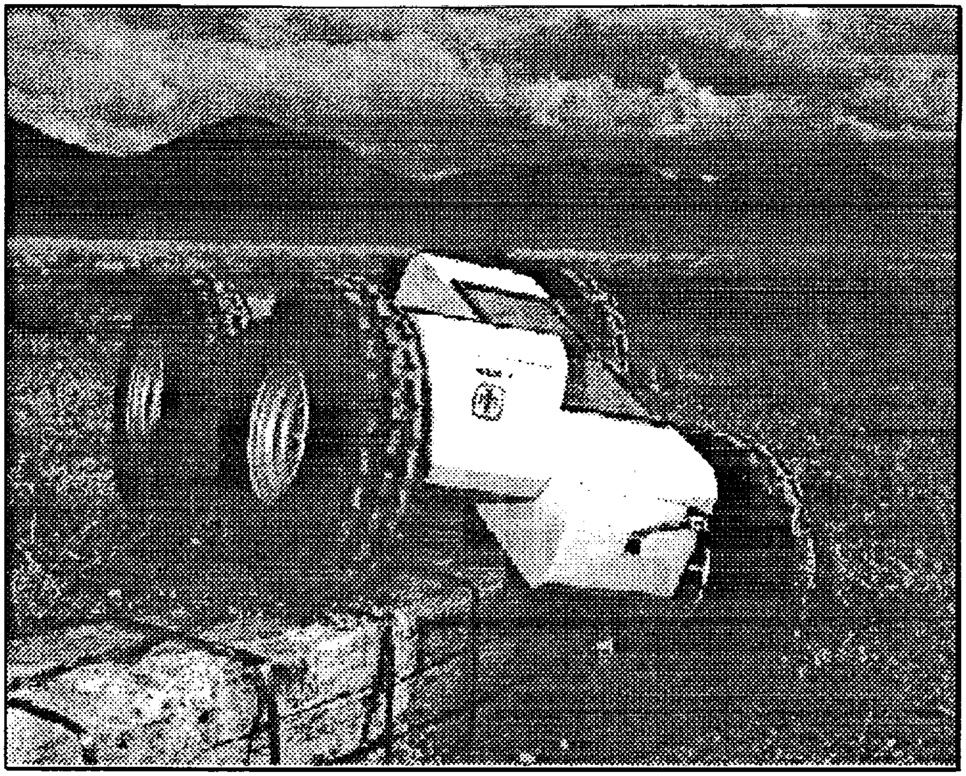

Figure 4. RATLER II Prototype

The RATLER II chassis consists of two bodies, connected by a passive central pivot aligned along the lateral axis of the vehicle. The bodies are constructed of an inner and outer skin of carbon fibers embedded in an epoxy matrix, laid over a cellulose honeycomb inner core. Each body is approximately 25 centimeters wide by 25 centimeters deep by 92 centimeters long, and masses approximately 3.2 kilograms empty. The complete system (not including science instruments) is projected to mass ~70 kilograms, including four lead-acid batteries and four rubber tires on steel rims. Table 1 lists the RATLER II's specifications and expected performance parameters.

Table 1. RATLER II Specifications

Parameter	Value	Units
Wheel Radius	28	cm
Wheel Width	25	cm
Wheelbase	72.4	cm
Stance (to center of contact patch)	81	cm
Total Vehicle Mass (TVM, no payload)	70	kg
Total Stored Volume (TSV)	0.6	meters^3
Maximum Single Dimension of TSV	122	cm
Maximum Speed	0.6	meters/second
Slope Stability	>45	degrees
Slope Climbing	~30	degrees
Obstacle Climbing	~75	cm
Maximum Payload Mass (additonal to TVM)	18	kg
Maximum Payload Power (planned)	100	watts (electric)
Maximum Internal Payload Volume	9600	cm^3

The drive system uses four wheel independent electric drive from four 24 volt DC permanent magnet gearhead motors, each of which provides ~22 Newton-meters of torque, and should provide a maximum speed of ~60 centimeters per second. The battery system is augmented with commercial photovoltaic arrays to provide a trickle charge capability, and is expected to provide ~6 hours of operation assuming a 50% duty cycle on the drive system. An internal payload space of ~9600 cubic centimeters and a maximum of 18 kilograms additional mass budget is provided for scientific instruments, which are allowed a total of up to 100 watts of on-board power.

The computing system being implemented on RATLER II is a commercial STD-32 system, which is based on the popular STD 80 backplane design but has been expanded to allow 32 bit data transfers. The STD-32 system supports multiple processors using a master/slave arrangement with bus arbitration and peripheral sharing support. The master processor is an Intel 80486 based machine equipped with 8 Mbytes of RAM and 1 Mbyte of EEPROM, and the single slave processor is an NEC V53 (80286/80386 clone) equipped with 1 Mbyte of RAM. Extra card slots have been budgeted to allow additional slave processors for future expansion. Shared peripheral devices on-board include a high speed, 12 bit, 32 channel Analog to Digital (A/D) converter, a 12 bit, 8 channel Digital to Analog (D/A) converter, Ethernet adapters, and a custom designed, 12 channel digital quadrature encoder board. Each of the two CPU's have on-board I/O ports which give the system a total of 5 serial (RS-232) ports and 72 Parallel Interface Adapter (PIA) ports, of which 24 are optically isolated. On-board sensors and instrumentation include a magnetic fluxgate compass, a Global Positioning System (GPS) receiver, pitch and roll axis inclinometers, an angular rate sensor for the yaw axis, a body-pivot angle encoder, individual wheel odometers, drive motor tachometers, drive motor temperature sensors, drive motor current monitors, battery voltage sensor, and a computer module temperature sensor. All of the internal components are mounted on removable payload module base plates, to allow easy access for maintenance or repair. Communications with the CDS during field operations are handled through a 4800 BAUD, full duplex digital RF modem, and an RF video/audio transmitter.

The Ethernet ports are used for development, and access a LAN at the SNL/RVR for software development tools and source code, so that code development can be accomplished directly on the target CPUs on-board the vehicle. The software architecture for each CPU incorporates a real-time, event driven, multitasking system, is written in C and C++, and accomplishes inter-CPU communications through dual ported RAM. The software system has been designed to allow future expansion of autonomous capabilities, and rapid prototyping of new experimental configurations for robotic control. Current program plans call for an initial operational capability demonstration of teleoperation in September 1993, with future work in FY94 to include the addition of autonomous navigation features.

Future Work

A major focus of the project team's efforts in FY94 will be the conduct of field trials with the RATLER II and its CDS. As noted above, a payload bay area has been allotted to carry scientific instruments weighing up to 18 kilograms and requiring up to 100 watts of power. The RATLER II program is intended to be a testbed for robotic lunar exploration, and as such provides mobility for the true focus of such a mission, i.e. the science package. Although the SNL/RVR is not developing any science packages for lunar exploration, we are offering essentially a 'free ride' during our ongoing field trials to developers of such instruments. We will provide the appropriate interface information to qualified instrument developers, to allow them access to RATLER II's support systems. With proper planning and coordination between the developer and the RATLER II project team, integrating the science package should be a relatively straightforward 'strap-down' process, and should allow several different science packages to be operated on-board the RATLER II during field operations over the course of FY94 (through September 1994). Each proposed payload will be evaluated on an individual basis, and support funding (if any) will be negotiated as required between the SNL/RVR and the instrument developer. As long as no significant modifications to the RATLER II hardware or software is required to support the instrument, no support funding to the SNL/RVR will be required from the instrument developer.

As noted above, one of the major efforts beginning in October of 1993 will be the extension of the RATLER II's navigation capabilities to include some autonomous features. Current plans call for a subsumption-like architecture [8,9], which will also necessitate the addition of obstacle detection sensors. Various configuration options are under consideration, and it is hoped that at least two different implementations will be developed and evaluated over the course of the RATLER II program.

A six degree-of-freedom manipulator is planned for FY94, and will be among the first tasks undertaken beginning in October 1993. A dedicated slave CPU will allow coordinated motion of the manipulator while the vehicle is in motion, with virtually no impact on other on-board processing tasks taking place. This capability will allow the entire system to act as a multi-degree-of-freedom (redundant) mobile manipulator, and should provide a useful platform for field trials and testing of planetary exploration mission scenarios. An initial payload lift capacity of ~2 kilograms at full arm extension is planned, as is a small suite of interchangeable end effectors.

The current video RF transmitter incorporates two sideband audio channels, which may be used to bring back stereo audio from the RATLER II to the CDS. Although the Moon has no atmosphere and therefore sound does not travel beyond the surface (however it does travel through the Lunar interior), potential terrestrial applications for the RATLER II could make use of such a feature and we plan to incorporate it. In addition, a set of stereo video cameras will be installed along with a duplexing system to allow stereo vision over a single RF transmitter. The use of a duplexer has been implemented previously at the SNL/RVR for this purpose, and has proven to be quite effective in improving perception without the penalty of doubling the bandwidth required for transmission of the real-time images.

Another item of interest for future work in the RATLER II program will be multi-vehicle control. A second RATLER II prototype will be constructed (essentially a twin of the first unit), and will be used to explore the advantages and disadvantages of simultaneously controlling more than one rover from a common control station, by a single operator. This issue is relevant to the argument that the use of robotic rover vehicles for lunar exploration makes sense, both economically and technically.

Obviously, the wheels, solar panels, computers, and batteries being used on the RATLER II are not types which would be suitable for a space qualified system. Conceptual designs for lunar-type wheels will be explored to the extent that at least one set of wheels will be constructed and evaluated, but a comprehensive program of wheel design is not currently planned. The subject of wheel design for lunar roving machines has been explored in some detail [10], and if incorporated in this development program might easily consume the entire budget. Trade studies may be done with regard to batteries, solar cells, and computing technologies, to identify space qualified (or qualifiable) systems, but the RATLER II prototype currently under development will remain Earthbound. It is intended that a space qualified, flight-ready system could be developed based on the RATLER II, if such a program was determined to be in the national interest, but that is beyond the scope of the RATLER II program as it is currently defined.

Summary

Sandia National Laboratories' Robotic Vehicle Range has brought the Robotic All Terrain Lunar Exploration Rover (RATLER) program from an initial concept to a full scale working prototype in ~19 months. The RATLER II is designed to provide mobility characteristics and payload capacity that are sufficient to realistically demonstrate lunar exploration activities by a mobile robotic vehicle, and is sized to be compatible with payload constraints imposed by the ARTEMIS Common Lunar Lander. The RATLER II prototype itself is not intended to be a space qualified system, but should provide design and engineering data which could be used in the future for a flight qualified lunar exploration rover. The RATLER II will be operational by the end of September 1993 in a teleoperation mode, and will begin field trials in October 1993. Activities planned for the remainder of 1993 and through September 1994 include the addition of a manipulator arm, additional sensing capabilities, autonomous behavioral control software, and field demonstrations of the system in a realistic environment. Developers of science instruments that could make constructive use of the RATLER II's mobility and manipulation characteristics are invited to contact the author to discuss cooperative field trials and demonstrations of their systems, carried as a payload on the RATLER II.

Acknowledgments:

The author would like to acknowledge the many individuals who have directly or indirectly contributed to the RATLER project: Jim Purvis and Kent Biringer, coinventors of the original concept; Adan Delgado, Leon Martine, and Patrick Wing, Sandia summer students who constructed and tested several of the prototypes; Wendy Amai, Roger Case, and Bryan Pletta who constitute the current project development team at Sandia National Laboratories; and finally our many colleagues at NASA, whose comments, constructive criticisms, enthusiastic encouragement and support have greatly influenced the RATLER development.

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Session R2: ROBOTICS AND TELEPRESENCE RESEARCH CHALLENGES: PANEL PRESENTATIONS

Session Chair: Capt. Paul Whalen

12.

Robotics & Telepresence Research Challenges: Panel Presentation

Dr. Chuck Weisbin, NASA/JPL

Planetary Rover Challenges

Programming Thrusts

- Code S Concurrence on Needs
- Alliances with Industry and the Universities
- International Collaboration (e.g., Russia, France)
- Lunar and Venus Exploration Options

Planetary Rover Challenges (cont'd)

Technical Thrusts

1. Real-time perception and goal identification
2. Onboard placement of science payloads and rock coring
3. Sparse terrain mapping
4. Systematic benchmark experiments (e.g., legs versus wheels)
5. Fault tolerance and error recovery
6. Autonomous navigation over the horizon

In-space Robotics Challenges

Programmatic Thrusts

- Flight Experiments
- Terrestrial Demos > Commercialization
- Alliances with Industry and Universities
- International Collaboration (e.g., JPL/MITI)
- Microtechnology (In-situ Spacelab Experiments)

In-space Robotics Challenges (cont'd)

Technical Thrusts

1. Automated operation of remote dexterous robots from ground
2. Compilation and concatenation of robot skills
3. Instrumented end effectors with improved dexterity
4. Object verification and pose refinement
5. Sensory skins for obstacle avoidance
6. Safe and robust control of manipulator/environment interaction (e.g., compound manipulators, fault tolerance)

Major Technology Challenges for DoD UGV program

1993-2000

Charles M. Shoemaker
Chief, Focus Program Office
for Advanced Automation and Robotics
Army Research Laboratory

[illegible]

Basic Premise:

Reductions in manpower without reductions in responsibility will result in increased DoD emphasis on supervisory control modality for UGVs.

Challenges:

- **Supervisory Control of UGV's: Mission and Mobility.**
- **Optional Robotic Functionality for Manned Systems.**
- **Innovative Mobility Platform Technology.**

[illegible]

Superisory Control of UGVs

Motivators:

- Minimum 60 megabit data rate for single video downlink in teleoperation mode. Requires data link in spectral region for which beyond line of sight propagation is problematic.
- Fiber Optic Data Link causes severe operational constraints.
- Multiple vehicle operation in high data rate mode causes frequency allocation problems.
- 1-on-1 teleoperation requires increased manpower

Superisory Control of UGVs

Technical Challenges:

- On-board autonomy: mission function/mobility.
- Data compression-reconstitution.
- Reconfigurable Man Machine Interface.

Supervisory Control of UGVs

Challenges (cont.)

Data Compression-Reconstitution

- Fractal Compression.
- Pyramidal Compression.
- DCT.
- Foveation.

[illegible]

Supervisory Control of UGVs

Challenges (cont.)

Limited Autonomous Mobility (near term)

- Retrotraverse.
- CARD.
- Leader Follower.
- Road Following.

[illegible]

Supervisory Control of UGVs

Challenges (cont.)

Mission Function Automation

- **Target Cueing.**
- **Target Detection Static and Mobile.**
- **Leveraging Strategy.**

Supervisory Control of UGVs

Challenges (cont.)

- **Reconfigurable Man Machine Interface.**
- **Requirement for OCU to operate both as a stand-alone and in various vehicle mounted configurations.**
- **Major emphasis on low power, flat panel displays; interface to helmet mounted displays; and synthetic binaural audio cueing to the operator.**

Optional Robotic Functionality for Manned Systems

Motivators:

- Large DoD investment in manned systems, parts, and training.
- New, specialized robotic platforms are difficult to field at this time, must compete with manned systems for scarce airlift, and have received only luke warm military acceptance at best.
- Optional robotic functionality offers low introduction cost and the opportunity to save lives in hazardous missions. It is a useful way to introduce robotics to the military community and explore possible new mission role (e.g. decoy).

Slide9-8/3/90

Optional Robotic Functionality for Manned Systems

Technical Challenges:

Optional robotic function design requirements

- Non-intrusive actuation and control packages.
- Minimum volume.
- Low power consumption.
- Rugged, reliable and maintainable.
- Quick disconnect/back-drivable.
- Built-in diagnostic functions.

Slide10-8/3/90

Innovative Mobility Platform Technology

Motivators:

- Loss of driver's "seat of the pants" sense of feel regarding wheel slip, vehicle position and estimate of obstacle size results in a near-term loss of mobility compared to manned systems.
- Unconventional platforms may offer a means to compensate for this mobility loss.

Innovative Mobility Platform Technology

Technical Challenges:

- Stability.
- Recovery from roll-over.
- Power consumption.

Depot Telerobotics:

The Challenges

M. B. Leahy, Jr., Ma., USAF, Ph.D.

Robotics and Automation Center of Excellence
San Antonio Air Logistics Center
Technology & Industrial Support Directorate
Advanced Process Technology Section

Background

- Depot Environment
- Race Mission
  - Command Focal Point
  - Technology Pull
  - Champion

Background (cont'd)

- Motivation: Judicious Tech Insertion
- Paradigm:Human Augmentation
- Application Examples:
  - Aircraft/Component Strip & Paint
  - Surface Finishing
  - Deriveting/Cutting
  - NDI
- Enabling Tech: Telerobotics

Challenges

- Technology Transfer
- Standards
- Workspace Sharing
- Robust Input Devices
- Cooperation

Robotics and Telepresence Research Challenges - A Department of Energy Perspective

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Discussion Outline ...

- Overview of US DOE Application Drivers
- Robotics and Telepresence Research Challenges

The US DOE Has Many Application Drivers for Robotics and Telepresence R&D

- **Environmental restoration and waste management**
  - storage tank and buried waste site remediation
  - decontamination & decommissioning of unused faciliaties
  - waste facility and processing operations
  - analytical process automation
- **Continued operations and upgrades to existing remote facilities**

The US DOE Has Many Application Drivers for Robotics and Telepresence R&D (cont.)

- **Developments for planned new facilities**
  - fusion TPX and ITER experiments
  - Superconducting Super-Collider
  - Advanced Neutron Source
  - etc

- **Ongoing basic energy research (ie CESAR)**

- **Improving US economic competitiveness through transfer of engineering and manufacturing technologies to US industry**
  - on-the-shelf now
  - cheap to implement

Robotics and Telepresence Research Challenges

1. Modular, reliable manipulation and mobility systems
   - quickly replace failed hardware in the hazardous environment
   - easy repair of failed modules of system
   - easier upgrades for system improvements
   - reconfiguration allows for more reusability of hardware across applications

Robotics and Telepresence Research Challenges

2. Improved, cost-effective control systems
   - general reusable control architectures
   - modular reusable software
   - eliminate "home cooking" to reduce costs
   - software for automatic generation of algorithms
   - push use of robust and simple intelligent control approaches (fuzzy logic, etc)

Robotics and Telepresence Research Challenges

3. Improved human-machine interfaces
   - generic human-machine interfaces
   - generalized master control for telerobotic systems
   - effective sensor-based operator assists for selective automation and collision detection
   - display of data in useable and concise formats
   - impact of virtual reality approaches unclear

Robotics and Telepresence Research Challenges

4. MOST IMPORTANTLY: Cost-effective evolution of systems from mainly laboratory environments to application environments
   - environmental and radiation hardening
   - constant attention to reliability, maintainability, and cost, a particularly difficult challenge for researchers
   - concerted attention to the machine-environment interfaces

SPACE ROBOTICS AND TELEPRESENCE RESEARCH CHALLENGES

CHARLES R. PRICE

ROBOTICS SYSTEMS TECHNOLOGY
BRANCH

ISSUE # 1

PROGRAM MANAGERS THINK THAT

SPACE ROBOTS DO TOO LITTLE AND

COST TOO MUCH.

ISSUE # 2

TECHNOLOGICAL REALITY IS THAT

SPACE ROBOTS DO TOO LITTLE AND

COST TOO MUCH.

"TODAY'S" SPACE ROBOT:

- CANNOT REACH INTO CONSTRAINED SPACES
- REQUIRES SPECIAL HANDLES ON WORKPIECES
- HAS TO BE CARRIED TO ITS WORKSITE
- IS HEAVY AND POWER HUNGRY
- REQUIRES EXTENSIVE OPERATOR TRAINING
- REQUIRES CONSTANT OPERATOR ATTENTION
- IS SLOW
- IS NOT FAIL OPERATIONAL

WHAT NEEDS TO BE INCREASED:

- DEXTERITY
- PACKAGING DENSITY
- STRENGTH / WEIGHT
- PORTABILITY
- RELIABILITY
- STANDARDIZATION
- INTELLIGENCE
    - VISION
    - PLANNING
    - CONTROL
- ROBUSTNESS
- SPEED

SPACE ROBOTICS CHALLENGES --

A FIVE ITEM SUMMARY:

- TRANSPORTABILITY
- GENUINE DEXTERITY
- ROBUST INTELLIGENCE
- OPERATIONAL EFFICIENCY
- CREATIVELY COST-LIMITED

WHAT NEEDS TO BE DECREASED:

- WEIGHT
- POWER CONSUMPTION
- VOLUME
- LABOR INTENSITY REQUIRED OF OPERATOR
- ROBOT / WORKPIECE INTERFACE OVERHEAD
- DEVELOPMENT SCHEDULE
- COST

THE BOTTOM LINE:

BUILD IT...

AND THEY WILL COME.

Session R3: ROBOTICS AND TELEPRESENCE RESEARCH CHALLENGES: PANEL DISCUSSION

Session Chair: Capt. Paul Whalen

Panel Discussion on
Robotics and Telepresence (R&T) Technology Challenges

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4 August 1993

Abstract

A two-session panel discussion was held at Space Technology Interdependency Group (STIG) Operations Applications and Research (SOAR) 93 to identify the key R&T technology challenges that various members of the STIG Operations Committee (SOC) thought were most important to their applications. Representatives of the National Aeronautics and Space Administration (NASA), US Army (USA), US Air Force (USAF), and Department of Energy (DOE) participated (see Table 1.). Panelists each presented a list of R&T technology challenges in the first session and an open-forum discussion was held in the second session. In addition to the open discussion of the second session, the items among the lists given by the panelists were compared and contrasted. The purpose of this paper is not to discuss in detail the topics that surfaced during the panel sessions, but rather to capture the essence of the discussion and its topics for archival purposes. Interested readers are encouraged to contact either the panelists or the session moderator for further discussion of the topics enumerated in the present work.

Objective of Panel Sessions

Among the explicit goals of the SOC which sponsors the SOAR are to encourage interdependent programs and to identify critical voids in technology programs. Consequently, the objectives of these panel sessions were to (1) identify the shortfalls of R&T technology that are of greatest concern to the various government agencies represented on the panel and, (2) enumerate areas of common interest that may be targets for increased interdependent research.

Format of Panel Sessions

The first session consisted of five presentations lasting 15 minutes each. Each of the panelists listed in Table 1 had a turn to present a list of three to five challenges for the R&T research community and briefly justify them.

Table 1: List of Panel Members and their credentials

Name and Mailing Address	Credentials
Mr. Joseph N. Herndon Oak Ridge National Lab (ORNL) P.O. Box 2008 Oak Ridge TN 37831-6304	Acting Division Director of the Robotics and Process Systems Division of ORNL. US DOE Task Leader for Remote Handling on the International Thermonuclear Experimental Reactor Project. Vice Chairman of the Robotics and Remote Systems Division of the ANS.
Maj Michael B. Leahy Jr, PhD SA-ALC/TIEST Bldg 183 450 Quentin Roosevelt Rd Kelly AFB TX 78241-6416	Chief of Advanced Process Technology Section of the Technology and Industrial Support Directorate of the San Antonio Air Logistics Center and Program Manager for the Air Force Materiel Command (AFMC) RACE.
Mr. Charles R. Price NASA Johnson Space Center (JSC) ER4 Houston TX 77058	Chief, Robotic Systems Technology Branch at JSC. Oversees many projects including the Manipulator Development Facility, Automated Maintenance for Space Station, and the Dexterous Anthropomorphic Robotic Testbed at JSC.
Mr. Charles M. Shoemaker US Army Human Engineering Lab Attn: ACAP Aberdeen Prov. Gnd. MD 21005	Chief, Robotics Focus Program Office at the Army Research Laboratory (ARL). Directs near-term technology base program for Office of the Secretary of Defense's Robotics Program. Managed DEMO I Unmanned Ground Vehicle program for Army.
Dr. Charles R. Weisbin NASA Jet Propulsion Laboratory (JPL) Mail Stop 196-219 4800 Oak Grove Dr Pasadena CA 91109-8099	JPL Program Manager for Rover and Telerobotic Technologies and Senior Member of the Technical Staff. Co-chairman of the R&T Subcommittee of the SOC and the NASA Telerobotics Intercenter Working Group.
Capt Paul V. Whalen (Moderator) AL/CFBA, Building 441 2610 Seventh St WPAFB OH 45433-7901	Program Manager for the Human Sensory Feedback (HSF) for Telepresence program at the Armstrong Lab. Member of the R&T Subcommittee of the SOC and one of the principal organizers of the R&T sessions of the SOAR Symposium.

The second session was an open discussion among the panelists, the audience, and the session moderator. During this session, panelists had the opportunity to advocate their list of challenges in view of those from the other panelists and further detail issues presented in the first session.

Overview of Session 1 Presentations

Copies of the viewgraphs for the five presentations are included in these SOAR Proceedings. Brief comments on each of the presentations follow.

DOE

The DOE was represented by Mr. Joe Herndon of ORNL. Most of the ORNL R&T technology is driven by environmental restoration and waste management efforts. The DOE has been working on cleaning up hazardous waste storage tanks and buried waste sites for some time. Since the condition of the containers is typically poor and the inventory data sparse, teleoperated manipulator systems must be used to extract the waste containers for repackaging. In addition, unused facilities which have been contaminated by radioactive materials must be decontaminated and decommissioned. These initiatives alone are significant applications for the R&T technology for DOE, but they are also pressed to make plans for new facilities such as the super-conducting super-collider (SSC)[1] and emphasize technology transition to industry.

The R&T challenges listed by ORNL were:

- Modular, reliable manipulation and mobility systems
- Improved, cost-effective control systems
- Improved human-machine interfaces
- Cost-effective evolution of systems from laboratory to application environments

USAF

The USAF was represented by Major Michael B. Leahy Jr. of the San Antonio Air Logistics Center (SA-ALC) Robotics and Automation Center of Excellence (RACE). The RACE is required to work in a depot maintenance environment. This is a cost-driven environment which demands *judicious* technology insertion rather than trying to use anything that is hot out of the laboratory. The processes and tasks that are targeted by the RACE are generically called Air Logistics Center (ALC) operations. Many of the tasks that must be performed in ALC operations are very low-volume, manpower intensive tasks. A typical task may consist of removing rivets from a damaged section of aircraft skin, cutting it out, cutting a new piece of skin to match the shape of the old piece, deburring the new skin, and re-riveting it in place. The RACE is looking towards telerobotics to achieve a higher degree of productivity and process improvement rather than just a higher degree of automation. They seek to augment humans rather than trying to replace them. However, to do this means that the telerobotic tools must be easier to use than the existing tools or the workmen will not adopt the new systems. This, of course, drives home the need for reliable systems with top-notch human-machine interface for ease of operation.

The R&T challenges listed by RACE were:

- Transfer of existing component technologies to commercial sector
- Community-wide standards for hardware and software
- Safe, reliable methods of allowing shop floor personnel to share workspace with robotic systems
- Robust input devices for operator-friendly user interface
- Cooperation among researchers at all levels in Department of Defense (DOD), national labs, NASA, and universities.

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[1] At the time of this writing, funding for the SSC is under Congressional scrutiny. By the time these proceedings are published, a decision should have been made about continuing support for the SSC.

NASA JSC

JSC identified the Achilles' heel of space robotics: robots, in fact, do too little for mission success and cost too much. To make matters worse, program managers are aware of this reality. Some of the limitations of current space robots that were cited included poor workspace due to oversized limbs, lack of self mobility, large weight and power consumption, extensive operator training, need for continual monitoring, and lack of fault tolerance. These observations led to a list of items which need to be increased. That list included dexterity, packaging density, strength-to-weight ratio, portability, reliability, standardization, intelligence, robustness, and speed. The items needing reduction were weight, power consumption, volume, operator intensity, robot/workpiece interface overhead, development time, and cost.

The R&T challenges listed by JSC were:

- Transportability (ground to orbit or ground to lunar)
- Genuine dexterity (manipulator dexterity equivalent to astronaut in space suit)
- Robust intelligence (integrated systems with fault tolerance)
- Operational efficiency (shorter training and less support required)
- Creatively cost-limiting development (need fresh ideas on design)

USA.

The USA was represented by Mr. Charles Shoemaker of the ARL. The ARL is primarily concerned with Unmanned Ground Vehicles (UGVs). Although they strive towards autonomous vehicles, their current thrust is teleoperated ground vehicles. Through the use of supervisory control of UGVs, they plan to make optimal use of a reduced manpower pool. In addition to the difficult technology challenges of complete autonomy, the acceptance of autonomous systems by operational users (field commanders) is generally not very high. This is due, in part, to poor demonstrated reliability of current systems and their lack of versatility. The ARL is currently retrofitting fielded combat vehicles, such as the High Mobility Multi-Wheeled Vehicle (HMMWV), with optional robotic functionality while maintaining its ability to be operated manually. This kind of system is far more acceptable to field commanders because it has back-up functionality and can be easily mobilized with other unmodified vehicles.

The R&T challenges listed by ARL were:

- Supervisory control of UGVs
    - On-board autonomy for mission function and mobility
    - Data compression and reconstitution
    - Reconfigurable man-machine interfaces
- Optional robotic functionality for manned systems
    - Non-intrusive actuation and control packages
    - Minimum volume, low-power consumption systems

  - Rugged, reliable, and maintainable systems
  - Capability for quick disconnect or back-drivable
  - Built-in diagnostic functions

- Innovative mobility platform technology
  - Stability
  - Recovery from rollover
  - Low power consumption

NASA JPL

Much of the research activity described by the JPL centered on mobility for planetary exploration and on-orbit robotic system teleoperation. Plans for a Mars rover which meets stringent weight, power consumption, and heat dissipation requirements appear to be the primary driver for the planetary rover research. The Mars rover must be extremely robust to environmental extremes (such as temperature, wind, etc.), and able to navigate in an unstructured (mostly unknown) environment with very sparse interaction from earth due to the communication delays. These requirements dictate conflicting requirements on the level of autonomy for the rover system. To cope with the difficult navigation requirements, it needs a powerful computing system with sophisticated reasoning algorithms. However, the low power, low weight, and environmentally hardened specifications eliminate all but the most primitive microprocessors because it must be a space qualified microprocessor. This, indeed, generates some difficult technology challenges which are listed below.

- Realtime perception and goal identification with limited computing power
- Ability to navigate with sparse terrain mapping data
- Need for systematic benchmark experiments to compare systems
- Increased fault tolerance and error recovery capability
- Ability to navigate autonomously when out of visual range from the lander platform

In addition to the rover research, the JPL is working to develop improved telerobotic systems for space and terrestrial operations. They have work underway in manipulator modelling and control, real-time planning and monitoring, navigation in outdoor terrain, real-time sensing and perception, human-machine interface and overall system architectures [2]. The R&T technology challenges cited by the JPL for space robotics were:

- Automated operation of remote dexterous robots from the ground
- Compilation and concatenation of robots' skills into publicly available libraries of motion primitives
- Need for instrumented end-effectors with improved dexterity
- Methods of determining object verification and pose refinement with limited computing resources
- Need for sensory skins for obstacle avoidance
- Methods for safe and robust control of manipulator/environment interaction

Overview of Session 2 Discussion

The moderator opened the second session by enumerating observations about commonalities between the various panel presentations in the first session. The list of items and the organizations that shared them included:

- Rover and mobility concerns (ARL, JPL, JSC)
- System concerns
  - Low-power, light-weight (ARL, JPL, JSC)
  - Modularity and reconfigurability (DOE, JSC, ARL, RACE)
  - Reuseable code and control architectures (DOE, RACE)
  - Standardization and metrics (DOE, RACE, JSC, JPL, ARL)
  - Reduced cost (DOE, JSC, RACE)
  - Low-bandwidth communication and control (ARL, JPL)
  - Improved end-effector dexterity (JPL, JSC, DOE)
  - Generic telerobotic (man-machine) interface (DOE, RACE, ARL)

Cultural Acceptance of R&T and Autonomy

The open discussion began with panelists voicing concern about the social acceptance of autonomy among the user community. The lack of faith in autonomous robotic solutions has hampered several attempts to field systems. For instance, ARL has been unable to gain any interest among its field commanders for autonomous vehicles that could be used for reconnaissance or targeting. Instead, the ARL has chosen the strategy of retrofitting already-accepted vehicles with *optional* teleoperated capabilities. Acceptance for such systems has been far greater than for specialized autonomous solutions. Using this strategy allows them to gradually introduce autonomy in the systems as the technology becomes proven.

RACE advocated semi-autonomous systems as a bridge between what the user community wants and what the research community wants to provide. The users want something simple, cheap, easy to operate, and reliable that will help improve their processes. The researchers, on the other hand, typically want to provide high-technology solutions that do not have proven reliability. Implementing semi-autonomous systems makes use of existing technology that has proven reliability but also allows new technology to grow *in* the application as it is proven. Thus, the autonomous function toolbox gains tools to draw upon as the technology develops. This tends to move the overall system farther from the manual teleoperation end of the spectrum and closer to the purely autonomous robot end as time goes on.

Along with the construction and manning of the proposed space station, the space community has a growing need for increased autonomy. As the number of missions and on-orbit hours increase over the years, space operations become more production oriented and less unique. Maintenance of space platforms, such as the space station, will require many routine operations that will necessarily be automated because of the time involved in doing them. The Flight Telerobotic Servicer (FTS) program was to design a fully autonomous vehicle for maintenance operations on the space station. After spending over $200M the program was cancelled before it could reach flight demonstration because of cost overruns and technical problems. This was a jolting reminder that space robotics is still technically in its infancy and appropriate "baby" steps should be taken before another overly ambitious project will receive support from NASA. The lessons learned from the FTS will likely not be forgotten soon.

Role of virtual reality (VR) in R&T

The role of VR in R&T was the next topic of discussion. There are obvious overlaps between technologies developed for VR and those developed for R&T. Several of its more obvious roles were identified. Examples were off-line simulation and training. In general, panelists agreed that realtime VR was still a tough challenge because of the computational burden and the bandwidth limitations imposed by the amount of data that must be communicated to the user.

Although the visual display is an integral part of both VR and R&T, the unique facet of R&T that has yet to be adequately addressed by the VR community is force and tactile feedback. There is a common tendency to focus one's attention on visual display when discussing VR systems. For a VR system to achieve full *immersion* of the operator, it must also have audio, force and tactile feedback. There is a widely recognized technology void in the area of developing force-reflecting exoskeleton systems for the whole arm as well as for the fingers of the hand. The fundamental limitation in design of force-reflecting exoskeletons is the lack of suitable actuator technology. The combined requirements for small size, light weight, high power density, and high actuation bandwidth leave virtually no actuator technology candidates standing. In the view of the author, this is perhaps the most serious limitation of future VR and R&T system development.

Importance of Force-feedback.

The importance of force-feedback became the next discussion topic. There were proponents of force-feedback who argued that it has been proven to increase teleoperator system performance in many tasks as demonstrated by the DOE and others. There were also people who stated unequivocally that their tasks did not benefit from the addition of force-feedback to the telerobotic system. One example of such an application is the teleoperation of heavy equipment for Rapid Runway Repair (RRR). In this case, a full-scale backhoe is teleoperated to excavate unexploded ordnance and repair craters in runways damaged by air attack. The Air Force Construction Robotics Program at Tyndall AFB FL (HQ AFCESA/RA) has evaluated force-feedback for this task and found that it is not beneficial. This is not surprising when one considers that a backhoe operator does not use force-feedback information even when manually operating his equipment. However, the benefit from force-feedback for other tasks is undeniable. For instance, part mating is inherently a force-domain task and providing force-feedback information to the operator has improved task performance in several studies (for example, see [1].) .

Customer Involvement

Panelists agreed that the research community in R&T, like that of many other technologies, has not been very good at understanding and addressing the constraints of their technology using customers. To be effective, researchers must recognize the constraints of their users and make serious attempts to work within them. Typical constraints may be size limitations, weight limitations, cost limitations, reliability requirements, etc. Some constraints are even time based such as deadlines for delivery. There are other options for most mission requirements and R&T solutions will not be welcome until they are competitive with the other options.

Need for Standards and Metrics among R&T Community

Cost, development time, and reliability are perhaps the weakest points for developing R&T solutions. All of these factors could be improved with accepted standards which would boost the commercialization of technology. Currently there are no commercial systems that allow systematic interface of various sensors into robotic systems. The R&T community needs to work towards standards that will allow researchers and system developers to pull component systems off the shelf and use them without the extensive integration work that is currently required. The idea of establishing standards for the whole field of R&T is overwhelming and, even if it were possible, it would probably stifle some areas of development. On the other hand, a "bottom-up" approach to establishing standards could benefit all parties. Well-formulated standards for component systems can be aggregated over time into more pervasive standards as they mature.

Metrics are also needed to make meaningful comparisons between similar solutions to the same problem. For instance, a mobility metric would be useful to compare unmanned ground vehicles that use completely different modes of mobility (e.g., legged, wheeled, tracked, etc.). Even within a single mode of mobility, there is currently no agreed-upon metric by which comparisons can be made. Although grey areas of comparison will always persist, a good metric could at least help identify the very good and very bad solutions.

Collision Detection and Avoidance

A brief discussion on collision detection and avoidance concluded that viable solutions are near maturity. The JPL is concluding a study on range sensors this year and will be using that information in its development of skin-type contact sensors. Most of the panel members said they would probably use collision detection and avoidance technology, but they were not actively pursuing it. The army mentioned that the type of collision detection they are interested in is the same kind that the Department of Transportation (DOT) is working on for the Intelligent Vehicle Highway System (IVHS). The IVHS is envisioned to eventually have autonomous vehicles shuttling people between destinations with little or no operator involvement. Avoiding collisions in emergency situations and maintaining safe spacing between vehicles on the highway are tasks that will require sophisticated collision detection and avoidance capability.

Conclusions

The two sessions were intended to identify important technology areas that the various member agencies of the SOC may have in common. There were several areas that were immediately obvious after the first of the two sessions which are listed herein. There are undoubtedly others that are common but are of lesser importance to the individual agencies as represented by the selected panelists. Having identified some common areas of interest, opportunities have been identified for increased interaction and interdependency among the participating agencies at various levels. This interaction may lead to reduced duplication and/or joint funding for specific programs in the future. This, of course, is the primary purpose of the SOC which sponsors the SOAR. It is this author's hope that these two panel discussion sessions have furthered that cause.

References

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Session R4: REMOTE INTERACTION WITH SYNETHETIC ENVIRONMENTS

Session Chair: Dr. Harold Hawkins

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