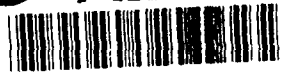AD-A252 567

A RAND NOTE

**Automation and Robotics for the
Space Exploration Initiative:
Results from Project Outreach**

D. Gonzales, D. Criswell, E. Heer

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PREFACE

This Note describes the findings of the Automation and Robotics panel, one of eight project panels established by RAND to evaluate submissions to the Space Exploration Initiative (SEI) Outreach Program, also called Project Outreach. Project Outreach is a NASA-sponsored program to elicit innovative ideas, concepts, and technologies for space exploration. The project was sponsored by Project AIR FORCE and by RAND's Domestic Research Division, with technical oversight provided by the Assistant Secretary of the Air Force (Space).

The findings of other RAND panels are reported in the publications listed below.

Space and Surface Power for the Space Exploration Initiative: Results from Project Outreach, C. Shipbaugh, K. Solomon, M. Juncosa, with D. Gonzales, T. Bauer, and R. Salter, N-3280-AF/NASA, 1991.

Space Transportation Systems, Launch Systems, and Propulsion for the Space Exploration Initiative: Results from Project Outreach, T. Garber, J. Hiland, D. Orletsky, B. Augenstein, and M. Miller, N-3283-AF/NASA, 1991.

Human Support Issues and Systems for the Space Exploration Initiative: Results from Project Outreach, J. Aroesty, R. Zimmerman, and J. Logan, N-3287-AF/NASA, 1991.

SUMMARY

BACKGROUND

President Bush stated his objectives for a Space Exploration Initiative (SEI) on July 20, 1989. He called for a program that includes establishing a permanent outpost on the Moon and sending a manned mission to Mars. In response to the President's announcement, NASA conducted a 90-day study that presented a variety of strategies for accomplishing those objectives.

Subsequently, Vice President Quayle, Chairman of The National Space Council, asked NASA to take the lead in identifying new and innovative approaches for traveling to the Moon and Mars and for living and working on both. Accordingly, NASA solicited ideas through the SEI Outreach Program, which had three principal components:

1. Direct solicitation of ideas from academic institutions, private enterprise and the general public.
2. Reviews of federally sponsored research.
3. A study by the American Institute of Aeronautics and Astronautics (AIAA).

NASA asked RAND to evaluate the results of the direct solicitation effort and provide that evaluation to the Synthesis Group chaired by Thomas P. Stafford, Lieutenant General, USAF (ret.). The results from the review of federally sponsored research and the AIAA study will also be available to the Synthesis Group. The Synthesis Group will make a further evaluation and synthesize at least two distinctively different SEI architectures and will submit its recommendations to NASA and The National Space Council.

A total of 52 submissions were received in the Automation and Robotics (A&R) area during Project Outreach. About half of the submissions (24) contained concepts that were judged to have high utility for the Space Exploration Initiative (SEI) and were analyzed further by the robotics panel. These 24 submissions are discussed and analyzed in this Note.

Three types of robots were proposed in the high-scoring submissions: structured-task robots (STRs), teleoperated robots (TORs), and surface exploration robots. Several advanced TOR control interface technologies were proposed in the submissions. Many A&R concepts or potential standards were presented or alluded to by the submitters, but few specific technologies or systems were suggested.

RECOMMENDATIONS

Review of the submissions and further research in A&R issues has led the Project Outreach A&R panel to make the following observations and to submit the following recommendations for consideration by the Synthesis Group:

- Systematically integrate SEI robots, work environments, and systems.
- Develop structured-task robots for SEI.
- Adapt and develop advanced TOR control interfaces that enable telepresence.
- Evaluate the architectural implications of using TOR telepresence control in SEI.
- Reevaluate and harmonize early SEI remote sensing data collection requirements with later SEI robotic mission requirements.
- Conduct tradeoff studies to select optimum mobility and navigational subsystems for SEI surface exploration robots. Teams of complementary exploration robots should be considered in these tradeoff analyses.
- Conduct tradeoff studies to determine the most cost-effective and productive development path towards autonomous robots.
- Review NASA's evaluations of A&R effort for Space Station Freedom.

Below we discuss these recommendations in more detail.

Integrate SEI Robots, Work Environments, and Systems

Most human work environments can be unstructured because humans can easily and rapidly adjust to unanticipated changes or events in their environment. Such human adaptability and flexibility result from our sophisticated sensing, planning, navigation, and movement skills. The current state of the art in robotics cannot provide systems that faithfully mimic these human capabilities; thus, SEI work environments in space and on the surface of the Moon or Mars must be carefully designed with the current limits of robotics in mind. SEI robot end-effectors should all be designed and manufactured to a limited set of end-effector design rules, so different robots can use the same end-effectors for several manipulation tasks. And SEI components should be designed in a complementary fashion so they can be manipulated efficiently by robots using such standardized end-effectors.

A critical area being ignored in the United States, but under consideration in Japan, is the development of space facilities that make extensive use of robots in their normal sequence of assembly, maintenance, and repair. Robots are still viewed in the United States

as gadgets or tools that are added to a structure to be constructed and maintained primarily by people. Extensive design exploration and demonstration efforts should be initiated to provide the United States with options for space and planetary systems that are primarily constructed, maintained, and repaired by robots. This theme was mentioned only tangentially in the Outreach submissions but has emerged as a critical recommendation from the A&R panel's own analysis.

Perhaps the most important issue involved in systemically integrating SEI robots, work environments, and systems is capturing and maintaining configuration control over SEI system designs. Detailed engineering design data should be captured in a common digital format and made portable so that it can be used by different system contractors during design and manufacturing and by robots in space during assembly and repair operations. Automated capture of SEI systems designs has been made possible with the advent of integrated Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) tools. Transportability of CAD/CAM files is also being improved with the introduction of commercial standards such as the emerging Electronic Data Interchange Format (EDIF) CAD/CAM standard [Ref. 1]. NASA should monitor the development and use of CAD/CAM tools and standards in the semiconductor and other industries and adapt these increasingly powerful design tools to SEI systems and robots.

Develop Structured Task Robots for SEI

The most productive robots on Earth are STRs. They have transformed the Japanese auto and semiconductor industries. Now the Japanese install as many robots every year as exist in the entire U.S. industrial base [Refs. 2, 3]. Even more productive robots will be needed for SEI if the President's ambitious mission goals are to be met within the specified time frame and within future budget constraints.

Much further research into the use of STRs in space is required. The work recommended in submission #100378 should be greatly expanded for SEI. Assembly tasks should be made easy and modular, enabling STRs to be used wherever feasible at extraterrestrial operations nodes.

Review of the submissions and this panel's research and inquiries indicate that NASA A&R research and development activities may be too tightly focused on expensive one-of-a-kind high-technology developments like the Flight Telerobotic Servicer (FTS).[1] It is nevertheless unfortunate that the FTS program has recently been cancelled. While the FTS

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[1]The FTS program has recently been downgraded from a full development program to a technology demonstration project.

program is a necessary and ambitious technology demonstration project, SEI funds should also be allocated towards development of STR work environments and STRs for specific SEI applications. These activities can help revive the moribund U.S. commercial robotics industry and will also provide a natural "upstream" technology base for the eventual colonization and industrialization of the Moon.

Adapt and Develop Advanced TOR Control Interfaces

Submissions #100695, #100338, #101469, #100827, #100336, #101317, and others propose that TORs be used for many SEI assembly, processing, repair, and exploration tasks. Because TORs can be remotely controlled by humans, they can operate in unstructured environments and are more flexible and adaptable than STRs. They also require much less complex real-time software than autonomous robots. As a consequence of this, a variety of TORs have been developed for commercial and space applications, while autonomous robots have yet to be realized. However, most TORs available today are cumbersome to operate and typically perform manipulation tasks much slower than humans. For example, it is estimated that the FTS in its initial configuration will perform manipulation tasks in space at a significantly slower rate than a well-trained astronaut in an extra vehicular activity (EVA) spacesuit. The performance limitations of current TORs have therefore prompted researchers to develop new TOR control interfaces to improve TOR productivity.

NASA researchers were among the first to develop new and innovative display and interactive computer control technologies, such as "eye phones" and "power gloves," which offer tremendous promise as TOR control interfaces. Now commercial companies, both in the United States and Japan, are racing to refine and extend these technologies for many different consumer, scientific, and business products. In addition, HDTV, high-resolution flat-panel displays, and new three-dimensional display volume systems are being developed. The leading edge of development for these technologies is now being pushed faster and harder in the commercial world. NASA needs to keep abreast of these new developments, test new systems for TOR control, and integrate those that demonstrate their worth into future TOR systems, such as the FTS. These new technologies will allow NASA astronauts and the general public alike to experience SEI missions first-hand through telepresence.[2]

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[2]Telepresence can be briefly defined as the creation for the individual user of a realistic, detailed, and complete artificial sensorium which "tricks" the user into believing he or she is present at a remote location. Computer and TOR control interfaces which exhibit telepresence have been called virtual environments, artificial realities, or cyberspaces by researchers, futurists, and science fiction writers.

New commercial speech synthesis and recognition products also are poised to enter the marketplace. NASA should monitor these developments so these capabilities can be quickly and cost-effectively integrated into new TOR control interfaces.

Emerging TOR control technologies and advances in computer simulation may also permit development of radically new control interfaces that promise great increase in TOR operator productivity and the effective radius of TOR control from thousands to millions of kilometers. Many Project Outreach submissions suggested development of advanced TOR control interfaces capable of telepresence. One submission in particular (#100317) described in broad conceptual terms the enormous potential benefits of using these new technologies for TOR control.

NASA needs to study these emerging technologies to see how they can best be used to control TORs and to see if they lead to new strategies for obtaining higher forms of machine autonomy.

Evaluate the Architectural Implications of TOR Telepresence Control

TORs may be used extensively in many phases of SEI operations. A significant amount of TOR coordination, mission planning, and real-time retasking will be required, especially for complex and TOR-intensive operations like assembly of Mars Transfer Vehicles (MTVs) or lunar base construction. If telepresence technology is used for TOR control, even more coordination may be necessary because TOR operators will be sensorially centered at the remote site where their TORs operate and not at their control stations.

By making analogies to certain military operations and practices, it is conjectured that TOR Command, Control, and Communications (C3) centers will be required to efficiently and safely perform TOR supervision, coordination, and task planning. Depending upon the sophistication of TOR control available in the time frame of SEI, TOR C3 centers may be required at each major extraterrestrial SEI operations center. Although different terminology is used by the author, submission #100337 suggests development of such TOR C3 centers.

TOR command and control manpower, power, habitat, and communications requirements must be studied by NASA and included in future SEI architecture studies. The most significant implication of the widespread use of TORs and the incorporation of telepresence control in SEI is the greatly increased communications burden SEI space networks may have to support. If one conjectures that HDTV-like display devices are used for stereoscopic control of each TOR, then approximately two HDTV channels will have to be

supplied for every TOR controlled from a distant location.[3] New developments in image compression and distributed simulation technologies will be required to reduce TOR command and control communications requirements and make SEI TOR telepresence control a reality. NASA should carefully monitor developments in these areas.[4]

Deepen SEI Robot Mission Planning

As the SEI program proceeds over the next quarter-century, SEI operations will increase in scope and complexity. Succeeding generations of SEI robots will depend upon and exploit data collected from previous SEI and NASA missions. Data collection requirements on early missions should therefore be carefully determined with later SEI mission needs in mind. Synergies may exist between early SEI data collection efforts and later exploratory, construction, or resource extraction missions. If high-resolution data are collected on early exploratory missions, they may prove useful for many purposes and could reduce the cost and complexity of follow-on robotic systems, such as lunar rovers or base-construction robots. For example, as pointed out in submission #101067, the size and cost of lunar rovers could be reduced if data collected in early lunar remote sensing missions could be used to determine lunar rover "road networks" free of obstacles larger than 0.1 m. In addition, such data collection efforts would provide scientists and prospectors with an unprecedented geologic record of the lunar and perhaps Martian surfaces.

High resolution imaging (0.1 m) of the Moon is feasible and could be carried out at a number of wavelengths. NASA should examine innovations in new sensor technologies and small satellite developments (Lightsats) to see if Lunar Observer or Martian Observer spacecraft should be augmented by new lightweight remote sensing systems that could not only provide higher resolution optical imagery but could also image permanently dark craters near the lunar poles [Ref. 5].

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[3]The FTS vision subsystem is composed of four ordinary (NTSC) video cameras: two anthropomorphically positioned on the robot's "head" and the other two placed at the wrist of each of the FTS's two robot arms [Ref. 4]. Some SEI TORs may also require more than two video channels even if high resolution imaging systems, such as HDTV, are used. Further TOR vision and control research is needed to answer these questions.

[4]The many other technologies beside high resolution image displays required for development of TOR telepresence control are described in detail in the body of this Note. However, the requirement to transmit high resolution imagery from the robot to the TOR controller places the greatest burden on the intermediate communications network. High resolution imagery is an essential component of telepresence, as it helps to embed the TOR controller in a realistic artificial sensorium.

Surface Exploration Robots

A number of surface exploration robots have been proposed in various Project Outreach submissions to perform exploration tasks over various types of terrain (submissions #100336, #101067, #100815, #100337, #101325, #100339, and #100343). They can be grouped according to the mobility and navigation concepts they employ. Tradeoff studies need to be conducted comparing various mobility and navigation concepts to select those that could best fulfill SEI mission objectives. Submission #100343 proposes that robot teams be used to explore the Martian and lunar surface. Such a team may offer more terrain flexibility and may be more cost-effective than employing a small number of identically configured multipurpose rovers.

Transition to Autonomous Robots

One key SEI robotics programmatic issue over the next twenty years will be the schedule development risk for semi-autonomous or autonomous robots. Versatile autonomous robots capable of operating in unstructured SEI environments (an unprepared planetary surface, or free-flying LEO) will require many sophisticated capabilities. These capabilities require development of large, error-free, software codes and, as with all software development, the risk must be considered high. Initial operating capability (IOC) dates for autonomous robots cannot be predicted and may not be achievable without an enormous investment in software development infrastructure.

Long-term tradeoff studies need to be performed by NASA and updated annually or biannually to determine the most cost-effective and technically feasible long-term autonomous robot development plan and to determine the balance between TOR and autonomous robot research and development. In addition, such assessments could also be used to determine which key subsystem technologies must be targeted for further development. If current technology trends continue, TORs equipped with telepresence control interfaces and limited forms of autonomy will prove to be the preferred development path.

Several submissions (#100342, #100345, #100348, #100442, and #100333) recommend that in order to develop autonomous robots, NASA should adapt or develop emerging artificial intelligence technologies, autonomous navigation software, and new modular robot control and software standards such as the NASA/NBS Standard Reference Model (NASREM) and the USAF Next Generation Controller Project for a Standard Open System Architecture Specification (SOSAS). While these standards are rather general in nature at

this time, NASA can certainly profit from examination of these systems. With regard to development of advanced software products such as expert systems, a careful examination by NASA of the associated software development risks will be needed.

Review NASA's Evaluation of A&R Effort for Space Station Freedom

The United States space program would be impossible without a level of automation and robotics that reflects, to some extent, the general state of the art. However, over the past twenty years, the dominant role of military and NASA agencies in A&R research and development has been sharply reduced while the role of commercial industry has increased proportionally. A major challenge to NASA is simply maintaining an awareness of A&R advances and how these technologies are being used in new ways in the commercial world (use of CAD/CAM tools in the semiconductor industry is one example). Implementation of evolving A&R technologies is an enormous challenge to the agency. At the direction of Congress, NASA has conducted a continual review of the implementation of A&R within the Space Station Freedom. A&R implementation efforts have been reviewed approximately every six months since 1985 [Refs. 6-15]. We recommend that the Synthesis committee review NASA's evaluations of the Space Station Freedom effort to see how advanced A&R could be incorporated into SEI. Such a review will reveal the many difficulties, both human and technological, that lie ahead and, at the same time, the great motivations for pressing ahead.

ACKNOWLEDGMENTS

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FIGURES

TABLES

ACRONYMS

A&R	Automation & Robotics
ADAM2	Astronautics Dexterous Anthropomorphic Manipulator
ADP	Advanced Data Processing
AI	Artificial Intelligence
AIAA	American Institute of Aeronautics and Astronautics
ARMS	Autonomous Resource Management System
ASCS	Automated Sampling and Collection System
C2	Command and Control
C3	Command, Control, and Communications
CAD/CAM	Computer Aided Design/Computer Aided Manufacturing
CAE	Computer Aided Engineering
CRT	Cathode Ray Tube
CSI	Cyberspace Interface
CST	Computer Simulated Teleoperation
DMS	Data Management System
DoD	Department of Defense
ES	Expert System
EVA	Extra Vehicular Activity
FDS	Fixed Depot Station
FOV	Field of View
FTS	Flight Telerobotic Servicer
HDTV	High Definition Television
IOC	Initial Operational Capability
JPL	Jet Propulsion Laboratory
Kg	Kilogram
KHz	Kilohertz
LCD	Liquid Crystal Display
LEO	Low Earth Orbit
Lightsats	Light Weight Satellites
LTV	Lunar Transfer Vehicle
MB	Mega Bit
MIT	Massachusetts Institute of Technology

MITI	Ministry of International Trade and Industry
MSRM	Mars Sample Return Mission
MTV	Mars Transfer Vehicle
NASREM	NASA/NBS Standard Reference Model
NTSC	National Television System Committee
PDDI	Product Definition Data Interface
PDES	Product Data Exchange Specification
R&D	Research and Development
RPV	Remotely Piloted Vehicle
RTV	Remote Tug Vehicle
SAR	Synthetic Aperture Radar
SEI	Space Exploration Initiative
SOSAS	Standard Open System Architecture Specification
SSF	Space Station Freedom
SSR	Speech Synthesis and Recognition
STR	Structured Task Robot
TC	Telepresence Control
TI	Texas Instruments
TMS	Telemanipulation System
TOR	Teleoperator Robot
TSR	Transportable Service Rover
VCR	Video Cassette Recorder
VHSIC	Very High Scale Integration Circuit
VLSI	Very Large Scale Integration
WARPM	Wheeled Articulating Rover Propulsion Methods

I. INTRODUCTION

This Note describes the results of RAND's management of the direct solicitation component of the Space Exploration Initiative (SEI) Outreach Program, a program designed to solicit creative ideas from academia, research institutions, private enterprise, and the general public to help in defining promising technical areas and program paths for more detailed study. In addition to managing and evaluating the responses or submissions to this public outreach program, RAND conducted its own analysis and evaluation relevant to SEI mission concepts, systems, and technologies. The screening and analysis of Outreach submissions was conducted between July and October 1990, and involved staff and consultants throughout RAND's departments and research divisions.

Eight panels were created to screen and analyze the submissions. These panels encompassed:

- Space and Surface Power
- Space Transportation Systems, Launch Systems, and Propulsion
- Automation and Robotics
- Human Support
- Structures, Materials, Mechanical Systems, and In-Situ Processing
- Communications
- Information Systems
- Architectures and Missions

This Introduction describes the overall methodology used in submission handling and analysis, as well as some general results and observations. The body of the Note contains the analyses and evaluations of the Automation and Robotics panel.

BACKGROUND

President Bush has called for a Space Exploration Initiative that includes establishing a permanent base on the Moon and sending a manned mission to Mars. The national space policy goals developed by the National Space Council and approved by President Bush on November 2, 1989, were the following:

- Strengthen the security of the United States;
- Obtain scientific, technological, and economic benefits;

- Encourage private sector investment;
- Promote international cooperative activities;
- Maintain freedom of space for all activities;
- Expand human presence and activity beyond Earth orbit into the solar system.

To support these goals, Vice President Quayle, Chairman of the National Space Council, has asked NASA to take the lead in identifying new and innovative approaches that will be required to travel to the Moon and Mars and to live and work productively on both worlds. Accordingly, NASA has begun to solicit new ideas and concepts for space exploration that will define promising mission paths for detailed study. The SEI Outreach Program has three principal components:

1. Direct solicitation of ideas from academia, nonprofit organizations, for-profit firms, and the general public.
2. Reviews of federally sponsored research.
3. A study by the American Institute of Aeronautics and Astronautics (AIAA).

The results of the three efforts listed above will be presented to a Synthesis Group chaired by Thomas P. Stafford, Lieutenant General USAF (ret.). The Synthesis Group received a number of ideas from various sources, collected additional information, and conducted detailed analysis. This process resulted in a synthesis of ideas. The recommendations of the Synthesis Group will be presented to the NASA Administrator and the National Space Council. From this process, a number of alternative mission paths will emerge for detailed study over the next few years. In addition, the process is expected to yield innovative technologies and system concepts for possible development.

GENERAL OBSERVATIONS ON THE SUBMISSIONS

Our first observation is that the submissions did not contain any new scientific laws, principles, or wholly new areas of technology. For example, some submissions suggested applications of high-temperature superconductivity, which five years ago could have been considered a "new" technology. However, superconductivity was first discovered in the early 1900s, and the possibility of high-temperature superconductors was discussed soon afterward, so it should be understood that "new" technology areas are a matter of perspective.

However, the submissions did contain a number of old ideas that have new implications in the context of the SEI. For example, several submissions included the

concept of a spacecraft hovering at a libration point, a concept that has been proven by NASA's International Sun-Earth Explorer-3, which was put into orbit around the Sun-Earth libration point, L-1, in 1978. Libration concepts take on considerably new meaning in the context of potential use as transportation nodes for a Mars mission. See R-4112-AF/NASA for further discussion.

The submissions also contained ideas that had not been heretofore supported by the submitter's organization, which may have been an industrial firm, university, or NASA itself. This is a natural consequence of the priority planning process and resource allocation decisions of each individual organization. Thus, many of the submitted ideas are not completely new, but simply have not received much support heretofore.

Lastly, we observe that the submissions were sufficiently diverse to support a wide range of SEI mission concepts and architectures.

THE SUBMISSION PROCESS

Figure 1 presents a flow diagram of the Outreach evaluation process. RAND mailed out 10,783 submission packets, in addition to the 34,500 that were mailed out by NASA. A total of 1697 submissions were received and were initially processed by a subcontractor firm, KPMG Peat Marwick. Of the 1697 submissions received, 1548 were judged by Peat Marwick to contain sufficient information for screening by RAND. The screening process selected approximately 140 submissions for more formal analysis. The output of that analysis process is a set of priority submissions and recommendations reported in this and several companion Notes.

For further discussion of the sources of submissions and their management by RAND, please see App. A.

THE SCREENING PROCESS

The screening process objectives were to:

- Assure relative insensitivity to the quantity of submissions;
- Select submissions to be analyzed at length;
- Review each submission by at least two technical experts working independently;
- Examine robustness by providing more than one ranking method;
- Maintain analytic rigor.
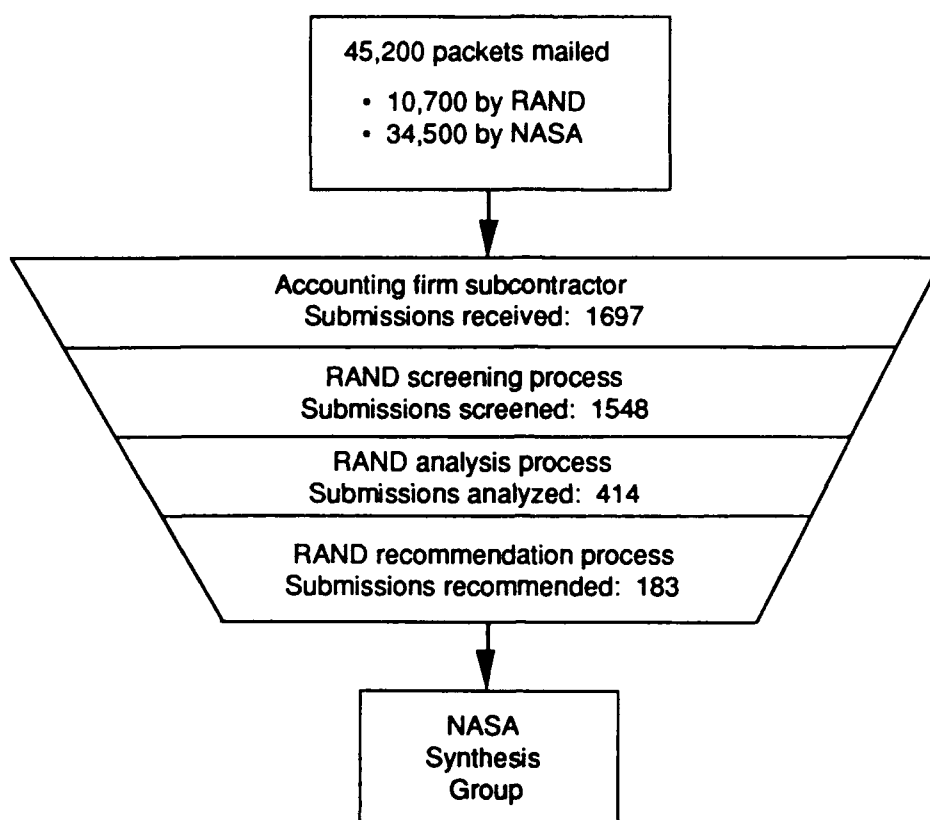
Fig. 1.1—RAND's outreach process

The first objective of the screening process was to assure a good capability to deal with the quantity of submissions, whatever their numbers. Therefore, we constructed a "production line" for processing that would enable insensitivity to the quantity of submissions.

The next task of the screening process was to decide which submissions would be analyzed. We decided that the range and depth of our analysis would have to be a function of (1) the resources available, (2) the perceived quality of submissions across panels, and (3) the relative importance of topics to the overall SEI program. One obvious pair of important panels (because of the tradeoffs between them) was the Human Support panel and Transportation panel.

In the screening process, each submission was reviewed by at least two technical experts working independently. We allowed for robustness by providing more than one ranking method. A related goal was to maintain analytic rigor through the maintenance of tracking systems to enable later analysis of our methodology.

"Multi-attribute decision theory" was used in the screening process; that is, a group of attributes was used to evaluate each submission. The panels chose to score their various submissions using the same five principal attributes:

- utility
- feasibility
- safety
- innovativeness
- relative cost

Each panel tailored its own criteria for scoring an attribute according to the panel's specific needs. For example, "safety" meant a very different thing to the Transportation panel than it did to the Communications panel.

Attributes were independently scored by two or more reviewers on a scale of one to five, with five being the best. Written justification for the scoring was input into the text field in the database. We used a widely accepted Macintosh relational database, Fourth Dimension by ACIUS, Inc., for storing and using the various information components of each submission.

If any attribute score varied by more than one among different reviews of the same submission, the submission was reviewed again, this time with the panel chairman participating with each of the original reviewers. However, there was no pressure to reach consensus.

A complete discussion of the quantitative means by which panels used their attribute criteria to rank and evaluate submissions is provided in App. A. The specific criteria used by the Automation and Robotics panel in assigning attribute scores are also discussed in App. A.

THE ANALYSIS PROCESS

The object of the analysis process was to select the submissions to be recommended for further consideration by the Outreach Synthesis group. Where possible, we analyzed the submissions quantitatively within the context of the important performance tradeoffs in their respective technical areas.

Each panel prepared a draft paper on the results of its analysis in its area of technical responsibility. Each draft paper is organized into technical discussions of the important technical sub-areas identified by that panel. Where possible, important performance tradeoffs in each sub-area are examined quantitatively.

Submissions that arrived with no backup paper—no detailed substantiating information or documentation—were analyzed in the context of the technical discussions of the appropriate sub-areas, thus providing necessary background. The majority of submissions did not, in fact, include backup papers, making an extended analytical discussion almost mandatory in most cases.

SCOPE OF THE AUTOMATION AND ROBOTICS PANEL

Project Outreach submissions that explicitly proposed the use or development of robots, automated systems, or robot control systems to accomplish SEI mission objectives were evaluated by the Automation and Robotics (A&R) panel. Submissions that proposed the use or development of specific technologies such as robotic or automated subsystems (Artificial Intelligence (AI), for example) were also evaluated by the A&R panel. Because A&R subsystems were evaluated, some overlap exists between the scope of the A&R panel and other panels of Project Outreach (for example, the Information Processing panel). Some overlap with the other panels is inevitable in the A&R area because robotics is a multidisciplinary field in which computer hardware, sensors, controllers, motors, displays, and advanced software products all play a key role.

STRUCTURE OF THE NOTE

Section II provides background on potential SEI robotics tasks and presents a robot classification scheme. The essential characteristics of robot work environments are also described.

Section III contains our discussion of the submissions. Submissions are grouped into several broad technical categories and themes to enable a coherent comparative discussion. In each category, a theme or set of themes is elaborated, to place each of the submissions in a common context. Section IV presents our conclusions. App. A describes the specific criteria we used in scoring submissions; App. B provides a list of all submissions reviewed by the Automation and Robotics panel.

II. CLASSIFICATION OF ROBOTIC TASKS AND ROBOTS

The use of manpower is extremely constrained in earth orbit and beyond, and will likely remain so for the foreseeable future. It is inefficient and potentially dangerous for an astronaut to work outside the cabin of a spacecraft or station. Inefficiencies arise from the restrictions imposed by the space suit, the necessity for lengthy preparation and desuiting, suit maintenance and repair, use of astronaut pairs (the buddy system), and the requirement for an on-board astronaut to continuously monitor the pair working outside.

Cosmonaut extra vehicular activity (EVA) experience has led the Soviets to start developing robots for construction and repair in space. During a recent MIR mission in which cosmonauts performed EVA, an air-lock hatch proved balky, and the cosmonauts almost lost their lives. Soviet experience has been that after three to four hours of EVA the cosmonaut is exhausted and cannot do useful work for a significant period of time afterwards.[1]

Even inside a space facility, manpower is in short supply due to small crew size, the need for sleep, and the pursuit of other duties. In addition, in low earth orbit (LEO) or on the lunar surface, an astronaut working outside may be exposed to hazardous high-speed debris, cosmic rays, and solar radiation. It would be advantageous for any task that must be performed outside inflight spacecraft, or at lunar and Martian bases, to be performed by robots rather than humans. The types of tasks that robots can perform will steadily increase as robotics technologies advance and the work situations are designed to accommodate robots. In this section, we discuss potential SEI robotic tasks and develop a robot classification scheme and definitions of structured and unstructured work environments.

POTENTIAL SEI ROBOTIC TASKS

Potential SEI robotic tasks fall into two main areas: (1) operations in space, and (2) operations on the lunar and Martian surfaces. We discuss each below.

Operations In Space

The first major construction task attempted by humans in space will be the assembly of Space Station Freedom (SSF). SSF construction is scheduled to take place over many years in the latter half of this decade. In its earliest design phases, SSF was to be assembled

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[1] Meeting of RAND Project Outreach panel leaders with Victor M. Surikov, Deputy Director, Central Research Institute of General Machinery, U.S.S.R., November 6, 1990.

completely by EVA astronauts. However, as the complexity of the assembly operation became more apparent, it became clear that too many astronaut hours would be required to perform this task with humans alone. The United States Congress mandated development of a robot, the Flight Telerobotic Servicer (FTS), as part of the Space Station Freedom program [Refs. 1, 16, 17]. This mandate was motivated by the desire to accelerate the technology for future industrial benefits. The FTS would have fortuitously enabled NASA to reduce the EVA demand for SSF assembly if this robot had not been removed from the SSF program [Ref. 43]. The billion-dollar program is now well under way. In addition, both Germany and Japan are developing FTS-like robots for use on SSF.

Many SSF assembly tasks could be performed by robots. Robots can assemble truss structures and secure habitats to other modules and to the central keel trusses of the space station. Solar arrays and other systems which can only be assembled or connected to other systems in space could also be handled by robots.

Robots equipped with video cameras or other sensors could also monitor the exterior and interior of SSF once assembly is complete. Video taken by EVA robots could be fed directly into habitat or laboratory modules of the station or via communications relays to NASA ground stations where people can safely monitor the status of SSF.

More advanced robots may be able to independently monitor the status of certain SSF subsystems. If a defective subsystem or module were detected during routine monitoring, the robot could then advise personnel in SSF or on Earth. Again, depending upon the capabilities of the robot, it could independently carry out repair or replacement operations.

In many of the reference architectures described in the NASA 90 Day Study [Ref. 18], the SSF plays a key role as an assembly and transportation hub; thus the robotic tasks described above could also be important components of SEI operations in space. In addition, LTVs, MTVs, and their cargo would be assembled, integrated, and tested at SSF or other space facilities. While LTVs may be brought to LEO in one piece, or may travel directly to low lunar orbit, robots may be required to service LTVs found to have problems after launch or after returning from the Moon.

Robot space probes will continue to be used in the exploration of space, and several remote sensing satellite systems are part of the reference architectures described in the NASA 90 Day Study. The Lunar Observer system will image and map large parts of the lunar surface and will help to enlarge the database on the Moon's geology, resources, and its historical part in the evolution of our solar system. The Mars Observer robot spacecraft will perform a similar mission. As SEI architectures are refined and further developed, more highly capable robot probes may be employed to characterize the surface and atmospheres of

both planets. These robot spacecraft will be capable of highly autonomous activity within their mission profiles and will also be capable of being redirected from Earth.

The most demanding space assembly and repair tasks may well be the assembly and servicing of Mars Transfer Vehicles (MTVs). MTVs may have to be huge vehicles. MTV habitats may have to be covered with enormous shields to protect the human crew from galactic and solar radiation. Large-volume chemical fuel tanks may have to be integrated with the spacecraft in space. Alternatively, large nuclear power plants may have to be integrated and fueled in high altitude, nuclear-safe orbits above the Earth. Finally, if effective and safe countermeasures to the biological effects of microgravity cannot be found, the habitat portions of MTVs will have to rotate to provide a biologically safe level of artificial gravity for its human crew members. All of the above MTV design options have implications concerning the complexity, size, and hazards of assembling, integrating, and checking out MTVs. It may take over a year to assemble and prepare such a craft for launch towards Mars. If robots are not used, it will take enormous manpower to perform these tasks. Large-scale application of robots is essential for MTV assembly, integration, and testing in space.

Robots will be an integral part of the MTV crew, ready at a moment's notice to carry out emergency EVA in interplanetary space or in orbit about Mars, especially if nuclear propulsion systems are employed.

Operations on the Lunar and Martian Surfaces

The few who may venture to the Moon or Mars in the next quarter century will not be able to carry out all the construction tasks on the lunar or Martian surfaces required if man is to establish a permanent presence on the Moon, travel to Mars, and return safely and in good health to Earth. Even before man ventures to those planets, robot probes will be needed to explore and map the lunar and Martian surfaces. Robots will be especially needed to construct a permanent Moon base that includes habitats, radiation protection systems, surface power sources, and cargo and space vehicle processing facilities. Lunar Transfer Vehicles (LTVs) will have to be serviced in areas without radiation protection, in preparation for return to Earth. Finally, if a true local industrial economy is to be developed on the Moon, robotic resource extraction and processing equipment will be needed to generate oxygen, water, rocket fuels, and perhaps other products.

On the surface of Mars, space vehicle processing, testing, and perhaps repair operations will likely be at least partially carried out by robots. Robot rovers and other types

of mobile robots will be used to extend the exploration activities of humans on the Martian surface.

CLASSIFICATION OF ROBOTS

Robots can be classified in the following general categories:

- structured task robots
- teleoperated robots
- semi-autonomous and autonomous robots

Below we discuss these categories in more detail.

Structured Task Robots

The simplest and most prevalent robots are Structured Task Robots (STRs). STRs are used widely in the automobile, electronics, and semiconductor industries. The largest concentration of STRs is in Japan, where most of the world's STRs are now made [Refs. 2, 3]. A typical STR is immobile and consists of a six-degree-of-freedom robot arm and a two-to six-degree-of-freedom end-effector. STR actions are completely programmed into an associated computer which scripts the robot's motion and manipulation activities. STRs will typically execute the same motion and manipulation script over and over again in a precisely controlled manner.

For an STR to perform useful work, it must be carefully integrated into the manufacturing or assembly process. Components that it manipulates must typically be oriented in a single direction and located in one correct position. If a component is left in the wrong position, the STR may damage it during manipulation or welding. The entire production line can easily be disrupted by one STR not doing its job correctly.

One of the most important applications of STRs is in semiconductor industry "clean rooms" where Very Large Scale Integration (VLSI) and Very High Scale Integration Circuit (VHSIC) chips are fabricated. High-density integrated circuits contain circuit patterns so small that almost all dust particles must be removed from clean-room air. Otherwise, circuits will be "smudged out" during fabrication. For example, in the NMB Semiconductor's state-of-the-art class 1 clean room,[2] where 4 Mb Dynamic Random Access Memory (DRAM) chips are fabricated, extensive use must be made of robotics because humans would

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[2]Meaning on average there is only one 0.5 micron size dust particle per cubic foot of air. This is one million times cleaner than typical air [Ref. 20].

contaminate chips in fabrication [Ref. 19]. This difficulty is made even more apparent when it is realized that the average human being exhales an average of 500 1-μm particles with every breath. Future generations of high density integrated circuits at crucial junctures in the fabrication process will be made completely by STRs.

Teleoperated Robots

The second class of robots is Teleoperated Robots (TORs). TORs are remotely controlled by a human controller, who receives feedback information from the robot and transmits command information to it via radio link or wire. Because TORs are controlled by humans, they can work much more flexibly and in more complex, unpredictable work environments. TOR motions and manipulation capabilities are directed by the human using a control interface like a joy stick or keyboard. An ideal TOR—from the controller's point of view—would have arms and hands that were a perfect substitute for a human's. In order to establish this type of control, high fidelity TOR control interfaces are required. Recent research and new technology developments which bear on this question will be discussed in some detail later in this Note. Finally, it should be mentioned that one of the primary advantages of employing TORs is that the robot can work in an environment hazardous to humans. TORs can extend human presence into regions or environments deadly to man. For example, TORs are used extensively in the commercial nuclear power industry in high-radiation environments. TORs are also used in deep under-water exploration and construction work [Ref. 21].

Semi-Autonomous and Autonomous Robots

A semi-autonomous robot is one which can perform many activities in its work environment without human intervention or guidance. Semi-autonomous robots are sometimes called telesupervised robots if they are controlled intermittently by a remote human controller. A good example of a semi-autonomous robot is the NASA/JPL Magellan space probe. It can perform many work activities autonomously, a capability that is needed for probes which may be located so far away from Earth that a significant time delay is incurred in communication. However, semi-autonomous robots are vulnerable to unanticipated or unpredictable changes in their operational environment. That is, they are autonomous only within their prescribed work environment or mission profile. This vulnerability was recently illustrated when NASA temporarily lost contact with the Magellan space probe. Some unanticipated event occurred in its operating environment, causing the probe to shut down and go into a safe mode.

An STR could be considered a semi-autonomous robot according to the simple definition given above. However, most STRs have no sensing capabilities and no world model (a model of its environment stored in its memory). Instead an STR has internalized only a prescribed set of actions. Here, autonomy or semi-autonomy shall refer to the capability to compare an internal world model with external stimuli collected by the robot's sensors, as well as the ability to work without human intervention.

What is an autonomous robot? This is a surprisingly difficult question to answer because it invariably refers back to capabilities ascribed to humans. Most humans are not autonomous in all their activities. They require help or guidance to do their jobs. An ant in an ant hill or following an ant trail searching for food appears autonomous. A chemist in a laboratory using equipment from a distant vendor is not. His tasks could not be completed without the equipment and "brain power" encapsulated within the chips of that equipment. Autonomy, viewed formally, depends on the context.

The ultimate autonomous robot would be able to take the place of a human and perform any physical or cognitive activity humans are capable of. In other words, for a fully autonomous robot, any possible human task should be equivalent to a set of robotic tasks. Therefore, to define robotic tasks for an autonomous robot one can use human activities as a model.

Although the concept of the autonomous robot was introduced sometime ago, such robots are still far from being realized and may never truly be created by human beings. There are a host of unsolved problems in robotics which make it appear that machine autonomy will not be achieved in the foreseeable future. For example, robots cannot "see" and understands images like humans do. Nor can they perform complex mechanical tasks in an unstructured, unpredictable work environment. Perhaps the real crux of the matter is that robots, even if equipped with artificial intelligence software programs or expert systems, are not capable of reproducing all the rich and varied cognitive decisionmaking processes the typical human can. Machines may win at chess, but they cannot think—yet.

STRUCTURED AND UNSTRUCTURED ENVIRONMENTS

As was discussed above, it is important to define the context or work environment of a robot or a human so that either entity could be considered to be autonomous. However, human work environments need not to be precisely defined for a human worker to function autonomously. Thus, typical human work environments are said to be unstructured.

It is relatively easy to describe an unstructured work environment. Imagine a typical auto repair shop cluttered with a wide assortment of tools and spare parts. Tools, good parts,

and trash may be put in no particular order. A novice mechanic would have to search carefully for every tool or part he needed. Because each type of auto is built to different specifications, the mechanic has to carefully devise the set of operations needed to replace a brake shoe, for example.

A mechanic, and certainly the designer of a robot work environment, can make it easier on the worker if the work environment is structured in a simple, orderly way. A veteran mechanic may, to ease the burden on his memory, develop a system to store his tools and spare parts. Wrenches go in one drawer, old hoses in a particular box, etc. The veteran mechanic remembers approximately where most things are (he has constructed a global or world model of his work environment).

Every now and then the mechanic may forget where something is and have to search for that one essential missing wrench. Because his work environment is not completely structured, he has to devise a search strategy and carefully look behind, under, and inside other items in the shop. In short, he behaves as if he is in an unstructured work environment and resorts to his full global sensing, navigation, and movement capabilities. It is these latter capabilities that are so difficult to emulate in a robot.

Consider a robot designed to repair cars in the partially structured work environment such as that of the veteran auto mechanic. Inside this robot's memory would be a model of its work environment which included the approximate position, number, and type of wrenches in each drawer of the tool cabinet, the position of spare parts, etc. This robot would move about the repair shop by following pre-programmed paths to the objects it needed.

Such a robot would also have local sensing, navigation, and movement skills to pick up and use tools. Its robot hand would have to orient itself correctly to grasp a particular wrench. It might also have to tuck its arm in close to its body when it moved about the shop to avoid hitting obstacles. Finally, it would have to align whatever tool it had in its grasp and guide it into position to assemble or disassemble the car it was working on. The robot would have to perceive the position of its own hands, the tool in use, and the object to be manipulated. Still, an event such as the robot finding one particular wrench out of place may stymie it. It would suddenly find itself in an unstructured work environment and would have to search the entire shop for a wrench without the benefit of its tool location database.

A robot that can find a lost wrench is more appropriately called a semi-autonomous robot. Such robots cannot yet be built with current computer vision and expert systems. On the other hand, a robot designed to operate in a highly structured environment could be of considerably simpler design than an autonomous robot and could be built today. It would not

have to be capable of independently constructing search strategies for lost objects or constructing arbitrary navigational paths through the clutter of a messy repair shop.

A robot's work environment can be refined still further by designing each task to be executed by the robot. If each elementary robot task is defined by precisely positioning all tools and parts to be manipulated and the object to be repaired or assembled, the work environment is said to be structured. If the essential geometrical characteristics of this work environment are inserted into the robot's memory and each robot movement is precisely programmed, this robot is essentially an STR. An STR does not require any of the global or local sensing characteristics described in the previous section. All the actions of an STR are prescribed in advance by its program.

How could one turn an auto repair shop into a completely structured environment? Every mechanic's tool would have to be precisely aligned to the model of work environment programmed into a STR's memory. Every spare part would also have to placed in a position coinciding with the STR's model of the environment. Nothing could be out of place with respect to this model. Using the position coordinates of all these objects as inputs, each specific robot action or work task could then be programmed into the robot's memory as well.

If one considers that several hundred tools may be needed to repair a single type of car, that a car is composed of many hundred parts, and that each robotic repair task may be composed of many discrete subtasks in which several tools and parts must be manipulated, it becomes apparent that an auto repair STR would require an enormously large memory. Its library of software codes would have to be quite large as well. The more complex the tasks an STR is programmed to perform, and the more complex its work environment, the larger and more sophisticated its computer hardware and software must be.

Nevertheless, STRs and structured work environments can provide an enormous benefit. If a robot's work environment and each robot task can be precisely defined, then, in principle at least, a well-defined software code can be written to govern an STR's actions. On the other hand, the software codes required to enable a robot to sense, navigate, and move in a work environment that cannot be modeled in a static fashion are much more conceptually complex. Such software codes must be based on general navigational algorithms that accept real-time inputs from the robot's sensors, and which instruct the robot's limbs or wheels how to move in real time. While an STR's software and hardware can easily be sized to operate in real time (because it operates using a static database), a robot operating in an unstructured environment must possess an operating speed margin to deal with the variable size and complexity of a dynamic database continuously being updated by the robot's sensors.

It should be noted that robotic software for operation in an unstructured environment is also more complex in other ways. Humans navigate and move in complex environments based on higher-order commands, such as "move over to the car's left rear wheel and take off the hub cap." Creating software capable of accepting such higher-order commands (or input instructions) is an extremely challenging task, and one which is as yet unsolved for navigation or locomotion systems.

How can current robot technology be used to support SEI operations in space and on the lunar and Martian surfaces? The above discussion of an auto repair shop work environment indicates how difficult it may be to develop autonomous robots to assemble or repair spacecraft in orbit. SEI assembly and repair work environments must be structured in as simple and as orderly a fashion as possible. Construction and assembly processes must be precisely defined—down to the last nut and bolt—and designed from the start to be performed by robots.

III. DISCUSSION OF SUBMISSIONS

Project Outreach submissions that scored highly were grouped according to several categories that represent the key A&R issues raised during review and analysis. The A&R issue categories are: system integration of robots and SEI systems, STRs and structured work environments, TORs and unstructured work environments, TOR control interfaces, SEI robot mission planning, and the transition to autonomous robots.

SYSTEM INTEGRATION OF ROBOTS AND SEI SYSTEMS

If robots are to assemble, inspect, and repair SEI systems in space, on the Moon, or on Mars, they will have to be compatible with SEI systems. To ensure compatibility, SEI robots and systems must be designed systemically. This design activity will be exceptionally challenging because comprehensive design rules must be developed for a large number of SEI systems, subsystems, and robots. Major SEI systems will be built by an array of U.S. contractors and potential international partners. System design efforts at all SEI contractors must track each other, and, through a consensus process overseen by NASA, systemic design standards must be developed. SEI robotic system design is further complicated because the field of robotics is still in its infancy. Nevertheless, the potential payoff of integrating robotic technologies with SEI systems is great. Truss assemblies, solar panels, habitats, aerobrakes, propellant tanks, nuclear power reactors, and many other SEI systems could be efficiently assembled, inspected, and repaired by robots if such standards were adopted.

Systemic design standards for SEI robots, work environments, and systems can only be achieved by capturing and maintaining configuration control over all SEI system design data. Large volumes of detailed engineering design data must be captured in a common digital format and made portable so that it can be used by different system contractors during design and manufacturing, and by robots in space during assembly and repair operations. Automated system design capture has been made possible with the advent of integrated Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) tools. CAD/CAM tools are now used extensively in the semiconductor industry to design, simulate, and manufacture advanced integrated circuits such as Application Specific Integrated Circuits (ASICs).

Design of a particular ASIC is accomplished by combining the designs of several smaller elementary circuits (standard cells) onto a single chip. The standard cell designs are integrated together and adjusted so that the overall chip functions as intended by means of

computer simulation. This system integration process has proven very cost-effective because a particular contractor can develop a limited standard cell library which can be used to design and manufacture a wide array of ASICs. Development time and costs for many newly ASIC designs can be greatly reduced. To speed this process even further, newly distributed CAD/CAM products and services are now being offered that tie together the ASIC customer and manufacturer into a single network, thereby reducing the number of design iterations even further [Ref. 22].

Transportability of CAD/CAM files is also being improved with the introduction of commercial standards such as the emerging Electronic Data Interchange Format (EDIF) CAD/CAM standard [Ref. 1]. However, because of the many different CAD/CAM system vendors and platforms in use in industry, a great deal of non-interoperability between CAD/CAM systems remains. NASA should monitor the development and use of CAD/CAM tools and standards in the semiconductor and other industries and adapt these increasingly powerful design tools to SEI systems and robots. NASA should consider adopting a single CAD/CAM standard of its own to be used in the design, simulation, and manufacturing of all SEI systems.

The digital capture of SEI system design knowledge will offer a tremendous benefit to robot assembly and repair operations. Imagine a CAD/CAM file of an SEI system such as a gas turbine generator in a dynamic power system. This CAD/CAM file and associated STR repair commands (similar to those used to manufacture the system on an STR assembly line on Earth) could be loaded into an STR tasked to repair the turbine generator in space. Once the STR was loaded with this data, it would "know how" to take apart the generator, and given appropriate intervening instructions, "how to" replace the faulty part with a new one. Similarly, if a comprehensive CAD/CAM database were available for SEI systems, a TOR operator could call up the original design drawings for the particular system he or she was assembling. In a more advanced autonomous robot, CAD/CAM files could be loaded via a local area network connection directly into the robot's memory. The autonomous robot's expert systems could then draw upon CAD/CAM data during assembly or repair operations.

However, as alluded to earlier, many difficult technical problems are as yet unsolved, and extensive research will be needed to create highly autonomous robots. Consequently, many SEI construction, inspection, and repair tasks must be designed to accommodate the limitations of current robots. Even twenty-five years from now, many SEI construction tasks or work environments will still be too complicated or demanding for robots, and humans will still have to perform them. One of the long-term objectives of an SEI R&D program should be to minimize the number of man-hours needed to perform dangerous, repetitive, or

physically demanding tasks. Robots can free astronauts from the drudgery of space exploration and enable them to devote their valuable time to scientific research, and the search for new resources, and to report what they see and discover on other worlds of our solar system.

Task Allocation Among Humans and Robots

Given the capabilities of robots developed to support SEI, individual assembly, inspection, and repair tasks must be evaluated to determine those that should be performed by robots and those that can only be accomplished by humans.

- **Task Allocation Among Humans, Teleoperated Devices, and Robots (#101440)**

Submission #101440 is a proposal to develop a methodology for systematically allocating tasks between robots and humans. Reference is made to robot and human task allocation studies performed in the nuclear power industry (an industry where the most sophisticated commercial robots are now used). A specific four-level approach is outlined in the submission. Because a backup document was not included, it is impossible to analyze in detail the specific approach advocated. Nevertheless, this submission was given a relatively high score because the problem it addresses is so important for systemic integration of SEI robots and systems. It is also a top-level system design task that must be addressed at the outset and executed in parallel with other SEI development activities.

The submission authors point out that certain types of robots, such as TORs, must be closely controlled by humans. TOR Command and Control (C2) can be extremely demanding and fatiguing for human operators. Thus, human capabilities must be considered carefully when allocating tasks to TORs and TOR controllers. TOR task allocation depends on the task to be performed by the robot, controller skill level, and the nature of the robot control interface. A well-designed methodology for allocating tasks among robots and human workers will significantly enhance the productivity of SEI robots and astronauts.

STRs AND STRUCTURED ENVIRONMENTS

If SEI systems and robotic construction processes are systematically developed, the capabilities required of corresponding construction robots can be simplified considerably. On the other hand, if SEI systems and construction processes are not so designed, assembly robots would have to possess sensing, manipulation, and navigation skills similar to those of a human being. Because such autonomous robots are far beyond the current state of the art, this type of robotic assembly would not be possible in the near term. Furthermore,

development of highly capable autonomous robots for SEI will be very costly. It is therefore important to constrain where possible the design of SEI structures and construction processes so they can be executed by robots within the current state of the art. One important way this can be accomplished is by developing highly structured environments for the construction process.

- **Robotic Assembly of Large Lunar Structures (#100378)**

This submission describes a robotic truss assembly system designed to operate in a highly structured environment. It is designed to assemble trusses in Earth orbit using a relatively simple commercial robot arm. The arm is programmed to pick up truss members from a bin and snap them into place in the truss. It is mounted on a planar X-Y motion base and a separate turntable platform. The arm can be arbitrarily oriented within a six by six meter area.

This robot system could be extended to perform a number of repetitive assembly tasks. If the system were moved as the construction process proceeded, large trusses or other periodic structures could be assembled. If SEI structures and construction processes are carefully defined, current industrial robotic technology can be used in the assembly process. Furthermore, because assembly occurs in a highly structured environment, the assembly process could be completely automated as system software is further developed and refined (the system could be made completely autonomous within its structured work environment). This type of robotic assembly system could therefore significantly reduce manpower requirements for SEI construction tasks.

The development of precisely these types of STRs and STR structured work environments has enabled the Japanese to continue to increase the productivity of their automobile and semiconductor industries and reduce associated manpower requirements to levels significantly below those of their international competitors. Similarly, development of STRs and STR structured work environments for SEI, as suggested in submission #100378, can significantly reduce associated SEI manpower requirements in space and on the surface of the Moon or Mars.

The system proposed in submission #100378 is being developed for low Earth orbit applications, such as space station construction. The submission authors propose that this system be adapted to construct large structures on the Moon. The suggestion is appealing in general terms; however, this particular system may have to be adapted to work effectively in the gravitational field of the Moon. Because trusses bend under the influence of gravity, the construction process and work environment may have to be modified. In particular, the positions through which the robot arm cycles during construction may have to be adjusted

sequentially to take into account truss deflections. While it is certainly possible to prepare lunar construction sites so the robotic assembly system can function in a highly structured environment, it should be pointed out that there are lunar construction tasks which cannot be performed in a structured environment, such as excavation of lunar soil or transportation of construction materials over lunar terrain. The latter activities will require robots with more sophisticated capabilities.

TORs AND UNSTRUCTURED ENVIRONMENTS

Not all SEI robot tasks can be designed so they can be executed in a structured environment. For example, during the initial stages of lunar base construction the lunar surface will be unprepared and may present unforeseen obstacles and problems for human and robot construction crews. The position, orientation, and shape of construction materials may vary so far from the assumed norm that STRs cannot be programmed to reliably manipulate them. Robots with more sophisticated sensing, navigation, movement, and manipulation capabilities will be needed to operate in such unstructured environments.

TORs, because they can be controlled by humans and make use of human sensing, navigation, and movement capabilities, can potentially operate in such unstructured environments. The human TOR controller is presented by means of communications and display devices with visual and kinesthetic sensor information from the robot, which can reveal unanticipated objects in the robot's environment. The human controller can therefore alter the robot's actions in real time (or near real time, depending upon the communications time delay) to compensate for the lack of structure in the work environment.

Submissions #100695 and #100338 propose to develop TORs which would be well suited for such tasks. Both submissions were given high scores because the proposed robotic systems are potentially capable of replacing humans in EVA construction or repair tasks. Astronaut EVA is potentially hazardous and requires long decompression times. Any robot which can reduce the necessity for human EVA will have high utility for SEI. The extent to which robots can replace humans in unstructured work environments depends upon how closely they can reproduce the functions of the human hand, how well they can be controlled, and how versatile they are. In regard to the first point, both robots can use anthropomorphic end-effectors compatible to a large degree with the human hand. Because both robot arm systems are controlled with mimetic exoskeletons, the robot arms can, in principle, easily be controlled to avoid obstacles, pick up tools, and apply carefully measured torques to bolts, nuts, or screws.

Both dual-armed TORs resemble the FTS and would be capable of operating in a dynamic and complex work environment. Also, like the FTS, both robots would be immobile and would have to be hauled to a surface work site by crane, or to a work space station site by the space shuttle's Remote Manipulator System (RMS) or a similar system.

- **Space Robotics: A Highly Dexterous Robot with Adaptable Control Strategies (#100695)**

This submission proposes developing a dual-armed anthropomorphic TOR called the Astronautics Dexterous Anthropomorphic Manipulator (ADAM2). ADAM2 will have interchangeable hand-wrist packages to increase system adaptability. The primary ADAM2 end-effector has been designed to an anthropomorphic end-effector design rule. It has three fingers and has been designed to nearly reproduce the force and grip of the human hand.

Such a design rule is highly desirable for SEI operations because a robot equipped with anthropomorphic end-effectors could potentially perform unanticipated tasks, such as emergency EVA, and take an astronaut's place in dangerous situations. As stated in the submission, an anthropomorphic design "minimizes the need to restructure tasks and work sites, and it allows human operators to control and train the system quickly." ADAM2 control is effected by a mimetic exoskeleton and zero-motion master fitted over the controller's arms and hands. This submission will be analyzed in greater detail below when TORs are discussed.

- **EVA Equivalent Space Telemanipulation System (#100338)**

This submission describes a similar dual-arm anthropomorphic TOR controlled by an exoskeleton dual arm-hand master controller. Its primary end-effectors are also designed to be compatible with the human hand. In addition, this TOR can be equipped with "a host of EVA tools, power tools, auxiliary and special purpose devices to perform many tasks." The submission does not describe these tools in detail, but presumably most of them would also be usable by a human EVA astronaut.

Robot End-Effector Design Rules

Submission #100378 illustrates an important potential design rule for SEI STR robots and SEI structures. The STR end-effector and truss members have been specifically designed so the arm can easily manipulate these truss members and lock nuts (the latter fasten truss members together). Other structures could be made compatible with this end-effector and could be manipulated by the same system. Comprehensive robot manipulator standards or design rules should be developed that include end-effectors, SEI structural components such as trusses, lock nuts, and the terminal wrist connectors of robot arms.

Then an end-effector could be taken from one type of SEI robot arm and used on another system. In the same way, one end-effector could be used to assemble several types of structures. Such a design rule would minimize the number of different end-effectors required for assembly and repair tasks. A single end-effector design could probably not perform all assembly tasks, and a set of differing sizes and capabilities will most likely be required.

The submissions above (#100378, #100344, #100338, and #100695) indicate the need for one anthropomorphic and one or more non-anthropomorphic end-effector design rules. A research program that cuts across all NASA and university programs in space robotics, space structure construction, and repair research is probably needed to establish a comprehensive set of standards and to eliminate needless duplication in robot end-effector development.

- **The Moon-Mars Autonomous Resource Management System (ARMS) (#101469)**

This submission presents a broad conceptual design for a family of SEI robots capable of performing the following tasks working in an unstructured lunar or Martian environment: remote surveying, facility construction and repair, transportation or installation of equipment, mining, and the handling of hazardous materials. In addition, ARMS robot rovers could be configured to provide SEI power or communications mission support. ARMS systems would be of modular design and could be reconfigured in the field to perform the different tasks mentioned above.

The ARMS proposal is notable for its emphasis on development of an integrated overall SEI A&R infrastructure and for its attempt to describe how this A&R infrastructure can be integrated with other SEI infrastructure elements (in particular, communications and surface power). There are three key elements to the A&R infrastructure proposed: Earth facilities, a LEO depot, and Moon-Mars facilities. These elements would be designed in an integrated fashion to facilitate transfer of digital data, spare parts, fuel, and materials between facilities.

Robot mission planning, simulation, testing, and teleoperational or telesupervisory control would be performed on Earth at the ARMS ground facility. Later this ground facility could be used by private or corporate users to pursue commercial ventures or scientific research at SSF, on the Moon, or on Mars.

The LEO depot, which would be located at SSF, would serve primarily as a logistics base and TOR communications node in support of lunar or Martian ARMS systems. ARMS Moon-Mars facilities would be comprised of two systems: a Transportable Service Rover (TSR) and a Fixed Depot Station (FDS).

The ARMS TSR would function independently of the FDS, but it is envisioned the two systems would be used together to extend the range and types of ARMS missions. The ARMS TSR would be equipped with standard power and controller interfaces so it could be easily reconfigured with power sources, data management modules, sensors, expert system computer modules, manipulation arms or shovels, etc. All these component subsystems would be standardized. These suites of equipment would all be designed so TSRs could cooperatively reconfigure themselves without direct human intervention.

The ARMS FDS would serve primarily as a protective berthing storehouse for TSRs and as a forward base for data management and man-tended operations. The FDS could also remotely control TSRs. The FDS would be comprised of storage facilities, power supply and distribution, computer, communication, and display and control equipment.

The ARMS concept lacks sufficient engineering detail in its present form, but reference is made towards evolving from TORs to autonomous rovers and depot stations. Hardware or software complexity of ARMS systems is not described; however, reference is made to previous NASA and Canadian robotic programs and tentative cost estimates are presented. The ARMS conceptual design is not new, but the authors have discussed standardized and modularized A&R concepts well and have shown how such systems may be integrated into SEI architectures. The technical feasibility of achieving the autonomous or semi-autonomous robots envisioned is not addressed.

Robot Locomotion, Stabilization, and SEI Systems

Space construction robots will have to move about and fix themselves to SEI space facilities or support structures. These robots could be free-flying, equipped with their own propulsion systems, "walkers" which move mechanically by using legs with specially designed cleats, or immobile like the FTS.

All these robots, whether mobile or immobile, must be equipped with grips or cleats to stabilize themselves on space structures. System engineering design rules are needed which establish "scars" [Refs. 1, 16, 17] for SEI space facilities to ensure compatibility with robot stabilizers. No submissions were received in this area.

While several submissions propose various locomotion systems for exploration robots, no highly ranked submissions were received that describe locomotion systems for space construction robots. In the literature, locomotion systems which exploit properties of structured environments, such as rails, have been proposed. Such "structured locomotion interfaces" could be developed and standardized to enable STRs to replace humans in simple EVA activities.

Robot Vision and SEI Systems

Space and surface structures to be assembled by the autonomous robots could be designed to permit robot vision systems to quickly recognize structure type and orientation. Bar codes similar to those used in the retail industry have been suggested by many in the literature [Ref. 1]. The performance of bar-code-reading laser scanners in a LEO or lunar surface environment should be evaluated. Bar code symbol size, laser wavelength, and solar and lunar noise levels are among the factors to be considered. Bar codes could also be useful for inventory control of space systems (e.g., a lunar base) even if autonomous robots are not used. Unfortunately, robot vision systems may still be too primitive to permit systematic study of alternative robot bar code and object recognition techniques. Indeed, the theory of mammalian visual processing is still in its infancy [Ref. 23]. No submissions were received in this area.

AUTOMATED SYSTEM MONITORING

Automated system monitoring can enhance mission safety and system reliability. Automated system monitoring is practiced to a great extent today in certain aerospace fields, such as rocketry. Continued advances in digital microelectronics and recent developments of analog microsensors may make many new types of smart components (systems with embedded automated system monitoring equipment) feasible and cost effective.

• **Smart Components (#101324)**

This submission proposes the widespread use of smart components in SEI systems. The submission is very general and brief. However, its potential advantages were so significant that the reviewers were compelled to score it highly. Smart components offer several potential advantages, especially if they can be made small and light enough so as not to significantly affect overall system design requirements.

Smart components can reduce the probability of catastrophic or initial component failure. They can collect useful data on component performance parameters and increase component life (by signaling when component failure is imminent and enabling changes to be made in system performance to preserve component life).

However, smart components present several challenges to SEI system designers by placing additional requirements on ancillary communications and Automated Data Processing (ADP) systems. Smart components must be linked via local area networks or communications buses to display systems, databases, or monitoring expert systems. Widespread deployment of smart components could greatly increase the communications

burden on local Data Management Systems (DMSs) and even perhaps on interplanetary SEI communications networks. Expert systems must be developed to interpret, manage, and filter smart component readouts to reduce the burden on mission crews or remote ground controllers. These downstream requirements imply that deployment of smart components should initially be limited to critical subsystems, such as life support, and their introduction should be coordinated with associated expert systems and communications networks or buses.

ROBOT CONTROL INTERFACES

Robot control interfaces can take many forms. Digital interfaces such as keyboard commands are used frequently in academic research. Joysticks can be used to control the orientation of a robot arm. Mimetic exoskeleton gloves can provide tactile and force reflection feedback. Autonomous robot control could be effected by speech commands and the presentation of visual graphical information to the robot, much like command and control of human workers would be accomplished.

Autonomous Robots would be the most desirable type of SEI robot because carefully designed work environments and many SEI system hooks and scars would not have to be developed (as required for STRs). Moreover, the additional manpower and communications requirements for TORs would not be needed. But versatile Autonomous Robots (AR), capable of operating in unstructured SEI environments such as a planetary surface or in free-flying LEO will require many sophisticated and as yet unrealized capabilities. As a consequence, IOC dates for Autonomous Robots cannot be predicted and may not be achievable within the timeframe of SEI.

Feedback mechanisms, by which an operator ascertains the orientation of the robot and its work environment, are key to the interface used to control the robot. A number of Project Outreach submissions were received that describe specific robot control interfaces or propose development of new highly capable ones. Most of these submissions consider development of more capable TOR control systems.

Teleoperated Robots (TORs)

- **Space Robotics: A Highly Dexterous Robot with Adaptable Control Strategies (#100695)**

A team of researchers proposes to extend an existing robot program for a single-arm robot, the Astronautics Dexterous Anthropomorphic Manipulator (ADAM), into a robotic system with dual, cooperative arms (ADAM2). ADAM2 would be relatively low mass (one

arm unit < 40 kg), modular, accept many types of end-effectors, provide force feedback to the user, and accommodate increasing supervisory-mode operation in defined tasks. Mobility, power, and control means are not described. Its size, tip speed (> 50 cm/sec), and seven degrees of freedom would allow ADAM2 to provide anthropomorphic motions and allow new users to become skillful in a short time. A standard approach is described for the development of ADAM2.

ADAM2 types of telerobots should be vigorously developed because they can permit humans to work in space from inside a space vehicle. In addition, telerobots will permit many tasks within cislunar space to be done by workers on Earth via telemetry. Anthropomorphic robots should be viewed as one of a spectrum of robot types ranging from relatively simple units (e.g., a roving TV eye) to those that are large, powerful, and specialized (e.g., heavy duty excavators and construction robots for lunar operations).

- **EVA Equivalent Space Telemanipulation System (#100338)**

FTS, now under way, will be a large version of the dual-arm space Telemanipulation System (TMS) described in this submission (< 100 kg, < 150 W). The TMS, brought to the work place by a boom or rover vehicle, is operated by a human in a pressurized environment via an exoskeleton dual arm-hand master controller. The operator also positions and controls the TMS support mount or vehicle. The end-effectors can be "hands" or special power tools. A test version of the device will fly in the early 1990s in the shuttle bay. It could be adapted for use in space or in protected environments on the Moon. There is no detailed discussion of problems of TMS utilization on the Moon as would be encountered with lunar dust fouling up bearings and contaminating manipulators or tools.

TMS-like devices would be extremely useful both inside and outside the space facility. Many small contracts should be let to provide a suite of robots of the size of TMS. Those robots should compete in many demonstration tasks, both to select the viable approaches and to stimulate thinking about how to use robots in space. Much work remains to be done beyond the design extension proposed in this submission.

- **Telerobotics in SEI Surface Operations (#100341)**

The summary and backup paper for this submission provide a good qualitative account of some of the uses and advantages of teleoperated robots in the exploration of a region on the Moon or Mars and for the emplacement of initial habitats. Early emplacement tasks would include site preparation, placing habitats in revetments, covering the habitats with soil for protection against galactic and solar cosmic rays, and mining for water-ice. There is virtually no engineering or technological data given. The broader implications of telerobotics for system design and mission operations are not discussed.

The paper draws extensive analogies between Moon and Mars SEI efforts and the 1700s and 1800s exploration and settling of the American frontier. Considerable emphasis is given to locating and extracting water on Mars. The analogies are likely to divert SEI R&D personnel from the primary challenges of human exploration and settlement of the Moon and Mars. In fact, NASA must aggressively move to achieve effectively complete recycling of water, carbon, nitrogen, and other life chemicals. Efficiently acquiring energy and rejecting waste heat to operate the recycling means must be the major engineering achievement if humans are to be supported beyond Earth. Water would be a "once mined" quantity and replacement kept to a very low level. Similarly, there is a picture of humans roaming about the Moon and Mars in the style of an early American prospector. This simply will not be the case. Exposure to galactic and solar cosmic rays and their induced products will severely limit the integrated, long-term presence of humans on the surface of either the Moon or Mars or outside a space facility. The importance of telerobotics in support of permanent human presence in space cannot be overemphasized.

One-of-a-kind robots, either autonomous or teleoperated, will be very expensive. Viking was not a cheap mission, had only limited telerobotic capability (1 meter reach, grasping, and placing), and provided only limited scientific return, especially with respect to determining the presence of life on Mars. Robots become very attractive in the absence of other choices or when they offer economies of scale. The latter alternative is not covered in this submission but has been addressed in the ARMS submission discussed earlier (#101469).

If telerobots can be equipped with interchangeable suites of sensors, lunar and Martian environments could be examined remotely and scientific or engineering research carried out. Such detailed remote experience of the environment can allow the operator to program the machine to perform operations repetitively by taking the machine through the sequence of moves. Teleoperation can be effective from Earth to orbit and in some cases, via shared control, out to the Moon. Scientists on Earth could be in close contact with experiments in LEO space facilities or with a processing plant on the Moon. Teleoperated robots could also perform field geology on the Moon or Mars.

Telerobots can be useful even when there is a long time delay for communication between the machine and operator via shared control. The teleoperated robot can conduct automatic routine operations and the procedures can be revised post real-time by the distant operator. Teleoperation from Earth to Mars would entail very long time delays, exceeding 10 minutes in the best case. In the Earth-Mars case, teleoperation would best be used to reprogram from Earth the complex local activities of a stationary robot on Mars.

There is always a need for placing many trained observers in a remote new area. Teleoperation offers a means to do so without risking people or entailing the great expenses associated with people. In addition, several teleoperated vehicles could be placed in a new region. Such vehicles could be designed so they could be taken apart, to some level of assembly, by one another. Thus, they could form their own spare parts pool (as described in #101469).

Telepresence

Present-day TOR control can be a fatiguing and difficult task for the operator. Because the operator must frequently interpret low-resolution feedback data from the robot's sensors, he may be forced to proceed at a very slow pace when directing the robot's limbs or end-effectors. If he swings the robot's arm too quickly and misinterprets or doesn't receive necessary feedback data, the arm may knock over or damage nearby objects. Lack of high fidelity TOR feedback can reduce operator productivity to the point where a human could perform the same tasks many times faster than the TOR. This limitation has prompted researchers to develop and investigate operator interfaces capable of presenting a more realistic and detailed representation of the robot's environment. Such high-resolution interfaces are said to provide telepresence to the TOR operator.

Present TORs, such as the FTS, are typically equipped with video equipment which conform to the National Television System Committee (NTSC) standard used in television broadcasting. When NTSC video is displayed on a 20-inch monitor and viewed at a standard computer-screen viewing distance, each pixel displayed subtends about four minutes of angle of the operator's visual field. This corresponds to an image resolution about four times worse than that of the average human eye [Ref. 24]. Consequently, a significant amount of visual information of a remote scene may be absent from such an NTSC display.

Although a U.S. standard HDTV display format has yet to be finalized, it will likely have the same approximate pixel count as Japanese and European HDTV display formats. Such an HDTV display format will increase visual resolution by a factor of two over the NTSC standard and will come to within a factor of two of the human eye's imaging capabilities. Thus, it is evident that the replacement of NTSC with HDTV visual interfaces will greatly increase the amount of visual data presented to the TOR operator. HDTV TOR interfaces will likely be one of the key enabling technologies necessary for achieving TOR Telepresence Control (TOR TC).

In TOR TC, the remote human operator should perceive the robot and its environment near the inherent resolution and bandwidth limits of the human senses. For example, a

large HDTV screen filling the op   r's entire visual field can convey a more precise and inclusive image of the TOR environment than a small, low-resolution TV displaying the limited field of a view (FOV) of a video camera. The significance of high-resolution imagery is easily overlooked but not easily quantified. Researchers at the Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, are now trying to determine the optimal level of visual sensory input data and the best geometrical presentation format for human teleoperators (two-dimensional flat screen display, two-dimensional binocular display, three-dimensional flat screen display, etc.) [Ref. 25]. In military programs to develop remotely piloted vehicles (RPVs), it has been found that remote pilots using low-resolution narrow FOV imagery have a much higher incidence of pilot error than real pilots. Many remote pilot errors may result from limitations of the operator interface. Likewise, TOR TC may significantly improve TOR operator awareness and productivity.

Many potentially revolutionary computer and entertainment interfaces are under development for commercial and military markets by a wide array of companies. This collection of technologies also holds tremendous promise for TOR TC. However, we note that large HDTV displays may not be desirable for extraterrestrial TOR command and control centers because of the weight and bulk of large Cathode Ray Tubes (CRTs). Lightweight flat-panel HDTV displays, such as those under development in Japan and the United States, would be preferred for TOR command and control centers at lunar or Martian bases.

Another new display technology is especially well-suited for extraterrestrial applications because of its light weight and small size. Goggle-like devices called "eye phones" are under development by several companies (e.g., Sense8 Inc., Stereographics Reflection Technology Inc.) that entirely replace TV or computer screens with a set of sealed eyeglasses [Refs. 26, 27]. The first eye phones were developed by Ivan Sutherland in the 1960s but were heavy and bulky because they used CRT displays. More recent eye phone systems are much lighter because of the lightweight LCD displays and compact integrated circuitry used.

Eye phones can potentially display images with extremely wide FOVs because of the proximity of the focal plane to the eye. They also naturally display stereoscopic imagery and can be used to completely block out visual stimuli from the real world, thereby giving the user the impression of immersion in a virtual environment. According to International Telepresence, a maker of RPVs, stereo eye phones are increasingly being used in RPV control systems [Ref. 28]. However, their use for RPV control has presented interesting new problems for researchers. For example, operators of ground RPVs sometimes suffer from

motion sickness when the RPV is driven at high speeds. Apparently the lack of kinesthetic feedback has been determined to make even some tough U.S. Marines nauseous [Ref. 29]. Nevertheless, the remarkable capability eye phones provide may prove especially useful for the virtual environment or cyberspace TOR control interfaces described below.

Researchers at Xerox's Palo Alto Research Center are developing new types of three-dimensional computer user interfaces which take the now-familiar two-dimensional Macintosh window interface one step further [Ref. 30]. Three-dimensional graphical user interfaces could also be useful in increasing TOR productivity and perhaps achieving three-dimensional TOC TC.

True three-dimensional displays are also under development at Texas Instruments' (TI) Computer Systems Laboratory in Dallas and at MIT's Media Lab in Cambridge, Massachusetts [Ref. 31]. TI is now developing system prototypes of its Omniview system for several military clients and expects to field operational systems by 1992. The MIT system can present more realistic 3-D imagery but is still in the research phase.

TI's Omniview system creates a 3-D display volume by rotating a disk around an axis perpendicular to the disk's center in its plane at 600 rpm. A low-power pulse laser beam modulated at 10 kHz illuminates the disk. Because of the system's high interlace rate, the sequential pattern of points of light created in the display volume is seen by the human eye as a solid three-dimensional display image. Red, green, and blue lasers can be mixed to produce a full-color 3-D display that can be viewed at any viewing angle. The one drawback of the Omniview system thus far is that it can only display transparent objects (nested objects are not occluded).

In the MIT system, real-time holographic images are created from CAD data files by using a massively parallel supercomputer—the Connection Machine built by Thinking Machines Inc. Supercomputer speeds are required because of the highly computer-intensive graphical imaging algorithms needed to account for object occlusion and viewer parallax effects. Even with supercomputer speeds, this system can only create small images (about 1.5 inches on a side) and they can only be viewed three-dimensionally from a small number of vantage points.

Although many of the display technologies described above are still in the development phase, they hold promise for powerful new TOR TC interfaces and bring telepresence closer to the ideal of actually being *there*, which is why commercial companies are now vigorously developing these systems. NASA needs to follow these commercial and military developments and integrate them into current robotics programs.

The second key set of technologies required for TOR TC interfaces relates to the tactile interface between controller and robot. Advanced remote kinesthetic control systems have recently reached the stage where remote operators can be provided with a "feel" of the objects being manipulated by a remote robot. Control signals sent back to the manipulators can include the effects of synthetic forces experienced by the remote operator. High-fidelity kinesthetic sensing is another important enabling technology for achieving TOR TC.

Finally, a third type of advanced technology could also greatly enhance the productivity and realism of TOR TC—Speech Synthesis and Recognition (SSR). If a TOR controller could verbally command a robot, other more cumbersome and slower control interfaces could be eliminated (keyboards, trackballs, etc.). SSR research has been ongoing for some time, but, to date, few if any real practical applications have emerged. However, it now appears that SSR technology will soon be emerging from the research lab and going into commercial products such as computers and VCRs. For example, Matsushita Corp. will introduce a VCR that can be programmed by voice command by 1991. Motorola, Intel, and AT&T have all recently introduced "Media Engine" chips destined for use in personal computers and work stations, which will allow users to store and retrieve audio, visual, and text data from a computer [Refs. 32, 33, 34]. Recently, AT&T and several other telecommunication equipment makers have introduced telephone message systems which recognize and interpret simple voice messages [Ref. 35]. IBM has also recently introduced a relatively low-cost personal computer, which after some training can be run entirely by voice command. This IBM PC runs several standard software programs and has a vocabulary of approximately 7,000 words [Ref. 36]. New software products will undoubtedly be created that will provide a verbal command interface with software application packages.

None of the submissions that scored highly in the review process specifically propose new technologies such as those described above, although several other submissions, which did not score as highly, refer to telepresence, HDTV, IMAX or other high-resolution display technologies for SEI robotic and remote monitoring systems.[1] The following submission, however, scored highly because it discusses how SEI telepresence systems could be used in innovative ways on space stations, to repair and retrieve satellites, and to support commercial research ventures in LEO and on the Moon.

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[1] IMAX is the name for the largest motion picture film format available commercially. Each IMAX film frame contains roughly eight times the number of pixels (film grains) as a 35mm film frame.

- **Telepresence and Commercial Mission Objectives (#100827)**

The submission proposes extensive use of telepresence technologies in space by NASA and argues that with the many competing commercial ventures in space in the time frame of Project Outreach (2019), private corporations will insist upon using TOR TC to reduce launch costs, astronaut time, and manpower. This is illustrated by the following example: TORs on a space station could provide an engineer on Earth with a simulation of the space station laboratory and allow the engineer to observe and manipulate experiments almost as if present at the station. It is proposed that laboratories in space be engineered, by 2019, to use telerobots and permit researchers on Earth to conduct experiments in space that are expected to be of commercial value. The proposer maintains that relatively small robots, < 0.3 meters in diameter, could provide a wide range of services under teleoperator control.

The use of telerobots to support a wide range of commercially motivated experiments, as well as many others, is reasonable now and will certainly be extensive by 2019. It is likely that many types of robots will be required. It is proposed that robots could be "ganged" together to do larger tasks. This is not possible now but could be in the future. It is certain that space facilities must be intentionally designed to accommodate such robots just as laboratories and shops are designed to accommodate equipment on Earth. Safety issues dealing with astronauts operating around robots were not discussed.

Virtual Environments, Artificial Realities, and Cyberspace

The integration of the advanced display, audio, and kinesthetic force-reflection technologies described above with new proprioceptive motion sensors and computer simulation techniques will bring about an entirely new type of entertainment and computer interface. This integration is now the focus of many academic and NASA researchers, U.S. and Japanese corporations, and the Japanese Ministry of International Trade and Industry (MITI) [Refs. 24, 27, 37]. The products of this integration effort have been called artificial realities, virtual environments, and cyberspace by various authors and researchers.[2]

Cyberspace has three components: sensory construct, behavior simulation, and user interaction. Realistic imagery, tactile forces, and sound present the user with a single inclusive sensory construct. This sensory construct is made to behave exactly as real objects would by computer simulation. Finally, the user interacts with the sensory construct much as he or she would in the real three-dimensional world: by moving, pointing, and picking things up, by talking, and by observing from many different angles. Cyberspace can be

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[2]The earliest discussion of virtual environments or artificial realities appears to be in *The Joy Makers* by James Gunn in 1961 [Ref. 38].

thought of as an artificial reality which by computer simulation obeys the laws of physics and the commands of the user.[3] Vitual environment software products are being developed by a number of firms. Autodesk, a maker of CAD/CAM software, is designing an artificial reality operating system which will enable other software developers to create their own virtual environments for entertainment, physical fitness, or education [Ref. 40].

Proprioceptive motion sensors that permit interaction with displayed or virtual objects are under development in many companies and research organizations (e.g., VPL Research Inc., MIT Artificial Intelligence Laboratory, Columbia University, Sense8 Inc., Mattel Co. [Refs. 24, 27, 30, 37]). The operator wears a "power or data glove" containing proprioceptive motion sensors. As the operator waves his gloved hand through space, he sees an image of his hand move through the space displayed on his screen or eye phones. In this way the operator grasps, moves, and rotates virtual objects. The application of these technologies to video games is obvious. Mattel's Power Glove has in fact recently been licensed to Nintendo for this use. Nintendo has also developed other motion sensors for video game interfaces. One of them is called "Power Pod," which uses switches embedded in a plastic floor mat to signal a player's motions or decisions.

These technologies also permit development of TOR Cyberspace Interfaces (CSIs), in which objects imaged by the TOR are presented to the TOR operator for manipulation. The TOR operator perceives his own arms to be those of the TOR, and the virtual objects in his visual field to be the real structures grasped and manipulated by the TOR manipulator arms. Increasingly sophisticated CSIs will no doubt be developed and used in the coming decades. Besides their clear utility for TOR control, CSIs could also be used by NASA in its public

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[3]Cyberspace is a concept that encompasses virtual reality. Within cyberspace one can view a simulation of a past or present reality, such as depicted in the novel *Neuromancer* [Ref. 39], the movie *Brainstorm*, or the holodeck on *Star Trek—The New Generation.* However, the novel *Neuromancer,* or to a lesser extent the Walt Disney movie *Tron,* depicts a broader manifestation of virtual reality in which physical, mathematical, and data structures of a computational system are made as visceral and observable as the real world. Within this visceral presentation of computational abstractions things like encryption algorithms might become visible as walls or moats. Algorithms might be viewed as carnivorous animals that consume one type of data "animal," and convert them into another form, new "organisms," or waste. Applied mathematicians now explore a small segment of this abstract virtual reality by using animated computer graphics to study new forms in topology or very complex and non-continuous transformations such as Mandelbrot sets.

A conceptional domain that is yet to be explored is the use of the broader form of "virtual reality" to study the control of robots in simple and complex environments and the strategies for obtaining progressively higher forms of autonomy. Cyberspace, a simple interactive version of which can be provided now, should be explored as a means of simplifying the control of robots in complex situations and under time delay.

relations efforts and allow the public to participate vicariously in a new and exciting aspect of the robotic exploration of space.

- **Creation of a Virtual Environment for Teleoperation (#101317)**

The concept of cyberspace is much broader than that of teleoperation. The operator interface of a teleoperation system presents the user, as closely as possible, with a representation of the environment of the robot at the time the signal is transmitted from the robot to the teleoperation center. Cyberspace interfaces can include such a slice of "reality" but can also extrapolate to future times by simulating the probable time evolution of the user's virtual environment.

CSIs can also present completely synthetic simulations, thereby extending for the operator the types of robot operations to be considered. CSI provides great safety for the remote operators, especially if other robots can repair a disabled robot. As the communication time between the robot and operator increases, CSIs will become more useful than simple teleoperation. Low-level CSIs, such as flight simulators or even video games, are now possible and extremely useful. The submission provides no technical details on how CSIs can be implemented and in particular how time delays in interplanetary teleoperation can be overcome using specific CSI simulation software. Nevertheless, the opportunities for innovation suggested by this submission are truly immense, and NASA will likely be hard-pressed in the future to make full use of the CSIs that will become commercially available. Communications links over vast distances and modeling non-terrestrial environments will be among the uses of CSIs NASA will want to consider.

- **Computer-Simulated Teleoperation (#100336)**

Computer-Simulated Teleoperation (CST) is a restricted form of a CSI. A slowly moving rover on a distant planet, say Mars, continually makes pictures of its proposed route and sends them to Earth. The pictures take X minutes to get to Earth. The CSI system on Earth presents the operator on Earth with computer extrapolations of where the rover will be on the basis of pictures taken at -X minutes earlier. The operator sends the commands based on the extrapolated pictures to the rover. At +X minutes the rover receives the control inputs from Earth that are based on extrapolations from -X minute observations with its observations and compares them with its observations at +X minutes. If there is reasonable similarity, then the commands are implemented. Such a system can be extensively tested on Earth.

This version of a CSI can increase human safety if people do not have to work around the device. The average rate of travel of a sequence of machines, a convoy, can be much faster than one machine operated through a time delay. The technology is reasonably

available for simple, structured environments. It is beyond the state of the art for unknown environments but is worthy of development.

- **On-Orbit Assembly, Servicing, and/or Maintenance Incorporating Teleoperations and Control-Structure-Interaction Technologies (#10081)**

This particular abstract poses research on a small but significant portion of the nonlinear controls problem. It is not highly innovative; many others have suggested similar motivations. It lacks details to provide insights as to unusual technical advances the group might use. However, nonlinear control systems will allow critical tasks to be done in space that are simply not possibly otherwise.

Assembly and maintenance of large, low-mass, extended structures such as space stations, large arrays, or incomplete structures will require robots and manipulators that are driven by nonlinear control systems. The dynamics can be nonlinear and very complex. Thus, nonlinear control systems will be required to ensure safety of the structure during assembly and maintenance.

Development of such systems will require much work on both simulations and real tasks. Great advances have been made in the past 20 years in the development of nonlinear systems. However, it is still an area of fertile research and will require continuing development of theoretical understanding, software, and computing techniques, as well as taking advantage of emerging hardware such as parallel computers and neural networks. Likely, there will always be a boundary of unsolved problems and a tradeoff between various engineering approaches, mathematical understanding, and what cannot be done. Use of proven and trustworthy nonlinear control techniques could lead to major savings in operational facilities in space. The technique development will be modest in costs compared to flight programs and the monies that might be saved.

TOR COMMAND, CONTROL, AND COMMUNICATIONS (C3) SYSTEMS

SEI TORs that will be used in LEO, on the Moon, or on Mars will be controlled by human operators located in the same area or possibly on a nearby planet such as Earth. For many tasks envisioned as part of SEI, several robots working in close proximity may be required. For example, construction of huge spacecraft such as MTVs in LEO or on the Moon may require many TORs working together like a construction crew. In such cases, TOR activities will have to be carefully planned and coordinated. TOR work difficulties may occur and real time coordination or retasking may be required. As more TORs are deployed on

space construction projects, complex task schedules will have to be developed and promulgated to the appropriate controllers.

The additional TOR tasking, planning, coordination, and control activities that will have to be handled in complex space or lunar construction activities suggest that TOR command, control, and communications (C3) centers will be needed to manage such operations. A TOR C3 center would be composed of TOR control stations, coordination managers, logistics managers, planners, and taskers. The requirement for such a facility is suggested by analogy with the types of C3 centers that have been developed for complex military operations. Real-time and nonreal-time management of complex systems like TORs, especially when several are working in the same vicinity, will likely require many unspecified but important group interactions among TOR controllers, taskers, and logistics personnel. Such a TOR C3 center is proposed in the following submission.

- **The Robotic Workshop (#100337)**

This submission proposes a workshop containing many different types of small TORs with many different capabilities—different speeds, strengths, precision, etc. Each TOR would be provided power, computing, control, and communications from a single source in the workshop. The robots would be in a single room or work area that could be fully observed by remote operators. The remote operators would be placed in a single room as well to closely cooperate in coordinating the control of several different robots at any one time. The workshop control center (TOR C3 center) could be in a developmental lab on Earth, in LEO, or on the Moon.

The concept is very good in that it can be implemented quickly and inexpensively for an Earth demonstration, and it would rapidly develop understanding of how robots can be coordinated to do complex tasks both with and without time delay. The workshop might be translated quickly to a LEO space facility and thereby greatly increase the productivity of a laboratory inside or outside the facility by allowing controlled access by the earthbound team.

Development of supervised autonomy and autonomous robots is not part of this workshop concept. The workshop could be used as a environment for development and demonstration of supervisory control and checking out of autonomous robots. As mentioned above, the fundamental concept is not new and can be rapidly developed.

SEI ROBOT MISSION PLANNING

As the SEI program proceeds over the next quarter century, SEI operations in space will increase in scope and complexity. As SEI robots become increasingly capable, they will be given greater responsibilities and more complex tasks to perform. Succeeding generations

of SEI robots will depend upon and exploit data collected from previous SEI and NASA missions. Data collection requirements on early missions should therefore be carefully determined with later SEI mission data needs in mind. In this way, synergies can be found between early SEI data collection efforts and later exploratory or colonization missions.

A second aspect of mission planning that also must be addressed has to do with capturing essential design information of SEI systems right at the start of the design stage by using integrated CAD/CAE tools. CAD/CAE data files will be essential in later robotic repair or assembly operations in space, as explained below. If CAD/CAE data are archived and configuration controlled, a significant increase in the productivity of SEI robots could be realized.

Remote Sensing, Route Planning, and Navigation
- **Image Processing by Lunar Rovers (#101067)**

This submission is an innovative proposal that uses image processing techniques to reduce the size, complexity, and cost of lunar rover exploration robots. The rover operating principles that would be employed will be discussed later in this section. This submission also demonstrates how data collected by early SEI probes (in this case the Lunar Observer (LO)) can be used for extensive and detailed mission planning for later lunar exploration missions (in this case by lunar rovers). This submission suggests an unprecedented data collection effort using remote-sensing techniques to construct high-resolution synthetic imagery (.1 m resolution) and maps of the lunar surface.

Although the submission suggests that LO imagery be transmitted to Earth, processed in real time, and then transmitted to the lunar rover, this type of real-time communications connectivity is not necessarily required. With the absence of an atmosphere to erode or move the lunar regolith, the lunar surface has been and will remain unchanged for centuries. LO imagery can be collected, buffered on the satellite, and transmitted back to Earth. On Earth, supercomputers would have ample time to develop high-quality synthetic ground-level imagery using sophisticated image processing and translation algorithms. Synthetic imagery could then be loaded into the lunar rover's memory in nonreal-time by radio link or by ferrying high-capacity memory cards or disks from Earth to the Moon.

High-resolution remote sensing of the Moon performed on the scale suggested (.1 m) will also provide an unprecedented geological record. Advanced high-density data storage systems based on first-generation optical storage techniques now available will be capable of preserving this record for centuries. The lunar database could not only be used by NASA mission planners, but also by scientists and private commercial ventures formed to prospect

for lunar resources. In addition, this high-resolution database can naturally be used to create cyberspace software for the general public. The new telepresence and CSI technologies described earlier could be used for educational and entertainment purposes by those interested in space exploration and experiencing first-hand the lunar surface.

Although the submission does not identify specific sensors to be used, optical photography is implied, since the current LO baseline system includes an optical camera capable of .5-1.0 m per pixel resolution [Ref. 41]. Optical imaging at .1 m resolution is clearly possible by upgrading the LO camera system. However, because ground-level imagery must be synthesized from high-altitude imagery, LO image resolution may have to be greater than .1 m. The question requires detailed study beyond the scope of this Note.

There is a significant drawback to employing only high-resolution optical photography. The permanently dark craters at the lunar poles could not be imaged, so rovers could not be provided for ground-level synthetic imagery for navigating these areas. An alternative approach is to employ active high-resolution imaging sensors such as Synthetic Aperture Radar (SAR). In addition, because the Moon has such a tenuous atmosphere, EHF and millimeter wave SARs could generate high-resolution imagery. To achieve the resolutions discussed, the current state of the art in these sensor technologies would have to advance. However, such developments would have many spinoffs for other remote sensing applications, including advanced tactical military imaging systems, environment monitoring sensors, and arms control verification systems. In addition, SAR data will provide surface and subsurface geological data which would be useful for resource prospecting in its own right.

Another approach to generating high-resolution optical imagery may also be feasible. Instead of employing an upgraded LO spacecraft in a 100 km circular orbit, smaller "lightsats" carrying a smaller array of instruments could be deployed in extreme low-altitude (10 km) orbits. Lightsats could simultaneously or subsequentially image the same surface swath from adjacent orbital planes. Distance measurements between a lightsat pair and the surface swath could be taken using laser range finders or by using precise satellite ephemeris data, thereby providing accurate cartography as well as images. Recent advances have led to a reduction in the size of space sensors and microelectronics. These advances have led to a variety of innovative lightsat concepts for commercial and military applications in various Earth orbits [Ref. 5]. NASA and JPL should examine these emerging technologies and see how they can be used to fulfill SEI mission objectives.

Remote Sensing and Lunar Base Construction

Submission #101067, discussed above, has important mission-planning implications for other aspects of SEI. The first settlements on the Moon and eventual lunar bases may be completely or partially assembled by robots. Robots will be needed to excavate, move, and smooth lunar regolith for roads, habitats, and power sources. Much of this activity will have to be performed in an unstructured robot work environment if mission planning for these activities relies only upon medium resolution imagery. In this case, TORs, which may have to be controlled from Earth in slow feedback loops, would have to be used. On the other hand, if the location for the lunar base could be imaged at high resolution, more detailed mission planning for base construction could be done on Earth, and it therefore may be possible to employ advanced STRs such as those suggested in submission #100378 for some assembly and construction activities. Such STRs, if appropriately programmed and equipped with limited autonomous small-obstacle avoidance capability, may be able to independently carry out lunar construction activities without direct control from Earth or lunar transfer vehicles (LTVs).

Computer Aided Design, Database Management, and Expert Systems

As discussed by many authors [Refs. 1, 4, 16, 17, 42], an essential aspect of mission planning for SEI robotic assembly and repair activities is provision of detailed CAD/CAE data for SEI robots. CAD/CAE data files can be applied in robotic repair or assembly operations in space as explained below. If this is done, a synergistic increase in the productivity of SEI robots could be obtained. While no high-scoring submissions directly advocated or addressed the utilization of CAD/CAE data by SEI robots, one submission dovetails nicely with these concepts.

Submission #100345 proposes the development by NASA of a modular robotic control architecture that can support a range of robot applications and integrated sensor systems. This modular design would be hierarchical, supporting, among other things, various control levels ranging from high-level mission and task planning down to macros (sets of specific robotic arm motion commands) and low-level primitive robotic and individual servo commands. This ambitious venture is only sketched out in the most general terms in the submission, and no backup is provided. Nevertheless, it suggests what might be possible if such a modular control architecture were available. Archived databases of sensory data from CAD/CAE designs, and later from robots and probes, could be downloaded into other systems and appropriately synthesized and filtered to provide deterministic programming

instructions for lower-level robots such as STRs. This concept requires much further study and refinement, but it may enable development of robot teams in which limited forms of shared autonomy could be realized in a cost-effective manner.

SEI EXPLORATION ROBOTS

A number of exploration robots have been proposed in various Project Outreach submissions. They can be grouped according to the propulsion/locomotion systems employed. Extensive research over the years has been conducted regarding the capabilities and limitations of various robot exploration concepts. The robots with the greatest range and payload carrying capacity are wheeled rovers. However, wheeled rovers can only cover unobstructed level terrain. Walking rovers cover territory at a much slower rate and carry less payload but can traverse more difficult terrain. Crawling rovers can penetrate more inhospitable terrain and potentially burrow underground, but carry only small payloads and cover small areas. Lightweight hopping robots can cover somewhat larger areas but also carry only small payloads. Small "all terrain" robots must have power and communications capabilities; power and communication tethers could connect these smaller systems to a mother rover and a local power cart. Alternatively, small robots could be operated intermittently using solar power and could communicate with a mother rover via radio link.

Still another class of exploration robots is ballistic probes, which are well suited for subsurface sampling and analysis. They could be fired from orbit or from a gun mounted on a rover. Ballistic probes could be useful for remote prospecting operations in steep craters, canyons, or mountain ranges. Ballistic probes would be equipped with radio transmitters for communication with passing satellites or nearby rovers.

The smaller the robot and the simpler its locomotion system, the simpler its guidance and control can be. Furthermore, if the robot is expendable, it could be completely unguided, with all of its payload devoted to sensor or power functions. Such smaller robots could be carried by a more sophisticated TOR rover, which would explore a wide region until it reached an interesting obstructed area. There it could release smaller hopping robots which could jump into and explore craters or canyons. Such unguided robots may be able randomly to explore difficult obstructed terrain at low cost relative to more sophisticated alternatives. Such a diverse team of robots would be useful in many different types of exploration missions because of their flexibility.

- **Competition for Design of Exploratory Robots (#101321)**

This submission proposes that NASA hold an open market competition for the design of exploration robots, which could possibly be sponsored by private corporations (perhaps

some form of tax writeoff or corporate advertising would be permitted to defray corporate costs). NASA would specify general robot characteristics, telemetry interfaces, and power supply. The robot could be capable of autonomous operation or be remotely controlled through teleoperation. Qualifying entries would compete in an "Exploration Competition" on a suitable piece of terrain on Earth. The top two contestants would be guaranteed a berth on the first manned Mars landing, where they would be used by the exploration team.

This submission is innovative and could provide a new impetus to academic and corporate researchers to develop new robotics technologies. It would also provide a small but perhaps significant way to side-step the difficult and often criticized government procurement process. Because of the publicity such a competition would engender, interest in SEI would also be promoted among the general public. For example, corporate sponsors could use their robots in advertising campaigns, and robots adorned with corporate logos would been seen on living-room HDTVs, moving about on the Martian surface.

Wheeled Rovers
  * **Computer Simulated Teleoperation (#100336)**

This submission was discussed above in the context of virtual reality and its applicability to operating rovers on Mars. A remote operator on Earth, or anyplace sufficiently far away to cause a delay in communications, will generally issue robot control commands on the basis of interactions with a computer projection of where the robot should be, based on post-event rather than real-time data. The submission proposes that experiments be conducted in Arroyo Seco, on the grounds of the Jet Propulsion Laboratory, using wheeled robots and communications schemes that introduce a time delay. Wheeled robots and adjustable time-delay equipment are readily available.

Development of virtual-reality software for vehicle control should be initiated. The main goals should be to minimize the information that must be transmitted and received from the robot and to determine how the robot can compare, at the least computational expense, its real-time environment with the simulated environment with which the operator is interacting. There is nothing particularly special about the use of wheels with respect to the control modality, except that a wheeled robot may be readily available at JPL.

  * **Image Processing by the Lunar Rover (#101067)**

The NASA 90-Day Study proposed placing a mapping satellite in orbit about the Moon that would take "moderate" resolution photographs of the surface. The proposers presume that moderate resolution is significantly greater than 0.1 m. We conjecture that if high-resolution remote sensors were employed, operation of unmanned rovers on the lunar surface

could be considerably simplified. Otherwise, the rover would have to have a high level of autonomy to navigate on the insufficiently resolved surface or a teleoperation would be required. The proposers view autonomous operation as unrealistic and teleoperation as slow.

The proposed solution requires four elements. The lunar orbiting satellite would have a 0.1 meter resolution mode for imaging areas to be explored by rovers. These images would be transmitted to Earth. Large computers on Earth would combine orbiter images taken from different perspectives and would synthesize from them highly accurate three-dimensional maps with ground-level reference imagery for use by the rover. Local maps and at-request synthetic imagery would be transmitted back to the rover to assist it in navigation, hazard detection, and other functions such as sample collection. The rover would also take high-resolution images from ground level and compare them with synthetic images to resolve any navigational problems which may be encountered. Resolved images would be transmitted back to Earth and could also be used to generate "virtual reality" representations of the lunar surface for use by scientists, engineers, and the general public.

By performing the complex image processing on Earth and transmitting processed images to the Moon at high power levels, the computational and power requirements on the rover can be easily met. The rover could be smaller because it could be designed to navigate around even small objects (< 0.1 meters). Teleoperation could be minimized because the rover would operate from an accurate map of the territory and the rover could operate at a relatively high speed (> 1 meter/sec).

These claims all seem reasonable and are based on technologies in use on Earth. The technique would be extendable to other planets and quite useful when the emphasis is on detailed exploration of a particular region in which optical photography is possible. Active imaging systems, such as synthetic aperture radar, may be needed to map dark regions such as the lunar craters near the poles of the Moon, where some scientists expect water-ice will be found, and on Titan where the surface is obscured by clouds. Costs may be driven by telemetry and remote-image sensor complexity. The approach should be carefully examined.

Walking, Hopping, and Crawling Robots

- **Wheeled Articulating Rover Propulsion Methods (WARPM) (#100815)**

A rover is proposed that has "legs" having "powered wheels" as feet. Walking motion would be used in rough terrain and rolling motion in smooth terrain. Wheeled travel would allow the robot to efficiently travel long distances over smooth terrain. However, there is concern that the complex wheel and power system will be subject to a wider range of failures

and significantly degrade the walking ability of a legged robot. Development costs are likely to be higher with two modes of travel. Two separate vehicles, one wheeled and one a walker, that can carry one another might also be considered. The concept has been proposed many times before. It should be considered in various SEI mission niches after a careful review of the available literature.

- **Solar Powered Cricket (#100377)**

Mechanical crickets of less than 10 kg mass would be provided that are equipped with solar cells for power, a mechanical arm for hopping, instrumentation for data-gathering, and telemetry for local transmission of data. Several crickets would be deployed from an unmanned lander for initial exploration of a particular area. They would periodically hop around the landing area and over a period of time gather detailed statistical data. The crickets would be expendable and equipped with minimal guidance mechanisms to recognize and clear major obstacles and with mechanical means of reorienting themselves after a landing.

This interesting concept should be explored. The approach offers a low-power method to explore a small region on the Moon or Mars. Advances in micro-mechanical and micro-chemical devices would enable a swarm of rugged crickets to gather a wealth of local data. The cost could be moderate and a swarm of crickets would be more reliable than a single rover.

- **Crawling Rover/Manipulator Project (#101325)**

A multibody vehicle is proposed that is composed of "leg pairs." Each leg pair consists of a payload box, two lateral, rigid legs, and an actuation mechanism, termed a Stewart's platform, connecting one payload box to the next. The Stewart's platform is an octahedral cell with six variable-length actuators that move one payload box (rotation, differential length) with respect to the preceding and following payload boxes to produce forward and turning motion in the style of a caterpillar. The combined units could serve as either a robotic arm or a mobility device. Thus, these types of units might find use in facility construction and surface mobility, a unique combination.

A detailed technical paper and outline proposal for development of the computer program to enable coordinated redundant control was included. The submission received mixed reviews. It was considered a very safe but slow approach to surface mobility. The device would have little stored energy and that energy would be restricted to a few of the body segments at a time. That is a significant safety feature. Various payload boxes could support different functions (mechanical, sensors, etc.), and great redundancy and stability is inherent. The multibody vehicle offers a unique combination of hard and soft automation

and can be demonstrated in a laboratory. However, the advantages gained by crawling could be negated operationally by the considerable mechanical and control complexity. The concept should be further considered by SEI. There are significant terrestrial applications such as repair and inspection inside pipelines or sampling of very rough terrain.

Ballistic Probes

- **Automated Subsurface Sampling by Coring Penetration (#100339)**

Several coring penetrators, described as optional exploration technology for a Mars Sample Return Mission (MSRM) defined by JPL, will be released from an orbiter and fall to Mars within a predetermined area. The various penetrators drive to different depths, all greater than 2 meters, and somehow provide their samples to an Automated Sampling and Collection System (ASCS). The ASCS is delivered to each penetrator by a rover that operates from its lander and sample-return vehicle.

This technique has been studied for Mars, asteroids, and the Moon, and penetrators have been demonstrated on Earth. Such penetrators would increase the initial costs and complexity of a sample return mission. Inevitably the samples would be modified by the penetration and collection processes in ways that would be hard to characterize without reference tests that are impossible in first missions. The penetrators would land randomly inside a given area and, except for penetration depth, would not necessarily return the widest variety of samples. The technique should be reexamined by SEI for future missions but only in competition with other more controllable techniques that would also not be as prone to single-point failures, such as might occur with a single rover and single ASCS. The unmanned system is seen as safe for humans but of relatively low reliability and of average utility and innovativeness in comparison with other approaches.

Diversity and Teamwork

- **The Lewis and Clark Expedition II (#100343)**

A general approach is sketched out for the use of three types of robots to conduct unmanned, remotely controlled exploration of specific traverses along the lunar surface. A transporter and base unit robot would take two different types of exploration robots (Lewis and Clark) to a particular site. The site, such as a crater wall, might be too rough for the base vehicle to traverse. Lewis and Clark, which are not described, would conduct separate surveys and provide backup to one another.

The general concept is interesting, because each robot could be specialized and therefore possibly cheaper to build and deliver. The use of several types of robots may

increase system reliability. The rover could be generally similar to the Soviet Lunokhod deployed in the early 1970s. The basic architecture is not innovative. SEI should consider the use of different types of robots in exploration, construction, repair, and other functions as suggested in several of the submissions.

TRANSITION TO AUTONOMOUS ROBOTS

Although the concept of the autonomous robot is an old one, it is still far from being realized and may never truly be created by human beings. Robotics has a host of unsolved problems, which make it appear that machine autonomy will not be achieved in the foreseeable future. For example, robots cannot "see" and understand images like humans do. Nor can they perform complex mechanical tasks in an unstructured, unpredictable work environment. Perhaps the real crux of the matter is that robots, even if equipped with AI software programs or expert systems, are not capable of reproducing all the rich and varied cognitive decision-making processes of the typical human. Nevertheless, it is informative to speculate on what capabilities an autonomous robot must have.

The ultimate autonomous robot should be able to take the place of a human and perform human physical or cognitive activities. A fully autonomous robot would be capable of performing any possible human task through an equivalent set of robotic tasks. Therefore, to define robotic tasks for an autonomous robot, one can use human capabilities and activities as a model.

Humans have many capabilities: high fidelity stereoscopic vision, speech or language interpretation, stereoscopic hearing, sophisticated goal-oriented navigation, dexterous tactile-sensing hands, legs for locomotion, and an inner-ear balance sensor for stability. All these human systems are marvelously well integrated.

Many simple human activities, such as searching for and picking up a coffee cup, require precise coordination of several of the human capabilities mentioned above. Let us delineate the fundamental physical and cognitive tasks in this simple case.

Consider a person who, wanting a cup of coffee, looks for a coffee cup in her office. After searching through the cluttered office, she spots a cup handle behind a stack of books. She moves to the book shelf by walking around a desk chair, stopping at arm's length from the cup. She directs her hand towards the cup, grips the cup handle, and picks it up without knocking over the stack of books.

It's a simple matter for a human to find a coffee cup. Now consider a robot directed to search for a coffee cup hidden in the same disordered office. What intermediate tasks would such a robot have to perform to retrieve the cup? These tasks are indeed fundamental to

autonomous robotic activity, including those which may be required to fulfill SEI mission objectives. They are:

- Global sensing, navigation, and movement
- Local sensing, navigation, and movement
- Image processing and understanding
- Expert systems and decisionmaking

Global Sensing, Navigation, and Movement

First, the robot would have to find the cup using its own array of imaging and perhaps other sensors. To conduct a thorough search, the robot would require a global model of the environment, in this case a model of the office. If it is assumed that the contents of the cluttered office change at random daily, the robot could not be programmed with an all-inclusive static model (a model of a structured environment). Instead, the robot would be programmed with a priori knowledge of only the simplest attributes of the room and its contents, such as the size of the room and a description of the furniture, books, and cups present. The robot vision system would have to distinguish between objects and select a coffee cup from the clutter. This simple task is a formidable and as yet unsolved problem in computer vision (the ability to discern specific objects in a "noisy" cluttered image).

Nevertheless, assume the robot has correctly imaged and identified the coffee cup. The robot would then determine its relative location and move toward it to pick it up. Because there is a chair in the way, the robot must construct and follow a path to avoid the obstacle, stopping within an "arm's length" of the cup. In other words, the robot must navigate within a global model of the environment constructed from static information "known" a priori and from new information acquired during global sensing. Then its locomotion systems must move it accurately to the desired location in the room.

Local Sensing, Navigation, and Movement

If it is assumed the robot has been successful at the global sensing, navigation, and movement tasks described above, it must still execute several additional maneuvers to retrieve the cup from behind the stack of books. It must sense the orientation of the coffee cup (e.g., the direction in which the cup handle is pointed) and the cup's position relative to any obstacles (the stack of books). Once this local sensing task is performed, the robot must determine an appropriate trajectory path for its hand so it can grasp the cup handle, pick it up, and carry it away without knocking over the books. After the local navigation program

has computed an appropriate hand trajectory, a sequence of motor commands would be sent to the robot arm. The robot's controllers, actuators, and motors would move the robot hand to within the vicinity of the cup. A similar set of commands would be sent to the robot's fingers to circle the cup handle. The arm would lift and carry away the coffee cup along the previously computed trajectory path.

Image Processing and Understanding

Global and local sensing capabilities of autonomous robots modeled after humans should be capable of processing visual information and extracting from it the position, identity, and orientation of objects in a cluttered and noisy environment. Indeed, human vision and associated image-understanding capabilities are understood in only the most general geometrical terms by current researchers. How the mind extracts object-oriented information from an image and understands the geometrical relationships between objects in a scene is still not understood.

One should be careful to distinguish other forms of image processing that are more well developed, such as three-dimensional computer graphics, from the notion of computer vision. Three-dimensional computer graphics is, in fact, the inverse of the process we are concerned with here. Computer graphics engines take mathematically defined geometrical objects placed in specific orientations (for example, some objects occluding others), the position of the scene light source, and the viewer's position, and through a series of mathematical operations construct an image of a scene. Unfortunately, only rarely does this image-construction process have a unique inverse process. The more complex or noisy the image, the more inverse-image processes and visible-object sets correspond to the image at hand. Many common optical illusions, such as the famous etchings of Escher, are in fact based upon this nonequivalence of images and visible-object sets. In order to understand images, the human mind uses many sophisticated and perhaps not always compatible image-processing algorithms. Many of these algorithms are still not understood, nor have they been translated into digital or photonic algorithms.

No submissions were received in the areas of image processing or image understanding.

Expert Systems and Decisionmaking

For a robot to perform globally and sense, navigate, and move in autonomous fashion locally, it must continually compare data it receives from its sensors or other subsystems with its own world model and the command directives it has been instructed to follow. In

this data comparison process, the robot will eventually come to decision points where it must determine what to do next. These decisionmaking processes occur on many levels. When do I turn left to find my way to my objective? When can I safely stop tightening this nut and still be sure I have fastened the storage tank to the truss? When must I return to the power cart to recharge my batteries?

Computer software systems, or expert systems, have been developed that can emulate these decisionmaking processes in some cases. Typical expert systems can make decisions on only a very limited but sometimes very detailed set of data or assumptions. In addition, these systems can sometimes be modified in real time when conflicting or new information is received. However, if unanticipated data or data not in the proper form or indirectly related to the data structures used in the expert system are received, the expert system may freeze up and not be able to incorporate the new data and make a decision. Because the fields of artificial intelligence and expert systems are still relatively new, it is not certain what capabilities will eventually be made available using expert systems. Several submissions were received in this area. All were fairly general endorsements of the technology and suggested what may be feasible if these systems are vigorously developed for SEI applications.

- **Self-adaptive, Scalable Real-time Control Architecture for Various Robotic Vehicles (#100342)**

This abstract, with no back-up paper, provides an extremely general description of some of the major goals of any effort to develop an autonomous robot. Such a system would "(a) accommodate a variety of sense-reason-act control models, (b) incorporate a 'compare' step in each model to dynamically modify its reasoning capability based on learned cases, (c) provide an exchange paradigm between the various models."

Computing systems with such capabilities would be extremely useful, especially if means can be provided to make sure the system is learning in a realistic manner and not developing capabilities to unexpectedly do harm to humans or critical elements of the mission. Unfortunately, the abstract does not provide pointers to the technical literature about technologies such as parallel processing, cooperative problem solving, or knowledge representations which are relevant to achieving autonomy.

- **Advanced Control Architecture to Support Various Missions, Robot Applications, and Integrated Advanced Sensor Systems (#100345)**

This abstract maintains that an object-oriented system of modular software can be developed that will provide progressively higher levels of autonomy as the development proceeds. The enabling technologies are stated to be the NASA/NBS Standard Reference

Model (NASREM) as developed for the Flight Telerobotic Servicer, the USAF Next Generation Controller Project for a Standard Open System Architecture Specification (SOSAS), the Product Data Exchange Specification (PDES), and the Product Definition Data Interface (PDDI). An extended paper with references and detailed logic was not provided.

The architectures and specifications cited are rather general and are aimed at advanced manufacturing systems and robots to be operated within well-defined environments. Considerable real-world experience can be obtained when they come into widespread use. However, except for NASREM, NASA has little involvement in their development or use. They are not the focus of research in machine autonomy. NASA can certainly profit from examination of the systems, their operation, their application to systems designed to be supported by robots, and their aspects unique to space (e.g., control laws with variable gravity and long time delays). Practical experience on Earth becomes important as any level of manufacturing off Earth is planned.

The generic concern is for NASA to systematically transfer terrestrial processing and manufacturing to the space environment and to support research on those aspects that are unique to space and therefore are not being developed on Earth.

- **Use of Next-generation Control Techniques for Robot/Machine Control Systems (#100348)**

The Air Force is heading the development of the next-generation control technology that is establishing the SOSAS for robotic and machine controllers. The market for devices using this system will be much larger than for any system currently specialized for space. Thus, NASA can learn much from the practical experience acquired by implementers and users of SOSAS. The challenges are: how to acquire knowledge of the practical experience that may be acquired worldwide (particularly from DoD), how to influence the development of devices, testing means, and data collection so as to transfer this experience to space systems, and how to recognize as early as possible the limitations of SOSAS for operations off the Earth.

NASA must vigorously examine SOSAS. Practical knowledge of actual applications and demonstrations is a precious commodity. Perhaps NASA should sponsor design and demonstration studies of models and simulations of SEI operations using SOSAS standards and virtual reality simulations. NASA should certainly participate in SOSAS definition now and in the future.

- **Artificial Intelligence Systems for Space Applications (#100442)**

This submission, which contains an abstract and no backup paper, proposes that expert systems (ES) be applied to the control of various ground and space systems to reduce

manpower requirements by recognizing potential system faults, by identifying maintenance and repair requirements and procedures, by providing repair guidance for the operator and by training personnel for unfamiliar tasks. A list of current operating expert systems is given: Helix (helicopter operation), IFIP (fault isolation), and Sherlock (jet engine maintenance). Use of ES in planning and simulations is noted.

Expert systems are now being developed for use on the space station and for future space experiments. They will be increasingly important in the future. A current fundamental limitation to their use is transferring data between program levels. For example, how can an expert system that provides a planning function receive information from an ES associated with supply of components and also from a lower system associated with monitoring maintenance needs of a unit of flight hardware? NASA must continuously study how ESs are applied in the economy at large as well as fund those ES applications that will reduce both ground and space personnel requirements. Expert systems are only one aspect of artificial intelligence (AI); thus, NASA should maintain a broad overview of the field. The aggressive use of AI in the development and operation of simulations will be especially useful in evolving AI and ESs from theory and commercial practice into the operation of the space program.

Autonomous Navigation

Development of true global navigational capabilities—especially for exploration rovers—for robots has been a subject of academic research for some time. Autonomous robots would have to possess such a capability and be able to formulate navigational cues quickly in order to traverse terrain or the space around a space station at high speed.

- **Three-Dimensional Reactive Navigation (#100333)**

This submission proposes development of an autonomous navigation program for three-dimensional movement that can also be reconfigured in real time in response to changes in the characteristics of the surrounding three-dimensional environment. The submission is accompanied by a backup paper whose subject is much more narrowly focused on three-dimensional obstacle avoidance techniques. Obstacles are modeled by a repulsive potential field, and the robot is guided along low-repulsive equipotential trajectories in the environment. The more ambitious claims of real-time reconfigurable reactive navigation are not substantiated in the backup article. Nevertheless, the submission touches on many interesting and important issues in autonomous navigation research. Such research needs to be funded to advance the state of the art of autonomous mobile robots, and especially that of exploratory robot rovers.

IV. CONCLUSIONS AND RECOMMENDATIONS

In this section, we discuss our main recommendations to the Synthesis Group, then examine some important implications they may want to consider in the development and use of automated systems and robotics.

A total of fifty-two submissions were received in the robotics area during Project Outreach. Most of the submissions were judged to be reasonable proposals, although there were a few submissions which seemed to fly in the face of both conventional wisdom and expert opinion. About half of the submissions (24) were judged to have high utility for SEI and were analyzed further by the robotics panel.

Three types of robots were proposed in the high-scoring submissions: structured-task robots, teleoperated robots (like the FTS), and surface exploration robots. Several advanced TOR control interface technologies were proposed in the submissions. Many A&R concepts were presented by the submitters, but few specific technologies were suggested. There are many potential explanations for this. Proprietary submissions were not accepted. The time scale for Project Outreach was very compressed, leaving little time for a submitter to provide additional information. And finally, most submitters probably had to prepare their submissions on their own time.

Review of the submissions and further research in A&R issues has led the Project Outreach A&R panel to submit the following recommendations to the Synthesis Group:

- SEI robots, work environments, and systems should be systemically integrated.
- Structured-task robots should be developed for SEI.
- NASA should adapt and develop advanced TOR control interfaces which enable telepresence.
- The architectural implications of using TOR telepresence control in SEI should be evaluated.
- Data collection requirements for early SEI remote sensing missions should be reevaluated and harmonized with later SEI robotic mission requirements.
- Tradeoff studies are needed to select optimum mobility and navigational subsystems for SEI surface exploration robots. Teams of complementary exploration robots should be considered in these tradeoff analyses.
- Tradeoff studies are needed to determine the most cost-effective and productive development path towards autonomous robots.

- NASA's evaluations of A&R effort for Space Station Freedom should be reviewed.

Below we discuss these recommendations in more detail.

INTEGRATE SEI ROBOTS, WORK ENVIRONMENTS, AND SYSTEMS

Most human work environments can be unstructured, because humans can easily and rapidly adjust to unanticipated changes or events in their environment. Such human adaptability and flexibility result from our sophisticated and not completely understood planning, sensing, navigation, and movement capabilities. The current state of the art in robotics cannot provide systems that faithfully mimic these human capabilities, so SEI work environments in space and on the surface of the Moon or Mars must be carefully designed with the current limits of robotics in mind. SEI systems to be manipulated by robots should be designed so that robots can productively use their end-effectors. Further, all SEI robot end-effectors should be designed and manufactured to a limited set of end-effector design rules to enable different robots to use the same end-effectors for several different manipulation tasks. In particular, there are a number of FTS-like robots being developed by NASA or its contractors (submissions #100695, #100338, etc.). All these robots should be able to use the same end-effectors and these should be compatible with the hooks and scars being put in SSF and other SEI systems.

A critical area that is not being considered in the United States but is under consideration in Japan is the development of space facilities that make extensive use of robots in assembly, maintenance, and repair. Robots are still viewed in the United States as gadgets or tools that are added to a structure to be constructed and maintained primarily by people. Extensive design exploration and demonstration efforts must be initiated to provide the United States with space and planetary systems that are primarily constructed, maintained, and repaired by robots. This critical theme was not explicitly mentioned by any of the submissions to the Automation and Robotics section of the RAND Outreach Panel.

Perhaps the most important issue involved in systemically integrating SEI robots, work environments, and systems is capturing and maintaining configuration control over SEI system designs. Detailed engineering design data must be captured in a common digital format and made portable, so that it can be used by different system contractors during design and manufacturing and by robots in space during assembly and repair operations. The automated capture of SEI system design knowledge has been made possible with the advent of integrated CAD/CAM tools. Transportability of CAD/CAM files is also being improved with the introduction of commercial standards such as the emerging Electronic

Data Interchange Format (EDIF) CAD/CAM standard. NASA should monitor the development and use of CAD/CAM tools and standards in the semiconductor and other industries and adapt these increasingly powerful design tools to SEI systems and robots.

DEVELOP STRUCTURED TASK ROBOTS FOR SEI

The most productive robots on earth are STRs. They have transformed the Japanese auto and semiconductor industries. Now the Japanese install as many robots every year as exist in the entire United States industrial base [Ref. 2]. Equally productive robots will be needed for SEI if the President's ambitious mission goals are to be met within the designated time frame and within future budget constraints.

Much further research into the use of STRs in space is required. The work being done in this field (submission #100378) should be greatly expanded for SEI. Assembly tasks should be made easy and modular, enabling STRs to be used wherever feasible at SEI extraterrestrial operations nodes.

Review of the submissions, and this panel's research and inquiries, indicate that NASA A&R research and development activities may have been too tightly focused on expensive high-technology developments like the recently cancelled FTS. While the FTS program was a necessary and ambitious technology demonstration project, SEI funds should also be allocated towards development of STR work environments and STRs for specific SEI applications. The adoption of commercial STR technology, as represented by submission #100378, should continue and be expanded. These efforts can lead to highly productive and cost-effective space and lunar construction concepts and may generate commercial spinoffs of their own. Such activities can only help revive the moribund U.S. commercial robotics industry and also provide a natural upstream technology base for the eventual colonization and industrialization of the Moon.

ADAPT AND DEVELOP ADVANCED TOR CONTROL INTERFACES

Submissions #100695, #100338, #101469, #100827, #100336, #101317, and others propose that TORs be used for many SEI assembly, processing, repair, and exploration tasks. Because TORs can be remotely controlled by humans, they can operate in unstructured environments and are more flexible and adaptable than STRs. They also require much less complex real-time software than autonomous robots would need. As a consequence a variety of TORs have been developed for commercial and space applications whereas autonomous robots have yet to be realized. However, most TORs available today are cumbersome to operate and typically perform manipulation tasks much more slowly than humans. For

example, it is estimated that the FTS in its initial configuration will perform manipulation tasks in space at a significantly slower rate than a well-trained astronaut in an EVA spacesuit. The performance limitations of current TORs have therefore prompted researchers to develop new TOR control interfaces to improve TOR productivity.

NASA researchers were some of the first to develop new and innovative display and interactive computer control technologies, such as "eye phones" and "power gloves," which offer tremendous promise as TOR control interfaces. Now commercial companies, both in the United States and Japan, are racing to refine and extend these technologies for various consumer, scientific, and business products. In addition, HDTV, high-resolution flat panel displays, and new three-dimensional display volume systems are being developed. The leading edge of development for these technologies is being pushed faster and harder in the commercial world. NASA needs to keep abreast of these new developments, test new systems for TOR control, and integrate those that demonstrate their worth into future TOR systems. These new technologies will allow NASA astronauts and the general public alike to experience SEI missions first-hand through telepresence.

Powerful new commercial speech synthesis and recognition products are also poised to enter the marketplace. NASA should monitor these developments so their capabilities can be quickly and cost-effectively integrated into new TOR control interfaces.

Emerging TOR control technologies and advances in computer simulation may also permit development of radically new control interfaces that can greatly increase TOR operator productivity and the effective radius of TOR control from thousands to millions of kilometers. These new control interfaces, or cyberspace interfaces (CSIs), need to be studied by NASA to see how they can best be used to control TORs, and if they lead to new strategies for obtaining higher forms of machine autonomy. Many Project Outreach submissions have suggested development of CSIs. One submission in particular (#100317) described in broad conceptual terms the enormous potential benefits of using these new technologies for TOR control.

IMPLICATIONS OF TOR, CSI, AND TELEPRESENCE CAPABILITIES

TORs may be used extensively in many phases of SEI operations. A significant amount of TOR coordination, mission planning, and real-time retasking will be required, especially for complex and TOR-intensive operations like MTV assembly or lunar base construction. If CSIs are used for TOR control, even more coordination may be necessary, because TOR operators will be sensorially centered at the remote site where their TOR operates, rather than at their control stations.

By making analogies to certain military operations and practices, it is conjectured that TOR command, control, and communications (C3) centers will be required to efficiently and safely perform TOR coordination and task planning. Depending upon the sophistication of TOR control available in the time frame of SEI, TOR C3 centers may be required at each major extraterrestrial SEI operations center. On the other hand, if CSIs can effectively extend man's control range over TORs and if TORs can eventually be given greater autonomy, a single TOR control station located on Earth could direct TOR operations in space, on the Moon, and perhaps even in the far term on Mars. Although different terminology is used by the author, submission #100337 suggests development of such TOR C3 centers.

The manpower, power, habitat, and communications requirements this suggestion implies must be studied by NASA and included in future SEI architecture studies. The most significant implication of widely using TORs and incorporating telepresence controls into SEI would be the greatly increased communications burden SEI space networks may have to support. If one conjectures that HDTV-like display devices are used for stereoscopic control of each TOR, then roughly two HDTV channels will have to be supplied for every TOR that is controlled from a distant location. New developments in image compression and distributed simulation technologies will be required to reduce TOR command and control communications requirements and make cyberspace interfaces a reality. NASA should carefully monitor developments in these areas.

SEI ROBOT MISSION PLANNING

As the SEI program proceeds over the next quarter century, SEI operations will increase in scope and complexity. Succeeding generations of SEI robots will depend upon and exploit data collected from previous SEI and NASA missions. Data collection requirements on early missions should therefore be carefully determined with later SEI mission-planning needs in mind. Synergies may exist between early SEI data collection efforts and later exploratory, construction, or resource extraction missions. If high-resolution data are collected on early exploratory missions, they may prove useful for many purposes and could reduce the cost and complexity of follow-on robotic systems, such as lunar rovers or base-construction robots. In addition, such data collection efforts will provide scientists and prospectors with an unprecedented geologic record of the lunar and perhaps Martian surfaces.

High-resolution imaging (0.1 m) of the Moon is feasible and could perhaps be carried out at a number of wavelengths. NASA should examine innovations in new sensor

technologies and in small satellite developments (Lightsats) to see if the Lunar Observer or Martian Observer spacecraft should be augmented by new lightweight remote sensing systems that could not only provide higher resolution optical imagery, but could also image deep, permanently dark craters near the lunar poles.

ROBOT EXPLORER TEAMS

A number of surface-exploration robots have been proposed in various Project Outreach submissions to perform exploration tasks over various types of terrain (submissions #100336, #100815, #100337, #101325, #100339, and #100343). They can be grouped according to the mobility and navigational concepts they employ. Tradeoff studies need to be conducted comparing various mobility and navigation concepts to select which could best fulfill SEI mission objectives. In addition, one submission (#100343) proposes that robot teams be used to explore the Martian and lunar surface. Such a team may offer more terrain flexibility and may be more cost effective than employing identically configured multipurpose complex rovers.

TRANSITION TO AUTONOMOUS ROBOTS

A key SEI robotics programmatic issue over the next twenty years will be the schedule-development risk for semi-autonomous or autonomous robots. Versatile autonomous robots capable of operating in unstructured SEI environments (a planetary surface or free-flying LEO) will require the following capabilities: goal-directed navigation, system control, propulsion, decisionmaking, image recognition, and perhaps voice recognition. These capabilities require development of large, error-free software codes. As with present AI software, software development risk must be considered to be very high. IOC dates for autonomous robots cannot be predicted and may not be achievable without an enormous investment in software development infrastructure. Semi-autonomous robot developments will likely trail other SEI development schedules.

Several submissions (#100342, #100345, #100348, #100442, and #100333) recommend that NASA should adapt or develop emerging artificial intelligence technologies, autonomous navigation software, and new modular robot control and software standards such as NASREM and SOSAS in order to develop autonomous robots. While these standards are rather general in nature at this time, NASA can certainly profit from examination of the systems.

Although TORs may be easier to develop than autonomous robots, the latter have an advantage in that significantly less manpower and communications may be necessary to

support their activities. Each TOR will be controlled by a human operator. For construction of SSF or other LEO-based space structures, TOR operators could be located on Earth. TOR manpower requirements for an Earth-based TOR C3 center will not be a major SEI architectural issue, although the associated communications requirements will be significant. On the other hand, TORs on the Moon or Mars may have to be directed from local C3 centers because of the communication time delays incurred from Earth. The 2.5-second round-trip time delay between the Earth and Moon would render present-day TOR feedback control loops unstable. With near-term technology, TORs performing dextrous or complex tasks on the Moon must be locally controlled. On the other hand, if advanced TOR control interfaces and semi-autonomous TORs can be developed, then TOR control could be extended over progressively greater distances.

Tradeoff studies need to be performed by NASA to find the most cost-effective and technically feasible SEI robot development plan, and to determine whether TOR or autonomous robot research and development should be emphasized. In addition, such assessments could also be used to determine which key subsystem technologies must be targeted for further development. If current technology trends continue, TORs equipped with CSI control interfaces and some autonomous capabilities will prove to be the preferred development option.

REVIEW NASA'S EVALUATION OF A&R EFFORT FOR SPACE STATION FREEDOM

The United States space program would be impossible without a level of automation and robotics that reflects, to some extent, the general state of the art. However, over the past twenty years the dominant role of military and NASA agencies in A&R research and development has been sharply reduced while the role of commercial industry has increased proportionally. A major challenge to NASA is simply maintaining an awareness of A&R advances and how these technologies are being used in new ways in the commercial world (use of CAD/CAM technologies in the semiconductor industry for the modular design of integrated circuits is one example). Implementation of evolving A&R technologies is an enormous challenge to the administration. At the direction of Congress, NASA has conducted a continual review of the implementation of A&R within the Space Station Freedom. A&R implementation efforts have been reviewed approximately every six months since 1985 [Refs. 7-15]. We recommend that the Synthesis Group review NASA's evaluations of the Space Station Freedom effort to see how advanced A&R could best be incorporated in to SEI. Such a review will reveal the many difficulties, both human and technological, that lie ahead, and at the same time the great motivations for pressing ahead.

Appendix A

SUBMISSION HANDLING, EVALUATION METHODOLOGY, AND AUTOMATION AND ROBOTICS PANEL CRITERIA FOR EVALUATING SUBMISSIONS

Submitters were asked to select the appropriate category for their ideas from among those listed in Table A.1. The table shows that all categories received a fair number of submissions. Of the 1697 submissions received, 149 (less than 9 percent) were judged to be incapable of being screened. Another 105 submissions were received after the cutoff date of August 31, 1990.

Table A.1

Submissions Distributed by Category

Category	Screened	Not Analyzed
Architecture	290	1
Systems	52	0
Transportation	350	0
Power	138	1
Life support	156	2
Processing	75	3
Structures	119	1
Communications	45	1
Automation	52	1
Information	21	1
Ground support	28	0
Others	194	4
Undetermined	28	134
Total	1548	149
Received after 8/31/90	105	

A submission was ruled incapable of being screened if it (1) was marked as classified or proprietary or (2) contained no supporting information of any kind. A submission marked as either proprietary or classified was automatically destroyed by the subcontractor. In such cases, the subcontractor noted who destroyed it, the date, and any particulars, then informed the submitter of the destruction of the submission and the reason for it.

As shown in Table A.2, the majority of submissions (63 percent) came from individuals, with 22 percent coming from for-profit firms and 5 percent from educational institutions. The relatively few submissions from educational institutions may have been

a problem of timing, because Project Outreach's publicity and submission process began in the summertime, when most lower-level schools are closed and most universities have reduced staffs and enrollments.

Table A.2

Sources of Submission

Source	Submissions	
	Number	% of Total
Individuals	1061	63
For-profit firms	381	22
Educational institutions	89	5
Nonprofit organizations	72	4
Other	46	3
Groups of individuals	48	3
Total	1697	100

Nevertheless, Project Outreach generated broad national interest. All of the states except Alaska, Arkansas, and Wyoming were represented, as were five foreign countries—Argentina, Australia, Canada, Israel, and Scotland. Interestingly, 40 percent of the submissions came from three states—California with 26 percent, Texas with 9 percent, and Florida with 5 percent.

NASA personnel also contributed to Project Outreach: submissions were received from the Johnson Space Center, Goddard Space Flight Center, Marshall Space Flight Center, Lewis Research Center, Ames Research Center, Jet Propulsion Laboratory, Langley Research Center, the Reston Space Station Program Office, and the Stennis Space Center. A total of 121 submissions were received from NASA locations.

SUBMISSION FORMAT

Submitters were asked for a two-page summary and simple outline of their idea. Submitters were also given the option of submitting an additional ten-page backup explanation of their idea. Only 22 percent of the total submissions included backups. This had implications for the analysis process, which we discuss below.

SUBMISSION HANDLING

Because of time constraints, RAND was obliged to follow an abbreviated six-month schedule. Figure A.1 shows the flow of the process we developed and implemented for handling the submissions. Our task involved simultaneously processing the submissions, developing a methodology, training the panels, and building the software. This time frame allowed no margin for error.
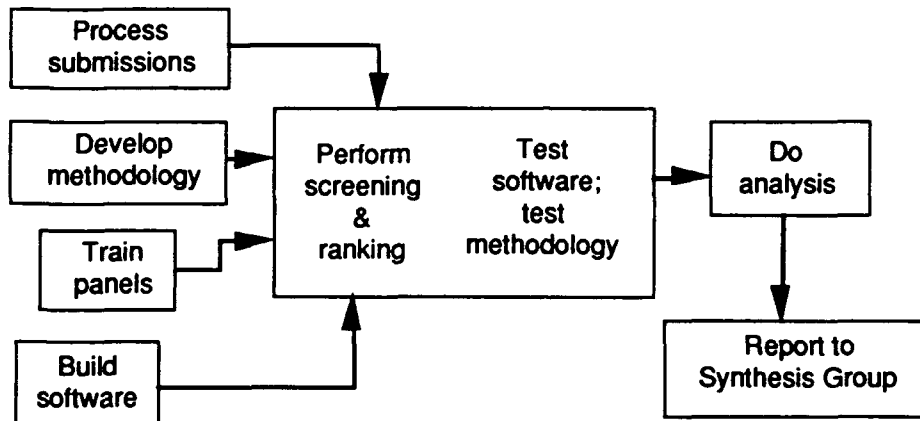

Fig. A.1—Flow of submission handling

During our screening and ranking process, we were, in effect, testing the software and the methodology, a highly risky process. We are happy to report they both performed well.

SUBMISSION DATABASE

For each submission, pertinent background information was logged into the database, including the unique ID number of the submission, the reviewer, the date, the name of the panel performing the review, and the title or subject of the review. To remove bias from the process, the panels did not have information concerning the submitter's name or organization. Reviews of the submissions were entered in a text field. Each reviewer was required to briefly explain the reasons for scoring a submission as he or she did.

PANEL RANKING OF SUBMISSIONS

Primary Ranking Method

Submissions were ranked initially using a method based on weighted sums of five attribute scores. In this case, the attribute weightings were numbers between zero and one that summed to one over the five attributes. These weightings represented the consensus of each panel concerning the relative importance of the attribute for the panel's particular technology/mission area.

Table A.3 presents the screening process weights determined by each panel for each of five common attributes. Each submission received a composite score, computed by summing over all attributes the product of the attribute score (1–5) and its weight. Thus, rankings represent the overall score of a submission relative to all the submissions within its panel. Rankings by composite score can be sorted within the Fourth Dimension database and recomputed using different attribute weights to perform sensitivity analysis.

Table A.3
Screening Process Weights Determined for Each Panel

Panel	Utility	Feasibility	Safety	Innovativeness	Cost
Architecture	0.30	0.30	0.15	0.20	0.05
Transportation	0.30	0.25	0.25	0.05	0.15
Power	0.25	0.25	0.25	0.10	0.15
Human Support	0.40	0.25	0.08	0.25	0.02
Structures	0.30	0.25	0.20	0.10	0.15
Robotics	0.30	0.25	0.01	0.04	0.20
Communications	0.50	0.25	0.01	0.04	0.20
Information	0.29	0.23	0.11	0.20	0.17

Prioritized Ranking Method

To test the robustness of the screening process, each panel also ranked submissions using prioritized attribute ranking methods. In these, the *most important* (primary) attribute is selected, and submissions are ranked according to their scores for that attribute alone. Submissions with equal scores on the primary attribute are then ranked by their score on the next most important, or secondary attribute. The panels found that it was rarely necessary to use a third attribute to rank all the submissions by this process. The prioritized ranking of a submission can then be compared with its general ranking results to determine if there are significant differences. The lack of significant differences in the two ranking systems would indicate that the results are somewhat robust.

In addition, a secondary prioritized ranking was created by reversing the order of the first two attributes in the primary ranking. Thus, if safety was the most important and utility the second most important attribute for a given panel, the order was reversed. This provided a further check on robustness.

Comparison of Methods

Figure A.2 shows an example comparison of the results of the rankings from the Structures panel submissions. The vertical axis represents the primary rank of a submission, and the horizontal axis measures its prioritized rank. The intersection points of these rankings are shown by small black boxes or squares. The figure contains a 45-degree line from the origin out through the total number of submissions. Submissions that had the same primary rank and the same prioritized rank would fall directly on the 45-degree line. The "best" submission for this panel would be the one closest to the origin, because it would be the one that ranked first in the primary ranking or first in the prioritized rankings, or first on both. Thus, the closer that each of the small black boxes falls to the 45-degree line, the better the congruence of the two ranking methods. Figure A.2 shows that the dark blocks representing the top 20 or 25 submissions are in the lower left-hand corner, indicating good agreement. The agreements of the two ranking methods become less congruent as one moves out into the lower-ranked submissions, which is to be expected.
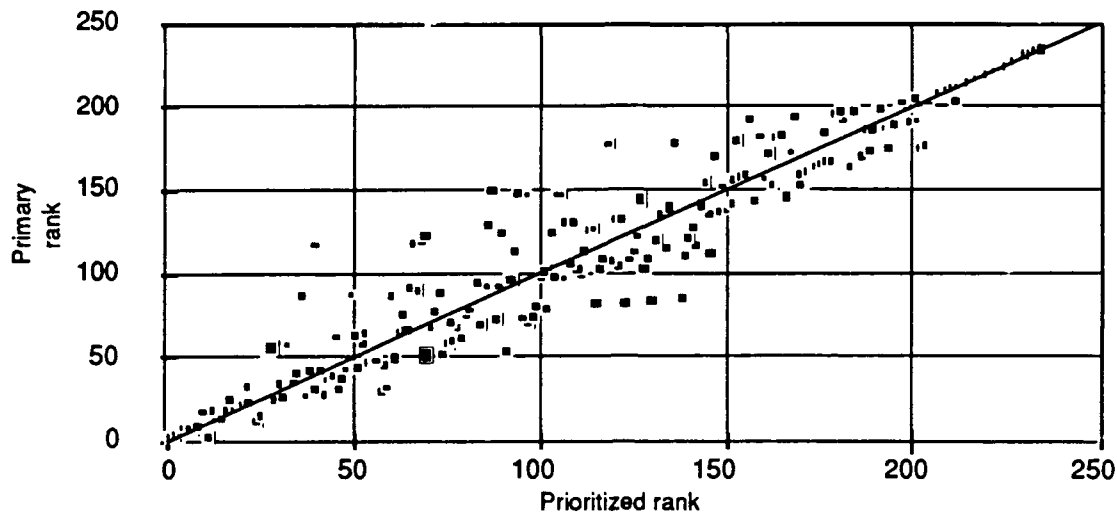
Fig. A.2—Flow of Submission Handling

Table A.4 compares the percentage of common submissions found in the lists of the top 20 submissions as created by the three ranking methods just discussed. The left-hand column shows the percentage of submissions that appeared on both the primary and "primary prioritized" lists; it indicates that the percentage of overlap of the top 20 submissions on both lists ranged from 75–85 percent. The right-hand column shows the commonalties among three lists: the primary rankings, the "primary prioritized" rankings, and the "secondary prioritized" rankings discussed above. This comparison was made as a more stringent test of robustness; it also reveals a fairly high correlation among the three ranking methods.

This correlation gives confidence in the consistency of the evaluation method used to screen submissions. It shows that whether we extracted the top 20 submissions using the prioritized or the primary methods, they would still be nearly the same.

Table A.4

Comparison of Ranking of Top 20 Submissions for Each Panel

Panel	Percentage of Submissions Appearing on 2 lists[a]	3 lists[b]
Architecture	75	40
Transportation	75	35
Power	85	75
Life Support	80	55
Structures	85	80
Communications	85	55
Robotics	85	55
Information	80	80

[a] Primary and prioritized.
[b] Primary, prioritized, and reverse prioritized.

CRITERIA USED BY AUTOMATION AND ROBOTICS PANEL IN EVALUATING SUBMISSIONS

Utility

The dimensions considered were performance, efficiency, ease of implementation, graceful degradation, complexity, and flexibility/adaptability.

A score of

(1) indicates low utility

(3) indicates moderate utility

(5) indicates high utility

Feasibility/Risk

The contextual dimensions of feasibility we considered included availability of devices, availability of techniques, availability of theory, time scale, and level of confidence.

A score of

(1) indicates low feasibility/high risk of failure

(3) indicates moderate feasibility moderate/risk of failure

(5) indicates high feasibility/low risk of failure

Safety

Safety in this case pertains to human safety. Its dimensions include the direct consequence of a failure, the system consequences of a failure, and fail-soft/fail-safe issues.

A score of

(1) indicates an unsafe concept

(3) indicates a moderately safe concept

(5) indicates a very safe concept

Relative Cost

Cost was considered within the dimensions of development cost, production cost, operation cost, and life-cycle cost.

A score of

(1) indicates a relatively high-cost concept

(3) indicates a medium-cost concept

(5) indicates a low-cost concept

Innovation

Innovation was considered within the dimensions of concept, application, and implementation.

A score of

(1) indicates the concept was not innovative or was innovative but did not bear upon SEI problems.

(2) indicates the concept was novel but not more useful than known solutions.

(3) indicates the concept was considered to be significantly better than known solutions to a given problem.

(5) indicates the concept provided a solution to a heretofore unknown problem.

Appendix B

LIST OF ALL AUTOMATION AND ROBOTICS SUBMISSIONS

Table B.1

List of Robotics Submissions

Submission ID	Title/Subject
100333	Three Dimensional Reactive Navigation
100334	Attempt to Introduce Human Life to Mars
100335	Homeostatic Control for Robot Survivability
100336	Computer Simulated Teleoperation
100337	The Robot Workshop
100338	EVA Equivalent Space Telemanipulation System
100339	Automated Subsurface Sampling by Coring Penetration
100340	Surface-to-Orbit Collection System
100341	Telerobotics in SEI Surface Operations
100342	Self-Adaptive, Sealable Real Time Control Architecture for Robot Vehicles
100343	Lewis and Clark Expedition II
100344	Surface Resource Extruder (SRE)
100345	Advanced Control Architecture to Support Various Missions, Robot Applications
100346	World Model
100347	Aluminum Coated Composite Robot Arms with Embedded Fiber Optic Sensors
100348	Use of Next Generation Control Techniques for Robot/Machine Control Systems
100349	Robotic Space (Walker) System
100375	Multi-Function Control Boards
100376	Sun Rover
100377	Solar-Powered Cricket
100378	Robotic Assembly of Large Lunar Structures
100442	Artificial Intelligence Systems for Space Applications

Submission ID	Title/Subject
100593	The Mass Distribution Construction System Automation, Robotics, and Teleoperator
100603	The Mass Distribution Construction System Ground Support, Simulation and Testing
100644	Orbital Assembly and Maintenance
100695	Space Robotics: A Highly Dexterous Robot with Adaptable Control Strategies
100788	Space Based Nondestructive Evaluation
100815	Wheeled Articulating Rover Propulsion
100827	Telepresence and Commercial Mission Objectives
100970	Five-Parameter Characterization of Robots
100971	Robotics: Waystation Carousels
101067	Image Processing by the Lunar Rovers
101293	Autonomous Free Flying Robots for 0-G Space
101317	Creation of a Virtual Environment for Teleoperation
101318	Integrated Kinematics, Dynamics, and Artificial Intelligence Robotic Development
101319	The Automation of Modular Structural Assemblies
101320	Small Space Dog Robot
101321	Competition for Design of Exploration Robots
101322	Roboman—A Man-Like Robot
101323	Repair Robot and Rover Vehicle for Robotic Maintenance
101324	Smart Components
101325	Crawling Rover/Manipulator Project
101439	Bayesian Control Systems
101440	Task Allocation Among Humans, Teleoperated Devices and Robots
101469	The Moon-Mars Autonomous Resource Management System
101514	Remote Tug Vehicle (RTV)
101536	Superiority of Supervised Robotics
101537	Magnetoencephalography for Reduced-Delay Control
101635	Robot Precursors to Planetary Surfaces
101668	Mars Exploration by Interactive Telepresence

Submission ID	Title/Subject
200881	On-Orbit Assembly, Servicing, and/or Maintenance Using Systems
401569	Exploration of Mars and the Moon

NOTE: There are 52 Robotics submissions.

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