SUPERVISED SPACE ROBOTS ARE NEEDED IN SPACE EXPLORATION

Jon D. Erickson*
National Aeronautics and Space Administration Lyndon B. Johnson Space Center
Houston, Texas 77058

Abstract

Recent studies of the types, numbers, and roles of robotic systems for use in human space exploration, including the First Lunar Outpost (FLO) mission, with a focus on planet surface systems are summarized in this paper. These high level systems engineering modeling and analysis activities have supported trade studies and development of preliminary requirements for intelligent systems, including supervised autonomous robotic systems. The analyses are summarized, results are presented, and conclusions and recommendations are made.

One conclusion is that space exploration will be "enabled" by the use of supervised intelligent systems on the planet surfaces. These intelligent systems include capabilities for control and monitoring of all elements, including supervised autonomous robotic systems. With the proper level of intelligent systems, the number and skills of humans on the planet surface will be determined predominantly by surface science and technology (not outpost) objectives and requirements.

Space robotics, especially those systems being developed to operate on planetary surfaces, can be considered a form of the emerging technology of field robotics on Earth. The solutions to the problems we will be solving to make the exploration of our solar system possible and practical will apply to the many critical problems we have that require operating in hazardous environments on Earth and to improving human productivity in many fields.

---

* Chief Scientist, Automation and Robotics Division, Member AIAA

1. Introduction

Human space exploration is a strategy for stimulating the United States, its people, and its economy as much as it is a strategy for exploring the Moon and Mars. A White House report [1] has outlined various visions and architectures for this crucial effort. We take the position in this paper that the greatest benefit to the U.S. economy of any space-exploration-related technology can come from the development of supervised intelligent systems, including supervised autonomous robotic systems. Such systems are mandatory for space exploration [2] to improve safety, reliability, and productivity, while enabling large cost savings through minimizing logistics [3]. Such systems are also needed in the U.S. economy [4,5].

Intelligence is the ability to acquire and apply knowledge and skills to achieve stated goals in the face of variations, difficulties, and complexities imposed by a dynamic environment having significant unpredictability. Intelligent systems are composed of sensors for sensing the "world," effectors for acting on the world, and computer hardware and hardware and software systems for connecting the sensors and effectors in which a part of the processing is symbolic (nonnumeric). This processing enables practical reasoning and behavior, which in humans we call intelligence.

Examples of artificial intelligence capabilities in intelligent systems are knowledge based systems, expert systems, natural language understanding systems, robotic visual perception systems, intelligent control and planning systems, qualitative and model-based reasoning systems, and supervised autonomous robots. Many supply an explanation facility that enables the user to ask what reasoning was used and why the conclusions were reached. Intelligent systems can be of four basic kinds: nonmobile, nonmanipulative systems such as monitoring and control systems; nonmobile, manipulative systems such as robot arms fixed in place at the shoulder; mobile, nonmanipulative systems such as inspection robots; and mobile, manipulative systems such as mobile robots with arms and end-effectors. While supercomputers, distributed computers, or parallel computers are

currently required to achieve real-time performance with large scale intelligent systems, CPU speeds double every 6 months, so such intelligent systems will be easier and cheaper to achieve in the future.

It is important to understand the advantages intelligent systems have over conventional automation. Some advantages are given by Erickson[6], which are primarily perception and flexibility in dealing with uncertainty and dynamics imposed by real environments.

The benefits of using intelligent systems in space missions are improved and increased safety, reliability, and productivity. These benefits are derived from applying more knowledge and reasoning in more flexible and appropriate ways than conventional automation.

The EVA helper/retriever effort[7] is an initial attempt to build and understand a limited version of a supervised autonomous robot for use in space. Many other efforts to build intelligent robotic systems, not necessarily for space, are under way[8].

2. Space Exploration Studies

Recent studies[9] of the types, numbers, and roles of robotic systems for use in the 20-year Option 5A space exploration mission[10], with a focus on planet surface systems, are summarized in this section. These studies employed high level systems engineering models that we developed. We now employ a software modeling tool, the mission simulation and analysis tool (MSAT)[11], which enables us to account for the nonlinear effects of resource allocation, parallel support and mission tasks, and occurrence of contingencies.

Mission feasibility is a paramount issue in requirements generation (along with verification, validation, and traceability). A useful device that exercises the skill and judgment of those concerned with requirements is to tell the story of the mission.

These stories form the basis of input to MSAT. Any mission story will be in the form of a process description. At the requirements stage, the story of any subprocess (such as landing on the surface, unloading, etc.) will be in terms of objects specified by functionality, not by actual design. As the stage progresses toward design, the stories will involve process designs and objects wherein performance and operational parameters can be quantified.

With the process description format, each mission story is told in terms of parallel processes, each with prescribed start times. Each process has a functionality type; at present the types used in MSAT are the following:

- Mission backbone (e.g., landing, launch, site preparation)
- Science
  - EVA: geologic traverses, astrophysics, geophysics
  - IVA: lab experiments, life sciences, analysis, packaging
- Maintenance
  - Dusting
  - Servicing
  - Repair (EVA, IVA)
  - Replacement
  - Testing
  - Inspection
- Logistics
- Support
  - Power
  - Thermal control
  - Communications
  - Crew safety and well-being

Each process is broken down into subprocesses, called stages, and each stage has a set of options corresponding to the different ways in which the stage can be carried out. Each stage option has a model assigned that enables computation of elapsed time versus stage option name and the types of agent resources to be used:

- EVA, IVA, and equipment
- EVA, robotics, and equipment
- IVA, robotics, and equipment
- EVA, IVA, robotics, and equipment
- Robotics only and equipment

MSAT is written in (interpreted) C, which is an application running under the Ellery Open System (EOS)[12]. EOS is a development and run-time environment for distributed computing applications. MSAT is a relational, table- and model-driven simulator that makes allowances for parallel processes and dependencies, for supply and demand of resources to accomplish processes, and for elapsed time in accomplishing mission processes and tasks.

In constructing the Option 5A models, we first reviewed the story of the mission from previous accounts that tells what is intended to be done during the mission with flight times, site layouts,

element and system descriptions, and manifests. Then we examined various advanced automation and robotics issues raised by the story. After establishing two differing points of view, a conventional systems view and an intelligent systems view (causing changes in the equipment manifests and in the way mission tasks are carried out), we redescribe the missions from those points of view (see Table 1) and construct two models corresponding to these views for the purpose of obtaining comparative results.

Numerical models were constructed only for control and monitoring, unloading, site survey and regolith handling, emplacement, servicing, and maintenance.

Figure 1 shows results from modeling crew workload demand for selected tasks versus crew EVA availability under the conventional systems model for four astronauts in 21 years of lunar missions. As can be seen, either more capable equipment, as in the intelligent systems model, or more crewmembers are required. This mission scenario, which calls for complex activities such as offloading of large equipment and construction of facilities in the absence of humans at the planet surface site, clearly makes intelligent robots mandatory. Figure 2 shows the crew EVA demand under the intelligent systems model and shows

primary crew time for creative activities of exploration, science, and planetary resources use. Science and engineering skills in the crew may now replace some pilots and technicians. A supervised autonomous outpost is thus seen as mandatory to preserve small crew sizes and ambitious surface mission objectives.

A broad range of robotic system uses in Earth orbit or during space transport is indicated by current studies. These include assembly of very large spacecraft systems such as propulsion systems and aerobraking structures [14]. Maintenance of onboard equipment in Earth orbit or during space transport is another robotic system use being studied.

3. First Lunar Outpost Studies

This section is based on Erickson [15], which has more details. The JSC Automation and Robotics Division (A&RD) has been performing high level systems engineering modeling and analysis activities to support trade studies and systems effectiveness analyses for proposed missions to the Moon and Mars. Preliminary requirements for intelligent systems, including supervised intelligent robots, have been the focus of our efforts.

Table 1 – Conventional systems versus intelligent systems

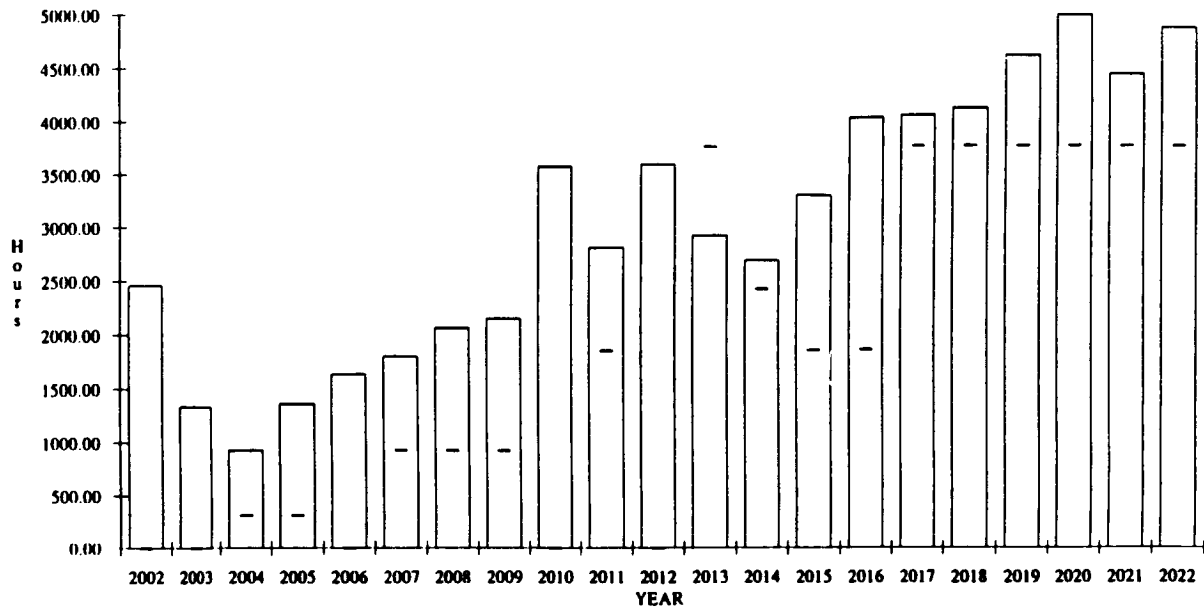| Conventional systems	Intelligent systems

● Use Fisher-Price[13] recommendations
● Conventional software
  – DDBMS for knowledge representation
  – Normal sensors
	● Use Fisher-Price recommendations
	● Intelligent system software
	  – State-of-affairs knowledge representation
	  – Extensive sensors/perception for knowledge acquisition
	  – Ability to use knowledge

● Mainly surface teleoperation, limited telerobotics ● Rudimentary, mainly Earth-based DOKSS ● Ground-based control and monitoring (for Moon) ● More-than-minimal computing power	● Supervised, autonomous robotics with structured environments ● Distributed DOKSS, real time where needed ● Surface-based, built-in control and monitoring with ground-based oversight ● Major computing power and information storage on surface

● Predetermined procedures	● Adaptable procedures with built-in precautions
	  – Rehearsals
	  – Interelement and interface testing

● Limited surface diagnosis and repair	● Design for ease of testing, diagnosis, servicing, maintenance, and repair
● Limited surface communication, major downlink	● Major surface communication, major downlink
● Crew used for outpost operations and maintenance, science and technology deployment	● Crew used for science and technology, minimal outpost operations and maintenance

Figure 1 – EVA allocation for conventional systems approach.

Simulation is concerned with identifying and solving problems by testing how well the operation of engineered designs will meet the mission objectives. Simulation of operations can provide early identification of performance problems of integrated design and operations concepts. When applied with alternative process and equipment designs, simulation of operations is used to obtain a less costly short cycle run-break-fix[16] approach that can be iterated until simulations do not "break" anymore. Specialty engineering analyses, particularly reliability and maintainability, are most effective when implemented early in the design process when they can have the greatest
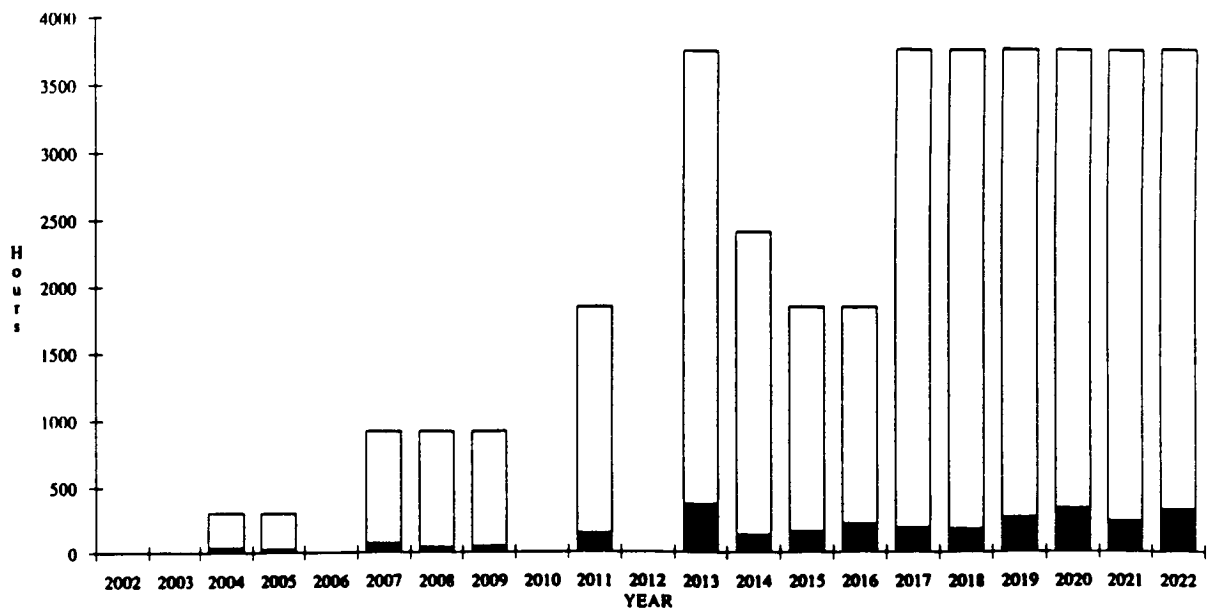
Figure 2 – EVA allocation for intelligent systems approach.

impact on overall design decisions. The JSC A&RD has developed MSAT for use in evaluating the feasibility and effectiveness of proposed mission concepts. We have also used a reliability and maintainability assessment tool (RMAT) developed by the JSC Reliability and Maintainability Division [17, 18] for SSF applications to estimate the amount of maintenance for the lunar surface habitation element.

The FLO mission, while being significantly more complex than any single Apollo flight, is vastly less complex than the Option 5A mission analyzed previously. Although there are periods when humans are not present, no offloading of equipment or construction of facilities is planned when crew is not present. Maintenance of facilities will still be required. We have continued to perform mission simulation and analysis to support system effectiveness studies of FLO and to understand the requirements for intelligent systems automation and robotics.

The FLO mission is envisioned as the first waypoint in expanding human presence in our solar system. FLO is established by the successful landing of an unoccupied human habitation element on the lunar surface and a subsequent 42-day visit by a crew of four that is transported to the lunar surface in a separate crew lander. The crew will arrive from 2 to 6 months after the cargo vehicle with the habitation element has landed. The habitat will be activated and checked out remotely before crew departure from Earth and will be in a ready state for crew arrival. Revisits to the outpost are projected at intervals of about 6 months. Humans are not present at the outpost during this interval; however, the outpost must be maintained sufficiently to allow reoccupancy.

During the 42-day (lunar day, night, day) FLO first mission, the crew will

- Perform equipment checkout and maintenance.
- Unload and transfer equipment and supplies between the crew lander and the habitat.
- Conduct local exploration and sample collection.
- Deploy scientific instrumentation (e.g., for space physics and astronomy).
- Deploy in situ resource utilization (ISRU) demonstration equipment.
- Conduct engineering and operations tests (e.g., human and equipment tests under varying and extreme thermal and illumination conditions).

- Perform life science experiments and IVA laboratory analyses.
- Perform crew self-sustenance and operational activities (e.g., housekeeping, training, planning, eating, resting, public affairs communications).

The habitation element provides all the facilities and subsystems (e.g., environmental control and life support, temperature and humidity control, data management) required to sustain the crew, except for food, personal items, and logistics resupplies that are transferred from the crew lander. The habitation element concept is an adaptation of the SSF habitation module with deployable solar panels, thermal radiator, and high-gain antenna. An airlock is provided for crew ingress and egress with provision for lunar dust abatement. Regenerative fuel cells provide power during the long lunar night.

3.1 Maintenance Simulation and Analysis

Maintenance has been investigated as a critical issue of the FLO mission. As a critical issue, maintenance or lack thereof impacts the following:

- Safety and survivability
- Mission goals
- Levels of performance
- Logistics and spares (and related mass and volume)
- Redundancies (and related mass and volume)
- Levels of commonality
- Designs for maintenance and repair
- Designs for diagnosis
- Control, monitoring, and fault diagnosis
- Tools and equipment
- Sensing and sensors
- Crew availability
- Amount and types of robotics
- Cost

The requirement addressed in analysis to date is to estimate the number of maintenance actions to be required as a function of time in the mission and the crew time required to accomplish the required maintenance. This will allow us to address the maintenance impact on the mission story as implemented in MSAT and those results. In

addition, it will give early insight into the alternative options and impacts to be considered.

A simulation tool for estimating maintenance demand has been developed for the SSF program and has been used for the FLO analysis reported here. This simulation tool is RMAT developed by the JSC Reliability and Maintainability Division and Loral Space Information Systems. The following discussion of this tool is paraphrased from Blumentritt[17] and the Assembly and Maintenance Implementation Definition Document[18].

RMAT is a stochastic, event-oriented simulation process written in Fortran and implemented on a personal computer. System maintenance is simulated at the individual component replaceable unit level of detail. Input to RMAT is a data base, which for each replaceable unit contains reliability data of the mean time between failure (MTBF), equipment reliability class (i.e., electronic, electrical, electromechanical, mechanical, structural, and structural-mechanical), and the life limits. Maintainability data includes the replaceable unit location (internal or external), mean time to replace (MTTR), mean time between preventive maintenance (MTBPM), and the number of crewmembers required for the maintenance. Robotic requirements can also be defined. Operations data in the data base includes the manifest and activation stages and the equipment duty cycles.

Factors that contribute to the generation of maintenance actions are the following:

- Random failures based on a lognormal distribution of the MTBF
- Early failures that are time-varying multipliers of the random failure rates and are based on a history of experience of spaceflights and satellites
- Preventive maintenance actions that are scheduled actions
- Life limit failures that are beyond the length of time of the current FLO study reported here

A Monte Carlo simulation approach is used to estimate failures. The duty cycle is a part of this calculation, as is a cold failure rate to account for failure rate contributions when equipment is not operating. K-factors[13] are applied as a failure rate multiplier to account for maintenance actions that occur for reasons other than the inherent component failure rate. For the FLO study, we used the default values that were developed by the SSF In-Flight Maintenance Working Group[18].

Maintenance time consists of work site time plus overhead time. Work site time is the time required to remove and replace the line replaceable unit (LRU) at the work site. Overhead time includes the time to get the replacement part and tools, travel to the work site, set up, close out the work site, and return parts and tools. A lognormal distribution is used to simulate the variability in the work site and overhead times. To estimate the amount of crew time required, maintenance actions are packaged into EVA and IVA crew shifts. SSF definitions were used: one IVA shift is composed of two crewmembers for 8 hr, each one performing 4 hr of maintenance; one EVA is composed of two crewmembers for 6 hr with 1 hr of sortie overhead.

In order to utilize RMAT to predict maintenance demands for FLO, a suitable reliability and maintainability data base was required. Since FLO was at the conceptual design stage, a representative data base was sufficient. The similarity of the FLO habitat elements and subsystems to the SSF habitation module and distributed subsystems suggested that SSF component reliability data can be used as a reasonable approximation for FLO habitat component reliability data. The SSF program developed a reliability and maintainability data base of predicted values for its own maintenance analyses[18]. We utilized that data (circa 1991) to build the FLO data base where elements were in "common" between FLO and SSF.

The mean work site time (MTTR) was estimated for each LRU and recorded in the data base. We used SSF times from the SSF data base, and where items were added we made separate estimates by comparison to SSF estimated times.

Overhead times can be input at the time of execution of RMAT. We used 0.5 hr for IVA overhead times. For EVA overhead times, we chose to perform a parametric analysis and used overhead times of 0.5 hr and 1.0 hr for each LRU. We view a mean overhead of 1.0 hr as an optimistic goal for FLO EVA maintenance actions.

3.1.1 Simulations and Results

Our approach to maintenance analysis is to perform parametric simulations that will provide answers (or insight into the answers) to key questions such as the following:

- What is the level of maintenance actions indicated?

- What is the crew demand time (work site plus overhead) to perform these maintenance actions?

- How many EVA and IVA shifts are required, and do they fit within the preliminary allocation?

- How does the number of maintenance actions vary when crew is present and is not present?

- What level of maintenance action backlogs exists?

- What is the effect of delays in crew arrival from 2 through 6 months after the habitat has landed?

- What is the maintenance load for follow-on outpost visits?

- What is the impact of backlogged maintenance on habitat functionality?

To answer these and other questions, we formulated two basic maintenance scenarios: (1) instantaneous replacement, which gives an estimate of the maintenance load (a maximum) required to maintain the habitat in a full-up operational capacity and (2) scheduled resources where maintenance is delayed until crew arrival, which gives backlog estimates and functionality impacts. Both scenarios assume 100 percent diagnosis of failures and no cascading failure effects. For each of the two scenarios, we simulate 2-, 4-, and 6-month delays of crew arrival. We estimate EVA, IVA, and total maintenance actions and use both 0.5 and 1.0 hr. for EVA maintenance action overheads. For each scenario, we also simulate two follow-up missions of 45 days at 6-month intervals after each crew departure back to Earth. For each simulation, 50 to 100 runs (more than sufficient) are made by RMAT to calculate the results.

We have also performed the simulations with and without the early failure model to establish the bounds on results. Although the early failure model is considered to overestimate the number of maintenance actions, it is considered the better estimator for planning purposes.

Figure 3 shows the bounds on cumulative maintenance actions with instantaneous replacement for the two cases: (1) all maintenance action (MA) types and (2) all MA types excluding early failures. We also show these for the two duty cycles – crew present and crew not present (standby mode). The failure rate for the standby duty cycle is 20 percent less than that for the duty cycle when crew is present. For most of the scenarios, however, the FLO is in standby mode for a greater period of time than with crew present; therefore, the cumulative error rate will be closer
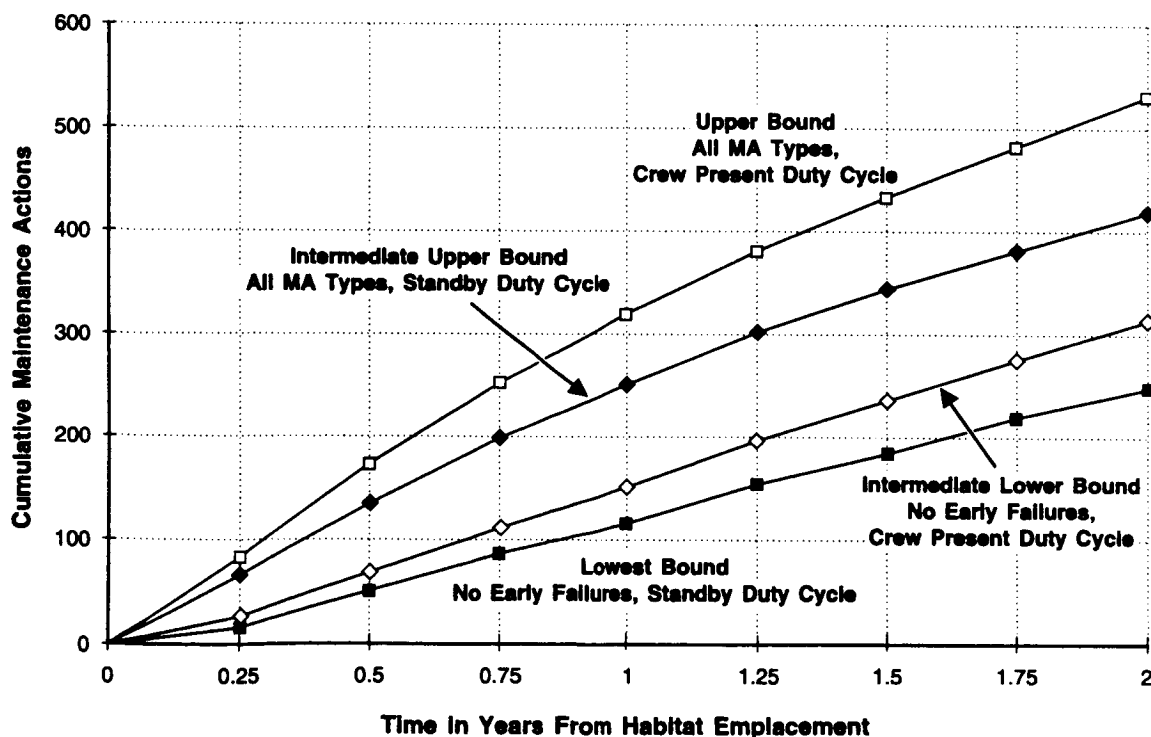

Figure 3 – Bounds for total maintenance actions – instantaneous replacement.

to the standby duty cycle plots. Separate EVA and IVA results are estimated but are not shown here.

Table 2 gives the mean number of maintenance actions for a variety of scenarios. The numbers are not cumulative. For example, the number of maintenance actions identified prior to the crew landing on the lunar surface is listed in the instantaneous replacement scenarios in the "visit 1 before" column. The number of new maintenance actions that arises while the crew is present is listed in the "visit 1 crew" column. The number of new maintenance actions that occurs after the visit 1 crew has departed the lunar surface until the time the second crew visits the lunar surface is listed in the "visit 2 before" column. For the scheduled resources scenarios, the "before" columns show the number of maintenance actions identified up to 2 weeks prior to the crew landing on the lunar surface. We speculate that the crew brings replacements for this set of maintenance actions. From these numbers, the backlogs can be calculated.

Table 3 gives the EVA and IVA requirements for maintenance by crew based on maintenance actions identified prior to crew departures from Earth. This scenario corresponds to a logistics support of carrying spares for failures diagnosed up to about 1 week prior to crew departure. Results are shown for 2-month and 6-month delays and for the first three visits to the outpost. Values given are for the maintenance actions identified before crew departure. The new maintenance actions that occur after crew departure from Earth through the time of return from the Moon are backlogged until the following crew visit. (In the 2-month scenarios, the number of EVA and IVA shifts backlogged to visit 2 exceeds the EVA's and IVA's that are in the "visit 1" column.) In the scenarios that include all failure types, the number of required EVA's exceeds the EVA allotment through all three visits. IVA shifts required are within the allotment for visit 1 but would exceed the same allotment for visits 2 and 3.

Table 2 – Number of maintenance actions.

Model scenario	Delay before first crew visit	Visit 1		Visit 2		Visit 3	
		Before	Crew	Before	Crew	Before	Crew
Instantaneous replacement, all MA types	2 months	42	56	127	36	99	31
	3 months	76	39	124	34	98	36
	4 months	96	40	118	43	89	31
	6 months	136	52	113	26	85	33
Scheduled resources, all MA types	2 months	31	63	93	41	87	29
	6 months	111	46	106	32	82	20
Scheduled resources, no early failures	2 months	12	33	41	16	61	16
	6 months	49	18	62	15	61	17

Before = Number prior to crew arrival, since last crew departure

Crew = Additional number occurring during crew visit

Table 3 – Number of EVA and IVA shifts required to perform maintenance actions identified prior to crew departure.

Model scenario	Delay before first crew visit	Visit 1		Visit 2		Visit 3	
		EVA	IVA	EVA	IVA	EVA	IVA
Scheduled resources, all MA types	2 months	5	3	12	14	10	12
	6 months	10	10	12	14	9	11
Scheduled resources, no early failures	2 months	3	1	6	7	6	7
	6 months	5	5	7	7	7	8

We have made a preliminary assessment of the functional impact each scenario has on the FLO habitation element. Although RMAT has the capability, our representative data base does not include functional block diagrams or comprehensive criticality identifiers. Redundant LRU's have shared duty cycles. The functional impact we have examined, as output by RMAT, is on the set of multiplexers/demultiplexers (MDM's). The MDM's are of particular significance because they provide the translation between the operative subsystems and the data management system for control and monitoring. Additionally, they are of sufficient number (31) to look at the results from a qualitative point of view. Scenarios with instantaneous replacement have no functional impact. Both the 2-month and 6-month delay scenarios with scheduled resources and all failure types have similar, and apparently significant, functional impacts. Approximately 15 percent of the time fewer than 50 percent of the MDM's are operating; 70 percent of the time fewer than 75 percent of the MDM's are operating. For the 2-month and 6-month scenarios with only random failures and preventive maintenance, 25 to 30 percent of the time fewer than 75 percent of the MDM's are operating.

The following are observations from the results of the simulations, including those discussed above. Unless otherwise specified, the observations are based on all MA types and for maintenance actions only by crew, with backlogs of maintenance actions not diagnosed prior to crew lander readiness (spares loaded 2 weeks before crew landing on the lunar surface).

- The number of maintenance actions for visit 1 is sizable, regardless of scenario, and ranges from 45 (2-month delay, scheduled resources, no early failures) to 188 (6-month delay, all MA types, instantaneous replacement). Furthermore, the number of maintenance actions for instantaneous replacement and for scheduled replacement is in the same ballpark; i.e., 98 versus 94 for first visit, 2-month delay and 445 versus 397 for three visits, 6-month delay (see Table 2).

- Except for the first visit of the 2-month delay scenario, the greatest demands for maintenance actions occur while crew is not present (see Table 2).

- The crews will be faced with a sizable backlog of (prediagnosed?) maintenance actions upon arrival and will have to contend with significant additional maintenance actions that occur after their departures from Earth (see Table 2).

- There are significantly fewer maintenance actions for the first visit if the time delay between habitat landing and crew landing is reduced (e.g., 94 for 2-month delay versus 157 for 6-month delay). But the number of these maintenance actions that occurs after the crew lander is ready for launch is greater for the reduced delay; e.g., 63 for 2-month delay versus 46 for 6-month delay (see Table 2).

- For delays up through 6 months, the peak number of maintenance actions occurs on the second visit (see Table 2).

- The number of IVA maintenance actions is greater than the EVA maintenance actions by a factor of 2 to 3 (interior LRU's outnumber exterior LRU's by approximately 7 to 1). However, the EVA total demand time (work site plus overhead plus sortie time) will be similar to the IVA total demand time for reasonable levels of overhead times (0.5 hr IVA, 1.0 hr EVA). Demand time is not shown here.

- The allocation of 10 shifts for IVA maintenance for the FLO first visit is sufficient to satisfy the demand, except for the maintenance actions arising after crew departure (6-month delay scenario). Additional allocation of IVA shifts will be required for visits 2 and 3 (see Table 3). (The allocation may be sufficient, depending upon further specifics of IVA definition.) All visits of scenarios without early failures fall within the allotment of 10 IVA shifts.

- A FLO first visit allotment of four EVA's for maintenance will not be sufficient; 5 to 10 EVA's will be required plus whatever is required to contend with the maintenance actions that will be backlogged. An even larger number of EVA's will be required on visits 2 and 3 because of the backlogged maintenance actions from previous visits (see Table 3).

3.1.2 Implications of Results

Implications derived from the simulations can provide early insight into the FLO mission design and the role of automation and robotics. Significant implications for FLO include the following:

- Science, exploration, and technology objectives will be impacted unless maintenance demands on the crew are minimized.

- The indicated number of maintenance actions will have a significant impact on logistics resupply and resources (spare parts, EVA's, IVA shifts, robots, data system, etc.).
- There will be significant impact to the functionality of the outpost if timely repairs are not made.
- The number of new maintenance actions after crew departure from Earth indicates special attention to levels of redundancy and commonality to the lowest level is indicated.
- Timely, reliable diagnosis of failures will be critical and must be designed for.
- The number of maintenance actions when the crew is not present must give rise to serious considerations for robotic repair capabilities.
- Design for ease of maintenance and repair will be important in minimizing crew (or robotics) maintenance demands.
- An onboard maintenance capability (workstation, tools, equipment, etc.) is indicated.

Several factors (sizable number of maintenance actions, majority when crew is not present, work site and overhead times, impacts on exploration and science) indicate a real need for robotics. Robotics are needed to

- Support diagnosis (test and inspection) for both EVA and IVA.
- Assist the crew by transporting and positioning parts, sensors, and tools and possibly positioning the crew.
- Perform robotic maintenance to minimize demands on crew, minimize backlogs of maintenance between crew visits (some maintenance will still require crew involvement), and free up the crew for science and exploration activities.
- Perform dusting, servicing, etc.

In addition to the maintenance actions described in this study, there will be other maintenance actions, including dusting of sensitive surfaces and repairs to parts not characterized as LRU's. These may be infrequent but time consuming. Maintenance of the rover, crew lander, and scientific instruments will also be required.

The results presented here were the first simulation results of the FLO mission and have demonstrated the merit of early simulations to evaluate mission feasibility. As the mission definition changes because of these results and other considerations, additional simulations should be made. The iterations of simulations with mission designs early in the mission definition stages can be of significant impact in making the mission feasible.

Requirements are characterized early when they can have the most benefit at least cost. FLO and all similar mission scenarios should adopt a design for reliability and maintainability early in the program. This design should include, as a minimum, consideration of provisions for the following:

- EVA and IVA repair robotics
- Full fault diagnosis, meaning design for diagnosis
- Critical levels of redundancy
- Commonality to the lowest level of design
- Provisions for spares and logistics
- Design for ease of maintenance and repair
- Adequate sensing and testing equipment
- Tools and equipment for maintenance
- Maintenance workstations
- Crew availability and training
- A knowledge support system

4. Advanced Life Support System Robotics

Neither of the above studies explicitly addressed the use of robotics to solve the problem of excessive crew time being required to operate various "subsystems," such as power, communications, thermal control, and life support for a permanently manned outpost. We briefly address life support here.

Since 1978 NASA has studied closed and controlled ecological life support systems (CELSS) or advanced life support systems (ALSS), which are bioregenerative and based on a combination of biological and physicochemical components that may be used on future missions in low-Earth orbit, in transit to other planetary bodies, and on lunar and planetary surfaces. Higher plants will be used in food production, water purification, carbon dioxide uptake, and oxygen release.

Agriculture can be very labor intensive or assisted by automation (robotics). Operations of an ALSS such as crop seeding, nutrient solution maintenance, transplanting, plant observation,

harvesting, edible biomass separation, transporting, and preventative maintenance, if carried out by intelligent robotic systems, could greatly reduce the excessive crew time requirements to a reasonable level. Ten crops are apparently needed to supply nutrition needs. JSC is working toward a year-long, high fidelity test in a Human Rated Test Facility (HRTF) with four 90-day stays by a crew of four aided by automation and robotics.

Experience from the Russian BIOS 3 experiments [19] indicated an average of greater than 4 hr per day for each crewmember was required to deal with food production. Biosphere 2 results indicated an average between 2 and 3 hr per day for each of eight crewmembers was required to operate the food production aspects. Intelligent robotics can be used to reduce these times to an acceptable minimum for the HRTF [20].

5. Usefulness of the Technology on Earth

Space robotics, especially those systems being developed to operate on planetary surfaces, can be considered a form of the emerging technology of field robotics on Earth. The solutions to the problems we will be solving to make the exploration of our solar system possible and practical will apply to the many problems we have that require operating in hazardous environments on Earth and critically improving human productivity in many fields. Service industries can also use these developments in relatively unstructured environments.

Compared to the applications of space robotics in the Shuttle or on Space Station, the supervised autonomous robotics needed to make space exploration planet surface activities reliable and productive are closer to the capabilities required on Earth for many productivity improvements that raise the standard of living for everyone. The greatest benefit to the U.S. economy of any space exploration related technology can come from the development of supervised autonomous systems [21].

6. Conclusions

Several conclusions are suggested by the results presented in this paper. One is that space exploration will be "enabled" by the use of supervised intelligent systems on the planet surfaces, including supervised autonomous robotic systems. With sufficient use of intelligent systems, the number and skills of humans on the planet surface will be determined predominantly by surface exploration, science, and local resource use (not outpost) objectives and requirements. Several other uses of intelligent systems in Earth orbit or during space transport are indicated by current studies.

Additional modeling studies should be carried out to provide further results and insight. Our MSAT modeling tool makes these studies easier to do relatively quickly.

Another conclusion is that more definitive requirements definition studies should be carried out for space exploration supervised intelligent (autonomous) robotic systems.

7. References

1. The Synthesis Group. "America at the Threshold." Superintendent of Documents, U.S. GPO, Washington, DC, May 3, 1991.

2. Erickson, Jon D.; et al. "SEI Planet Surface Systems Humans/Automation/Robotics/ Telerobotics Integrated Summary." JSC-45100, NASA JSC, Houston, TX, Mar. 1991.

3. Erickson, Jon D.; et al. "A&RD Response to the Synthesis Group Report." Briefing to Level II Lunar and Mars Exploration Program, NASA JSC, Houston, TX, July 17, 1991.

4. Bureau of Export Administration. "National Security Assessment of the U.S. Robotics Industry." Department of Commerce, Washington, DC, Apr. 1991.

5. Engelberger, Joseph F. "Robotics in Service." MIT Press, Cambridge, MA, Jan. 1991.

6. Erickson, Jon D. "The Role of Intelligent Systems in Space." Proceedings of International Conference AI91: Frontiers in Innovative Computing for the Nuclear Industry, American Nuclear Society, Jackson, WY, September 1991.

7. Erickson, Jon D.; et al. "An Intelligent Space Robot for Crew Help and Crew and Equipment Retrieval." International Journal of Applied Intelligence, accepted for publication in 1994.

8. IEEE Transactions on Systems, Man, and Cybernetics. "Special Issue on Unmanned Vehicle and Intelligent Robotic Systems." Vol 20, No. 6, Nov./Dec. 1990.

9. Aucoin, P. J.; and Graves, P. L. "SEI PSS H/A/R/T Option 5A Mission Analysis." JSC-45105, NASA JSC, Houston, TX, Mar. 1991.

10. Cohen, Aaron. "Report on the 90-Day Study on Human Exploration of the Moon and Mars." NASA JSC, Nov. 1989.

11. Erickson, J.D.; Aucoin, P.J., Jr.; and Dragg, J.L. "A Tool for Simulating SEI Operations As a Means of Obtaining Intelligent System Requirements." Proceedings of SPIE 1829 Conference on Cooperative Intelligent Robotics in Space III, Boston, MA, Nov. 1992.

12. Ellery Systems, Inc. "C-Lite Function Reference Guide for Ellery Open Systems." Boulder, CO, Feb. 1992.

13. Fisher, William F.; and Price, Charles R. "SSF External Maintenance Task Team Final Report." NASA JSC, Houston, TX, July 1990.

14. Katzberg, Steven J.; et al. "Aerobrake Assembly With Minimum Space Station Accommodation." NASA Tech Memo 102778, NASA Langley Research Center, Hampton, VA, Apr. 1991.

15. Erickson, J.D.; et al. "Some Results of System Effectiveness Simulations for the First Lunar Outpost." AIAA 93-4136, AIAA Space Programs and Technologies Conference and Exhibit, Sep. 1993.

16. Livingston, W.L. "TQM, Total Quality Management." Conference of the Quality Assurance Institute, Washington, DC, May 22, 1991.

17. Blumentritt, W. "The Space Station Freedom Reliability and Maintainability Assessment Tool and Its Use for Prediction of Maintenance Demand." NASA JSC Reliability and Maintainability Division Analysis Activity, May through July, 1992.

18. Space Station Freedom Program. "Assembly and Maintenance Implementation Definition Document (AMIDD)." NASA, Sep. 15, 1991.

19. Schwartzkopf, Steven H. "Prioritizing Automation and Robotics Applications in Life Support System Design." Lockheed Missiles and Space Co., Sunnyvale, CA, 1992.

20. Miles, G.E.; and Erickson, J.D. "Robotics in Controlled Environment Agriculture." Proceedings of AIAA/NASA Conference on Intelligent Robotics in Field, Factory, Service, and Space, Houston, TX, Mar. 1994.

21. Office of Technology Assessment. "Exploring the Moon and Mars: Choices for the Nation." Congress of the United States, Washington, DC, Aug. 1991.