The Lunar Split Mission: Concepts for Robotically Constructed Lunar Bases

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Abstract. In this paper, we consider the development of a lunar base at the Moon's southern pole to simultaneously support NASA's exploration and science goals. From such a vantage point, both lunar resource utilization and very-long baseline interferometry for astrophysics and astrobiology could be carried out. The work is an outgrowth of a study performed in the summer of 1988 at the NASA Johnson Space Center by a multi-disciplinary team of graduate students. The problem addressed was the development of a permanently manned lunar base, taking into consideration the constraints of the high cost of transporting materials to the moon and the high risk associated with astronaut extra-vehicular activity. The objective of the study was to develop a scenario for the build-up of a lunar base which minimizes the mass delivered to the lunar surface, provides the initial crew with an immediate long stay capability, and minimizes risk both to lunar astronauts and to the lunar exploration program. The result was the development of the Lunar Split Mission concept, which posits that lunar bases will be assembled and readied for use by autonomous and human-controlled robots prior to the arrival of astronauts. The concept is updated herein to incorporate technological advances that have occurred in the past 17 years, particularly in telerobotics, automation and autonomy, communications, navigation and information technology.

INTRODUCTION

The current approach to NASA's manned space program under the Exploration Initiative (EI) is focused on the establishment of a lunar base as a precursor to eventual the eventual human exploration of Mars. Such a facility would provide an outpost for the demonstration of in-situ resource utilization (ISRU) and for confirmation of the human ability to live and work in harsh extraterrestrial environments. It would also provide a unique vantage point from which to conduct science. The required technologies for such an effort, as well as the operational knowledge and experience gained, will then be applied to missions to Mars, thus reducing risk from one program to the next and providing a path towards a sustainable program of exploration.

In this paper, we consider the use of robotics, via teleoperation and autonomous operation, to construct a lunar base prior to the arrival of astronauts. It builds upon the work of a multi-disciplinary team of graduates students working at the NASA Johnson Space Center in 1988 to develop concepts for minimum-mass, minimum-risk lunar base development strategies in the post-Space Station era [Davis et al., 1988]. We assume a lunar base will be developed at a southern polar site for the purposes of ISRU proof-of-concept demonstration and for Moon-based astronomy. There are overlapping requirements for these two objectives, and their convergence identifies a mission concept that addresses both science and exploration. The scenario presented is used to help explore the strategies and technologies needed to carry out robotic construction operations on the Moon, so that future research and development areas can be identified.

MOTIVATION

The strategy for lunar and Mars exploration as we currently know it is to returns human to the Moon in the 2020 timeframe to establish a human presence, conduct science, and develop ISRU capabilities, all in preparation for eventual missions to Mars. A southern polar site such the Aitken Basin is the likely destination, mainly because the theorized presence of solar wind-implanted hydrogen and comet-implanted ice. It is important to understand, however, that our concepts are not constrained to the south pole, but could be applied to a base at the equator as well. Lowman (1995) has proposed Riccioli or Grimaldi as sites, for example, and these should be kept in consideration. Regardless of the site, we seek to develop a mission concept from which both exploration *and* science objectives can be achieved. This is the type of "win-win" scenario needed by the science community in NASA's new era of exploration. We also seek lunar base development strategies that reduce the risks to astronauts in the early phases of sustained exploration.

Science Objectives

The scientific objectives of the lunar split mission (LSM) fall into two classes: one focused on the Moon as an object of study, i.e., a geological site, and one focused on using the Moon as a base for study of the universe, i.e. as an astronomical site.

The Moon as an Object of Study

Despite the Apollo missions and dozens of unmanned ones, landing and orbital, many scientific questions remain unanswered, and in fact many new ones have been discovered since Apollo. Some of the specific ones to be approached with the LSM are the following.

The composition, structure, and origin of the lunar highland crust are still not well understood. Three Apollo missions landed on or near highland crust, but all these sites were blanketed by the nearly ubiquitous lunar regolith formed by some 4 billion years of meteoritic impact. Furthermore, all were relatively low-latitude, near-side missions. A south polar location would give access to a much wider sample of the highland crust.

The late-heavy bombardment of the Moon, thought to have formed the mare basins, is still controversial. Discovery of the enormous South Pole - Aitken Basin since Apollo, and its confirmation by Clementine altimetry, adds to the controversy. A south polar mission would be close to, or within, the SPA, and would help answer the question of what body formed it and when?

One of the most surprising post-Apollo discoveries was the finding by the Clementine bi-static radar experiment of 1995 of what appeared to be ice in permanently shaded areas near the south and north poles [Nozette et al., 1994]. The existence of hydrogen concentrations in the areas of anomalous radar backscatter was confirmed by the Lunar Prospector neutron spectrometer [Feldman et al., 1998]. However, it has been argued that it may be implanted solar wind hydrogen, rather than water ice. Both mechanisms may well have been effective. A south polar mission should provide a definitive answer. This answer, however, may not support either of the two current hypotheses. The hydrogen or water ice might turn out to be of internal origin, since the Moon is by no means a dead body.

The Moon as a Site for Astronomy

Before the achievement of space flight, the astronomical advantages of an observatory on the Moon were obvious, but it mainly comes down to the freedom from cloud cover and an unlimited spectral window. Of course, these advantages were also usable by orbiting instruments, as long since demonstrated by dozens of space-borne facilities since the mid-1960s, the best-known one being of the Hubble Space Telescope. Future space-borne instruments, such as the James Webb Space Telescope (JWST), are in development. It can be reasonably asked if the Moon offers any unique advantages for astronomy. The answer is a definite "yes" [Lowman, 1995].

A south polar site in particular would have the following advantages over space-borne instruments. First, the lunar surface offers a stable platform on which large interferometer arrays, optical or infrared, could be emplaced by robotic methods. Moon-based interferometry has long been recognized as uniquely promising [Burke, 1990; Burns et al., 1992; Lowman, 1995]. Second, the low ambient temperatures near the south pole, estimated at lower than 100 K, would permit passive cooling for infrared instruments. A lunar site shares this attribute with a Lagrangian point, which is why JWST will be placed in such a location. However, the Moon's proximity to Earth and its solid surface make it competitive with a Lagrangian point for infrared astronomy. Third, the Moon is only 1.3 light seconds distant from Earth, permitting straightforward real-time telerobotic control of instruments on the lunar surface. Fourth, the lunar surface would permit emplacement of large multi-instrument complexes occupying large areas and with minimal interference among the individual instruments. Problems of mutual compatibility and interference, a major expense in large orbital complexes such as the Orbiting Geophysical Observatories of the 1960s, would be minimized. Fifth, instruments emplaced on the lunar surface will not go anywhere, eliminating the need for long-term station-keeping and orbit correction encountered by space-borne instruments.

Exploration Objectives

From an exploration perspective, the primary goal of lunar exploration is to develop the capability for, and reduce the risk of, humans exploring Mars. This will come from the operational experience gained by the astronauts working on the lunar surface, as well as by the ground-based crews that will support them. Lunar astronauts, for example, must become accustomed to a gravitational field that is about one-sixth that of Earth. For Mars, it is about one-third. This is indeed quite different from working in the zero-g environment of the International Space Station (ISS). The astronauts will still have to work in pressurized suits since there is little or no atmosphere, as is done on the ISS. It is still very difficult, however, as attested to by NASA's recently announced Centennial Challenge to design a high performance astronaut working glove.

These difficulties suggest that robotic assistants will be extremely important in the exploration of other worlds. The Spirit and Opportunity rovers on Mars have shown just how much can be done with robots. They have also shown the limitations. Humans are clearly needed for robust exploration operations, both in-situ and on Earth. Only through lunar exploration will we truly understand the challenges that face us at Mars.

The experience needed for the long-term objective of human exploration of Mars can be gained from a series of stepping stone missions that serve no other purpose than to provide analogs for Martian exploration. For a sustainable and affordable long-term exploration program, however, it will be necessary to exploit the local environment for resources that would otherwise have to be brought from Earth. ISRU then becomes a priority.

ISRU refers to the use of materials and energy sources native to the Moon and Mars that are collected and processed to support human and robotic exploration. The lunar equatorial mare regolith, for example, was found on the Apollo missions to contain usable concentrations of solar-implanted hydrogen and helium-3 (Schmitt, 2002), as well as lesser amounts of volatiles such as nitrogen. Oxygen extraction from lunar silicates has been well-demonstrated by numerous techniques (Schrunk et al., 1999), although whether this would be cost-effective compared with use of ice at the lunar poles is not known. The main metals of any lunar mare or highland site are Fe, Mg, Ti, and Al. Ilmenite is found in apparently all mare basalts and regolith. It would be useful not only for Ti but as an oxygen source.

Consumable resources extracted from the lunar and Martian regolith could be used locally by the astronauts to help make exploration more sustainable. Propellant production for use in the Earth-Moon and Earth-Mars transportation infrastructure, or for the long-range exploration of the lunar and Martian surfaces via hoppers and other such vehicles, could substantially lower the amount of mass that must be delivered from Earth. Silicon, iron, glass, and oxygen could be used to fabricate structures, solar panels, and tools for long-term sustainability. Until the extraction, processing, and manufacturing processes are demonstrated, however, the long-term potential value of ISRU will not be fully understood. We can gain insight into this problem with so-called "simulants", but ultimately it will take operational experience in the lunar environment to perfect the technologies.

THE SPLIT MISSION CONCEPT

A key consideration in the development of a permanently manned lunar base is the high risk associated with astronaut extra-vehicular activity (EVA) during construction and even during normal surface operations. There are many risks, including life support system failures, radiation exposure, meteor strikes, construction accidents, etc. As evidenced by the tragic Challenger and Columbia missions, the loss of life in the U.S. space program can result in multi-year stand-downs. The death of an astronaut to, from or on the Moon could result in cancellation of the EI altogether. It is therefore incumbent upon systems engineers and mission planners to come up with lunar base development strategies that minimize risk to the astronauts.

Another consideration is the high cost of delivering mass to the surface of the Moon. The long-term operational costs for a lunar base could be excessive if ISRU is not feasible and all supplies for life support, construction, science and transportation must be delivered from Earth. Mining the regolith for hydrogen, oxygen, helium-3 and other useful materials could have a tremendous impact on the base development strategy.

One approach to reducing the risk to astronauts and to lowering the mass delivered in the early stages of lunar base development is to use robotics. Robots, either controlled from the Earth or from the lunar surface, or even acting autonomously, can be used to perform many of the tasks needed to prepare and construct the base, deploy mining infrastructure, and perform science operations. Robots do not need life support systems, and they can be fixed or replaced if damaged in an accident. They can tirelessly work as long as their parts allow.

The split mission concept was first developed for manned missions to Mars by a senior design class at The University of Texas in 1985 [University of Texas, 1985]. The Mars split mission (MSM) was developed because: (1) large Earth-Mars spacecraft require large amounts of fuel - even for the minimum energy Hohmann transfer, (2) a mission using Hohmann transfers to and from Mars require about 1000 days and would subject the crew to an extended periods of weightlessness, isolation, and radiation exposure, (3) most of the mass, i.e., equipment for surface operations, is not extremely sensitive to time of flight and could travel to Mars on low energy trajectories, and (4) a lightweight manned vehicle capable of a fast transfer, or sprint, from Earth to Mars and return is feasible.

These considerations led to a mission concept that split the transfer of cargo and crew into two vehicles. The first vehicle would employ a Hohmann transfer or a low thrust transfer to deliver most of the equipment to Mars. It would also deliver the fuel for a rapid return of the crewed vehicle. When the cargo vehicle has been safely inserted into circular orbit about Mars and all systems have been checked out via telemetry, the smaller crew sprint vehicle would leave Earth to deliver the crew. The cargo vehicle would be used as a Mars space station, a staging platform for Martian exploration, and as a jump-off point for the trip home.

The LSM is similar to the MSM in that its primary motivation is to minimize exposure of the astronauts to many of the hazards associated with extraterrestrial environments. It represents a scenario for the build-up of a lunar base that is aggressive in driving technology toward advanced robotics and artificial intelligence. If the LSM can be successfully carried out on the Moon, it could then be applied to Mars exploration.

LUNAR BASE DEVELOPEMNT SCENARIO

To explore the concept of robotically constructed lunar bases, and to identify the key technologies that are required to carry out such missions, a high-level lunar base description and development scenario are presented. To do so, we begin with the original LSM and update it to account for the present state of the art in technology, and for where it will conceivably lead over the next decade. Many of the assumptions that underlie the LSM when it was first conceived in 1988 have to change, while others do not. The Earth-Moon transportation infrastructure, for example, will be much different than was originally assumed.

Background

To provide some context for the discussion, it is helpful to review the original LSM scenario and how it was derived. In 1988, there were three lunar base studies being analyzed at JSC for post-Space Station exploration activities: one from General Research Corporation [Reese et al., 1987], one from Eagle Engineering Inc. [Eagle Engineering, 1987], and one from the JSC Advanced Programs Office [Alred et al., 1988]. The GRC study produced the Civil Needs Database, and Option III provided the basis for the Eagle and JSC studies. A brief narrative of the CNDB scenario, using the original proposed timeline, is given as follows:

1999 An unmanned and a manned mission are landed at the base site, which has been selected by previous orbital surface mapping and unmanned sample return missions, for site certification.

2000 A communication relay station, initial power plant, rover, and construction vehicle are delivered unmanned. Two manned missions are flown with 8-day surface stays: one to the base site and one to a far side location for deployment of an astronomy payload.

2001 A module interconnect node, a liquid oxygen (LOX) plant, two more initial power plants, and an optical interferometer are delivered. Three manned missions with 8 day surface stays are also flown in this year.

2002 A habitation module is delivered and surface stay times are increased to 24 days. Mining and excavation equipment are delivered. Four manned mission are flown in this year.

2003 Additional pressurized modules are delivered for use as a geochemical and materials science laboratory, along with another module interconnect node. A nuclear power plant is landed, in addition to a third of a full scale LOX production plant. Four manned missions are also flown in this year.

2004 The rest of the LOX plant is delivered along with another pressurized rover. Four manned missions are flown with one being landed on the far side site to service a UV telescope placed during an earlier mission.

2005 Surface stay time is increased to 180 days and the crew size increases from four members to a permanent staff of 8. An orbital propellant depot comes on line in low lunar orbit (LLO). Delivery of two life science laboratories, a life science research node, and a standard module interconnect node greatly increase the pressurized module set. Another communication relay station is delivered along with deep drilling equipment.

The Eagle and JSC studies used the above scenario as a baseline reference from which to develop alternative build-up strategies: habitation as soon as possible (JSC), and science as soon as possible (Eagle). All three assumed many manned sorties to the lunar surface to establish a permanent base capability. The LSM strived to eliminate these through the use of advanced robotics and automation.

Assumptions

While at the time of this writing the results of NASA's 60-day study have yet to be released, an initial look into the strategy and architecture to be employed has been released to, and reported by, the press [Cabbage, 2005]. Some things will change over the coming years, but it does provide a preliminary vision for how the U.S. will return astronauts to the Moon by the 2020 timeframe to prepare for future missions to Mars. We will assume the same transportation infrastructure for the LSM as presented herein. The following summarizes the salient features:

- Shuttle-derived launch vehicles (SDLVs) will be used for transporting crew and cargo from the Earth's surface to low Earth orbit (LEO). The Crew Exploration Vehicle (CEV) as it is currently being designed is for transportation to the ISS. A derivative of this vehicle will be used to transport crews to the Moon.

- Crews bound for the Moon will rendezvous in LEO with an Earth Departure Stage (EDS), which is mated to a lunar descent/ascent module (LDAM) and launched separately on the cargo version of the SDLV.

- The EDS is jettisoned after sending the CEV/LDAM to LLO. The LDAM will separate from the CEV and descend to the surface while the CEV remains in LLO.

- After the manned mission ends, the astronauts will enter the LDAM, and the upper stage will transport the crew to LLO for rendezvous with the CEV. This stage is jettisoned after sending the CEV back to Earth, where it will re-enter and touchdown on land.

- Cargo will be transported to the Moon using the EDS and the unmanned SDLV. A derivative of the LDAM lower stage will be used to deliver it to the lunar surface, one that is capable of transporting significantly more mass than the manned version.

The LSM scenario as originally conceived assumed a much different Earth-Moon transportation infrastructure than that above. A space transportation node (STN) in LEO for staging missions to the Moon was a key element. Reusable low-thrust and high-thrust orbit transfer vehicles for delivering cargo and crew respectively to LLO, like an EDS, were assumed to be stored and refurbished at the STN. This is clearly no longer viable. All payloads destined for the Moon will rely on rendezvous and docking with the EDS in LEO. A heavy lift launch vehicle other than the Shuttle was also assumed, and this is still valid. Up to 125 metric tons of cargo capacity on the unmanned version of the SDLV is currently being considered.

Regarding the lunar base itself, the LSM scenario depended heavily on advanced technologies that had yet to be developed. Given the difficulty predict whether enabling technologies, would be available in 1995, 2005, or 2015, two scenarios that represented optimistic (upside) and pessimistic (downside) assumptions on the rate of technology development were assumed [Driggers, 1982]. The "upside" scenario assumed that all advanced technologies critical to the achievement of the lunar base would be developed within the time frame of the proposed program. The "downside" scenario assumed that for various political and economic reasons, certain advanced technologies would not be developed.

The downside scenario is driven by present technology or conservative assessments of future technology and does little to identify which key technologies should receive attention for research and development. Given today's cost-constrained space program, it would seem wise to assume a downside scenario for the updated LSM. The problem with that is that even in the 1980's, no one could predict the rapid technological advances in computing, information technology, communications, and networking that occurred in just the last ten years. Enabling technologies from these domains will make it easier to implement the robotics and the automation and autonomy needed to carry out the LSM concept. Nonetheless, a more conservative approach is taken in this treatment. The following assumptions are made accordingly:

- The lunar base will be established at the lunar south pole around 2020 after initial unmanned missions have been flown to confirm the existence of significant quantities of water-ice and/or solar wind-implanted hydrogen. The purpose of the base is to support long-stay manned missions in support of ISRU and science operations.

- Teleoperation of robots will be used for most construction tasks, especially those whose Earth analogs assume human operators, including the unloading of lunar landers, the excavation, transportation and redistribution of lunar regolith, etc. The time lag in Earth-Moon communications will require some autonomous capabilities in the robots, but the majority of tasks will be supervised by humans, either on Earth or on the Moon.

- Global navigation and communication support for lunar ascent/descent will be provided from TDRSS-like satellites orbiting the Moon. This nav/comm infrastructure will be sufficient to support automated LADM operations, as well as support mid-to-long-range surface navigation.

- Local navigation and communication will be provided by terrestrial technologies and will be available throughout the base. This nav/comm infrastructure will be sufficient to support short-range navigation and will provide the precision, latency, reliability, etc. to support precision teleoperation and autonomous robot operations.

- Power will be provided to the base via solar arrays, as the southern pole is in continuous sunlight. For the science instruments and ISRU equipment, however, power will be provide by ALSEP-type radioisotope thermoelectric generators (RTGs), which are nuclear power generators built specifically for space and special terrestrial uses.

Lunar Base Elements

The original LSM scenario assumed a lunar base complement similar to that of the CNDB, Eagle and JSC scenarios, with considerable amounts of equipment delivered to establish a permanently manned lunar base capability. Today's missions are cost-constrained, and so it is not likely that such aggressive plans can be carried out. We therefore assume that the lunar base will consist of the minimum number of surface elements needed to support early ISRU and science operations, and that they will be delivered after ISRU and science feasibility demonstrations are successfully conducted.

Habitation Elements

The LSM lunar base will consist of one habitation module, two airlocks, and two connecting nodes. The habitation module will be buried under about 4 m of regolith for thermal control and radiation protection. The connecting nodes will remain exposed for accessibility and for accommodation of future base expansion. Two airlocks within these nodes provide redundant base egress/ingress. The habitation module, interconnect nodes, and airlocks will be based on ISS-heritage hardware. Support systems include thermal control, environmental control and life support, communications, navigation, and power.

Science and ISRU Equipment

Exploration and ISRU evaluation are synergistic. An obvious analogy is petroleum exploration of a previously-charted region. Such exploration on land generally begins with orbital surveys of the geology and structure, which permit focusing surface geologic mapping and then geophysical surveys of the most promising areas within a property. Drilling and well-logging are the ultimate stages before production. Note that there is a continuous gradation from exploration to utilization. The same thing will be true of renewed lunar exploration. The main instruments to be emplaced on the LSM in order of priority would be the following.

Surface Composition Mapping
Years of experience with lunar and Martian missions show the importance of mobility on the surface, as opposed to single site missions such as those of the Surveyor and Viking missions. We therefore recommend emplacement and operation of small telerobotic rovers carrying a complement of analytical instruments. Their functions should include as a minimum: X-ray fluorescence; X-ray diffraction; neutron spectroscopy; high-resolution surface imagery; electrical properties measurements; magnetic field measurements. If possible, ground-penetrating radar should be carried; microwave frequencies, i.e. L-band, should provide useful information on the shallow structure and composition of the surface.

Shallow Drilling and Logging
If the hydrogen deposits near the south pole are indeed water ice, it will be important to determine their distribution in depth. Accordingly, drilling to depths of several meters and emplacement of well-logging instruments will be important. Heat-flow measurements similar to those carried out on Apollo 15 would be valuable.

Geophysical Instrument Emplacement
The Apollo Lunar Surface Experiment Packages (ALSEPs) were highly successful, operating for several years until turned off for budgetary reasons. They provided valuable information on the local radiation environment, the charged particle environment, and seismic activity among other phenomena. Improved versions of the ALSEPs should be emplaced by the LSM. A laser retro-reflector similar to those of the ALSEPs, should be included for basic physics research. Solar or nuclear powered radio beacons should be included for guidance of later landings.

Astronomical Instrument Emplacement
The initial astronomical instrument packages would be essentially feasibility tests, to confirm that the south polar environment is suitable for astronomy. Lowman (1995) provides a comprehensive list of astronomical instruments for eventual emplacement at a lunar observatory. In order of priority, we suggest the following sequence.

First, one or more one-meter class UVOIR reflectors, similar to those suggested by Sykes et al (1990), to demonstrate the basic feasibility of Moon-based instruments. Consideration should be given to designing these initial telescopes for eventual incorporation in a network of optical interferometry instruments. Second, a small radio telescope for centimeter wavelength radio astronomy, using an ultra-light weight dish comparable to the Apollo S-band antennas. Ideally such a dish would be steerable, but even acting as a transit telescope it would provide information on the microwave environment of the lunar surface, in particular the severity of terrestrial radio frequency interference. Third, a sub-mm telescope with a single dish of perhaps 3 meters (Lowman, 2003). Such an instrument, even used as a fixed transit telescope, would be valuable for the study of interstellar molecules because of the absence of an interfering atmosphere. Such an instrument should be designed for eventual use as a sub-mm interferometer by connecting it to similar instruments by fiber optic links. Analysis of the hydrogen deposits at the south pole may provide ground truth for Moon-based sub-mm astronomy if the hydrogen was deposited by infalling comets, presumably representing the molecular cloud from which the solar system formed.

Robotic Construction Equipment

The construction equipment for the LSM is based on the Lunar Construction Utility Vehicle (LCUV), a generic set of base mobility units to which various modular implements can be attached to perform different construction tasks. These implements include such elements as a crane, a backhoe, a forklift, a shovel, and a robot arm to perform heavy operations such as transporting, lifting and excavation. One of the key attachments is the Lunar Telerobotic Servicer (LTS), which is used to perform precision tasks that normally would require the skill and dexterity of an astronaut.

The LTS is a robot designed for tasks that would normally be done by a suited astronaut, such as reconfiguring or repairing the LCUVs, connecting power cables, etc. It can be controlled through teleoperation or it can act autonomously. It is basically a detachable torso that can be placed on different LCUV mobility units depending upon the application. It can even be attached to the robot arm on the LCUV.

Lunar Base Development Scenario

Given the assumptions and the elements described above, the following provides a scenario for how the LSM approach could be employed to develop a lunar base:

- An unmanned mission lands at the base site to prepare for future missions. The first LCUV and LTS are delivered for this purpose. They provide detailed maps of the local surface topography. They emplace the navigation and communications equipment.

- A subsequent unmanned mission lands at the base site to deploy the second LCUV and LTS. They are used to conduct parallel construction operations and to provide redundancy in case of failures. Using imagery from the previous mission, as well as satellites such as the Lunar Reconnaissance Orbiter, the LCUVs grade the site for future landings, as well as that for the lunar base, and clear paths for easy traversing between the two.

- A subsequent unmanned mission lands at the base site and delivers the habitation module, the connect nodes with airlocks, the solar array power plant and the thermal control system. The LCUV are used to unload the landers and move the equipment from the landing site to the base site. They are used to connect the habitation module and connect nodes, and then to bury the habitation module in lunar regolith. The LTS are used for fine dexterity tasks such as connecting cables from the habitation module to the thermal control system and power plant, erecting tubing/scaffolding to support burying the habitation module under regolith, setting up the solar array power plant and the communications station, etc.

- A subsequent unmanned mission lands at the base site to deploy the science rovers for surface composition mapping, shallow drilling and logging, and geophysical instrument emplacement. The astronomical equipment is also delivered. The LCUV are used to move the equipment from the landing site to the astronomy and ISRU sites. The LTS are used for fine dexterity tasks such as connecting power and networking cables from the telescope to the power plant.

- A subsequent manned mission lands at the base site and delivers the first crew and their supplies. They finish any remaining tasks not accomplished by the teleoperated robots, effect repairs where necessary, and begin occupying the base. Exploration and science operations start immediately.

From the above scenario, tasks that the robotic equipment must accomplish include: unloading, transportation, and emplacement of base elements and equipment; paving/grading/clearing of the landing, lunar base, science, and ISRU sites; lunar regolith excavation, transportation, and redistribution; changing the LCUV implements for the proper task, and effecting repairs when necessary; and servicing the ISRU and science equipment. Such tasks can either be done via telerobotics, which is the remote computer-assisted manipulation of equipment and materials, or via autonomous robots, which incorporate intelligent, automated diagnosis, monitoring, and control. The LSM must use both in concert.

TECHNOLOGY CONSIDERATIONS

The LSM is a technology driven concept that seeks to minimize the risk to astronauts associated with EVA early in the development of the base, especially during construction where the tasks are hazardous and repetitive. Having astronauts perform such operations make little sense. Of course, this assumes robotics technology will sufficiently advance in the 2020 timeframe to make such an approach possible. Much has changed in the 17 years since the LSM was first conceived, and significant advances have been in robotics, systems autonomy, computing, communications, navigation, and information technology. The pace at which technology is advancing suggests that even more advancement will be made in the next 10 years. The following examines the state of the art in some of these technology areas.

First and foremost, the LSM assumes advanced robotic capabilities, mainly in telerobotics but also in systems autonomy. [Pederson et al., 2003] provide an excellent overview of the current state of space robotics, and discusses many of the advances expected over the next decade. Based on surveys and interviews with experts in the field of robotics, automation, and autonomy, they predict most of the advances needed to carry out the LSM will be achieved with focused research and development and adequate funding.

The authors decomposed space robotics into seven applications, assessed the state of the art in each, and then suggested metrics against which advancement could be compared. The seven applications included: In-Space Assembly, In-Space Inspection, In-Space Maintenance, Human EVA Interaction, Surface Mobility, Science Planning and Perception, and Instrument Deployment and Sample Manipulation. Interestingly, the construction of Moon or Mars bases via robotics is not mentioned. It is easy, however, to make the leap that combinations of these applications, e.g., in-space assembly, human EVA interaction, and surface mobility, feed into construction capabilities.

Telerobotics has been an active area of research and development in many different domains, including nuclear, space, undersea, medical and military applications. For space, we see telerobotics at use in the Shuttle and ISS programs, as well as in the Mars exploration program. The former is focused on in-space assembly, maintenance and repair, while the latter is focused on surface exploration. Technology advances in both areas will benefit the LSM concept.

For the gross component manipulation operations, we look to the Shuttle and ISS remote manipulator system (RMS) [McGregor and Oshinowo, 2001]. It is an electromechanical arm that, on the Shuttle, deploys payloads from the orbiter payload bay, or grasps a free-flying payload, like a satellite, and maneuvers it to the payload bay of the orbiter for berthing. The RMS could provide the basis for the grappling arm used by the LCUVs for heavy lifting and for moving large components, like unloading landers or switching out implements. The difference between low gravity and microgravity must be accounted for, but this should be straightforward.

The RMS can not, however, perform the dexterous operations associated with humans working in space. For this purpose, active research and development efforts are producing robots such as Ranger [Aiken, 2001] and Robonaut [Diftler and Ambrose, 2001]. They are being designed to develop and demonstrate a human-like robot that can function as a suited EVA astronaut. "Suited" is the keyword here, since developing a robot with the dexterity and versatility of the human hand appears well beyond the timeframe of 2020. These teleoperated robots were being considered for the Hubble Space Telescope – Hubble Robotic Vehicle (HST-HRV) repair mission prior to its cancellation. Although designed for on-orbit applications, they clearly could provide the basis for the LTS. One of the main obstacles that must be overcome, however, is the time delay in Earth/Moon communications versus that of Earth/Shuttle/ISS communications.

Our most current experience with robots on extraterrestrial surfaces comes from the Spirit and Opportunity rovers. They are teleoperated explorers that, with human assistance, can traverse long distances, avoid obstacles, and deploy instruments such as drills to rocks of interest. While seemingly simple as compared to in-space assembly, the tasks often took days to complete. Part of the problem is due to the long delays in transmission of video and sensor data from Mars, and in the return of task-specific command sequences. For Mars, this delay is on the order of 20 minutes. For the Moon, it is on the order of 3 seconds. While considerably smaller when compared to that for Mars, when compared to that for terrestrial or LEO operations, it is not inconsequential. In the time it takes for the system to relay fault detection data to an operator on Earth, and then to receive corrective action, permanent damage to a major element could occur.

For Earth-based teleoperated lunar construction to be feasible, the robots will at some level have to be able to sense their environment, reason about it and the task at hand, and make decisions. They will have to work in concert with their human operators, but they can not solely rely upon them. This is generally referred to as supervised or shared autonomy where commands are generated by an operator and sent for autonomous execution by a robot. The level of the commands sent (from "turn joint x 45 degrees clockwise" to "grasp tool y" to "prepare for excavation") will depend on the level of onboard autonomy. There will necessarily be local, low-level onboard controllers for stability and robustness purposes as well as various levels of onboard fault detection and recovery. As advanced onboard planning and scheduling techniques continue to be developed, such as enhancements to JPL's CASPER system [Knight et al., 2001], these can be incorporated into LSM components and thus enable higher levels of interaction between operators and surface vehicles.

To decrease the amount of reliance upon systems autonomy, the base and the robots should be designed in such a way that maintenance and repair is as simple as possible. Modularity, upgradeability and maintainability are important, even if it means incurring a mass penalty. Modular spacecraft are now being researched and developed for military and scientific [Esper et al., 2004] applications, mainly as a means to dramatically reduce the life cycle development time, but many of the concepts hold for exploration systems in general. For a lunar or Mars base, we want modular systems so that they are easier to repair should a component, subsystem, or system fail. The following addresses some of the related issues.

Modularity: Hardware and software should be developed with isolatable, reusable modules. This would simplify repair and maintenance of the systems by utilizing the line or orbital replacement concept. Modular components such as processor, electronics cards or power supplies would allow for simple removal and replacement. Equally important, modularity would facilitate upgrades to accommodate new technology in both hardware and software. It is too costly to simply replace habitation modules or rovers. They must be upgradeable and maintainable over long periods of time.

Fault Detection and Recovery: The detection of infrequent or slow developing faults is better suited for computers than for humans. Major advances in the use of artificial intelligence applications in modeling and diagnosing sophisticated systems [Williams and Nayak, 1996, Bernard et al., 1999] make it possible do develop robots that are capable of autonomously monitoring all construction activity, diagnosing system failures, and then recommending/performing recovery operations. The normal wear and tear of moving mechanical parts will be made potentially worse by the lunar dust.

Robustness and Reliability: Since the initial construction will be done robotically, the equipment must be designed to survive in the harsh lunar environment. Degradation of the systems from micrometeorite bombardment, damage from the abrasive lunar dust, and fatigue from thermal cycling of the materials will severely affect the systems endurance and reliability. Excavation activities will kick up tremendous amounts of lunar dust that can cover solar panels or get lodged in the joints and gears of moving parts. Self-cleaning solar panels and machinery as well as self-lubricating joints will improve the robustness of the system. Realistically, the replacement of components or of completely failed systems must be expected so redundant units and modular spare components will be required.

Deployability: To minimize the amount of on-surface construction required, it would be advantageous to land as complete a base on the surface as possible. The habitation module, connecting, nodes and airlocks could be docked in LEO so they can be inspected by astronauts, if necessary. The primary construction task on the lunar surface would then only be burying the habitation module in regolith. Similarly, the solar power station should be designed to simply unfurl itself to avoid having the LTS having to assemble fine structures. Clever mechanical engineering design will be important in this regard.

Computational Reliability: All of the above recommendations assume sophisticated computing capability on-board lunar surface systems. The computers must be radiation hardened and also must be ruggedized for lunar surface travel. Laptops, GPS receivers, modems, transceivers, etc. used by the military in battlefield deployments have recently been ruggedized for use in "netcentric" warfare. For use on the Moon, they must also be radiation hardened.

Significant progress has been made in the technologies that will support robotic lunar construction, including computing, networking, communication, and information technology. Except for perhaps in computing, where Moore's law seems to hold well, advances in the other areas could not have been predicted 17 years ago when the

LSM was first conceived. Suffice it to say that there will be more than enough processing power and memory to support all aspects of the lunar base. Most of the data will be processed, analyzed and stored on Earth anyway.

Communication links are critical for teleoperation. Enough information for the remote operator to make decisions and to issue control commands in a correct and timely manner must be reliably provided. This means a variety of video feeds must be downlinked from the base to the Earth. The engineering data (system health and status) and the science and ISRU data can be folded in with these streams, or sent down on separate links. These problems are not hard to solve. The interesting problems are those associated with communications within the base perimeter, include inside the habitation modules, and communications between the various elements, including the robots. High-speed, wireless, broadband equipment used on Earth could be readily adapted for use on the Moon. A variety of technologies are currently under development, including Ultra-Wideband, Wi-Fi, WiMAX, and 3G cellular. WiMax via the emerging 802.16d standard, for example, promises bandwidth of up to 75 Mbps over a range of 4-6 miles [Intel, 2005]. By 2025 a suitable option with even more bandwidth and range will be available.

Navigation is also an important consideration: The Spirit and Opportunity rovers move on the order of a few to tens of meters per day under human supervision. They have limited capabilities when it comes to avoiding obstacles, such as rocks in their paths. The ability to use robots for lunar base construction implies a high degree of precision in absolute and relative navigation capabilities. The robots will need to regularly traverse paths to excavate and transport regolith, service the science and ISRU equipment, etc., and doing this via solely teleoperation will be tedious and time consuming for human operators. For the robots to do much of it themselves, they will need real-time position, velocity, heading, and timing information, both with respect to reference points within the site and with respect to one another. They will need to be able to characterize terrain, and to sense and avoid obstacles and collisions with one another. Recent studies suggest that absolute navigation accuracies on the order of 400 m are attainable simply with star trackers and inertial navigation systems, and can be reduced to 50 m with accelerometer bias reduction methods [Malay et al., 2005]. Navigation satellites supporting the lunar base will likely reduce this level of error even further. This will be useful for long distance exploration excursions. Within the site perimeter, it is possible to implement a tracking system based on triangulation techniques over the wireless broadband network. Such technologies are being developed for military and civilian sensor network applications.

Collaboration and cooperation amongst the robots will be needed if they are used in parallel operations or if they are needed to work together to perform some objective. For example, in burying the habitation module under lunar regolith, it would be advantageous for one LCUV to be excavating the regolith while another transports it to the base site. It would be similarly advantageous for both LCUVs to then work together in burying the module. Such cooperation can not be solely achieved by the humans operating the robots, particularly if the tasks are again repetitive and tedious. JPL's Robotic Work Crew team investigated and developed software for tightly coupled multi-robot coordination tasks such as transporting and handling of long objects on challenging planetary terrain [Trebi-Ollennu 2002]. Results from this research and from other groups that are studying the issues of robotic collaboration (including RoboCup and other areas discussed at the IEEE International Conference on Robotics and Automation) and robotic construction can be applied to the LSM.

CONCLUSIONS

In this paper, we considered the development of a lunar base at the Moon's southern pole for lunar in-situ resource utilization and for astronomy, astrophysics, and astrobiology. The Lunar Split Mission (LSM), a concept from nearly 20 years ago which presumes the base would be constructed by robots prior to the arrival of astronauts, was assumed. The LSM concept is updated herein to incorporate technological advances that have occurred in the past 15 years, particularly in telerobotics, power generation, habitation, communications, and information technology. Experts in robotics predict that many of the capabilities needed for robotic construction of lunar bases via shared autonomy, a combination of teleoperation and autonomous operation, are attainable within the next 10 years given focused research and development and adequate funding. This strategy of reducing the risk to astronauts in early lunar base development should therefore be seriously considered amongst the options available to NASA and the international community.

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