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Can Robots Build a Lunar Habitat?

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Paper Session: Lunar Industrialization and Colonization

ABSTRACT

Developing a human habitat on the lunar surface will require an extensive infrastructure with a large number of assembled and tested components. Automating the development of this infrastructure using robotic systems would greatly reduce the cost. However, advances in the technology must be realized for robots to be used in such typical tasks as mating module and equipment interfaces and connecting umbilicals and fasteners.

This paper addresses the challenges in automating the assembly of lunar components. The specific tasks which must be automated and the corresponding technology advances required are discussed here. This is an attempt to foster discussion of the issues of automating lunar surface operations and to highlight the most critical areas of technology that must be addressed to make lunar habitation a reality.

1. INTRODUCTION

Although we have the will to further explore the moon and other planets, the cost of this enormous undertaking using available technology and manned assembly remains beyond the reach of the current total international budget for space exploration. A lower cost alternative must be found to make the development of an international lunar habitat a reality. The use of robotic devices and other automated systems will reduce the overall cost of establishing a manned presence on the moon. Reducing the number of manned missions and the overall EVA activity required to assemble the components and systems needed will greatly reduce the cost. Can the technology that we now have or expect soon perform the needed automated assembly of a complete lunar habitat? This paper provides part of the answer.

2. LUNAR HABITAT COMPONENTS

The components of lunar surface operations will be significantly influenced by whether a lunar base will be permanently manned or only man-tended. Permanently manned lunar operations will require significantly more infrastructure, such as that associated with long-duration storage of launch vehicles and their support equipment. Most components of a lunar habitat can be grouped into five general categories:

- Launch and Landing Vehicles
- Transportation Vehicles
- Habitation Modules
- Support Subsystems
- Support Equipment

Launch and landing vehicles enabling crew access to the lunar surface will be required to support regular habitat operations. For permanently manned operations, these vehicles will have to be based on the surface with dedicated storage areas and support equipment. Man-tended operations might not require such extensive capabilities, since surface operations support equipment could be stored in low lunar orbit.

Transportation vehicles could range from simple, unpressurized rovers used for a man-tended habitat to fully pressurized rovers, excavators, regolith movers, and cargo haulers for developing and sustaining a permanent colony [References 1,2,3]. Many of these vehicles could be designed to function autonomously or remotely controlled by humans.

Habitation modules would include crew living quarters, laboratories, and fresh food production chambers. Initial habitation might be satisfied through the use of a standardized prefabricated structure, while additional structures could be constructed from modular components. The use of robotics would greatly enhance habitat construction activities. Conceptually, many consider the type of modules used in Space Station Alpha as baselines when exploring habitat designs. Habitat components designed for use with robotic systems would facilitate automated construction and maintenance by using "robot-friendly" fixtures, tool-points, and assembly designs.

Support subsystems and equipment could range from line-replaceable units (for example, power or computer systems) to portable lighting or scientific instruments.

An operational lunar base could also include fluid and power lines.

3. TYPICAL ASSEMBLY TASKS

Construction of a lunar colony will encompass a wide range of activities, including many complex physical and nonphysical tasks [Reference 4]. These tasks will involve structural assembly, repair, and maintenance; operation of simple mechanisms such as latches and handles, joining and fastening (connector and umbilical mating and demating); parts handling and positioning; and a variety of inspection activities. Additionally, some derivative of traditional construction equipment will be needed in the more ambitious scenarios envisioned for excavation, hauling, and other regolith handling functions [References 1,2,3].

Previous studies have identified various mission scenarios based on humans performing groups of work functions to complete a definable high-level activity, such as assembling a structure or transferring cargo from a landing site to a storage location [References 1,2,3]. These scenarios all typify construction and assembly tasks required for a lunar habitat. Some of these could be performed through teleoperation, either from Earth or from a lunar flight crew, while others could be performed semiautonomously by groups of intelligent robots under human observation [Reference 5]. In general, high-level work functions have very similar characteristics and would require similar automation and robotics capabilities. For example, cargo transportation and regolith hauling would both involve the use of a mechanism capable of transporting objects from one location to another. Landing site inspection and solar cell surface damage assessment would both require sensors capable of identifying anomalies.

The work that would be performed during lunar habitat construction and operation falls within several general high-level categories. These categories, shown in Table 1, can be further divided into more detailed and generic components defining specific functions to be performed by robotic devices.

There are several different definitions and interpretations of smaller, more generic work tasks falling within these categories. A standard set of these primitives would have to be defined, establishing a relationship between manual and "robotic" tasks. The task primitives shown in Table 2 are representative of the types of manual effort which would have to be performed by robots.

Table 1. Types of Work

Task Category	Definition
Assembly	Physically connecting mechanical or electrical components.
Servicing	Removal and replacement, adjustment, refurbishment, or reconfiguration of components.
Maintenance	Maintenance of systems or components to ensure they remain in good operational condition.
Inspection	Use of sensing systems to determine the integrity of systems and components.
Material Handling	Transporting and manipulating supplies, equipment, structures or material.

Table 2. Manual Task Primitives

Adjust	Demate	Release
Fasten	Grasp	Activate
Insert	Inspect	Unfasten
Locate	Mate	Configure
Monitor	Move	Stop
Plan	Schedule	Replace
Test	Track	Align
Verify	Translate	Retract

Robots capable of performing these types of manual tasks on the moon will have to be designed to provide reliable performance with minimal human supervision or assistance.

4. UNIQUE DESIGN REQUIREMENTS FOR LUNAR ENVIRONMENT

Lunar surface operations will involve long-duration exposure to hostile and hazardous conditions for both humans and machines. Attention to these conditions will be required during the design of robots destined for a lunar outpost. Characteristics unique to the lunar environment include low gravity, micrometeoroids, thermal extremes, and solar radiation surges. The introduction of human operations such as vehicle launching and landing will present additional considerations such as close-range rocket exhaust and spreading lunar dust. Robots designed for this nonterrestrial environment must include provisions for these extreme conditions in addition to meeting operational requirements.

The lunar surface is covered by a very fine dust often compared to abrasive talcum powder. The dust adheres to surfaces of EVA suits and spacecraft. The engine exhaust plume from Apollo 12, which landed 160 meters from Surveyor III, caused micrometeoroid and/or ejecta impact damage to the Surveyor spacecraft [Reference 2]. Some method of protection such as regolith berms will be needed in regular launch and landing operations. Micrometeoroids as well as human

surface operations also raise the potential for impact damage. Robots will encounter some form of ejecta and will require some degree of designed-in protection. Normal robot operations will also disturb lunar soil, randomly distributing dust. Protection from dust immersion will also be necessary to ensure reliable robot operations.

Natural factors in the lunar environment such as thermal extremes and solar radiation flares will also influence robot designs [Reference 2]. Robots designed for normal operation in the extreme temperature ranges found on the lunar surface must be considered early in the design cycle, although some protection for both thermal and solar artifacts could be provided by specially designed shelters. Shelters or storage facilities developed for other uses, such as housing spacecraft, would most likely also include design considerations addressing these factors. Storage facilities designed to also accommodate robots would provide needed protection from the elements while reducing the "as-built" design requirements for the robots themselves.

Another significant design consideration involves operating in the low-gravity conditions found on the moon. Robots designed for terrestrial operations would not perform as effectively or efficiently on the moon. These low-gravity operations will also affect robot design.

5. ROBOT CONTROL METHODS AND REQUIREMENTS

A robotic system performing tasks on the lunar surface can be controlled using various techniques. Each of these options requires a varying degree of onboard intelligence and human interaction, the primary difference being the level of interaction provided by the human. On one end of the spectrum the human provides high-level, long-term tasks and goals to be accomplished and the systems autonomously perform the entire task. This is typically referred to as autonomous or supervised autonomous operation. With the exception of the most trivial planned tasks, this mode of operation cannot be accomplished with current technology. The other options, used in most field operations today, involve a human operator interacting with the system at all times include telepresence and intuitive-based control.

5.1 Ground-Based Telepresence

Telepresence involves direct physical interaction between an operator and a robotic device, that is, the physical motion and forces generated by a human's extremities (arms, head, body etc.) are directly mapped to the corresponding device components or links. In re-

turn, the position and forces of the robotic devices are fed back to the operator. Thus, the operator feels as if he were performing the task at the site. This virtual control method requires an extensive amount of motion and force data to be communicated between the operator and the robotic system. In addition to a position/force control device, or joystick, high-quality stereo images of the worksite must be available to the operator. All of this data must be sent at a reasonably high rate to achieve smooth motion and realistic feedback. Typically, the minimal acceptable rate is between 10 and 20 Hz. This requires a fairly large data communications rate between an Earth-based operator and the lunar surface. Table 3 presents a summary of the estimated total data that must be communicated.

The table indicates the minimum data required to feed back information to the operator. For realistic control, this data must be fed back at a rate of at least 20 Hz, which results in a total data rate of 11.6 Mbps (assuming 10 bits/byte). This control method requires a minimum level of onboard computing and intelligence. The lunar-based controller simply processes the arm and sensor data and sends the data to motor/sensor real-time controllers. Any delays in the required data stream, whether due to slow transmission rate or delays between transmissions, may cause either unsafe operations or the need for extremely slow movement.

Table 3. Data Required for Telepresent Control

DATA ITEM	DATA TYPE AND SIZE (bytes)	TOTAL DATA (bytes)
Arm Joint Position (7 joints, 2 arms)	real = 8	112
Arm Joint Velocity	real = 8	112
Arm Joint Acceleration	real = 8	112
Arm Wrist Force	long integer = 2 (6 force components)	24
Arm Gripper Forces (3 fingers)	long integer = 2 x 3 = 6	12
	Total Arm Data:	372
Video Feedback (2 cameras)	8-bit integers = 1.440K (per camera)	57.6K
600x800 Color Camera	50:1 compressed = 28.8K	
	Total Video Data:	57.6K

5.2 Ground-Based Intuitive Interface

The alternative to human control via physical motion is intuitive or command-based control. In this mode of control, an operator controls robotic devices (rovers, arms, grippers, moveable stages etc.) via a window-based computer interface. The interface provides the ability to monitor all devices, systems, and sensor data. It also allows simple verb-like commands or even scripts of numerous simple commands. An example command might be: *move left arm to "Sample 1*

Pickup" point. It should be noted that this is not the same as autonomous operations where much more complex, time consuming commands would be sent. Instead, the operator is sending commands that take on the order of a few seconds to perform. Thus, the human remains in the control loop, but at a slower update rate of perhaps 1 to 5 Hz or in some cases even slower.

The data that must be sent from the system to the operator is nearly identical to the data required for telepresence. Command strings, sensor data, and device position must be sent along with the same video data in most cases (velocity and acceleration are not required). Thus, the overall data to be downloaded is slightly reduced, and in some cases low-resolution video data may be acceptable. The primary difference is that a delay of 1 to 5 seconds (round trip time) between data transmissions is acceptable because this is the update rate of the operator's commands. The onboard computing intelligence to accomplish this is much greater than what is needed for telepresence control. The onboard system must have enough intelligence to process commands such as requests to move an arm's gripper to a location. As a minimum, an onboard model of the environment and a path planning capability must be present.

5.3 Lunar-Based Control

One possibility for controlling lunar-based robot systems that has not been mentioned is the use of IVA astronauts housed in a control habitat on the surface itself. Although this seems to defeat the purpose of robotic assembly in the first place, it does eliminate the need for extravehicular activity in and around a large habitat that is being constructed. In this situation, both data communication and visual feedback is greatly enhanced. Using wireless, or cable-based communication without any significant delays allows for a very realistic telepresence control capability. For small habitats being built near the control station, this mode of control would be very effective. For tasks the operator cannot adequately view an intuitive interface may be more appropriate. All of the control technologies used for remote operation can also be used in this situation where the operators are near the work environment. However, the demands placed on the technology are greatly reduced.

6. TECHNOLOGY CAPABILITIES

A number of technologies must be available to support the previously mentioned modes of control and perform required lunar-based robotic tasks. Both onboard intelligence and data communications are demanding requirements, depending on the control mode used. The current state of the art and the near-term expected ca-

pability are outlined below in order to answer the question of whether ground-based robot control and thus robotic assembly are feasible.

6.1 Data Communications

Terrestrial and space-based data communication capabilities are advancing at a rapid rate. Within the next few years, television-quality, full-motion digitized video will be available in homes via fiber-optic and coaxial cable and satellite transmission. Current and near-term satellite communications capability is indicated by NASA's Advanced Communication Technology Satellite, or ACTS [Reference 6, 7]. This satellite, launched in 1993, is NASA's attempt to develop and test leading-edge satellite communications capability. The various data rates that ACTS is capable of, depending on the access type and other variables, are shown in Table 4 below:

Table 4. ACTS Data Rates

Type of Communications	Data Rate (Mbps)
Burst mode down link with VSAT terminals	110
Continuous capacity with VSAT terminal	1.54
Continuous capacity with NASA Lewis terminal	50
Single carrier with 50 watt amplifier	203

Table 4 clearly shows that the 11-Mbps rate required for telepresence control, which requires the highest communications rates, is achievable with current technology for Earth-based communication. In space, satellite-to-satellite links using optical communications have reached a capacity of 300 Mbps [Reference 8]. Thus, the 11-Mbps data rate required for telepresence control could be achieved in an Earth to moon communications link as well. Although the data rate could be met, the distance between the Earth and the moon is such that an inherent delay due to the limiting factor, the speed of light, is approximately 2.5 seconds. Assuming certain processing and other satellite and ground switching delays, the total round trip delay may be as much as 6 seconds. This delay becomes the limiting factor in controlling robotic systems on the lunar surface. It should be noted that the requirements in Section 5 represent a very realistic, sensory-rich teleoperated environment. It is possible to do certain tasks such as moving material with low-resolution black-and-white images and position data only. NASA-Ames routinely controls various teleoperated devices by remote means using 56 Kbps data lines. They have proposed a discovery mission to the moon to remotely control rovers and are expecting an available 768 Kbps data rate. This will allow for smooth motion control but provide only low-resolution imaging. However, the problem of data delay is still present and must be dealt with for more difficult tasks.

6.2 Onboard Device Intelligence

The degree of onboard intelligence required varies depending on the type of interface being used. With an intuitive-based interface the minimum level of intelligence must be available to plan the motion of mobile devices and manipulator arms. In addition to this, the local lunar based system must plan and supervise the commanded tasks over a short time horizon, typically on the order of a few seconds. Thus, planning, task decomposition, and intelligent monitoring are required for realistic lunar operations. The state of the art is now approaching this capability. A number of intelligent, remotely operated mobile devices have been demonstrated. The Dante and Dante II legged rovers developed by Carnegie Mellon University have been used to explore active volcanoes under remote operation. These systems have measurement sensors capable of constructing a three-dimensional map of the local terrain and planning their own obstacle-free motion within a small localized area. McDonnell Douglas is developing the Marsokohd Rover, a wheeled vehicle obtained from Russia that contains a 6-degree-of-freedom sampling arm. This device is also remotely operated and has enough onboard intelligence to operate via telepresent control. International Robotic Systems Inc. has developed an autonomous marine platform, the Owl Mark II, a small water craft controllable via an intuitive interface. The onboard intelligence is sophisticated enough to communicate with a wide array of sensor devices and control its own path based on operator-sent trajectories. These examples show that the state-of-the-art in onboard intelligence is currently at the minimal level for telepresent control and is just beginning to reach the level required for intuitive-based control.

7. CONCLUSIONS

The tasks required to assemble a lunar habitat include a number of relatively simple tasks such as transporting large pieces of equipment. There are also more difficult tasks such as covering an item with insulation blankets or connecting electrical connectors. Thus, it becomes difficult to say that today's robotic devices can perform all of the required lunar habitat assembly tasks. Many of the tasks, however, can be performed using robotic devices working under ground control. Current technology and use of telepresent control devices are adequate to perform certain tasks. However, the delay time makes delicate and precision tasks extremely difficult. The use of intuitive interfaces, which send up commands that span a few seconds of activity, allows even more difficult tasks to be performed provided the onboard intelligence can support these commands. Although certain tasks can be accomplished a number of technology enhancements and capabilities must be de-

veloped before a complete robotic assembly system can be developed. These technologies include increased intelligence onboard and improved sensors, including more capable image processing and recognition. The communications capabilities appear adequate to support the command and data streams required by most robotic systems. Thus, it appears that lunar habitats can and should be built using robotic devices. Specific technology advances are required to ensure that this can be done in a reliable manner.

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