The Use of Automation and Robotic Systems to Establish and Maintain Lunar Base Operations

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Abstract

Robotic systems provide a means of performing many of the operations required to establish and maintain a lunar base. They form a synergistic system when properly used in concert with human activities. This paper discusses the various areas where roboticsand automation may be used to enhance lunar base operations. Robots are particularly well suited for surface operations (exterior to the base habitat modules) because they can be designed to operate in the extreme temperatures and vacuum conditions of the Moon (or Mars). In this environment, the capabilities of semi-autonomous robots would surpass that of humans in all but the most complex tasks. Robotic surface operations include such activities as long range geological and mineralogical surveys with sample return, materials movement in and around the base, construction of radiation barriers around habitats, transfer of materials over large distances, and construction of outposts. Most of the above operations could be performed with minor modifications to a single basic robotic rover. Within the lunar base habitats there are a few areas where robotic operations would be preferable to human operations. Such areas in include routine inspections for leakage in the habitat and its systems, underground transfer of materials between habitats, and replacement of consumables. In these and many other activities, robotic systems will greatly enhance lunar base operations. The robotic systems described in this paper are based on what is realistically achievable with relatively near term technology. A lunar base can be built and maintained if we are willing.

Introduction

Robotic systems provide a means of performing many of the operations required to establish and maintain a lunar base. They form a synergistic system when properly used in concert with human activities. This paper discusses the environmental and operation characteristics of a lunar base, the various areas where robotics and automation may be used to enhance lunar base operations, and the lunar base system architectural features necessary for the successful application of robotics and automation.

Lunar Base Characteristics

A lunar base has several characteristics that strongly influence decisions regarding the use and types of automation and robotics. The most prominent of these characteristics is the hostile environment in which the base is situated. With the exception of the interior of habitats, most activities will require man or machine to withstand exposure to lunar environmental hazards that include hard vacuum, thermal extremes, dust, and radiation. Another characteristic of a lunar base is that there will be limited external support of the base. It is not practical to use Earth resupply to replace entire systems each time a component fails; therefore, it is essential that key base operations be able to continue through the use of maintenance activities. Maintenance and many other activities at a lunar base will require moving men and materials from place to place, which leads to the conclusion that extensive local surface operations will occur at the lunar base. The final key characteristic of a lunar base is that utilization of indigenous resources will be advantageous in reducing Earth resupply requirements. This leads to further surface operations to gather the necessary surface materials. In summary, the ability to perform surface operations quickly and efficiently will be essential to the success of a lunar base. Due to the severity of the lunar surface environment, automation and robotics must play a key role.

Lunar Base Operations

To determine the areas where automation and robotics would most benefit lunar base operations, we first assess the types of lunar base activities. Activities may be broken into three broad categories: habitat activities, local surface operations, and extended range surface operations. Habitat activities are those that can be performed from within a lunar base habitat where there is a controlled environment. These activities include scientific experiments and maintenance of in-habitat equipment. In this environment, automation and robotics would not be the preferred solution unless the tasks were very repetitive, hazardous, or had to be completed in the absence of human occupants. Automation of activities within a habitat is expected to be minimal, and as such will not be discussed further.

The second category of lunar base operations is the local[1] surface operations. These operations are characterized by movement of men and materials in the vicinity of the lunar base. A lunar base will require the movement of large amounts of material to handle launch (and landing) operations. To reduce the damage to the lunar base from rocket blast effects, the launch area must be located remotely from the lunar base, possibly several kilometers away. The use of soil deflection shields may make it possible to place the launch area relatively close to the lunar base; however, virtually nothing will be landed at its point of use or launched from its point of production. Therefore, regardless of the location of the launch area, all incoming and outgoing cargo will need to be transported to some other location. Because incoming equipment systems from Earth will most likely arrive fully assembled, some large modules to be transported may weigh over 10 tons even at 1/6 g. Another constituent of local surface operations is soil relocation. Soil shields are a very effective barrier to radiation and thermal extremes and their construction requires collection and movement of many tons of mass. Significantly larger amounts of soil collection and disposition will

[1]"Local is defined as being within the round-trip range of mobile equipment.

be required to support oxygen production utilizing lunar soil. Additional local surface operations include transporting astronauts around the base, and maintenance operations on equipment. Astronaut transportation requires a lunar rover type vehicle, either open or with a pressurized compartment, which would normally be manually driven. Maintenance operations involve some of the most complex activities that will occur on the lunar surface. These activities require a combination of mobility, positioning, sensing, tool use, task sequencing, and handling dexterity. Proper design of lunar base equipment will minimize the difficulty with these operations, and at the same time permit robotic maintenance.

The third category of lunar operations is extended range surface operations. These operations are characterized by the need for a power system independent of the lunar base and the ability to navigate long distances over rugged terrain. These operations are primarily lunar exploration activities such as geological survey, resource survey, and sample returns. Operations in this category are almost entirely performed by robotic rovers. It may also be necessary to robotic rovers to construct and resupply outposts that would act as safe way stations for astronauts conducting long-range travel.

In evaluating the above listing of lunar base operations it is possible to draw some conclusions about the role of automation and robotics in lunar base operations. First, direct human activity will dominate operations that can be performed within lunar base habitats. Second, mobile robots will dominate extended range surface activities. In local surface operations there is a less definitive choice. On Earth, humans are the primary operators (excluding the factory environment), either directly or through the use of manually controlled equipment. On the Moon, the surface environment poses a significant hazard and the need for a space suit that greatly reduces a human's dexterity. To facilitate human surface operations on lunar base equipment, particularly maintenance, all equipment will need to be designed to minimize dexterity requirements. This requirement, however, is also a prelude to the application of robotics systems. While automation and robotics cannot replace human activity, on the lunar surface they should play a very strong synergistic role.

System Requirements for Surface Automation Equipment

The primary role of automation and robotics will be in lunar surface operations, both local and extended range. This section describes the generic requirements for lunar base equipment in general, and automation systems in particular, that are to be used on the lunar surface. The requirements are broken into four categories: surface environmental hardness, modularity, autonomous operation, and system reliability.

Any equipment that is to operate on the lunar surface must contend with numerous environmental hazards. The system must be able to operate in a vacuum. This imposes severe limitations on the choices for lubrication and thermal management within the equipment. The temperature extremes on the lunar surface ($\pm$100 C) further complicate lubrication and thermal management. Although not all equipment will be required to remain operable throughout the lunar day/night cycle, as a minimum the equipment must be capable of passive storage on the lunar surface. Another hazard is lunar dust. Despite the lunar vacuum, movement and electrostatic potentials will cause dust to coat all exposed surfaces. This is primarily a concern for moving joints and bearing surfaces where the dust can cause excessive wear and/or binding. Unlike prior space missions, equipment with exposed moving parts must function for extended periods of time with little or no maintenance. A final environmental hazard is radiation. For equipment design, this particular hazard is easily quantified and has known solutions.

Modularity will be a key requirement for lunar base equipment. This will apply to all equipment regardless of the level of automation and robotics applied to lunar base operations. Because of the difficulties in surface operations, base equipment should be easily disassembled into man-handleable modules. This would allow either a man or a robotic system to perform the task. Such modules could be moved into a habitat through an airlock for detailed maintenance. To facilitate module removal or reattachment, the connections between the module and the base equipment should be self aligning, self sealing, and require simple translational assembly with minimal fasteners. Lead-ins for alignment should be sized to match the dexterity of the performer and the size of the module. The benefits of modularity are enhanced by standardization of modules. The more copies of a module that are utilized in the lunar base, the fewer spares are required to guarantee the operation of critical systems.

A generic requirement of lunar base equipment will be high reliability and maintainability. Reliability minimizes the number of equipment failures, whereas maintainability ensures that equipment will be on-line quickly following a failure. While high reliability is a requirement, 100% reliability is not attainable and much of the lunar base equipment will consist of large complex systems that must operate for long periods of time. To minimize the mass of equipment delivered to the lunar base, there must be a good mix of redundancy versus replaceability. Hard components such as metal frames need not be redundant, whereas failure prone components need to be redundant if they are small or be located in replaceable modules if they are large.

Equipment for automation of surface activities will require a high degree of autonomy such that a majority of the operations can be performed without direct human control. While self control and monitoring is within state-of-the-art for fixed process equipment, automation of surface operations is a challenge. As discussed earlier, many of the surface activities will requirement the movement of materials and maintenance of equipment. These activities require surface navigation capability and a knowledge of placement and assembly requirements. While this can be done with teleoperated systems, the productivity will be very low unless the operator is at the lunar base due to the time delays to an Earth-based operator. A fully automated robotic system with modern integrated control hierarchy, task sensing, and computer intelligence, is capable of performing all routine surface operations with minimal human supervision if the necessary features are integrated into the lunar base system architecture.

Surface Operations System Architecture

The lunar base system architecture will define base equipment and operations. The base will consist of large prefabricated equipment platforms such as habitats and lunar resource process equipment. Surface operations will be performed by astronauts in space suits and by mobile robotic equipment. Extended range surface exploration will be performed by robotic rovers. The ability of the lunar base to utilize automation and robotics for surface operations will depend on how well the overall system is integrated. The discussion that follows describes what will be required to ensure maximum utilization of automated systems.[2]

Utilization of automation and robotics on a lunar base and for surface operations in particular will require an integrated approach to the base architecture in which the lunar base equipment is designed with interfaces for the automated systems handling. In short, the lunar base must be designed for remote handling and maintenance. The design features leading to remotely maintainable systems have been established in the process lines for radioactive nuclear materials. Features to facilitate remote handling include standardized captive fasteners, self aligning parts, simple assembly motions, and modules small enough to be easily manipulated. *Figure 1* shows a typical captive fastener with lead-in. The lead-in greatly reduces the accuracy with which a rotary driver needs to be positioned. Making the fastener captive eliminates the need for starting threads and prevents the fastener from being dropped. Part assembly orientation is a key feature of remote maintenance design. Every part should have designated lift point(s) such that the part assumes

[2]Fixed, self-contained automatic equipment systems are not considered to be part of automation and robotics.

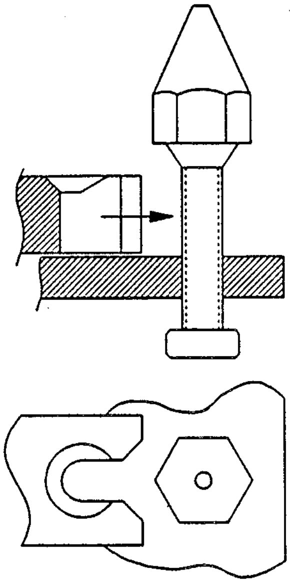

FIGURE 1 - Typical Captive Fastener

the proper orientation for assembly. This minimizes the rotational forces that must be applied concurrent with the assembly process. Assembly of a module onto an equipment platform should involve one, or at most two, translational motions to complete emplacement. The module should rest in position without supplemental support while fasteners and connections are secured.

Design features such as those listed above reduce the complexity of maintenance operations whether they performed by astronauts or teleoperated robots; however, additional design interfaces will be required to allow surface operations to be truly automated. Automated surface operation systems must possess task knowledge and mobility. The lunar base design for its part must supply navigational aids and local indexing. The task knowledge is a computerized data base which directs the automated system through the sequences necessary to perform specified operations such as acquiring parts or materials, transporting them to a designated area, and emplacing them. As implied in the previous sentence, surface mobility will be a requirement for most surface operations. Mobility requires the capability of traversing the lunar terrain with the ability to navigate without colliding with other base equipment. Autonomous navigation in the local area around the base can be greatly simplified by affixing navigational beacons at various locations through the base. The beacons (such as modulated infrared emitters) would allow mobile equipment to unambiguously determine position without resorting the machine vision. To complete an automated surface operations system, the equipment to be handled must possess fixturing to allow the automated system to accurately index to the equipment. Fixturing is a positioning aid intermediate between

lead-ins and navigational aids that provides relative positional information for the automated system at close range. Fixturing may take to form of protrusions, reflective markers, etc. Surface operations automation will best be served through the use of robotic manipulators mounted on mobile platforms. To provide full coverage of the various surface operations will require a minimum of three types of mobile platforms and manipulators. The most frequently used mobile platform will be a short-range light utility vehicle. This platform would be 3 to 4 meters long with the capability of transporting a few tons of payload. The vehicle could be configured as a manually operated manned lunar rover (with or without a pressurized cabin), as a soil mover, or as a mobile base for a robotic manipulator. As a soil mover, the platform would be equipped with a bucket and/or plow and would be capable of manual, remote, or possibly autonomous operation. As a base for a robotic system, the vehicle would be equipped to autonomously navigate around the lunar base and position the robotic manipulator as needed to perform activities such as maintenance. The dexterity and payload capabilities of the utility vehicle with manipulator would match or exceed those of an astronaut in a space suit and would allow either to perform most activities.

The second type of mobile platform would be the lunar equivalent of a traveling crane. Much of the equipment arriving at the lunar surface will come as large preassembled equipment platforms. To disassemble, move, and reassemble large equipment platforms is both time consuming and invites malfunction. Also, it may not be feasible to design habitats that may be broken into small parts for transport. As mentioned above, it is not possible to land equipment at its exact point of use. These considerations dictate the need for a heavy lift and transport capability on the lunar surface. One appealing approach to providing this capability is to modify one or more of the lunar landers such that they possess crawler tracks on their landing pads and have a lift boom to one side. Once the lander is on the surface, its descent engine is removed and the lander itself becomes a traveling crane. This approach provides efficient utilization of the mass landed on the surface without forcing every lander to incur the mass penalty associated with adding mobility features. The traveling crane generally would be remotely manually operated and would not include a robotic manipulator. However, it may occasionally be necessary to perform detailed manipulator work at locations beyond the reach the utility vehicle platform. For this situation, the traveling crane must have the capability to act as a base for a manipulator.

The third type of mobile platform that is required is the extended range lunar rover. This platform is roughly the size of the utility vehicle, but is designed to traverse rugged lunar terrain. The distinguishing features of this vehicle are that its power source is independent of the lunar base such that it can travel over vast distances on the lunar surface, and its level of autonomy is much greater than that of the other surface automation systems. The most likely mode of operation for this lunar rover is to travel during the lunar day using sunlight for power and hibernate during the lunar night if it hasn't returned to base. This platform will support the attachment of scientific packages and of a manipulator that will be required for many of the exploratory activities such as soil sampling.

Each of the mobile platforms described above will require an attached robotic manipulator to perform at least part of their tasks. All of the manipulators used at the lunar base should follow from a single modular design. The manipulators would consist of a base mountable on any of the mobile platforms, a series of linkages, and a tool mount to hold end effectors. Ideally the links would be identical self contained units that are easily connected in series to form a robotic arm. Connections among the manipulator links will be required to support structural loads, convey power, and transmit communications. The manipulator control could be distributed with some of the control hardware located in each link; however, the higher level task control functions and sensor interpretation will need to be centralized into a more complex processor located in the manipulator base or the mobile platform to which it is attached. All the lunar base automation and robotic systems would be coordinated at the highest level by a central command center that semiautonomously directs the activities of the lunar base.

Summary

The severe lunar environment makes the use of automation and robotics highly desirable for surface operations. A considerable portion of the surface operations will involve transportation and/or maintenance (maintenance also includes initial assembly). With proper equipment design for remote handling, these activities can be performed equally well by humans or automated machines allowing for considerable flexibility in lunar operations. Automation of surface operations will require three basic mobile platforms: utility vehicle, traveling crane, and an extended range rover. These platforms combined with a man-equivalent robotic manipulator and high level machine intelligence will be able to support all the necessary surface operations at a lunar base.