Mobile Surface Systems in a Moonbase System of Systems

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Abstract - Establishment of a future human lunar settlement for utilization of the Moon is one of many endeavors that could take place after NASA lunar exploration initiatives have completed. A study, referred to as Moonbase Arusha, is underway to explore a concept of operations for such an endeavor. This paper focuses on aspects of the concept related to its fleet of mobile surface systems. Ideas for their uses and configurations that are presently guiding development of their conceptual designs are presented. System elements that would provide solutions for local transportation between Arusha and lunar landers as well as surface expeditions away from Arusha are covered with a focus on baseline considerations for mobile surface system power, drive train, mechanisms, and navigation. System of systems engineering considerations for subsystem components are discussed for lunar settlements like Arusha.

Keywords: Moonbase Arusha, lunar rovers, mobile surface systems.

1 Introduction

The U.S. Vision for Space Exploration defines a program of several decades for human and robotic exploration in low-Earth orbit and beyond. Part of the Vision includes missions to the Moon that will prove technologies, engineering capabilities, and exploration approaches to enable eventual and sustained human exploration of Mars. A vision for what might be done on the Moon after technologies and capabilities have matured to enable human Mars exploration is not clear today. The Space Special Interest Group of the National Society of Black Engineers is conducting a long-term project to investigate a concept of operations for a future human lunar settlement. The project, referred to as Moonbase Arusha, is an unsolicited, grass roots study to provide a future vision for human space activity and utilization of the Moon after lunar exploration initiatives of the U.S. Vision. Such a venture conducted by international governments and commercial collaborations would accelerate commercial use of the Moon in line with the provisions of the National Aeronautics and Space Act. It is our vision that a lunar facility should be established to serve as an incubator for lunar corporations, providing a process to grow Moon-based industries and spin them off to build independent settlements.

The scope of Moonbase Arusha presumes a 48-person lunar facility in the polar region that would combine government, industry, and civilian space activities under a central complex. Critical spacecraft required for Moonbase Arusha are a passenger transport and a cislunar freighter, both of which would be launched by a super-heavy lift vehicle. The Moonbase would also require the development of freight and passenger-carrying ascent-descent vehicles for lunar surface to orbit transport, pressurized surface transports and other surface vehicles, as well as habitats and systems for surface module construction and energy production. While there are a near-limitless number of commercial opportunities possible on the Moon, Arusha would initially cater to the development of lunar industries such as solar power production and transmission, fuel production, manufacturing/regolith processing, and tourism. These aspects of the vision for Moonbase Arusha would leverage parts of the NASA exploration system of systems while requiring development of additional systems, technologies, and capabilities. In and of itself, Arusha would be a permanent system of systems (SoS) on the lunar surface.

To enable a large scale and sustained lunar presence, core elements of this surface SoS must include mobile surface systems of various types. Many concepts for such vehicles have been imagined and proposed; comparisons of number of promising concepts are covered in [1, 2]. This paper focuses on aspects of the Moonbase Arusha concept of operations related to its fleet of mobile surface systems. Ideas for their uses and configurations that are presently guiding development of their conceptual designs are presented. The paper covers those elements of the Moonbase Arusha SoS that would provide solutions for local transportation between Arusha and lunar landers as well as surface expeditions away from Arusha for scientific research or commercial industry activities. The scope of this paper is limited to baseline considerations for mobile surface system power, drive train, mechanisms, and navigation.

2 Arusha mobile surface systems

Among the most critical surface systems for the Arusha Moonbase are pressurized and unpressurized transport rovers, utility rovers for construction and assembly, and mobile robotic assistants for exploration and service tasks.
An excerpt of a mind mapping for the Arusha SoS that shows its mobile surface systems branch is shown in Fig. 1. Top-level activities within the SoS would include tasks such as exploration, construction, road development, excavation and equipment towing, with subsystem objectives such as site assembly, servicing, material transport, and navigation. These would be accomplished within defined system variables and engineering metrics such as traverse range, fuel cost, and endurance. Some of the design issues and details are discussed below that would support the system objectives.

2.1 Pressurized Transport Rover

We assume a Moonbase Arusha configuration including six pressurized rovers, with rotating maintenance down periods, such that four are available at any given time [3]. The pressurized component of the rover is a module twelve meters in length and four meters in width and height with a maximum range of 300 km. The total rover mass is constrained to within a 20-24 metric ton limit. Fig. 1 is a rough illustration of the concept.

A pressurized garage facility is assumed, allowing for major servicing of one rover and minor servicing for a second rover at any given time. The lunar base would include docking ports where the pressurized rovers can dock with base elements, allowing pressurized transfer between the rover and the base.

2.2 Small Transport Rovers

For short-range transport, Moonbase Arusha will field a variety of rovers similar in size and operating range to the NASA Apollo lunar rovers. These rovers will include a mix of cargo and personnel capabilities. Some may be pressurized and/or carry pressurized cargo modules in support of astronaut Extra-Vehicular Activities (EVA).

2.3 Utility Robotics and Rovers

Large rover and/or robotic systems will be needed to remove Arusha modules from lunar landers and position them within the base. Additionally, vehicles will be needed for field site assembly, servicing, and material transport tasks associated with base construction projects, road development, excavation, and equipment towing. EVA robotic assistants will often be required for these tasks. Depending on the specific robotic application, these robots may be transported inside the pressure vessel of a pressurized rover, on its exterior, or potentially towed behind. These missions typically will also require a separate cargo rover to transport processed fuels, manufactured/processed regolith, servicing equipment, or assembly components. Existing prototype examples of such systems for Mars missions are discussed in [6] as components in a human and robotic SoS for on-orbit and surface construction.

3 Rover subsystem considerations

Modularity is one of the most important factors in the development of viable mobile surface systems [1]. Modular subsystem concepts proven for lunar missions could be used for eventual Mars missions. Arusha rovers may share some common modular subsystems amongst respective specialized subsystems (e.g., pressurized modules) in their overall configurations. This holds for certain electrical and mechanical systems used across each rover type. Below we discuss some of the common subsystems that could be considered for the several types of Arusha mobile surface systems. Since the pressurized rover represents a superset of subsystems relevant to each rover type, we discuss them in the context of the pressurized rover concept unless otherwise noted.

3.1 Power

Thus far, the Arusha study has based power concepts on an assessment of existing regenerative fuel cells with application to surface vehicle propulsion. This led to the baseline decision that pressurized rover power needs would
be handled by a proton exchange membrane (PEM) fuel cell power system. Fuel cells produce electricity from an external supply of reactants (as opposed to the limited internal energy storage capacity of a battery) and are designed for continuous replenishment of the reactants consumed. Compared to other types of fuel cells, PEM fuel cells generate more power for a given volume or weight of fuel cell. This high-power density characteristic makes them compact and lightweight. In addition, the operating temperature is less than 100ºC, which allows for rapid start-up. These qualities and the ability to rapidly change power output are some of the characteristics that make PEM fuel cells the top candidate for automotive power applications.

The electrical energy produced by the rover fuel cell stack(s) can be fed to a motor inverter directly. In some cases, it may be attractive to use a buffer system, such as a battery, super capacitor, or flywheel. The buffer will supply peak power, which may be needed during start-up, or during acceleration. The buffer can also be used to absorb energy during regenerative braking. Fuel cell stacks will be located on the rover, vertically offset from the center of gravity beneath the pressure vessel.

Exploration sorties away from Moonbase Arusha by 6-person crews could last on the order of 15 days as a baseline. Regardless of sortie duration, reusable fuel cells would be needed, although they would not need to be regenerable away from Arusha (unless mass limitations call for regeneration during a sortie). As a baseline, fuel cells would generate electricity during the mission and store the water byproduct, using some as crew drinking water. On return to Arusha, recycling systems on the base would recover the water and recharge the rover's reactant tanks.

Such design choices for rover power systems have a direct impact on other subsystems (e.g., the drive train), and their designs. The reason for this is that the efficiency at which the PEM fuel cell converts hydrogen into electricity is proportional to the voltage at which the cell is operated [7]; a tradeoff must be made between size of the fuel cell stack and the fuel cost.

### 3.2 Drive train

The primary drive train types proposed for Arusha rovers are a 6-wheel system for pressurized rovers, as depicted in Fig. 2, and 4-wheel independent suspensions for smaller unpressurized and utility rovers. The suspensions to the wheel assemblies will resemble a double-Ackerman steering system such that all four corner wheels are steerable providing a tighter turn radius. This is similar to the steering system used on the NASA Mars Exploration Rovers.

The drive train specifications are governed by the operating environment and the specifics of wheel geometry and loading. We adopt several factors of the BURRO utility rover drive train specifications [8] for which the operating environment is described by soil properties and terrain inclination. The general geometry of the BURRO wheels varies based upon the design. In addition, the wheel loading is influenced by the weight of the rover and varies as weight is transferred between wheels due to suspension action. With respect to the BURRO design, the Arusha pressurized rover chassis and suspension must support a larger payload given the proposed size relative to traditional pressurized rover concepts such as LUNOX [5].

The drive train suspension is also influenced by military design concepts, one being an In-Arm hydrogas-trailing arm suspension design due to its compactness and minimal hull intrusion [9]. In a hydrogas unit, oil is forced through a damper and pushes on a separator, which provides springing due to compliance of the gas, thus providing nonlinear suspension stiffness, which is desirable for off-road vehicles. Hydrogas suspensions have been proven on many off-road vehicles and have been shown to be robust and reliable. Since the Hydrogas system is completely enclosed, operation in space environments should be feasible, notwithstanding certain issues related to thermal constraints, materials, and potential out-gassing, which require more detailed analysis.

The wheel hub concept is an integrated assembly including a traction motor, brake, two-stage gearing, and bearings to withstand large wheel loads. Wheel material compositions are envisioned consisting of a spun aluminum hub and tire made of zinc-coated, woven steel strands attached to the rim and discs of formed aluminum, with titanium chevrons covering a percentage of the contact area to enhance traction (similar to the wheels used on the Apollo lunar rover). The hub design is revolutionary in that it facilitates even distribution of drive power across all rover wheels using electric motors built directly into the hub of each wheel. A purported advantage of this design is that no additional transmission system is needed, thereby increasing the efficiency of the drive system.

Automotive technologies such as the electronic wedge brake (EWB) may apply for lunar rover application pending lunar environmental compatibility. EWBs allow varying degrees of braking force to be generated with little effort and kinetic energy of the vehicle can be directly converted into braking energy under intelligent control [10]. Intelligent controls based on fuzzy logic controllers used in critical aerospace safety systems have been adapted for automotive EWB use.

### 3.3 Mechanisms

In addition to robust locomotion systems, Arusha mobile surface systems will need a variety of mechanisms to fulfill their respective purposes. The spectrum includes mechanisms that will enable the following functions:

- Disengagement from the physical connections that secure rovers to landers after delivery to the surface.
- Wheel lift systems that facilitate lander egress and docking with surface elements at varying heights
- Lifting and excavation (cranes, augers, backhoes)
- Manipulation (using multiple tool and instrument attachments for science, logistics, and some repair)
- Sensor and antenna pointing
• Extending inflatable docking tunnels (to any pressurized element rovers docks with) and correcting for small misalignments in both position and rotation.

Mechanisms that enable these functions may be classified into the following key categories: Pointing Mechanisms (e.g. antennas and active sensors), Docking Mechanisms (e.g. latches and hatches), Lift Mechanisms, and Construction mechanisms. Desirable characteristics for these for Moonbase Arusha are discussed in turn.

3.3.1 Pointing mechanisms

Communications antennae, cameras, other optical sensors or instruments are among the candidate subsystem components that would require active pointing. For most pointing mechanisms, two-axis motor driven gimbaled assemblies would suffice for antenna pointing. This class of mechanisms includes pan-tilt units that are commonly used to point active sensors. Such pointing systems have been used on many current and past space missions and would be useful not only on Arusha mobile surface systems, but on stationary elements distributed around the moonbase as well.

3.3.2 Lift mechanisms

Lunar landers are expected to have very large fuel tanks, which will cause the ground clearances of lander vehicle passenger sections to be very high. Similarly, habitats will be landed on cargo landers that are also very high off the ground. A variable-height pressurized rover will be able to dock with these structures by raising its pressurized section to the proper height to connect to docking ports. Lift systems similar to those used on the Plane-Mate™ passenger shuttles at airports are envisioned for this purpose (see Fig. 3).

3.3.3 Manipulation mechanisms

Pressurized rovers will need manipulators for astronauts to be able to interact with the environment and external structures without requiring EVA necessarily. Utility rovers will also need manipulation capabilities for a variety of teleoperated and autonomous robotic functions. Some common task classes include acquisition and manipulation of samples as well as visual inspection or repair. Various arm configurations and placements on rovers would be driven by the manipulation tasks the arm or end-effector would be required to perform.

3.3.4 Docking mechanisms

Rovers will connect to Moonbase Arusha modules, lunar landers, and other rovers with a variation on the Common Berthing Mechanism (CBM) used to connect modules on the International Space Station. The rover will not dock in the true sense of the word. Instead, the rover will maneuver to a target position and extend an androgynous berthing ring towards the counterpart ring on the other vehicle or module. The rover’s CBM is connected to the rover via a flexible, inflatable fabric, comparable to the fabric of a spacesuit and forming a docking tunnel to the other vehicle or module. The flexibility will allow the rover to correct for angular and lateral misalignments between the two CBMs. In any docking, the rover can act as the active or passive vehicle.

Docking operations would occur in stages. That is, the rover would first navigate to (or be teleoperated) within meters of the stationary base module (or rover) to a target position where it can orient itself relative to the stationary module to achieve gross alignment of its CBM with that of the base module. Vision-guided maneuvers will be used during the extension of its androgynous berthing ring towards the counterpart ring on the stationary vehicle or module. This operation will be facilitated by visual recognition of fiducials on the base structure CBM that are used to refine the alignment precision while the berthing ring carefully approaches the counterpart ring. Once within centimeters with acceptable visual alignment, proximity sensors will be used to facilitate final CBM docking maneuvers until a good pressure seal is achieved.

4 Navigation subsystems

The Arusha rover concepts will employ a navigation system that provides for autonomous navigation without the use of navigation beacons or other external systems. Below we describe a representative guidance, navigation, and control sensor suite and navigation approach.

4.1 Sensors

Sensors for lunar navigation and mobility include stereo camera sets, star tracker, LIDAR, and mm-wave radar as well as an inertial measurement unit (IMU) and mobility drive system and suspension sensors such as wheel encoders and potentiometers. The IMU will provide rover attitude measurements on the lunar surface including roll, pitch, and yaw/heading and their angular rates. Wheel
encoders will enable dead-reckoned navigation while encoders (and possible potentiometer backups) provide state knowledge of articulated joints (passive or active). In order to deal with IMU drift over time, a star tracker will be used for periodic corrections to rover inertial position and orientation on the lunar surface. Any available lunar orbiter may be used to assist with position updates as well.

Stereo cameras (forward and rearward at a minimum) will be used for terrain perception and surface navigation. This will be supplemented by LIDAR for accurate 3D terrain modeling supporting terrain hazard detection and avoidance, and by mm-wave radar for detection of dust pits and similar negative obstacles that cannot be detected using stereo vision or LIDAR. LIDAR and mm-wave radar may be used for night-time navigation or navigation into terrain areas that are in deep shadow. The mm-wave radar combined with software-based visual odometry will be useful for compensating for wheel slip and sinkage without compromising accuracy of odometry on soft regolith and steep slopes.

All GNC sensor data and data products such as terrain maps generated by the sensor suite and supporting software will be viewable on consoles at the crew members’ work stations in pressurized rovers or at the remote Moonbase.

4.2 Lunar surface navigation

The navigation system must be able to operate autonomously and via teleoperation as well as in mixed modes between these extremes. The navigation sensor data and data products may be used to supplement a crew member’s own perception of the terrain when the rover is driven by a crew member onboard or via teleoperation remotely. In autonomous mode, the rover onboard computer systems process data and generate motion commands. At all times, the autonomous control system may be overridden by a crew member as a transition to manual driving mode, or as a transition to teleoperation mode.

Pressurized rovers would be used for transportation between Moonbase Arusha and lunar landers and for science or industrial expeditions significantly far away from the base. With a maximum range of 300 km, global maps of the region will be used to facilitate global route planning by the crew and the rover. Global maps of the region, including relevant landmarks useful for surface navigation, would be derived from high-resolution topographical data previously acquired by low-orbiting satellites.

The local topological maps generated by the perception system during traverses can further aid crew members in driving rovers across the lunar surface. In autonomous mode, the rover would operate on global paths represented in global maps onboard while performing hazard detection and avoidance to negotiate safe local navigation paths along the way. Local navigation paths will be decided in real-time and will refine global paths to account for hazards that are not represented in lower-resolution global maps as well as to incorporate motion adjustments necessary to maintain rover stability and operational health. Existing global and local path planning algorithms can be used to accomplish the lunar-base-to-lander navigation and expedition navigation functions.

5 Surface SoS communications

As part of Moonbase Arusha SoS infrastructure, we assume connectivity to a satellite constellation providing constant line of sight communications throughout the maximum possible rover traverse ranges. This constellation could be leveraged in part from the NASA exploration SoS.

The Mission Operations portion of the Arusha project will consist of three control centers. An Earth control center will act as a backup to all operations. A Moonbase control center will be the main center of all surface operations; it will be capable of handling data communications between Earth and the moonbase and between the moonbase and the Arusha rover fleet. A control center will exist onboard each utility or unpresurized rover, and internal to each pressurized rover. Rover onboard control centers will be less complex than the moonbase and Earth control centers. They will communicate with the moonbase for high-level command and control, and perform some rover self-diagnostics and troubleshooting should the need arise.

6 Conclusions

The Moonbase Arusha concept represents a future system of systems on the lunar surface with potentially many component systems that will operate as a permanent outpost for several lunar industries. The mobile surface systems in the SoS are core elements that will contribute to the establishment, operability, and sustained settlement of the moonbase. The mobile systems alone represent a heterogeneous set of independent systems with varying degrees of autonomy within the SoS. An overview of common subsystem components for pressurized, unpresurized, and utility rovers that comprise Arusha mobile surface systems was presented with a focus on power, drive train, mechanisms, and navigation.

Design considerations for these vehicles, and how they would fit into the SoS, harbor certain implications for the SoS and how it could be engineered [12]. The implications relate to concepts for their deployment and operation. Details about certain subsystem components were provided in the context of SoS engineering considerations for lunar settlements like Arusha. Further research, conceptual design, and analyses are needed to better understand implications that mobile surface system designs will have on other system components of the overall Moonbase Arusha SoS. In this regard, future work on the Arusha project will address topics including launch, transfer and landing vehicles, habitability and crew accommodations, structures, and radiation effects.
References


