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Plug-in Hardware Concepts for Mobile Modular Surface Habitats

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This paper discusses a mobile modular habitat concept called "Mobitat", that was conceived for use on the Moon, Mars, and other planetary surfaces (Howe & Howe, 2004). The Mobitat (roughly based on the Mankins "Habot" concept) consists of three major components: a) a descent engine jettisoned upon landing, b) a highly maneuverable multi-use robotic mobility platform, and c) detachable modular construction and robotic elements, including habitat pressure vessels. Multiple Mobitat landers will land autonomously on the surface at safe distances from each other and traverse an obstacle-strewn landscape to congregate at a single target location. Modules can dock together to form a larger base awaiting crew arrival. After mission completion and departure of the crew, the modules can detach and relocate themselves to another location. A Mobitat can also be piloted by crew members directly or through teleoperation, allowing them to function as highly maneuverable pressurized rovers, making dedicated pressurized rovers unneccessary. Additionally, the modules are detachable, allowing the mobility platform to be used by itself for other tasks using plug-in robotic implements. The significance of developing detachable modular habitat / mobility systems will become apparent in the long run, specifically with various phases or classes of planetary surface construction: 1) Class I: Pre-integrated hard shell modules ready to use immediately on delivery, 2) Class II: Prefabricated kit-of-parts or inflatables that are assembled after delivery, and 3) Class III: ISRU derived structure with integrated Earth components. The Mobitat concept will bridge between each class of surface construction, and create a phased approach to human habitation. The Mobitat can function as a rover and relocatable Class I habitat for early exploration. Modules can dock together to make larger bases of assembled Class II structures in semi-permanent base infrastructures. Finally, the mobility platform can be teleoperated independently as construction equipment for digging, earth moving, tunneling, and drilling for in-situ mining and habitat construction. A whole suite of compact modular tools can be developed that dock with the platform to construct ISRU drived pressurized and non-pressurized Class III structures.

I. Introduction

For the success of surface Exploration missions, a reusable, modular, reconfigurable habitat construction system is needed that can be inserted autonomously and build up base infrastructures at geographical areas of interest. Innovation in mobile habitat technologies will be central to this success, reducing cost and overcoming logistical challenges. This proposal seeks to further develop under the ASTP-ASCT category a mobile modular habitat concept called "Mobitat", that was conceived for use on the Moon, Mars, and other planetary surfaces.

The Mobitat (roughly based on, and inspired by, the Mankins "Habot" concept) consists of three major components: a) a descent engine jettisoned upon landing, b) a highly maneuverable multi-use robotic mobility platform, and c) detachable modular construction and robotic elements, including habitat pressure vessels.

Multiple Mobitat landers will land autonomously on the surface at safe distances from each other and traverse an obstacle-strewn landscape to congregate at a single target location. Modules can dock together to form a larger base awaiting crew arrival. After mission completion and departure of the crew, the modules can detach and relocate

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themselves to another location. A Mobitat can also be piloted by crew members directly or through teleoperation, allowing them to function as highly maneuverable pressurized rovers, making dedicated pressurized rovers unneccessary. Additionally, the modules are detachable, allowing the mobility platform to be used by itself for other tasks using plug-in robotic implements.

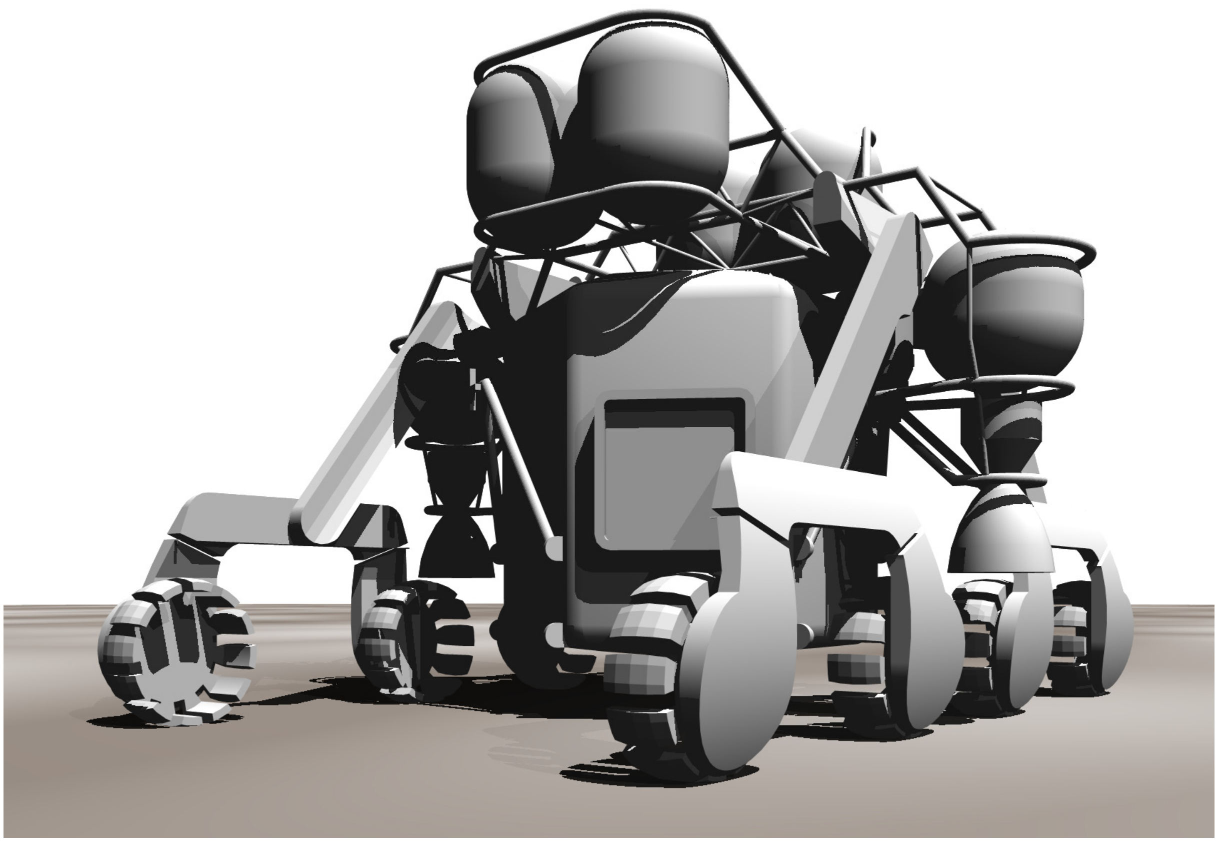

Figure 1: Mobitat pre-study configuration

The Mobitat concept will have a cost-effective system-of-systems impact on the lunar exploration enterprise and establish a phased approach to human presence in deep space.

The current version of the Mobitat concept is at TRL2, having gone through computational analysis for kinematic functionality and modularity. This proposal seeks to achieve a TRL4 rating. Expected challenges include:

- System configuration: Develop schemes and design grammars for modular assembly of a variety of base habitat configurations, and develop strategies for independent leveling, power control connections, and mobility system docking.
- Robotic mobility platform system: Contribute to the development of modular mobile platform technologies, specifically the All Terrain Hex Legged Extra Terrestrial Explorer (ATHLETE) platform (see TMP funded proposal "Rough and steep terrain lunar surface mobility").
- Modular pressure vessel concept: Develop and validate through working mockups and prototypes a modular universal habitat that docks with the mobility platform and can be adapted to a variety of needs, including laboratory, EVA, living, and working requirements. This will include strategies for reconfigurable Environmental Control / Life Support Subsystems (ECLSS).

We have assembled an exceptional team, which will follow the Earned Value Management (EVM) model. System configuration, scale mockups, and modular robotic concepts will be developed by Plug-in Creations (Howe & Nixon), with engineering concept analysis by Langley (Antol). JPL Robotic Vehicles Group will work on mobility issues (Matthews) and interfacing with ATHLETE testbed platform variations. Multi-agent coordination for autonomous assembly will be by NASA Ames (Colombano). Habitat human factors and habitability issues will be by JSC (Connolly), and radiation shielding, mobile laboratory planning, and suitport integration issues by NASA Ames (Cohen). Reconfigurable MESR-ECLSS strategies will be by Hamilton Sundstrand (Nalette). We stress that our team would like to work our concept into the overarching architecture integration team that will be established by ASTP-ASCT Advanced Concepts group (in connection with ASTP funded proposals "Revolutionary Aerospace Systems Concepts (RASC)" and "Human-centered design").

The development of a modular mobile habitat concept should begin immediately. Achieving a TRL4 for the Mobitat concept will validate this surface construction strategy in time for follow-up technology maturation under the ASTP program.

The significance of developing detachable modular habitat / mobility systems will become apparent in the long run, specifically with various phases or classes of planetary surface construction:

- Class I: Pre-integrated hard shell modules ready to use immediately on delivery.
- Class II: Prefabricated kit-of-parts or inflatables that are assembled after delivery.
- Class III: ISRU derived structure with integrated Earth components.

The Mobitat concept will bridge between each class of surface construction, and create a phased approach to human habitation. The Mobitat can function as a rover and relocatable Class I habitat for early exploration. Modules can dock together to make larger bases of assembled Class II structures in semi-permanent base infrastructures. Finally, the mobility platform can be teleoperated independently as construction equipment for digging, earth moving, tunneling, and drilling for in-situ mining and habitat construction. A whole suite of compact modular tools can be developed that dock with the platform to construct ISRU drived pressurized and non-pressurized Class III structures.

The development of Mobitat modular mobile habitat technology provides a critical capability necessary for the phased establishment of deep space exploration infrastructure, in providing for sustainable human presence on planetary surface missions. In particular, this capability addresses several H&RT strategic technical challenges, which are deemed essential for sustained space exploration:

- Multiple, redundant, low-cost Mobitat habitat modules can be used to establish planetary surface bases and infrastructure, which can later be expanded, reconfigured, relocated, or reduced in capacity according to future needs. Failed modules with fully independent ECLSS systems can be removed or upgraded easily without endangering the remaining base infrastructures, thereby providing *margins of safety and redundancy* in operations.
- The self-mobility aspect of the Mobitat allows *pre-positioning* and autonomous relocation, thereby achieving a high degree of *reusability* and *reconfigurability*. Each Mobitat can be separated from the main base to become an independent rover, eliminating the need to develop a separate rover technology.
- Interface standards for mobility platform docking allow for a *modular* approach to mounting habitat modules, scientific instruments, exploration tools, and construction implements that may have mobility requirements on future missions. *Modularity* is also achieved by Mobitat to Mobitat connections that allow indefinite expansion of base habitat infrastructure, where any individual module can be replaced by any other.
- Redundant modules and the ability to create double egress circulation loops allow for *"as safe as reasonably achievable" (ASARA) deep-space human presence* for lunar or Mars surface operations.
- Mobitats with fully *autonomous* mobility platforms will help build up *robotic networks* and infrastructure. Using distributed robotics, the mobility platforms can coordinate among themselves for a variety of remote, autonomous tasks, including habitat placement, explorative drilling, digging, towing, and transportation.
- The detachable habitats can be placed in a base configuration, while the mobility platforms are put to work elsewhere, including digging and accumulating local regolith for additional shielding or building materials for *in-situ resource utilization*.

In order for sustained space exploration to be successful, a gradual phased, mobile-modular approach to surface infrastructure development is required. We believe the mobile-modular surface habitat approach should be given a similar priority status as the Crew Exploration Vehicle (CEV) development, as a critical component addressing surface missions, in the suite of vehicles developed for deep space human and robotic exploration. We believe that the development of the Mobitat system must begin immediately in order to achieve the objectives of the H&RT program in a timely manner. Specifically, Mobitat technology has the potential to provide technological solutions satisfying all three of the primary technical challenges to sustainability:

- *Affordability* – A modular mobile approach to the build up of surface base infrastructures allows an affordable phased approach to human and robotic presence.
- *Reliability and Safety* – Redundant modules and configurations that form double egress circulation loops provide for safety and reliability of the crew and critical mission systems.
- *Effectiveness* – The simple habitat module / mobility platform combination creates a powerfully effective hardware for reusability on different phases of the same mission, or across several missions.

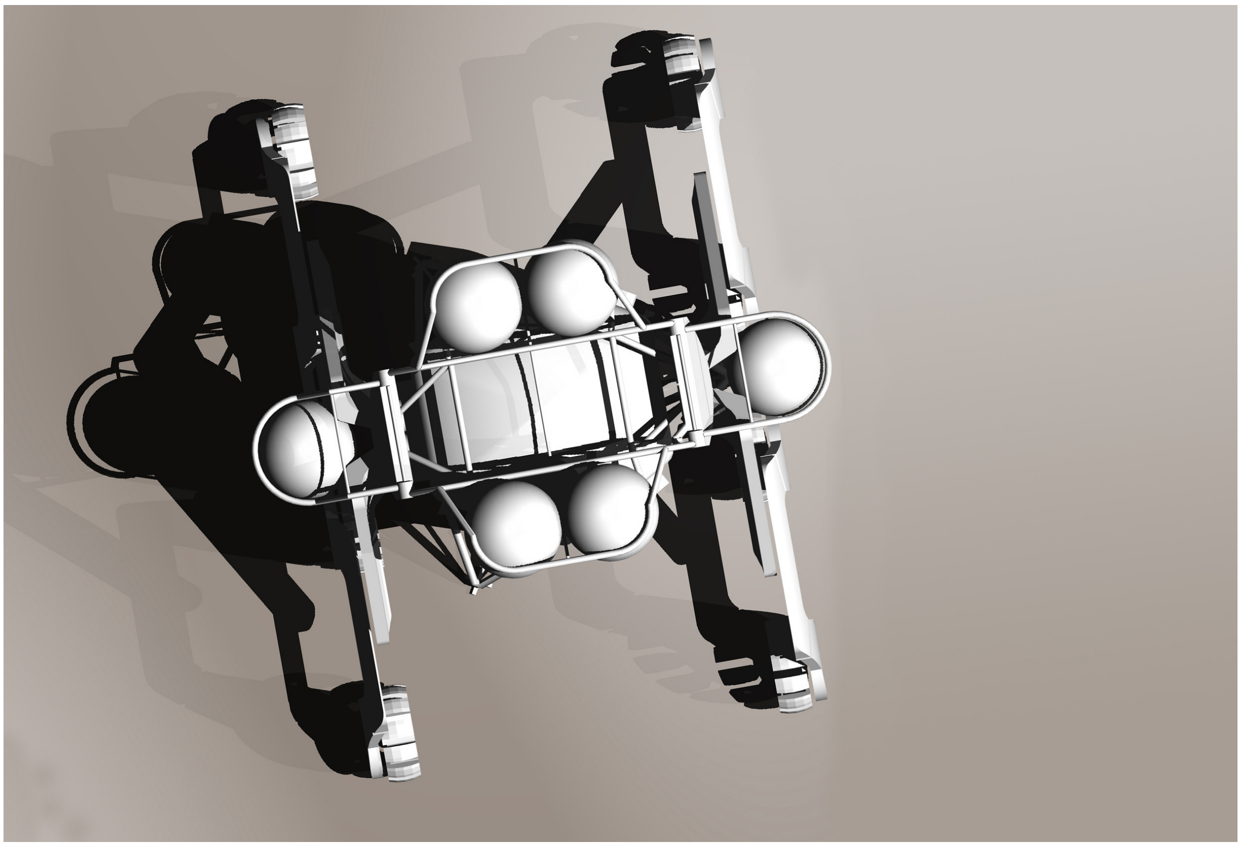

Figure 2: Mobitat pre-study top view

II. Mobitat Technology and Pre-study

In January 2004, NASA established a long-term program to extend human presence across the solar system, a primary goal of which will be to establish a human presence on the moon no later than 2020, as a precursor to human exploration of Mars. A central concept of this new vision is that future space exploration activities must include a reusable, modular, reconfigurable planetary surface habitat construction system in order to achieve a long-term and well-orchestrated campaign of space exploration (H&RT Formulation Plan). In addition, sustained exploration will likely require a mobile solution, in order to quickly facilitate human habitation in the vicinity of geographical areas of interest. Thus, in order to meet these technological challenges, a mobile modular habitat like the Mobitat (Figure 1) will be a necessity for future space exploration endeavors.

The success of the Exploration mission depends on the development of advanced mobile habitat technology that: (1) can be inserted autonomously and build up base infrastructures; (2) can provide for local and long-distance rover mobility; (3) is reliable, survivable, modular, and reusable; (4) is low-cost; and (5) enhances safety. The Mobitat technology (roughly based on the Mankins "Habot" concept) will include a highly maneuverable multi-use robotic mobility platform with detachable modular construction and robotic elements, including habitat pressure vessels.

The effectiveness of this technology will have a major impact on planetary surface infrastructure in exploration missions.

Previous design studies on the Mobitat have been completed that puts the system currently at a TRL2 technology readiness level. Herein we describe the Mobitat pre-studies as a concept that can be used as a modular surface exploration vehicle and habitat. Since the pressure vessel and mobile platform can be separated, the combined vehicle can be used as a rover, or separated as a fixed modular base with an un-crewed, remotely controlled heavy duty work platform. Note that all pre-study illustrations are drawn to show how mechanical systems will function – the mechanical systems on the actual Mobitat will be covered with protective closures and seals made of fabrics or other flexible materials to protect all the working parts against dust intrusion.

The Mobitat system falls within the Class I category of pre-integrated hard-shell habitat ready for immediate use on delivery, since the deployable systems activate before arrival. The Mobitat concept will bridge between each class of surface construction, and create a phased approach to human habitation. The Mobitat can function as a rover and relocatable Class I habitat for early exploration. Modules can dock together to make larger bases of assembled Class II structures in semi-permanent base infrastructures. Finally, the mobility platform can be teleoperated independently as construction equipment for digging, earth moving, tunneling, and drilling for in-situ mining and habitat construction. A whole suite of compact modular tools can be developed that dock with the platform to construct ISRU drived pressurized and non-pressurized Class III structures.

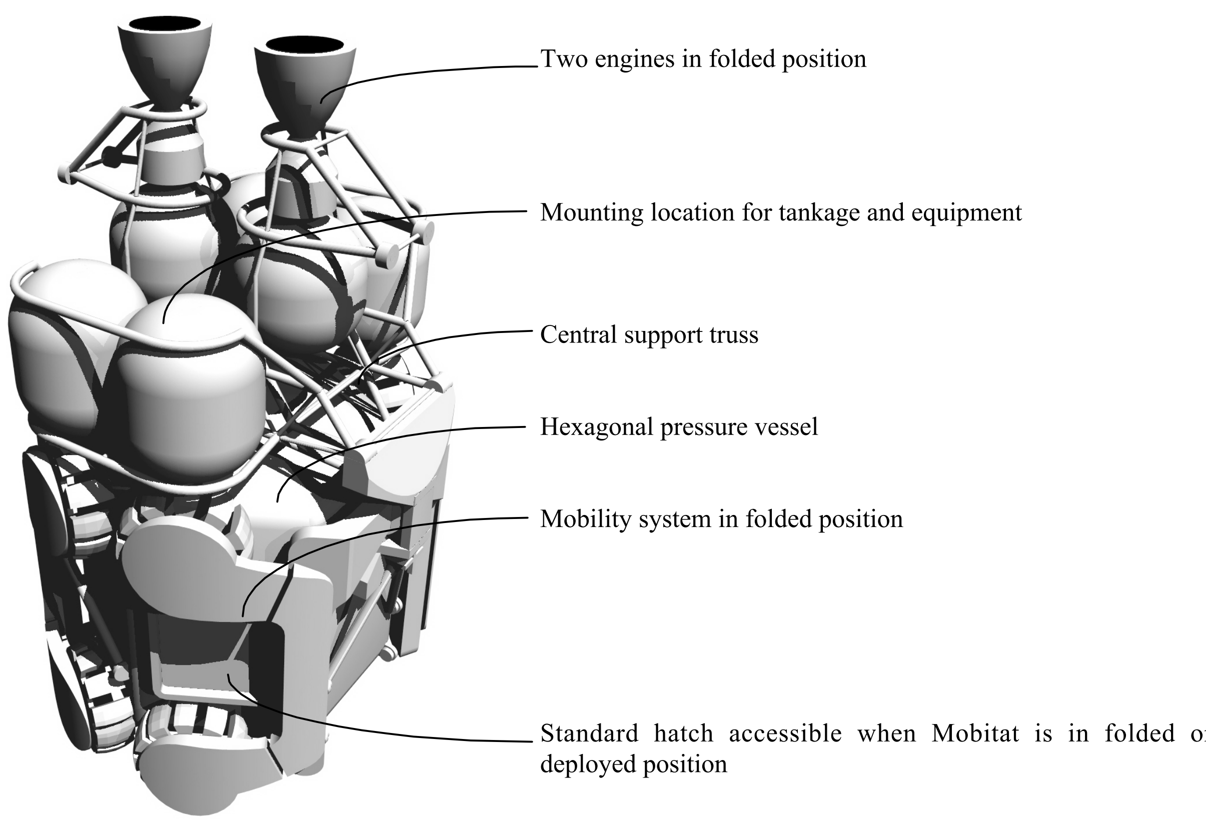

Figure 3: Rendered view of pre-study Mobitat in folded position

The Mobitat system can negotiate over bolders up to 1 meter high and navigate steep slopes both transversely and directly. In travel the pressure vessel hangs from the mobile platform, allowing the habitat to keep a level stance, even through rough terrain. This feature allows the Mobitat to function as a rover able to reach speeds upwards of 20mph across uneven surfaces. In addition, the pressure vessel can be detached from the mobile platform to establish a fixed outpost, where the mobile platform can be manipulated remotely through tele-operation to perform a variety of construction, excavation, and other tasks needing craneage, or other heavy work implements. The Mobitat system is modular, based on Kit-of-parts Theory (Howe, 2002).

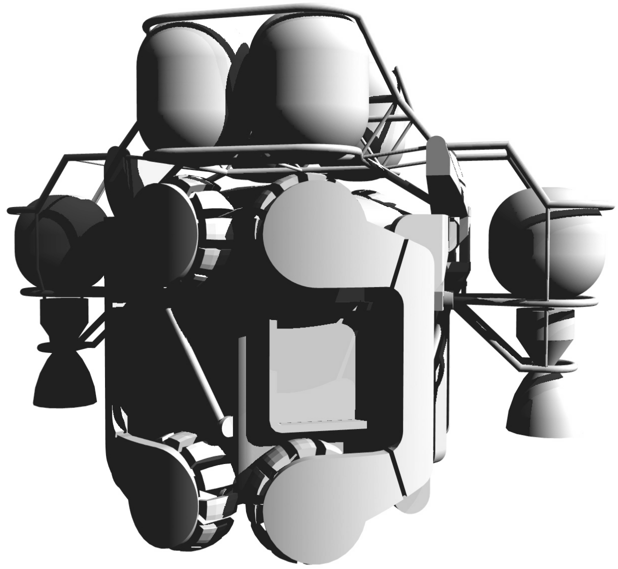

Figure 4: Pre-study Mobitat in lander configuration

The original design folds into a package 7.2 meters long by 4.2 meters in diameter. This size will fit into a variety of launch vehicles including the Shuttle payload bay (Figure 3). Preliminary versions of the Mobitat have two major deployable systems. In the current version, the engines in their deployed position are mounted on either side of the main body (Figure 4).The thrust force is directed to either end of the central supporting truss, affecting lift for the vehicle. Later concepts of the Mobitat drop the engines upon landing (however, eccentric placement of engines is not standard, so future Mobitat concepts will need to consider axially loaded descent motors).

The landing sequence begins with (1) delivery of folded package to lunar orbit, whereupon (2) the engines deploy to either side of main body. During the descent the mobility system deploys leaving (4) the wheel carriage assemblies clear of the thrust exhaust. (5) The wheel carriage assemblies lower themselves just before landing to (6) affect a smooth touchdown on a variety of even or uneven surfaces (Figure 6).

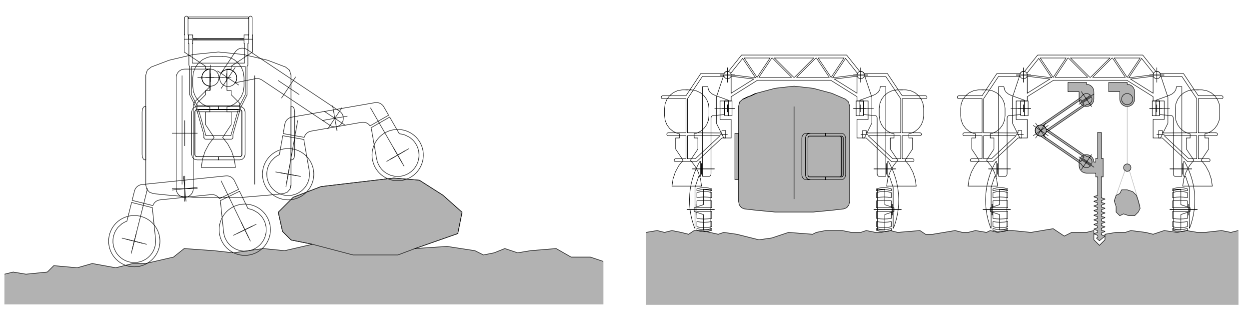

Figure 5: Pre-study Mobitat can "step over" some obstacles by shifting center of gravity (left), alternative uses for mobility platform (right)

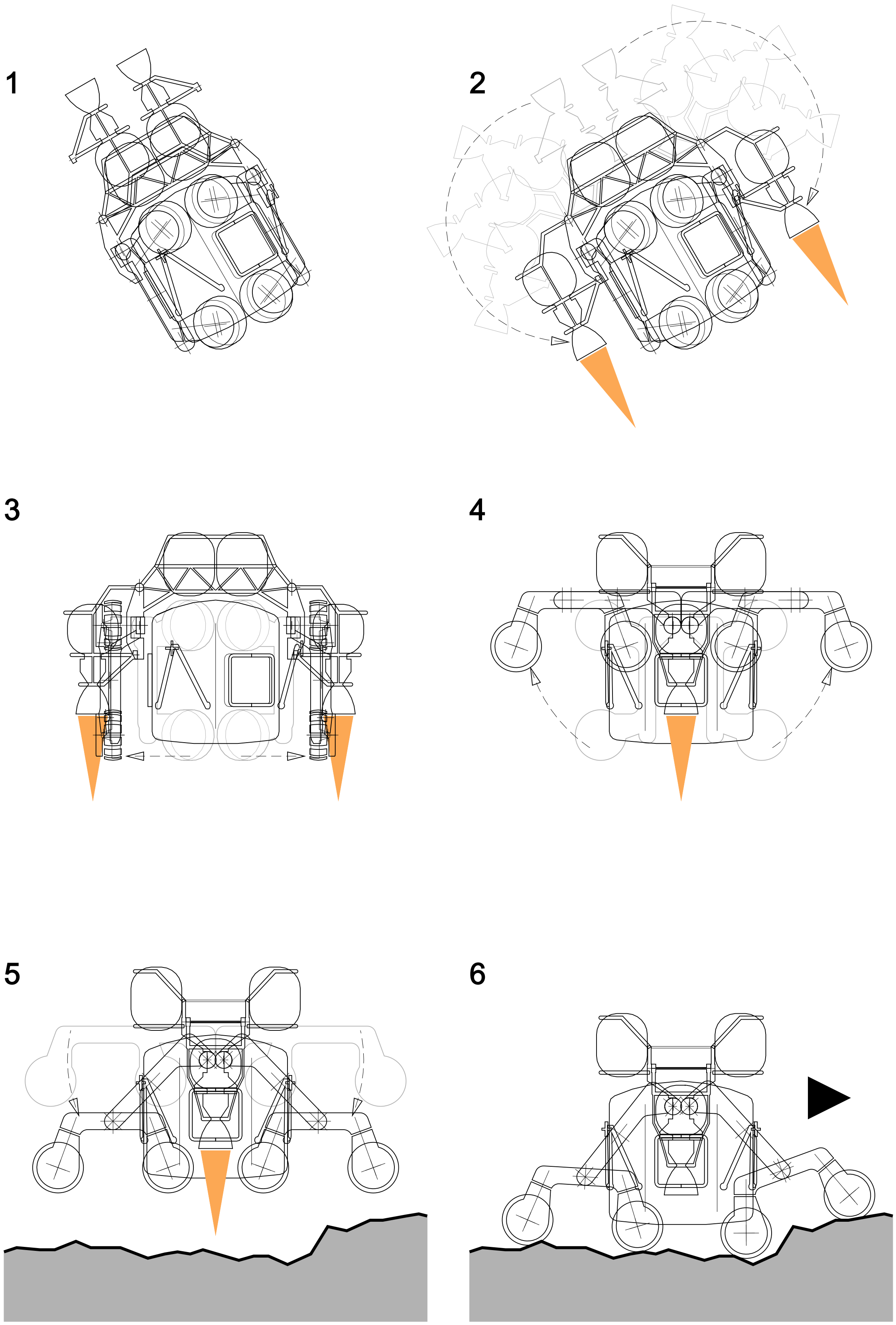

Figure 6: Pre-study landing sequence: mobility system deployment, touch down, and landing complete

The Mobitat mobility system is designed to handle severe obstacles and slopes while keeping the pressure vessel module level. In most cases, the traction of the wheels on the surface will fail well before the maximum climbing angle is reached. Also, a capacity for shifting the center of gravity is possible to allow “stepping over” large obstacles while maintaining a level stance for the pressure vessel module (Figure 5, left).

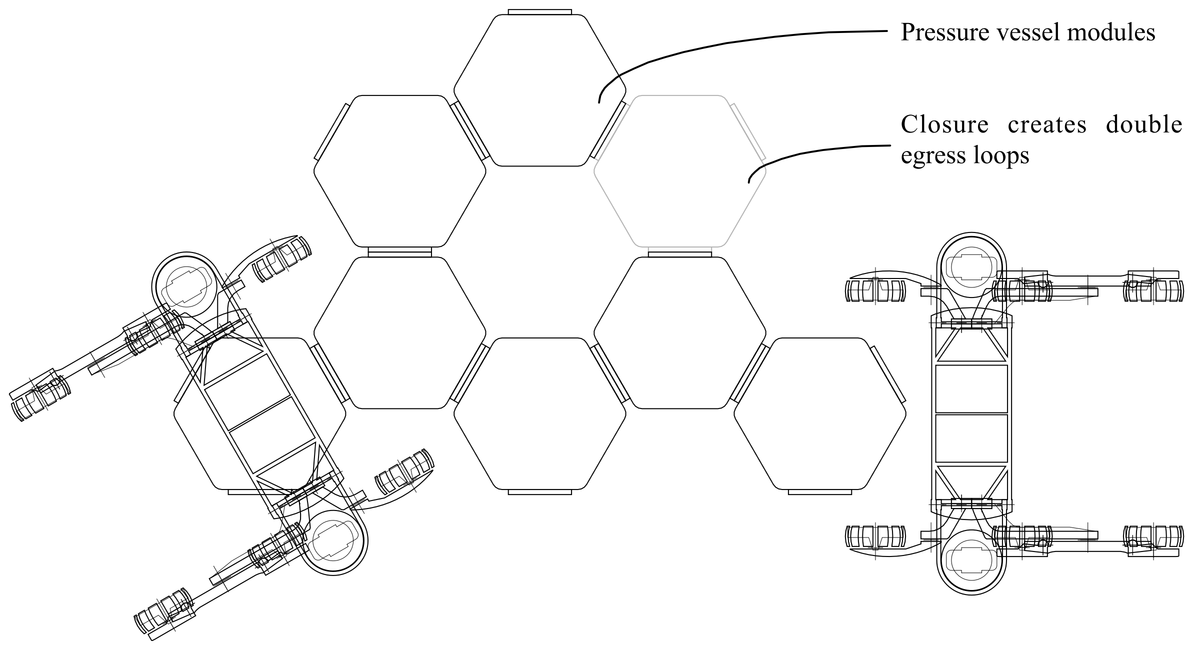

Figure 7: Pre-study module assembly into larger outposts or bases

The pressure vessel module is a hexagonal shape. In order to fold in the wheel assembly carriages of the mobility system, the 4.2 meter allowed maximum envelope dictates that the habitable module be 3.0 meters wide. The module is 3.4 meters high. Pressure vessel modules can be assembled into larger complexes to form outposts or bases (Figure 7).

The mobility platform can be detached from the module once it has been placed. However, modules cannot maintain attachment to the platforms if they are assembled into groups. Also, preliminary versions of the system do not allow complete closure of circulation and egress loops, which will be addressed in future design studies. In a modular base, entire modules can be dedicated to egress and EVA functions, such as airlock or rover interface. Since no site is level, large assemblies of modules would need to have small local adjustment capacity at each hatch.

The mobile platform can be used for a variety of tasks in addition to carrying pressure vessel modules (Figure 5, right). These tasks can include crane, drilling platform, mobility for excavation and construction implements, etc. On transverse slopes, the Mobitat has the ability to manipulate wheel carriage assemblies independently in order to maintain a level stance for the pressure vessel module. The mobile platform has an inside turning radius of 6.0 meters, and outside turning radius of 11.0 meters. In its extended position, the central support truss has 5.0 meters of clearance above a level surface. The minimum clearance is 1.9 meters.

The pre-study design has been analyzed computationally, mainly concentrating on the kinematic functionality. The kinematics and robotic systems are workable, but several questions remain, such as the robustness and size of a deployable engine, including flexible fuel connections, etc. As a lander the dual engine approach provides eccentric thrust and therefore does not follow engine placement geometry conventions. As a hopper such an issue would not be as critical, or dropping the motors after landing would increase the flexibility of the mobile platform.

III. Technology Development / Maturation

The current version of the Mobitat concept is at TRL2, having gone through computational analysis for kinematic functionality and modularity. This proposal seeks to achieve a TRL4 rating. The technical challenges we expect to encounter are (1) system integration challenges (docking, interfaces, etc); (2) mobility system concept development; (3) modular habitat pressure vessel concept development, and (4) payload delivery / mission operations challenges. It is expected that after TRL4 level has been achieved in this study, additional team members including major space hardware contractors (Boeing, Lockheed Martin, etc) will become involved for TRL5 and above development.

A. System Integration:
A modular, extensible, scaleable, and reconfigurable (MESR) design and integration philosophy will be used for the design and integration of all elements into the Mobitat. The MESR design philosophy is consistent with the goals set by the Office of Exploration Systems, and is further defined as follows:

- Modular – Systems and subsystems are designed such that discrete unit processes can be replaced with upgraded/enhanced technology as it becomes available.
- Extensible – Initial components and subsystems delivered with a vehicle are not discarded or replaced as additional unit processes are added during subsequent stages of development.
- Scaleable – Components and subsystems can be coupled/decoupled as required to accommodate mission-specific loads.
- Reconfigurable – Components and subsystems can be moved between locations and/or subsystems to perform a similar or identical function.

The MESR approach is combined with Kit-of-parts Theory for a quantified approach to geometry and configuration, optimizing relationships between joint-based (linear geometry), panel-based (planar geometry), module-based (volumetric geometry), and deployable (time geometry) structures (Howe, 2002).

In addition, the development ensures that certain key design drivers are prioritized and embodied in the final system designs. Those drivers are:

- Minimal mass, volume, power and crew time, i.e. minimal equivalent system mass (ESM) – These are the standard drivers that are common to all space flight system and hardware development programs, and they are key drivers particularly for extended duration crewed missions where crew metabolic needs result in large expendable penalties if regenerative technologies are not utilized. However, a narrow focus on minimizing ESM will not lead to sustainable and affordable design solutions. Rather, the characteristics described below must be considered and addressed in parallel with minimization of mass, power, volume, and crew time.
- Reliability – Reliability is related to mission success; it is directly proportional to safety and generally inversely proportional to equivalent system mass (ESM). Safety is maximized when the reliability of key systems can be quantifiably measured and used to predict lifetime, consumable use rate, maintenance frequency, etc. Alternatively, poor or uncharacterized reliability drives up mission mass as increased spares have to be manifested to ensure mission success.
- Maintainability – The very nature of Mobitat implies that hardware will not be returned to earth for periodic maintenance and repair as has been the case for both the Space Shuttle and the International Space Station (ISS). Consequently, systems and components need to be designed so that highly skilled, but minimally trained crewmembers (or potentially robots) can easily perform maintenance, repair, and/or replacement tasks.

B. Mobility Platform Concept:
Various alternatives for robotic mobility are being considered, including expanding on the original Mobitat concept for further refinement. A major effort will be to develop the habitat concept to be compatible with JPL's Code-T robot known as All Terrain Hex Legged Extra Terrestrial Explorer ATHLETE, mindful of the eventual mission requirements (Figure 8). We will continue to refine the Mobitat mobility system concept and develop quick-connect / quick-release docking strategies for structure, power, and control interfaces, and develop strategies for connection and self-leveling between multiple Mobitat units. JPL will allow for occasional use of the ATHLETE prototype mobility system (to be created in FY05) for the purposes of demonstrating a scale, integrated Mobitat system. To accomplish this, we will develop strategies and hardware to produce concept analogs for mating the scale habitat to the ATHLETE mobility platform and conduct performance testing of the integrated system in relevant terrain.

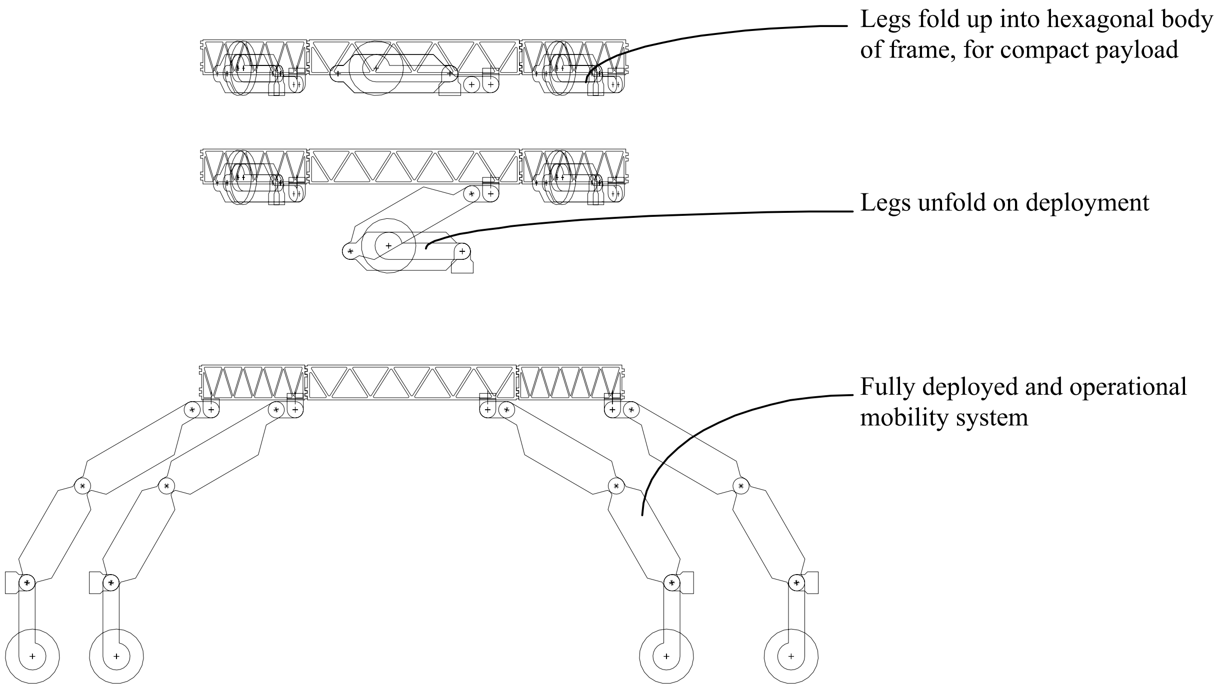

Figure 8: ATHLETE-Mobitat mobility platform pre-study schematic

C. Modular Pressure Vessel Concept:

By its very nature, a mobile habitat requires the incorporation of a human-centric approach for the development of systems directly related to crew comfort, productivity, and survivability. The three primary systems directly related to these factors are the Environmental Control and Life Support System (ECLSS), Thermal Control System (TCS), and Extra Vehicular Activity (EVA). A modular, extensible, scaleable, and reconfigurable (MESR) design and integration philosophy has been incorporated for the design and integration of ECLSS, TCS, and EVA elements into Mobitat.

Other important design philosophies that will be incorporated into this effort include dissimilar redundancy (utilization of alternative technologies to perform a similar function) and maximum utilization of existing flight hardware when feasible. Balance of plant components (pumps, valves, controllers, heat exchangers, etc.) should be secured directly from existing ISS designs/configurations whenever possible, or derived from other aerospace commercial off the shelf (COTS) hardware when practical. It is recognized that some inefficiency will be introduced into the process because these components will not be optimized for each application. However, the potential development cost savings from this approach could significantly contribute to the OExS top-level requirement of affordability. Also, overall risk can be reduced since the performance of operational flight hardware can be quantified and accurate component reliability can be factored into the ECLSS design. Dissimilar redundancy (utilization of alternative technologies to perform a similar function) should be assessed as a potential method to achieve high ECLSS reliability, and therefore reduced risk.

The Mobitat is fully compatible with, and will benefit from, EVA design initiatives focused on the same goals of modularity, extensibility and reconfigurability as well as EVA architectures intended to minimize design impacts on host vehicles through the use of system features like the suitport entry/exit approach. The focus of EVA study activity under this project will not be the design of EVA Portable Life Support Systems or Pressure Suits, but the identification of design features and attributes that will contribute to an effective integrated system so these may be reflected in both the Mobitat design and in evolving EVA system designs under development in other parallel activities. This will benefit from HS intimate involvement in both the current NASA EMU and in the development of advanced EVA concepts and technologies.

Conceptual / preliminary system design considers:

- The impact, potential benefits and integration of modular PLSS designs that feature commonality between PLSS and habitat functions where appropriate to enable reductions in system mass and volume and increased redundancy.
- The significance of suitport concepts for flexible Mobitat support of EVA in both docked and mobile configurations, implied interactions between Mobitat and EVA suit internal pressures, and potential benefits of specific implementations that may reduce system mass and enhance design safety.
- Human factors for EVA suit ingress and egress in the context of the Mobitat design
- Implications of modular designs for EVA support interfaces and possible Mobitat design benefits
- Possibilities for common and consistent human/machine interfaces including multi-modal personal information support systems enabled by modularity in both the Mobitat and EVA system designs and their implications for integration with robotic assets, tools, etc.

D. Payload Delivery / Mission Operations:

Pre-studies have provided several options for payload delivery. A Direct Descent Mode (DDM) payload delivery scenario would use an Atlas 552 (an Atlas V with 5 solid strap-on boosters, and a 2 engine centaur upper stage) to put 20.5MT to LEO at about 28.3 degree inclination. Assuming the entire 20.5MT payload is Mobitat, TLI and descent propellant (assuming direct descent) only 3.28MT can be delivered to the lunar surface.

An Earth Orbit Rendezvous (EOR) scenario would deliver a centaur upper stage to LEO with one Atlas V, then launch the Mobitat with a second Atlas V and docking them on orbit. The stack would initiate TLI and the Mobitat would provide its own terminal descent capability. This would get 12.8MT to the lunar surface. If a habitat is to be integrated with the mobility system, we can consider a third Atlas V launch, assuming the habitat is less than 20.5MT. However, assembly at the ISS would require a high launch inclination resulting in a greater expenditure of propellant.

Other considerations include the use of the Delta IV that is advertised as being able to insert 25MT to LEO, or using Protons and Kourou with Ariane V for multiple launches in a short period of time from Baikonur.

Consideration has been made of the use of airbags for surface delivery, as an alternative or supplement to descent engines. In addition to payload delivery and launch scenarios, survival of the Mobitat over a lunar night creates challenges for power systems and multiple articulated joints due to lack of photovoltaic exposure and extremes in the thermal environment. Challenges will include creating lubrication strategies over day / night cycles and in harsh vacuum. Also, it will be very difficult for a mobile habitat to survive a lunar night without a nuclear power element (along with radiation protection). The Mobitat will need to overcome these potential power problems that previous lunar surface habitat studies (FLO, LESA, etc) did not need to address. A possible solution would be to limit operations to the lunar day with solar power augmentation at 1.4Kw/m2 solar panel area, and use an RTG stack providing a thermal / fluid conduit, and put the system in a lunar night nuclear hibernation cycle to reduce power requirements.

Finally, the relationship of the Mobitat with Crew Return Vehicle (CRV) will be a critical mission operations challenge. Options for establishing a common modular propulsion system that can be used by both the Mobitat and CRV will be studied.

IV. Technology Metrics:

Continued development of Mobitat will require advancement in (1) system integration interface standards and quick-connect / quick-release hardware docking technologies; (2) robotic modular mobility platform technologies; and (3) modular habitat technologies for docking, human factors, EVA, ECLSS subsystems in order to meet these goals. We will address these challenges by following a modular, extensible, scaleable, and reconfigurable (MESR) design and integration philosophy We will use the following metrics to track and define our development/maturation progress:

Performance characteristics of the Mobitat can be evaluated based on robustness of deployable systems and hardware performance. It is proposed that the Mobitat technology maturity can be measured by the following qualitative capability characteristics:

- Performance of deployable systems: Various systems must deploy properly upon initial insertion, and subsequent delivery to the surface. The deployment process must be robust since its success is mission critical.
- Performance of mobility system: The mobility system has multiple mechanical elements that can possibly malfunction. The various joints and connections must be protected from dust and thermal expansion.
- Stability: On a variety of terrains it will be clear where the highly maneuverable mobility system may have weaknesses in stability for resistance to overturning, etc.
- Adequacy of landing systems: Since the landing / descent engine is mission critical, the performance of Mobitat can be evaluated on the performance of the system.
- Adequacy of power subsystems: The ability to maintain power through both lunar day and night cycles will be critical, either through operations scenarios (nightly power-down, etc), or through supplemental power supplies.
- Performance of modular pressure vessel system: Pressure vessel thermal and radiation protection, access hatch design, leveling capability for uneven connections between modules, etc are mission critical elements that must perform well.
- Hardware performance: Statistical analysis of sensors, drivers, actuators, etc will be critical.
- Software / control performance: Coordinated autonomous actions between robotic agents must function consistently and reliably, regardless of prior unknowns in the terrain and site.

V. Future Impact and Benefits

NASA space architects have given a recommended roadmap for technology and development of planetary habitats (Cohen & Kennedy, 1997). The roadmap divides planetary surface construction into three classes, coinciding with a phased schedule for habitation:

- Class I: Pre-integrated hard shell modules ready to use immediately upon delivery.
- Class II: Prefabricated kit-of-parts that is surface assembled after delivery.
- Class III: In-Situ Resource Utilization (ISRU) derived structure with integrated Earth components.

Class I structures are prepared and tested on Earth, and are designed to be fully self-contained habitats that can be delivered to the surface of other planets. In an initial mission to put human explorers on Mars, a Class I habitat would provide the bare minimum habitable facilities when continued support from Earth is not possible.

The Class II structures call for a pre-manufactured kit-of-parts system that has flexible capacity for demountability and reuse. Class II structures can be used to expand the facilities established by the initial Class I habitat, and can allow for the assembly of additional structures either before the crew arrives, or after their occupancy of the pre-integrated habitat.

The purpose of Class III structures is to allow for the construction of additional facilities that would support a larger population, and to develop the capacity for the local production of building materials and structures without the need for resupply from Earth.

To facilitate the development of technology required to implement the three phases, Cohen and Kennedy stress the need to explore robust robotic system concepts that can be used to assist in the construction process, or perform the tasks autonomously. Among other things, the roadmap stresses the need for adapting structural components for robotic assembly, and determining appropriate levels of modularity, assembly, and component packaging. The roadmap also sets the development of experimental construction systems in parallel with components as an important milestone. The Mobitat system falls within the Class I category of pre-integrated hard-shell habitat ready for immediate use on delivery, since the deployable systems activate before arrival.

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