From Simulations Towards a Functional Base: the Moon and Mars Base Analog (MaMBA)

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Human space flight is currently gaining new momentum for leaving low Earth orbit. The Gateway, new launch technologies – space agencies and industry alike are working on reaching goals as distant as the Moon and even Mars. Meanwhile, scientists and volunteers are simulating life on these celestial bodies.

Over the last decades, more than a dozen habitats have been built and inhabited worldwide. The main purpose of these habitats are often human factor studies or the testing of single technological components, particularly life support systems. Nevertheless, no existing habitat is suitable for use on an actual mission to the real Moon or to real Mars. The habitat planned within project MaMBA is intended to provide a first prototype that could function on both planetary bodies. The habitat is developed at the Center of Applied Space Technology and Microgravity (ZARM) in Bremen, Germany, and comprises up to six connected, but independent modules. In its final state, the habitat is intended to serve as a test facility for technologies such as life support systems, power systems, and robotic set-up and maintenance. In addition, the facility will be used for investigating technologies and protocols for dust mitigation and planetary protection.

The first step is to develop the scientific module, which will contain a laboratory to be used by geologists, (astro-)biologists and scientists of adjacent disciplines. A mock-up of the laboratory module is currently under construction at the ZARM in Bremen. The selection of scientific instrumentation is based on synergetic considerations and open research questions relating to Moon and Mars. Two short simulations will be conducted (~3 days each). Scientists using the laboratory will be monitored during and interviewed after experimentation, in order to improve the interior design.

Following this preliminary design, the module will be upgraded in the future to a technologically functional habitat module step by step.

Acronyms

BFR = Big Falcon Rocket
ATHLETE = All-Terrain Hex-Limbed Extra-Terrestrial Explorer
HESTIA = Human Exploration Spacecraft Test-bed for Integration & Advancement
HI-SEAS = Hawaii Space Exploration Analog and Simulation
NEK = Nazemnyy eksperimental'ney kompleks (Ground-based Experiment Complex)
SIRIUS = Scientific International Research in Unique Terrestrial Station
SLS = Space Launch System
ZARM = Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation (Center of Applied Space Technology and Microgravity)

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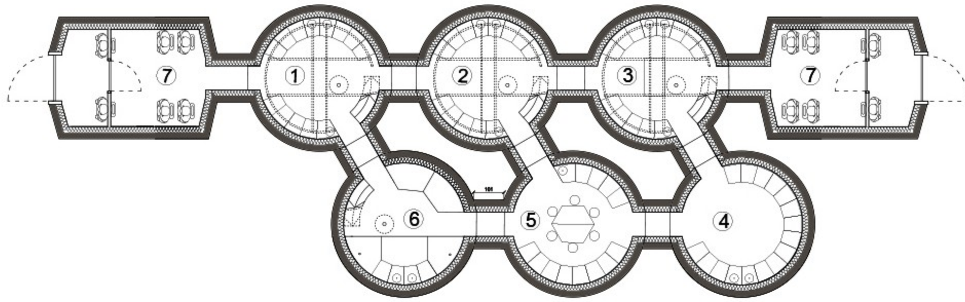

Figure 1. Base layout: MaMBA consists of 6 connected but separable modules, each dedicated to one or two specific functions: (1) workshop, (2) laboratory module, (3) greenhouse/ gym, (4) leisure module, (5) kitchen module, (6) sleeping module, (7) airlocks. Note that the upper three modules are dedicated to work, whereas the lower row of modules is reserved for habitation and leisure.

I. Introduction

EXACTLY 50 years after the first landing of humans on the Moon, the international community is readying itself to venture beyond low earth orbit again. Space agencies and private actors alike are pushing for a more permanent presence of humans on the Moon, and some are already aiming even further, to Mars.

At least three spacefaring nations are actively developing heavy launch vehicles for this endeavor (the American SLS and BFR, the Russian Yenisei, and the Chinese Long March). At the same time, plans are more vague when it comes to technologies to support human life once they have reached the surface of either Moon are Mars. Although there exist more than a dozen simulated extraterrestrial habitats worldwide (such as HI-SEAS[1], HESTIA[2], or Lunar Palace 1[3], NEK[4]), none of these would be suitable for actual use on either planetary body. Rather, their main purpose is to conduct terrestrial simulations to study certain aspects of a long-duration mission to Moon or Mars, usually related to human factors. Such simulations are undoubtedly necessary for preparing a real mission, however, they are inherently insufficient in providing a reasonable testbed for habitat technologies.

The most common flaws of simulation habitats are: single or central module design, non-pressure resistant geometry, open resource loops (esp. air and water), no adequate radiation shield (and no concept how such a shield could reasonably be added), poorly functional laboratories. In some cases the design is such that it becomes unusable for crew members suffering from temporary or permanent disabilities, either following an accident or due to deteriorating physical health.

Project MaMBA, which is short for Moon and Mars Base Analog, is aiming to address these issues and develop a functional concept of a lunar and Martian base. For example, one of the most notable differences of MAMBA to the HI-SEAS and HESTIA habitats is the assembly of the station from several base modules, similar to how the International Space Station (ISS) is assembled from a number of modules (see sections 2 and 3 for details). Perhaps more importantly for the scientific community, MaMBA has been including scientists of various disciplines in the design of the laboratory from the early start, in order to find an as efficient design as possible (more details on the MaMBA laboratory can be found in section VII).

The base concept of MaMBA shall be suitable for both celestial bodies, with a slight preference for the Moon. We believe that the Moon is a recommendable testing and training ground for Mars, at least in terms of habitat technologies. If a habitat can function on the Moon, it can surely withstand the somewhat more favorable conditions on Mars (higher atmospheric pressure, less cosmic radiation, regolith that is more similar to Earth particles in composition and erosion, similar day and night cycle, etc.). For this reason we believe it would be advisable to erect

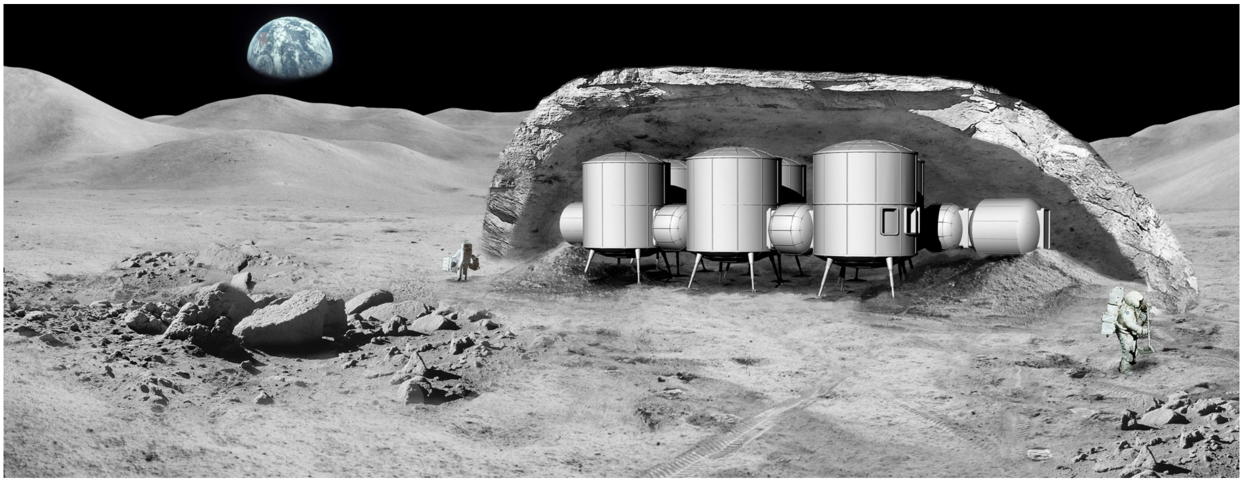

Figure 2. Artistic depiction of the habitat on the lunar surface, protected from radiation by an artificial cave.

a habitat on the Moon first, that is in relative vicinity to the Earth, and later erect an improved version of the same habitat on the more distant planet Mars.

II. Goals and Timeline

The long-term goal of project MaMBA is to build a functional prototype of a habitat that is suitable for both the Moon and Mars, with only slight changes to the design concept. To this end, major components shall be constructed, such as the pressure vessel, coupling between modules, and doors or hatches. For subsystems such as life support, energy, communication or waste management systems, we aim to incorporate existing technologies rather than develop our own. In turn, the prototype of MaMBA may serve as a test facility for these and other mission critical technologies. Over time, we will run various simulations with and without human inhabitants of increasing duration, beginning with short test runs of several hours each.

In the short-term (to be completed within the next year), we are setting up a wooden mock-up of a habitat module in order to test the architectural design of said module. The purpose of the mock-up is to confirm the usability of the design with the help of human inhabitants before tackling the engineering challenges. Overall, our focus is on technology development rather than a quick setup of a habitat primarily for simulation purposes, nevertheless we believe it is necessary to ensure the well-being of the inhabitants, so we will run simulations from early on in the design process to constantly evaluate crew comfort.

The whole habitat is planned to consist of 6 base modules plus two airlocks (see Figure 1), with the center piece being the laboratory module. We are currently building a mock-up version of this laboratory module, which is planned to be completed in summer 2019. In the coming years, we plan to (1) upgrade the design of the module to that of a functional pressure vessel accommodating a life support system and basic waste management, and (2) develop an airlock that incorporates technologies and strategies for dust mitigation and planetary protection (see section IX).

In the long-term, we plan to replicate the base module to form a full base, integrating the base modules, the air locks, and connector modules.

Note that the name “MaMBA” refers to both the base and the project directed at building the initial mock-up: While this may be confusing at times, we are hoping to be able to avoid renaming the base with every change in funding set up.

III. Base Layout

The full MaMBA facility is designed for a crew of 6, and will consist of 6 modules plus 2 airlocks. One possible configuration of the modules is shown in Figure 1. In this configuration, one half of the base is dedicated to habitation and leisure activities (sleeping, eating, relaxing), while the other half is dedicated to working (laboratory, greenhouse and gym, workshop; airlocks). Generally, the work modules will have two stories each for efficient use

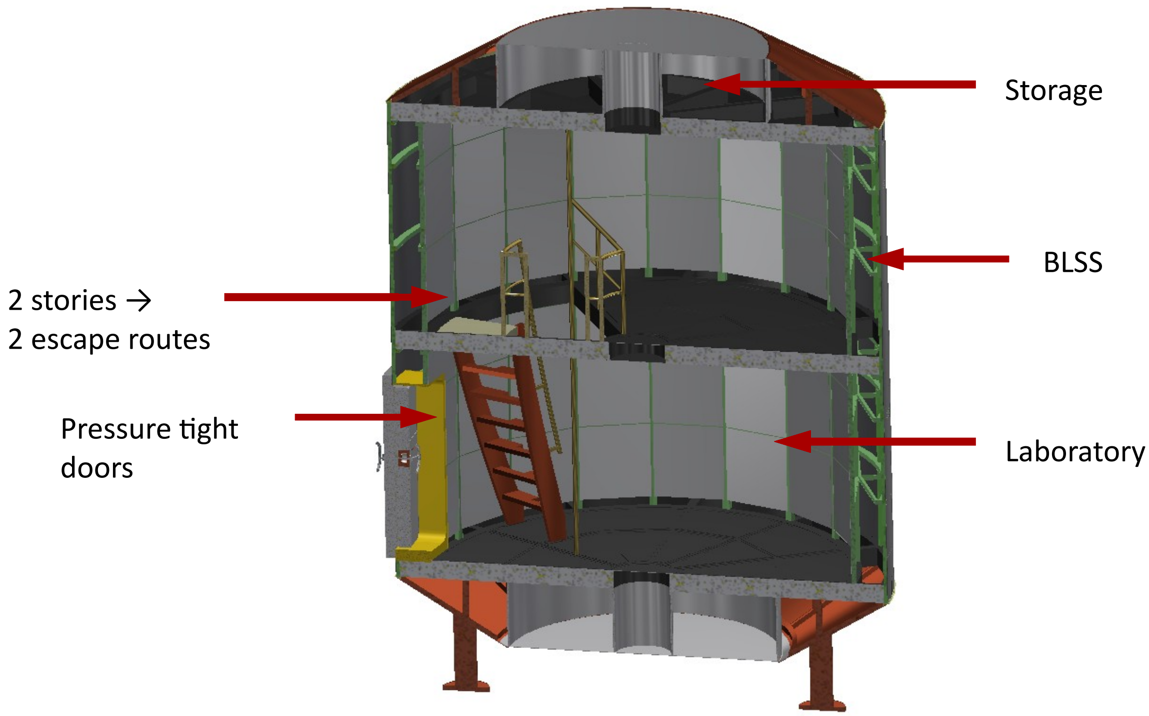

Figure 3. Concept for the shell of the base module. The module consists of two stories, with two ways to transfer between. The bioregenerative life support system (BLSS) is integrated into the walls, where a large surface area is available. Doors are primarily for indoor use, however, in case of emergency, they can be shut and will withstand the pressure difference to the lunar vacuum environment (similar to the hatches on the ISS). The main (=first) floor contains the laboratory.

of volume, while the leisure modules will have a single story. The resulting high ceiling will help astronauts battling the feeling of confinement. Any module can be locked off from the rest of the base without compromising the functionality of the entire base (although the crew's comfort may be somewhat reduced).

Each module is an upright rigid cylinder, with an outer diameter of slightly more than 5m and a height of roughly 6m. The corridors between the cylindrical modules are formed by inflatable modules which are docked to the cylinders via pressure-tight doors. While the configuration shown in Figure 1 has 2-3 doors per module, the symmetry of the cylinders allows up to 6 doors, which means the base can be readily expanded to more modules.

We chose the cylinder diameter such that it is comparable to modules of past and existing space stations, since there is no launcher currently in use (although several are in development, as mentioned above) that would be capable of transporting such a large payload to the Moon, let alone to Mars. Nevertheless, we chose the outer diameter of the modules to be only slightly more than 5m, partly because this is a size that has been lifted in the past, most notably the modules of the International Space Station.

Furthermore, we decided for rigid shell modules, rather than inflatables as the base modules or modules created from in situ resources, for the following reasons: First, too little is known[5] about the material properties of in situ resources such as regolith to build a reliable habitat in an environment that cannot be replicated sufficiently well on Earth for testing purposes. Second, while inflatables are much easier and cheaper to transport, they are much more difficult to set up. Once inflated, all subsystems have to be transferred into the module from the outside, i.e. from the lunar dust environment. As long as there is no efficient strategy for removing dust adhering to objects on the Moon, the best strategy for dust mitigation is to not expose any critical components to the lunar dust environment in the first place. Third, rigid modules allow for pre-integration of all components while still on Earth. As the Lunar Base Handbook[6] so eloquently puts it, anything that can be integrated on Earth, should be integrated on Earth.

IV. Radiation Shielding Concept

The entire base is expected to be built underground for radiation shielding. There are three options for accomplishing this on either Moon or Mars: (1) erect the base inside a natural cave such as a lava tube, (2) bury the base in regolith, (3) build an artificial cave wall around the base, as depicted in Figure 2. There are more options for radiation shielding, such as integrating tanks of water into the habitat walls[7], however, such solutions require an enormous amount of extra materials to be shipped from Earth, while the underground solution suffices with in situ materials and some excavating and processing equipment. Besides, the extra rock wall around the base doubles as protection against micro meteorites and mitigates the extreme temperature fluctuations that otherwise would occur on the lunar surface.

For the purpose of MaMBA, any of the three above options is acceptable, although (3) is the preferred option: Natural caves that have been found on the Moon so far are lava tubes with access through skylights with dozens of meters of depth, which pose considerable logistical problems. Besides, such lava tubes have only been found in equatorial regions, whereas the favored location for a first lunar base is near the lunar South Pole. Erecting an artificial cave, on the other hand, requires considerable effort compared to simply piling up loose regolith, yet offers the added benefit of providing a garage for rovers not in use.

In any case, there are plenty of promising projects[8-10] aimed at creating such wall structures on the Moon robotically. Therefore, for the purpose of MaMBA we assume the construction of a radiation shield from regolith to be feasible, and leave the engineering details to others. Nevertheless, we do look into the necessary regolith wall thickness for our specific module setup. A student project is currently underway to determine possible geometries and thicknesses of the regolith wall, and material combinations for the habitat module wall.

V. Transportation and Setup

There is no doubt that the base must be set up robotically on the Moon. The habitat site must be different from the landing site of the modules, so all modules must be transported horizontally across the lunar surface after landing, positioned relative to each other, and coupled. While the coupling may be easier to accomplish with the help of human astronauts, it is prohibitive to send humans to the surface of a planetary body before the habitat is fully set up and tested to confirm functionality. While it might be possible for a crew to reside inside a lander during setup on the lunar surface at least for short amounts of time, this would impose incredible psychological strain on a crew on Mars, not to mention the risks due to space radiation or the possibility of the habitat set up becoming delayed or, worse, proving impossible.

Given the size of the modules, we have determined that a small swarm of rovers (similar to the Robotic Construction Crew in Stroupe et al.[11], perhaps with a design similar to the NASA's ATHLETE[12,13]) is best suited to lift and translate each module. This not only distributes the weight of the module over several rovers and therefore wheels, but also makes it possible to keep the size of each individual rover rather small. After the setup of the base is complete, the rovers can exchange their lifting tools for other tools and continue serving various puposes around the habitat.

Note that we will not develop the rover concept in detail (or the rovers), but rather we will incorporate the findings from this aspect into the refined module design (placement of feet; reinforcement of lower beams to enhance structural strength, etc.).

VI. Interior Design

In the case of the laboratory, which serves as the template for all modules of the base, the module consists of two stories as shown in Figure 3, plus extra space in the upper and lower conical ends. Transfer between the stories is possible via a flight of stairs and, especially for descent from the upper floor during emergencies, a pole similar to the poles used in firefighting stations. It is expected that such poles are safer and more convenient to use than on Earth, and might even end up being the preferred means of ascending and descending within the module. In any case, the opening between both stories is large enough to move large objects such as racks or a person on a stretcher up or down between the floors.

The racks are different from the standard payload racks used on board the ISS today, since the presence of a gravitational force requires work places to be shaped differently from those for use in microgravity. In fact, astronauts' movements on the surface of the Moon will be more similar to human movements on Earth than in microgravity, and therefore the rack design should reflect the similarities in ergonomy, as well. We use a rack

Figure 4. Mock-up version of the base module during construction. Approximate outer dimensions: height 6.5 m, diameter 5.2 m. The interior is split into 18 segments, such that the overall floor layout is almost circular, but the walls consist of plane, rather than curved panels. As shown with module 2 in Figure 1, the module has three doors (in the mock-up, one of the doors is blind), and the walls between the doors are lined with custom-made racks (see section VI). The longest continuous wall section houses 7 racks which carry biological and materials science equipment, and the second longest section houses 4 neighboring racks with the geological equipment. The shortest section is occupied by the stairs leading to the upper floor which serves no specific purpose during the test runs, but is intended for communication and a medical bay area later on. At the time of writing, the racks are being assembled – first photos of the equipped interior are expected to be available during the conference.

system of 3 different types, which are made up of the same building blocks: (1) a standing rack of 1m height with a workbench at the top, (2) a hanging rack similar to kitchen cupboards in terms of depth, and height above the work area, and (3) a tall rack extending all the way from the floor to the ceiling that contains an additional pull-out work desk. All rack types have a width of the standard 19-inch.

Perhaps the largest deviation from space station design, however, is the planned location of the life support system. Long-term missions will greatly benefit from biological life support systems, rather than physico-chemical ones.[14] One of the most volume-efficient life support systems is based on algae or bacteria which can provide oxygen and be used for production of food and fuel, among other things[15]. These organisms grow well in flat tanks that are lighted from one side, that is, they work best with a large surface area. Placing these tanks inside racks is an option, however, placing them inside the module walls not only frees more space for crew use on the interior, but also adds to the shielding against cosmic radiation. The drawback of placing a life support system in the shell wall is of course its accessibility for maintenance and repairs. Therefore, we design all racks and wall panels such that they can be removed easily and quickly.

Last, to enhance crew comfort, we chose lighting with an adjustable spectrum to follow the circadian rhythm of the inhabitants, and we plan to place sound insulating materials on selected rack surfaces in order to reduce the noise level inside the laboratory.[16]

VII. Laboratory Module

The laboratory is intended to provide a facility for conducting experiments in the lunar gravity environment, analysing a relatively large amount of samples, and for determining which samples should be selected for transport to Earth for more in-depth analysis. The laboratory module will thus be equipped with instrumentation for geological, materials sciences, astrochemical, astrobiological, and medical research.

The selection of appropriate instrumentation will be made based on the recommendations developed by representatives of each of these disciplines.[17] For the upcoming test runs in the mock-up version of the laboratory module we will adapt these recommendations based on actually planned experiment protocols and budgetary requirements.

Beside the work equipment for the scientist volunteers, the laboratory is equipped with sensors for monitoring air quality and temperature, detailed monitoring of power consumption, a light meter (ceiling lights can be adjusted in wavelength and intensity), and a network to monitor all of these and, in the future, control these functions.

VIII. Mock-Up and Test Runs

Mock-up construction is underway (at the time of writing, see Figure 4) and is projected to be finished in summer 2019. In its final state it will be equipped with electricity, air conditioning, lighting system, racks and the selection of scientific instrumentation mentioned above.

Following the completion of the mock-up, we expect to do 2 test runs of 3-4 days duration each, ideally 3-4 months apart. During these test runs, up to four scientist volunteers will conduct experiments simultaneously inside the laboratory module, particularly experiments related to geology, materials science, and astrobiology.

The scientists will be monitored during their work and interviewed regarding the usability of the laboratory. In particular, their workflow will be tracked using a depth camera in order to later analyze the ergonomics and efficiency of the module and rack designs. During their stay inside the mock-up, the scientists will have access to a simulated artificial intelligence[18] which will answer any questions they may have. As mentioned above, the primary use of this mock-up is evaluate the overall usability of the module; only after satisfactory evaluation will we proceed with the engineering aspects.

IX. Outlook and Potential Areas of Collaboration

MaMBA is still in its very early phase. Note that all of the aspects of the project presented here are ongoing work and intended to give an understanding of the direction of the project.

Following the completion of the mock-up construction and the two test runs, we plan to pursue two distinct lines of attack: (1) we plan to design and construct a functional prototype of the laboratory module and (2) we plan to create a mock-up of the airlocks.

The functional prototype shall include the pressure vessel and part of the life support system, starting with the oxygen production and possibly water reclamation. This is expected to take approximately 5 years. The airlock shall be focused on incorporating technical and procedural solutions for dust mitigation and planetary protection. Particularly the latter may be worthy to incorporate in a lunar base–to test its functionality in an operational environment before actually depending on it on Mars.

After these two, we plan to develop the interior design of the other modules.

This is obviously not an endeavor that can be carried out by a single institute, not even by a single country. We therefore expressly invite researchers who are interested in collaboration to contact the author of this paper, either for the design of parts of the habitat or the conducting of test runs/simulations of habitat components in an operational environment. Some fields that we are particularly interested in are:

- life support functions (our initial focus is on oxygen production and water reclamation, but will extend to include food production and waste management),
- communication/data transfer systems,
- energy production, storage, and distribution,
- vacuum systems,
- surface suits,
- planetary protection and dust mitigation,
- robotics (habitat setup, maintenance, crew support) and human-computer interaction, and
- interior design.

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