

# Lessons from the first simulations at the Moon and Mars Base Analog (MaMBA)

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The Moon and Mars Base Analog (MaMBA) is a habitat design currently developed at the ZARM in Bremen, Germany. It combines engineering requirements to support human life in a planetary surface station and architectural needs to create a livable, rather than (only) survivable home for astronauts.

In 2019, a mock-up of the first module of the MaMBA was constructed at the ZARM. The module is a two-story upright cylinder that houses the habitat's laboratory. The laboratory is equipped with instruments for geological, biological and material sciences analysis.

Subsequently, scientists volunteered to use the MaMBA laboratory for conducting experiments according to pre-defined protocols during two test runs (on the order of several days). The scientists were monitored with depth cameras to track their movements. In addition, the scientists had access to a conversational user interface which supported them in their work. At the end of the test runs, the scientists were interviewed and asked to provide feedback on the laboratory and recommendations for improvement.

In this paper, we will present preliminary results from the test runs. We will focus on lessons learned from the MaMBA mock-up in terms of architectural and interior design. One key result is that the size and layout of the laboratory as well as the selection of equipment was considered appropriate by all scientists. The crews relocated some equipment during the test runs; some of these adjustments have become permanent in the lab. Finally, the crew used the conversational user interface frequently and generally found it very helpful. The results we found can be applied to future extraterrestrial habitats and may generally help optimize work spaces for crews under extreme conditions.

## I. Introduction

In general, an extraterrestrial base must be *habitable*, that is, it must “support human health, safety and well-being to enable productive and reliable mission operation and success”<sup>1,2</sup>. Habitability can be divided into the following three pillars (adapted from Haeuplik-Meusburger et al.<sup>2</sup>): (1) life support, (2) behavioral health, and (3) safety.

A number of habitats have been built in the past few decades, and simulations that have been conducted in them have provided valuable insights into each of these three pillars. Notable habitats are Bios-2<sup>3</sup> and Lunar Palace<sup>4</sup> for life support, HERA<sup>5</sup> and HI-SEAS<sup>6</sup> for behavioral health. Safety, on the other hand has been considered for more operational bases, such as Antarctic overwintering bases, but has actually been an issue in some simulation bases<sup>7</sup>. In any case, most if not all contingency plans at simulation bases take advantage of being in a terrestrial environment; in the event of a catastrophic failure in a part of a habitat the crews are advised to leave (anything else would be unethical), rather than try to save their home (what would have to be done on Mars, for example).

To date, there is no habitat that could serve as a functional prototype for a lunar or Martian base (see the recent review of existing analog bases by Heinicke & Arnhof<sup>8</sup>). Standards have been developed<sup>9,10,11</sup>, and there are various concepts that have been drafted; however, the overwhelming majority of these have never been built or tested. At the same time, space agencies and private companies are aiming to erect a permanent settlement on the lunar surface within the next decade or so<sup>12</sup>. Given the complexity of a surface habitat and the many partly conflicting requirements (e.g., architects generally prefer spacious habitats, but engineers prefer to minimize mass and therefore

volume in most cases), it is high time for concepts that find the right balance between the three pillars and that can be built and tested before being erected on the Moon.

The Moon and Mars Base Analog (MaMBA)<sup>13</sup> is a project aimed at developing such a concept and therefore bridge the gap between terrestrial simulations and the engineering requirements of an actual extraterrestrial habitat. One major aspect of our design process is the construction and testing of various habitat parts and mock-ups of these. Currently, we focus on the laboratory as the first module, which we use for validating the architectural design and usability of the laboratory. Later on, we will use the mock-up for simulations with different focus, and the current simulations will help improve the module design to better suit the crew's needs.

In this paper, we will first present an overview of the MaMBA concept (section II), followed by an overview of the mock-up of the laboratory module that has been constructed at the ZARM and equipped with scientific instrumentation<sup>14</sup> during the first half of 2019 (section III). In section IV we present the test runs we conducted in the summer of 2019, and the preliminary results from these in section V. We end our paper with a brief outlook on our future work (section VI).

## II. Concept for the habitat and its modules

The long-term goal of project MaMBA is to build a functional prototype of a habitat that is suitable for the Moon, and can later—after testing on the Moon—be adapted for use on Mars. The concept is aimed at first arrivals, rather than long-term settlers: In the long run, it may be preferable to construct habitats from local resources such as regolith. However, until such constructions are verified to be reliable under local conditions, it is safer to bring complete, pre-integrated habitat modules from Earth that “only” need to be transferred from the landing site to the base site and connected.

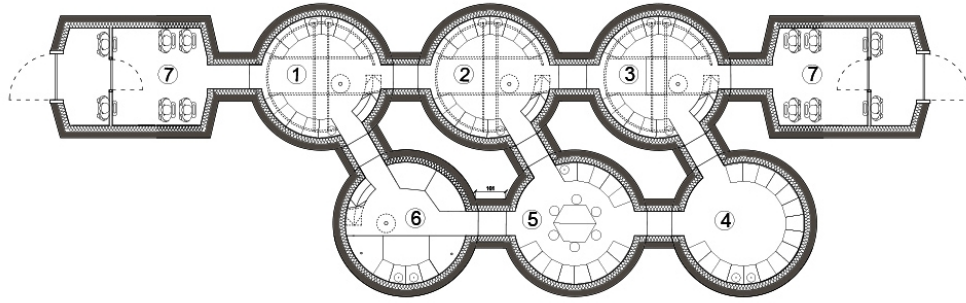
Our base is designed for an initial crew of 6 which is expected to have a strong scientific focus, although the concept is flexible and can be expanded to house larger crews, or crews with other needs than scientific exploration. Furthermore, the MaMBA concept should be viewed as part of a larger “village”, that is the habitat must be surrounded by infrastructure such as a radiation shield, electrical power plants, and factories for mining in-situ resources, to name a few. Also, a crew on an exploration mission will need surface suits to explore the surroundings of their home. However, we consider these as corollary systems; MaMBA is limited explicitly to the habitat itself.

In its basic configuration, the full MaMBA facility consists of 6 modules plus 2 airlocks. All modules are hard-shell pressure vessels, connected via small inflatable corridor modules, as depicted in Figure 1. The main modules are upright cylinders with an outer diameter of slightly more than 5m and a height of roughly 6m. Note that we chose a diameter that is comparable to the diameters of the modules on the International Space Station, i.e. to modules that have already been transported to space. Each module could in theory have up to six doors; however, in practice it is better to have only 2 or 3 doors, since otherwise the module would serve only as a hub but not provide any usable space. The airlock modules are horizontal cylinders.

One possible arrangement of the modules is shown in Figure 2. 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 have two stories, in order to accommodate as many functionalities as possible, while the habitation modules have a high ceiling in order to



**Figure 1. Artistic rendering of the habitat on the lunar surface, protected from radiation by an artificial cave (here depicted as under construction).**



**Figure 2. 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 modules 1-3 are dedicated to work, whereas the row of modules 4-6 is reserved for habitation and leisure.**

counteract the feeling of confinement (except for the sleep module, where each inhabitant shall have their own private quarter).

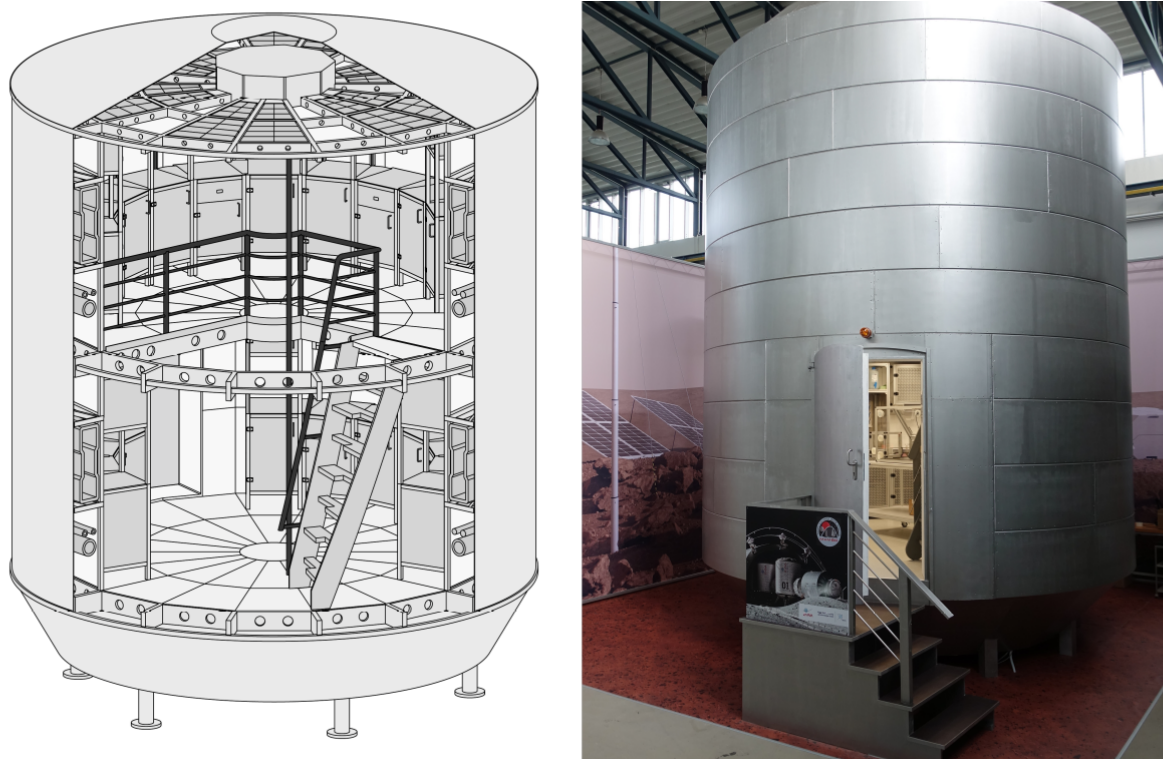
Given the long duration of future missions to the Moon and particularly to Mars, special attention must be paid to the crew's behavioral health. Therefore, we included some design features to alleviate the crew's confinement: (1) One of the modules (module 4 in fig. 2) contains an array of windows that allows the crew to see the outside. The radiation shield has a gap at that position such that the crew can view the landscape outside the shield while still being largely protected from space radiation. Geometrically, the gap would allow less than 1% of the radiation to enter into the artificial cave. (2) Work and leisure modules are in two distinct strands of the habitat, making it easier for the crew to make a distinction between working hours and freetime. (3) A small greenhouse (in module 3) is located at the intersection between the scientific laboratory and the leisure module. The plants grown there are envisioned to be used for food supply and experiments; perhaps more importantly, the growing plants are expected to have a positive impact on the crew's psychological well-being.

Life support systems are distributed among the modules; two or three modules together house one complete life support system capable of sustaining the entire crew of six, such that any one 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). The life support systems are adapted to partial-g conditions (not microgravity), making use of gravity-driven flows. We expect only relatively minor design changes to be necessary when adapting the habitat from lunar gravity to Martian gravity: Any mechanisms using or supporting movement in the direction of gravity may have to be adapted in dimensioning; however, the general functionality remains the same. Perhaps this becomes clearer with a concrete example: The doors between the modules are planned to be sliding doors, with the resting position of the doors above the passageway. In case of an emergency the doors can be released and merely "fall down" to shut. On the Moon, the "fall" will be too slow for many scenarios, so a motor should be added to speed up the process. On Mars, this motor would likely still be necessary, but could perhaps be less powerful.

More generally, the Mars-version of the habitat is intended to be very similar to the Moon-version of the habitat, with as minimal changes as possible. The Moon-version would serve as the blueprint for the Mars-version, and any remaining issues that are identified on the Moon could be improved or eliminated before sending the Mars-version on its way, perhaps 5-10 years after the Moon-version has been established.

On both the Moon and on Mars the crew would have a mission support, although the role of the mission support will be somewhat different from the role of mission control for the ISS. Routine operations of the habitat, monitoring of systems, and planning of routine tasks can certainly be done by mission support, as can the majority of the scientific experiments. However, compared to ISS operations today, the crew will have to have much more autonomy and any protocols that rely on near-instantaneous communication between crew and mission control will have to be adapted to the longer lag times. With the advancement of artificial intelligence, some of the tasks performed by mission control today might be transferred to computer systems or automated altogether.

Further details on the base concept including some measures against emergencies can be found in Heinicke et al.<sup>13</sup>



**Figure 3. Base module.** Left: Concept drawing of the basic MaMBA module. The module consists of two stories, with two ways to transfer between (stairs + pole). The bioregenerative life support system is integrated into the walls, where a large surface area is available. Doors can be shut to withstand the pressure difference to the lunar vacuum environment. The laboratory is located on the ground floor. The upper floor contains a communications area and the medical bay; there is a pulley (not shown) to lift an injured person on a stretcher through the opening in the floor. Right: Photo of the mock-up based on the model on the left. Some modifications had to be made during construction, e.g., the core structure is constructed from wood, and air is drawn from the surrounding hall rather than provided by a life support system. Approximate outer dimensions: height 6.5 m, diameter 5.2 m. During the test runs, only the lower floor was fully equipped; the upper floor was left empty and not used.

### III. Mock-up of the laboratory 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, because we believe it is necessary to ensure the well-being of the inhabitants, we constructed a mock-up of a single module in order to conduct usability tests. It is our plan to run simulations from early on in the design process to constantly evaluate crew comfort and usability of all modules.

The single module we constructed is the laboratory module as representative for the work modules. As the other work modules, the laboratory module consists of two stories, of which the lower one contains the actual laboratory. The upper story houses a control center and a medical bay. Since the life support system is to be integrated in the walls, the walls are roughly 30cm thick. There is extra storage space in the upper and lower conical ends. Transfer between the stories is possible via a flight of stairs or a pole, which is intended especially for quick descents during emergencies. The opening between both stories is large enough to move large objects such as racks or an injured person on a stretcher up or down between the floors.

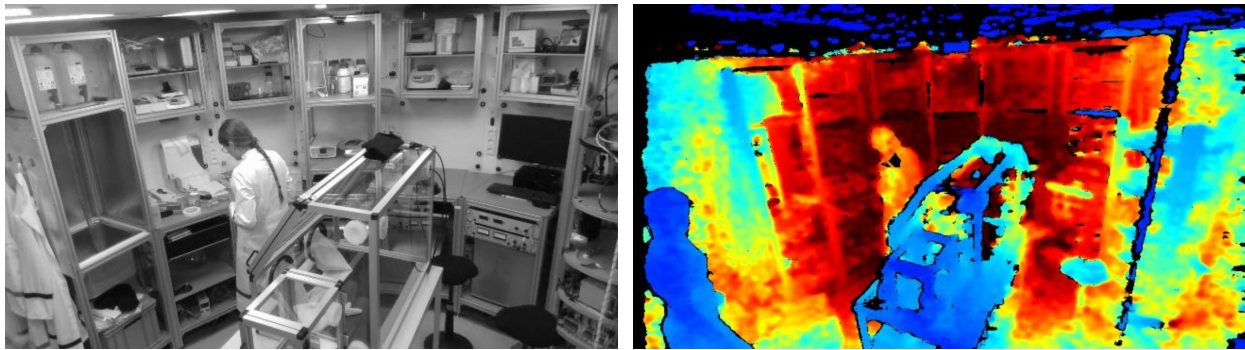


**Figure 4. View of the mock-up interior showing part of the laboratory. The interior wall is split into 18 segments, such that the overall floor layout is almost circular, but the walls consist of plane, rather than curved panels. The walls are lined with custom-made racks (see section III). Two bench top racks are joined to form a working area; the tall racks and hanging racks are used for equipment storage. Note that one of the cameras used in this study is placed at the top right corner of the middle rack; it is attached to the rack with a green flexible tripod. The second camera is located opposite to this one, and just below the ceiling as well. The crew has access to distilled water (rack on the far left) and to a glovebox (somewhat visible behind the stairs on the right edge of the photo). In the current configuration, the glovebox is placed on a mobile lab table.**

Generally, all functions that are necessary for immediate survival are placed on the lower stories. The medical bay, however, is located on the upper story of the laboratory module, above the laboratory proper. This might seem counter-intuitive at first glance, since an injured crew member would have to be transported upstairs prior to treatment. However, if any severe injury does occur, the affected crew member would need to rest and should not be placed on the ground floor, next to the passage between modules. More in-depth considerations for the medical bay are published in a conjoint paper at this conference (paper number 157<sup>15</sup>).

Figure 3 shows both a CAD-model for the laboratory module and a photo of the mock-up that has been constructed on the basis of this CAD model. Some modifications had to be made, as the mock-up is constructed from wood, whereas the real-life habitat modules would need to be constructed from a pressure-tight material such as aluminum, steel or some compound material.

The laboratory is equipped with racks that hold various pieces of scientific equipment. 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 ergonomics, as well. We use a system of 3 different racks types (shown in Figure 4), which are made up of the same building components: (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)



**Figure 5. Screenshot of the depth-sensing (RGB-D) camera: View onto the racks during the first test run (Figure 4 was taken at a later time, when the racks were closed with side walls and doors). Left: RGB screen capture. Right: The same screenshot, but the pixel colors represent the distance from the camera, i.e. warm, reddish colors are farther away from the camera than cool, bluish colors.**

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 racks.

The racks can accommodate a variety of experiments. We expect experiments on the Moon or on Mars to range from pre-integrated experiments similar to the ISS to basic laboratory analysis, where samples from the lunar or Martian surface are examined. Since we consider the “free” sample analyses more crucial to the usability of the laboratory than the pre-integrated experiments, we focus on these with our mock-up: We built the mock-up so that it could be used for activities that are equivalent to (1) experiments utilizing the lunar/Martian environment (reduced-gravity, vacuum, and radiation), (2) analyses of samples of lunar rock and regolith in significant number and mass, (3) preliminary analyses and selection of samples to be sent to Earth for more detailed, specialized analysis.

The laboratory module was thus equipped with instrumentation for research in geology, materials sciences, astrochemistry, and astrobiology. The selection of appropriate instrumentation was based on the recommendations developed by representatives of each of these disciplines<sup>14</sup>, although some adjustments were made according to actually planned experiment protocols and budgetary requirements.

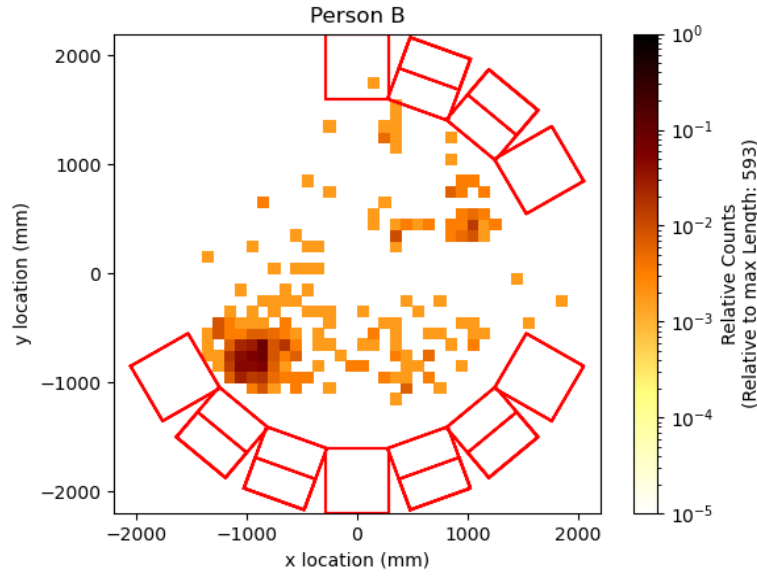
#### IV. Test runs: the mock-up in use

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, and two depth-perception cameras that help reconstruct the volunteers’ positions in 3D space. The tracking helps evaluate the usability of the laboratory: the main purpose of the mock-up is to validate the conceptual design and dimensions of the laboratory for routine laboratory work.

In order to obtain meaningful results regarding the design of the laboratory interior and equipment, our top requirement for our scientist volunteers is to have significant experience with lab work in their respective fields of study. The majority of our volunteers has a PhD in geology, biology, or materials science; the remaining volunteers were advanced PhD candidates at the time of the test run. The scientists prepared their own protocols for the experiments they planned to conduct inside the laboratory module; these experiments are representative of analyses that could likely be conducted on the Moon or on Mars.

During the test runs, the volunteers have access to a simulated conversational user interface using artificial intelligence, which is dubbed Marvin. Marvin is an in-house, “Wizard of Oz”-type of setup<sup>16</sup>, which consists of a microphone connected to a little figurine and loudspeakers; study personnel can respond to the scientists’ oral requests via text-to-speech through the loudspeakers. Marvin is active throughout the entire test run and the crew can interact with him whenever they wish (typically by starting their query with “Hey Marvin”). The conversations between crew and Marvin are recorded.

In addition to the passive monitoring, the scientists fill out questionnaires before and after, and are interviewed after conducting their experiments inside the laboratory. The focus of the questionnaires and interviews is to determine the usability of the laboratory and to obtain suggestions for improvement from the scientist users.



**Figure 6: Example image of one of the participants' locations during the test runs. The red boxes represent the locations of the racks (halved boxes correspond to hanging rack locations). Each colored pixel corresponds to a location that was detected by the cameras: The darker the color of the pixel, the more times the person was recorded at that location. Cameras were located on the two racks at  $x=0$ .**

In 2019, we conducted two tests runs, the first from 24 to 28 June and the second from 30 September to 4 October. Both were structured such that the first day (Monday) was reserved for safety briefings, familiarization with the laboratory, and last-minute adjustments. The time for training and preparations was deemed sufficient by the participants. The actual experiments took place on 3 days (Tuesday-Thursday), and the week ended on Friday with interviews, questionnaires, and finalization of experiments (first test run only).

The first test run consisted of 10 sessions, each of which lasted typically 2.5h; the final session was necessary due to technical issues during one of the previous sessions. The second test run consisted of 9 sessions, which again lasted typically 2.5h, although some were longer.

There were 4 volunteers working inside the mock-up during the first test run (there were 6 sessions with 4 people working simultaneously, 3 sessions with 3 volunteers; the final session was mostly for repeating selected experiments and volunteers were starting to be extracted for interviews). Their ages ranged from late twenties to mid-forties; their sizes from approx. 160 cm to 190 cm. Their specialties were geology, materials science, and biology. All volunteers but one had a PhD in their respective field; one volunteer was an advanced PhD student.

For the second test run, three volunteers were recruited, who were present during all 9 sessions. Their ages ranged from late twenties to mid-thirties; and their sizes from approx. 170 cm to 190 cm. Their fields were biology and geology/materials sciences; two had a PhD, and one person was an advanced PhD student. All participants were of normal health and mobility.

## V. Preliminary results and lessons learned from the test runs

The purpose of the test runs was to assess if the size of the laboratory was large enough for 3 or 4 crew members to work in simultaneously. While the data from the depth-perception cameras is still under analysis, the results from the interviews are already available: The consensus of all volunteers was that the laboratory space was sufficient for 3 persons; 4 persons working together was considered feasible, especially if two were working on the same experiment. Note that the lab had three work areas (two are shown in Figure 4; Figure 6 shows the locations of all three work benches) plus the glovebox. The glovebox could provide an additional work space or it could be removed and the table underneath used as additional space.

In fact, even though the glovebox was initially placed in front of the middle rack in Figure 4 (corresponds to approx. (0, -1000mm) in Figure 6), that is between two work spaces, the table with the glovebox was often moved towards the center of the module: the crew commented that this position not only let them move around more easily, but it made it easier to communicate with each other, rather than standing with the back towards the center of the module.

Generally, the crew was in favor of the fundamental layout of the racks. In particular, they enjoyed the durable, easy-to-clean (stainless steel) work benches, combined with the flexibility of the aluminum frames that could be used to attach items and rearrange work places. Yet, they wished for more work surfaces—which could (only) be achieved by adding extendable tabletops to the racks. Moreover, even though the crews commented before the test runs that they preferred to stand during lab work, and had sit-stands available to them, most commented afterwards that an (additional) option to sit down properly at a desk would be preferable.

Another comment of the crew that was made after the first test run was that the racks should be closed (notice that they lack sides and doors in Figure 5). This was planned anyway; after the second test run the crew commented that they preferred the closed version because items could not fall out anymore and it was “optically nicer”. Another optical item appreciated by the crews where the adjustable ceiling lights: they could be changed from warm to colder colors, and their brightness could be adjusted. Even though each work place had additional LED lights, the ceiling lights helped the crew combat fatigue of their eyes and generally be able to control and change their environment.

The analysis of video data retrieved from the depth-perception cameras is still ongoing. As a first step, we have extracted the locations of all crew members over the course of each session (we used the position of their necks, to be precise). An example of the positioning of a crew member can be seen in Figure 6. We hope to detect differences in the locations between the different sessions: For example, we expect the location “pattern” of all crew members to confirm the crew’s observation that each crew member has been using their own work space when the laboratory was occupied with 3 test subjects. We expect that pattern to change when the occupancy is increased to 4 test subjects. Apart from this, we hope to detect behavioral patterns in the video analysis that have gone unnoticed by the crews and have therefore not yet been extracted from the interviews.

Finally, the crew used Marvin for researching technical information, which includes accessing manuals, looking up general data and formulas (for example, one question was related to the solubility of a specific chemical). In theory, the crew and Marvin had access to the same information (e.g. manuals were stored as physical copies inside the laboratory). In practice, Marvin assisted the crew with finding information, often serving as a shortcut, or researched information for the crew (e.g. physical properties of specific chemicals) as they did not have internet access during the test runs. In some cases, Marvin also contacted support personnel, typically for time-keeping questions or for trouble-shooting.

Most conversations consisted of only a handful of exchanges; these were conversations with a simple question-answer pattern. Some conversations, however, lasted much longer, up to 37 exchanges in one case when the crew had to collaborate with Marvin for trouble shooting. Apart from the mostly technical conversations, the crew also tested Marvin’s limits and used him for fun: during both test runs Marvin was asked to play music or read poems. Further information on the results on Marvin from the first test run can be found in Nahas et al.<sup>17</sup>; an extended version was published at ACM CHI 2021<sup>18</sup>.

A more technical result of the experimental use of the conversational user interface was that the figure or transmitter and receiver should either be placed in a central location, accessible to the crew without leaving their places, or every crew member could have their personal interface. Also, initially Marvin was intended to be activated via pressing a button—this was quickly abandoned because the necessity to use a button would render Marvin useless during many activities in the lab, most notably to anyone working at the glovebox. Aside from the CUI itself, it became clear that the module design must pay close attention to acoustics: The general background noise of a laboratory with running equipment combined with the reflective surfaces of the racks and walls can otherwise quickly lead to auditory stress for the crew and render the CUI unintelligible.

## VI. Future work

MaMBA is still in its early phase. We presented here ongoing work with data analysis of the two test runs still being underway. In addition, we currently plan to conduct further test runs with different goals than the usability rating and provide other groups access to the mock-up for specific studies in other fields.

Beside test runs, we plan to construct further mock-ups in the future with increasing technology readiness level (TRL) and habitation readiness level (HRL); at the moment our design is what Cohen<sup>19</sup> considers TRL 2 (“modeling and simulation afford the opportunity to experiment in human-scale with the architectural parameters”), and Connolly et al.<sup>20</sup> consider HRL 4 (full-scale mock-ups whose subsystems are mostly non-functional, but which can be used for verifying the compatibility of human operations with the design<sup>12</sup>). We plan to advance the project in to distinct directions: (1) design and construct a functional prototype of the laboratory module that could be used for technology testing and (2) create a mock-up of the airlocks that incorporates technical and procedural solutions for dust mitigation and planetary protection.

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