The Repair Maintenance and Fabrication Facility in the Common Habitat Architecture

Robert L. Howard, Jr.[1]
NASA Johnson Space Center, Houston, Texas, 77058, USA

Tracie Prater[2]
NASA Marshall Space Flight Center, Huntsville, Alabama, 35808, USA

James Stott[3]
NASA Marshall Space Flight Center, Huntsville, Alabama, 35808, USA

Abstract*—The Common Habitat Architecture seeks to increase the habitability of long-duration human spaceflight systems. A key aspect of this is vehicle survivability. Missions beyond low Earth orbit need onboard capabilities for Repair, Maintenance, And Fabrication (RMAF) to overcome potential contingency scenarios. Strategies employed in historic human spaceflight such as redundancy management, reliability, sparing, orbital replacement units, and aborts may be insufficient by themselves. Based on subject matter input, a list of 53 critical failures defining a set of incidents that can render a key spacecraft subsystem inoperable were generated. A subsequent analysis found that a robust in-space RMAF system capable of performing 14 key functions can potentially repair a subsystem plagued by any of these failures. An ancillary benefit is this capability may provide psychological benefits to the crew, by enabling greater self-sufficiency in earth-independent problem solving. A basic RMAF facility has been defined for the Common Habitat, consisting of five workstations. A work bench and computer workstation provide a multipurpose horizontal work surface, computing interface, and tools storage. A CNC machining center provides a subtractive manufacturing capability for metals and plastics. A multi-material 3D printing facility provides additive manufacturing capabilities for plastic, metals, and printed electronics. A welding facility is used for joining metal components where a higher strength is needed than can be achieved with fasteners or adhesives. A glovebox facility is used to perform work that is too hazardous for any of the other workstations. This may include hardware brought in from outside the spacecraft that could potentially contaminate the cabin environment. Forward work includes considering the accommodation of additional manufacturing processes not modeled in the current system, assessing the ability of systems to operate in partial gravity and microgravity environments, incorporation of the system into the Common Habitat Computer Aided Design (CAD) model, bottoms-up mass estimating, and a crew time analysis.

I. Introduction

A. Common Habitat Architecture Overview

The Common Habitat Architecture is an exploratory study intended to maximize habitability in long-duration human spaceflight. It leverages the Skylab-inspired approach of outfitting a propellant tank on the ground as a habitat and launching it as a payload. [1] The habitat itself is never used as an actual propellant tank. But unlike Skylab, it uses a common internal design for all gravity environments. This means that the same production model can be used for habitation in 0g, 1/6g (lunar surface), 3/8g (Mars surface), and 1g. The Common Habitat would use the Space Launch System (SLS) core stage Liquid Oxygen (LOX) tank as its pressure vessel and primary structure. [1] Figure 1 shows the SLS LOX tank as fabricated. Figure 2 is a CAD rendering of the common habitat which can be derived from it.

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[1] Habitability Domain Lead, Human Systems Engineering and Integration Division, AIAA Senior Member.
[2] NextSTEP Habitat Technical Monitor, Habitation Systems Development Office, AIAA Senior Member.
[3] In-Space Manufacturing Project Portfolio Manager.

Figure 1. SLS LOX Tank

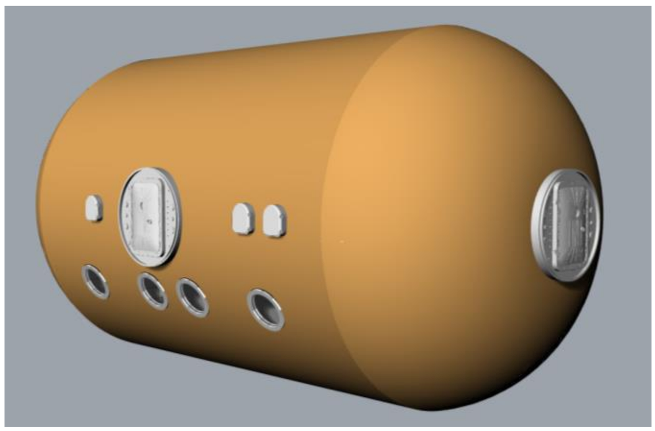

Figure 2. SLS LOX Tank as the Common Habitat

The Common Habitat Architecture Study is a feasibility study and is not part of current NASA Moon to Mars mission planning and acquisitions. It is instead an ongoing study of potential options that – should viability be demonstrated – could potentially be applied to future human exploration programs. The hope is that Common Habitat studies will identify systems, architectures, and elements with potential to significantly advance NASA human space exploration. Where appropriate, results of studies these may be infused into NASA mission architectures as they continue to develop.

The Common Habitat is not a standalone element but must instead be docked to additional elements to form a habitable system. On the Moon or Mars, it becomes part of a surface base camp, [2] as shown in Figure 3. NASA's Artemis campaign, which calls for a sustained return to the lunar surface, envisions a base camp with multiple elements, including surface habitation. [3] The Common Habitat Architecture builds on Artemis experience and similarly forms a base camp for surface activities and is docked to an external airlock, logistics modules, and pressurized rovers. Other base camp elements are distributed in the vicinity.

Figure 3. Common Habitat Docked with Airlock, Logistics Modules, and Pressurized Rovers

In its microgravity application, the Common Habitat would form the core living and working volumes of the Deep Space Exploration Vehicle (DSEV), [4] shown in Figure 4. The DSEV is the Common Habitat mated with a Mars propulsion system. The extensibility of the Common Habitat to multiple mission scenarios represents a key advantage.

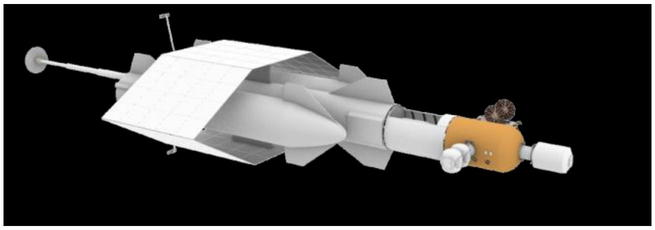

Figure 4. Common Habitat within the Deep Space Exploration Vehicle

Students from the University of Houston's Space Architecture graduate program participated in an exercise to develop four internal layouts of the Common Habitat in support of the objective to determine the optimum use of space for various mission scenarios. Their work was subsequently enhanced under an Innovation Charge Account grant and additional volunteer labor, with the resulting layouts further assessed a trade study comparing crew size and orientation, leading to the eventual selection of the eight-crew horizontal orientation as the habitat variant to carry forward. [5] The three-deck habitat places maintenance facilities on the mid-deck, between exercise and science laboratories, [6] as shown in Figure 5. This placement was driven partially by the placement of docking ports on this deck – the RMAF lies at the intersection of all entrances to the Common Habitat, making it easier to deliver elements from outside the spacecraft to the RMAF for servicing. Additionally, the mid-deck is allocated to working functions, as opposed to the individual privacy on the lower deck and the group social, medical, and commanding functions on the upper deck.

Figure 5. Common Habitat Mid-deck

B. Repair, Maintenance, and Fabrication

Missions beyond Low Earth Orbit (LEO) are challenging for traditional survivability paradigms of human spaceflight. These include redundancy management, reliability, sparing, orbital replacement, and mission aborts. Distances, transit durations, crew time limitations, onboard expertise, vehicle capabilities, and other factors significantly limit the ability of human spaceflight crews to respond to in-flight anomalies relative to low earth orbit scenarios. The Common RMAF facility increases the capability of the crew to recover from spacecraft component failures by combining aspects of a machine shop, a softgoods lab (e.g., textile and thermoplastic materials – anything from spacesuits or other inflatable softgoods, O-rings, bladders, or similar materials), and repair shop into an IVA capability for both microgravity and surface habitats.

The terms repair, maintenance, and fabrication are often used with overlapping connotations or even interchangeably in some cases, but for purposes of the Common Habitat Architecture they are defined with distinct differences:

Repair—as used here, refers to restoring a failed or degraded hardware or software facility, system, or component to such a condition that it may once again be effectively used for its original functional purpose.

Maintenance—as used here, refers to inspecting, monitoring, calibrating, resetting, or otherwise manipulating a hardware or software facility, system, or component for the purpose of correction of incipient failures, either before they occur or before they develop to a level such that it cannot be effectively used for its designated functional purpose.

Fabrication—as used here, refers to the creation of a hardware or software facility, system, or component from raw stock, prefabricated, or scavenged items.

Repair, maintenance, and fabrication can all be planned / scheduled or unplanned / unscheduled activities. It is well understood that routine maintenance is typically planned and scheduled for spacecraft systems. For instance, if there are known degradation rates (e.g., erosion of gear teeth) there may be planned fabrication activities to construct replacement gears with either scheduled maintenance periods for their installation, or an unscheduled repair should one fail earlier than expected.

The RMAF is responsible for restoring damaged components to working order (repair), keeping components in service or functioning (maintenance), and creating new components from raw or scavenged materials (fabrication). This responsibility extends not only to the habitat, but to all other adjacent elements, namely any within transportation distances. Whether it is servicing components from the Common Habitat, a rover, a crane, an airlock, or even a lander, the RMAF is a key contributor to maintaining the operational state of the surface base camp [2] or Deep Space Exploration Vehicle. [4] This makes the RMAF in part responsible for crew and vehicle survivability.

C. Analog Mission and Study Team Examples

Examples from analog missions further illustrate scenarios which would benefit from an RMAF capability. Over the past fifteen years, several NASA analog studies have considered the implications of vehicle survivability for missions beyond LEO. Several of these analog missions either conducted repair or maintenance tasks or explored scenarios that would have led to a repair or maintenance task had they occurred in an actual space mission. These tasks help to understand how repair, maintenance, and fabrication beyond LEO requires capabilities not needed on the International Space Station (ISS) or predecessor long-duration spacecraft in LEO.

For example, the 2009 Desert Research and Technology Studies (DRATS) conducted a test of two pressurized rover architectures where the Cabin 1A rover prototype played the role of a disabled vehicle and the Cabin 1B rover prototype had to find the disabled vehicle and rescue its crew. This test was successfully performed, but the study did not consider the question of what happens to the disabled vehicle in the future. How can it be restored to functionality for subsequent crews? In a real lunar architecture, the only way to avoid having to replace the entire vehicle – likely a multi-billion-dollar asset – would be to have a surface infrastructure capable of, at a minimum, inspecting the failed components, removing any components too damaged for continued reuse, and replacing them with operational equivalents. If Earth resupply is limited such that replacements cannot be provided within the time needed, the capability to either restore those damaged components or locally construct new ones would also be needed.

The 2010 DRATS conducted a demonstration activity where a single rover transmission was cleaned inside the habitat at its General Maintenance Workstation (GMWS). This is a basic activity that was viewed as a potentially necessary preventive maintenance activity for a Small Pressurized Rover on the Moon.

During the 2012 Mission Operations Test (MOT), the Habitat Demonstration Unit (HDU) conducted an inspection and repair task on a surplus Interim Resistive Exercise Device (iRED) unit. Like the 2010 GMWS exercise, this was also viewed as representative of potential habitat preventive maintenance events which could also be served by RMAF.

Also, during the 2012 MOT, the HDU crew was tasked to fabricate a simplistic electronics box as a replacement to one that had been destroyed by a micrometeorite strike. The task involved sheet metal cutting, bending, drilling, and soldering.

During the development of the Common Habitat internal layout, a down-selection of four candidate configurations examined nineteen maintenance, repair, and fabrication scenarios encompassing the habitat itself, landers and ascent vehicles, rovers, spacesuits, robotic assets, and the DSEV propulsion system. [5] Capabilities of the RMAF were scoped to enable effective response to these envisioned scenarios.

These examples illustrate the range of scenarios that will call upon the capabilities of the RMAF in the Common Habitat Architecture. The purpose of this paper is to discuss the needs of an in-flight maintenance system for missions beyond LEO and illustrate preliminary design concepts to increase crew and vehicle survivability.

II. Limitations of Traditional Strategies for Missions Beyond LEO

Why are additional strategies needed in spacecraft operating beyond LEO? In LEO, the crew always the option to return to Earth ahead of schedule. If an emergency develops aboard the ISS, the crew can abandon the station to a waiting entry vehicle (e.g., Soyuz, Dragon, etc.) and be back on the surface of Earth in a couple of hours at most. With multiple regularly scheduled crew and cargo launches to LEO, if a crewed repair mission is needed, it should be possible to launch one within a small number of months.

The value proposition for the RMAF becomes even more clear upon examination of differences between historical human spaceflight missions and the long endurance missions envisioned as part of the Artemis program. In this paradigm shift, traditional approaches to sparing, repair, and logistics become less viable due to higher upmass costs as we move beyond LEO, due to much more limited resupply opportunities and the vastly increased testing needed to demonstrate system reliability in long endurance scenarios. [7]

D. Redundancy Management

Redundancy management was employed by the Space Shuttle program to meet fail operational / fail safe requirements for the avionics system. [7] Redundancy management was implemented by having multiple avionics units (e.g., three inertial measurement units) operating in parallel and comparing the data from all of them, using various voting schemes to determine if one unit is not providing trustworthy data. This accepts a degradation in total system health that accumulates over time. For the short durations of a shuttle mission this is acceptable, but for spacecraft in continuous operation for decades like those in the Common Habitat Architecture, this is insufficient by itself. Additionally, if all redundant units are equally vulnerable to a single event, then that one event could take out all redundant units at the same time.

E. Reliability

With the advent of much longer missions relative to Space Shuttle, the International Space Station increased the focus on reliability strategies. Reliability requirements are often structured as the probability of properly performing a mission phase or objective without a failure or sequence of failures that will terminate the mission phase. [8] The challenge with a reliability strategy is that given sufficient time, even a low probability event may eventually occur. While a particular failure mode may represent a rare event or one that only manifests with very long-term cumulative operations, the possibility of failure cannot be engineered out of the system completely.

F. Sparing / Orbital Replacement Units

The ISS combines its reliability strategy with a sparing strategy that is unique to low earth orbit scenarios. ISS components are designed based on an Orbital Replacement Unit (ORU) architecture, where subsystems and components are designed to be easily replaced with spare units which are available onboard or able to be readily flown on a resupply mission. The sparing strategy uses estimates of ORU failure rates to determine the number of spares that should be carried aboard the station. [9] However, with a large, complex architecture such as the Common Habitat Architecture, carrying enough ORUs to account for even the failures that might occur during a single crew expedition can lead to a staggering amount of payload mass and volume which quickly exceed reasonable allocations.

G. Abort

Finally, if all else fails, the ISS crew members (as the shuttle crew members before them) always have the option to execute a mission abort. Each crew member on the ISS always has a seat available on a docked spacecraft and should conditions warrant, the ISS crew can abandon the station and be on the surface of the Earth in a few hours at most. This option does not translate well beyond LEO. From the Moon a contingency return to Earth will take days and a contingency return from Mars will take months to years.

All of the traditional survival strategies – redundancy management, reliability, sparing / ORUs, and abort have their limitations for missions beyond LEO. While they remain useful in other mission scenarios, additional capabilities and approaches are needed for the crew and vehicle to survive long duration operations.

III. Derivation of RMAF Needs

H. Critical Capabilities

Many reliability or maintenance studies utilize probabilistic risk assessment to prioritize systems for redundancy or sparing, or to identify reliability targets. The Common Habitat Architecture takes a different approach. Because the systems are permanently deployed beyond LEO, it is possible that low probability failures will eventually occur. Thus, there is a need is to develop a capability that can enable or enhance recovery from those failures. Figure 6 shows a list of 53 critical failures that have been identified based on mission control and safety subject matter expert opinion. [10] These failures are component-level failures that could render a subsystem or element inoperable.

Critical Failures Requiring RMAF Capability

1. Actuator FOD
2. Actuator overpressure
3. Actuator underpressure
4. Adhesive failure
5. Bad wireless connection
6. Belt break
7. Broken cables
8. Broken electrical connection
9. Broken physical structure
10. Bulb burnout
11. Bulb shatter
12. C&W software failure
13. Connector overtorque
14. Connector pin/connection failure
15. Connector under torque
16. Consumable depletion
17. Cracked housing
18. Cracked screen
19. Debris clog
20. Debris impact damage
21. Debris in motor
22. Diaphragm damage (digital)
23. Electrical lead failure
24. Electrical short
25. Fabric erosion
26. Fabric tear
27. Failed electrical connection
28. Fin breakage / bending/ding
29. Fluid line rupture
30. Fuse blown
31. Kinked line
32. Material abrasion / erosion
33. Material corrosion
34. Material delamination
35. Material stretching
36. Motor failure
37. Physical obstruction
38. Potting failure
39. Power surge
40. Pressure bladder puncture, tear, or rip
41. Spring too weak or too stiff
42. Structural bending
43. Structural buckling
44. Structural burst
45. Structural crack/fracture
46. Structural deformation
47. Structural gouge
48. Structural membrane disjoin
49. Structural rupture / puncture
50. Structural seal failure
51. Structural shear
52. Surface chemical contamination
53. Wire detach, split, tear, rip, or break

Figure 6. Critical Failures That Can Render a Subsystem or Element Inoperable

I. Critical Functions

There are 14 repair, maintenance, and fabrication functions that have been identified [10] as collectively being able to recover a system from any of these failures. These functions, shown in Figure 7, establish the target capabilities of the RMAF. The design philosophy for the RMAF is to incorporate these functions, considering the Surface Base Camps and DSEV as architectural infusion points, and minimize the necessary volume to contain this system.

Generic RMAF Functions to Repair Critical Failures

1. Soldering
2. Drilling
3. Metal cutting and bending
4. Metallurgical analysis
5. Bonding metal, composite, and other surfaces
6. Electronics analysis and repair
7. Computer/Avionics inspection/testing and repair
8. CAD Modeling / Software Coding / Computer Analysis
9. Material Handling (inclusive of the range from large ORUs and small fasteners)
10. Precision Maintenance (manipulation, inspection, repair of small/delicate components)
11. 3D Printing (metal, plastic, and printed electronics)
12. Soft goods (including thermoplastics, sewing, cutting, and patching)
13. Dust/Particle/Fume Mitigation
14. Welding

Figure 7. List of Functions to Repair Critical Failures

J. Nolens Volens Capabilities

The RMAF will also take on capabilities that are present nolens volens (meaning whether one likes it or not). The critical functions above by definition give rise to additional benefits in a mission scenario. Whether the capabilities listed are currently viewed as enabling to the mission architecture or not (thus the nolens volens characterization), the ability to recover from the identified 53 critical failures has an inherent ability to alter the crew's environment in many positive ways that might not have been predicted in advance by either designers or ground operations personnel. In-space manufacturing and repair technologies are generally thought of primarily as technologies the crew would use to respond to failure scenarios or reduce logistics, but they could also have numerous potential benefits for crew psychology, creative reuse, and habitat interior outfitting/aesthetics.

Recreational and Relaxation—The RMAF 0functionality can be used to create items specifically for crew member recreation and relaxation. This may be as simple as 3D printing a frisbee, or as complex as designing and building a lounge chair, mood lighting, and sound system.

Reconfiguration and Repurposing—The functionality of the RMAF can be used to fundamentally alter a system or component, for instance, adding a muffler to reduce the sound of a piece of equipment, or adding heating elements to turn a normal fan into a space heater, or even combining multiple sensors to create a new science instrument.

Rearrangement and Redecorating—The RMAF can be used to alter the architectural design of the internal or external environment. Closeouts can be altered in design or finishing, new structures such as arches or columns can be created, new secondary structures can be built or installed.

These activities need not be limited to a single crew. The astronauts might take on personal projects that encompass multiple crews over many years, each contributing portions until an environment that represents the preferences and interests of the astronaut community is realized.

K. Psychological Value

The RMAF serves both the physical needs of the architectural systems and contributes in several ways to the psychological well-being of the crew.

The first is the peace of mind from understanding the capacity to respond to failure. Without the RMAF's capabilities, certain failures could place a Mars surface or transit crew in a long-term survival mode state, where they are using a small portion of the spacecraft as a lifeboat/safe haven, with the remainder having been rendered uninhabitable by a contingency event. But with the RMAF, the crew have the ability to try to repair the associated failed systems without dependence on earth.

The second is the capacity to fabricate items that serve recreational or relaxation purposes. A crew might spend a month fabricating components to use in some team game, then spend several months playing the game. Both the development and operational phases provide the crew with a psychological outlet not otherwise available.

The ability to use the RMAF to reconfigure and repurpose gives them options to get new uses out of hardware or software that has already completed, or failed to complete, its primary purpose. As a notional example, a crew might remove heating elements from a retired science instrument and fabricate a housing around them to construct a crude iron to use on their clothing. Thus, the ability to repurpose elements using RMAF could reduce waste and also enable an outlet for the crew's creative expression.

Finally, using the RMAF for rearrangement and redecorating can allow the crew, for instance, to create custom decorations for holidays or simply create personalized architectural enhancements in their crew quarters. These relatively minor changes to their living environment and opportunity for customization can have profound impacts on crew morale.

L. Initial Design of the RMAF

While the mission benefits of the RMAF previously articulated, we now turn our attention to the placement of the RMAF in the habitat and the system design. The RMAF is located at the center of the mid-deck of the Common Habitat. The area shown in Figure 8 is the portion of the mid-deck allocated to the RMAF. There is no exact volume allocation, but the RMAF is bounded on one side by the Exercise Facility, on another by the Life Science Laboratory and Physical Science Laboratory and is also bounded by the habitat pressure vessel walls, and deck floor and ceiling. It further cannot obstruct the vertical translation passageway. The outfitting in the CAD model is a notional initial configuration and was only intended to define the general RMAF region as opposed to the adjacent exercise and science facilities.

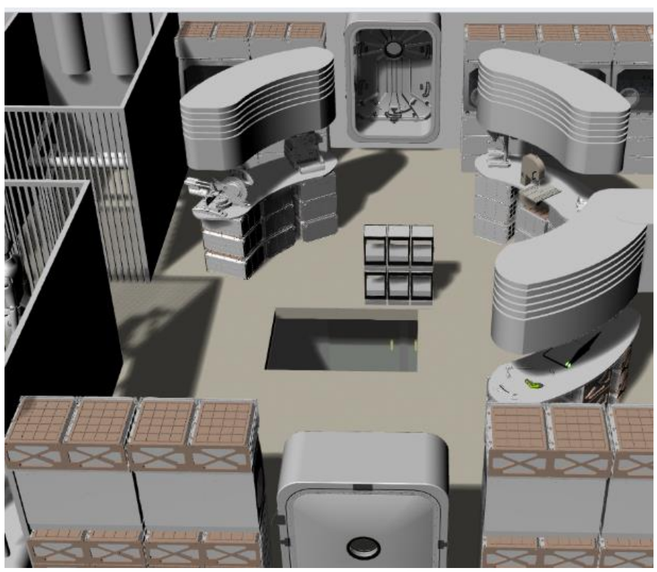

Figure 8. RMAF Facility Volume in the Common Habitat Mid-deck

Work performed by a student intern has organized the RMAF capabilities into five distinct workstations to be located in the RMAF allocated volume. These workstations, and their respective tools and work volumes, are used as needed to perform repair, manufacturing, or fabrication tasks to sustain operation of the associated base camp or DSEV.

The general design philosophy was to minimize the volume needed for work and stowage. This is achieved by developing the previously mentioned workstations as multi-use facilities, each of which incorporates related functions. The five workstations include a work bench and computer station, a CNC machining center, a 3D printing facility, a glovebox facility, and a welding facility. These workstations have not yet been integrated into the Common Habitat CAD model, but they serve as an upgrade to the initial design configuration.

In general, all of the workstations within the RMAF may be called upon for tasks that: a) generate foreign object debris, b) process and/or analyze materials collected from or exposed to a planetary surface, and c) repair hardware that may harbor contaminants which can escape into the crewed environment (such as lunar dust). This invokes considerations not addressed in the original, notional University of Houston layouts. A full treatment lies beyond the scope of this paper and is noted as forward work, but some introductory allocations are addressed for each RMAF workstation.

IV. Work Bench and Computer Station

The Work Bench and Computer Station performs the functions of soldering; drilling; metal cutting and bending; metallurgical analysis; bonding metal, composite, and other surfaces; electronics analysis and repair; computer/avionics inspection/testing and repair; CAD modeling, software coding, and computer analysis; material handling; precision maintenance; softgoods; and dust, particle, and fume mitigation.

The work bench provides storage for benchtop tools, hand tools, small parts, and limited raw materials. It also stows tools that are mounted to the work bench for use, such as a vise, inspection microscopes, arbor press, sewing machine, and thermoplastic film welder.

It also provides a horizontal work surface for maintenance and repair activities including assembly, disassembly, inspection, cleaning, cutting, drilling, soldering, sewing. It is not a clean room, though it does have some containment capability. It does not nominally produce contaminants, except for grease, uncured adhesives, and some vapors. It is primarily used for operations that do not produce chips or shavings.

The computer workstation supports CAD modeling, coding, computer-based analyses, instrument remote access, and other software tools. An initial CAD model of the work bench is shown in Figure 9.

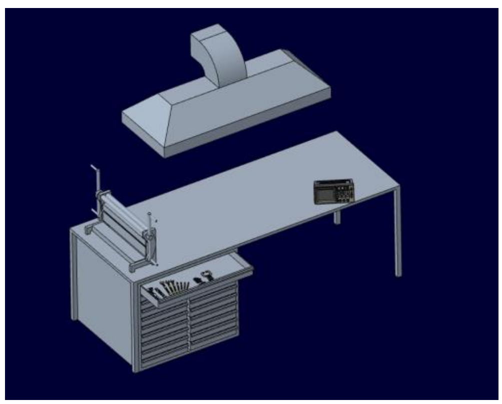

Figure 9. Notional Work Bench

The initial concept makes use of a vent hood to capture fumes and small particulates generated at the workstation. When necessary, additional transparent material can be deployed between the horizontal work surface or floor and the vent hood to create a greater level of containment.

A tool cart embedded in the work bench holds more than 65 basic hand tools, including small power tools. Drawers also contain small parts, diagnostic items, and limited raw materials. A combination shear brake roll machine is permanently mounted on the edge of the work surface.

V. CNC Machining Center

The CNC Machining Center performs the functions of drilling; metal cutting; metallurgical analysis; material handling; precision maintenance; and dust, particle, and fume mitigation.

The CNC Machining Center is used for subtractive manufacturing of metal and plastic parts. It provides storage for a variety of machining bits as well as sensors that can be positioned to support metallurgical analysis of machined parts.

While the notional CAD model in Figure 10 depicts a CNC mill / lathe combination machine, this is only a notional, intern-produced model and at minimum a 5-axis CNC is expected to be incorporated in the RMAF for a mission. However, a key consideration is the working volume – particularly the volume within the enclosed area to accommodate the raw material being worked on.

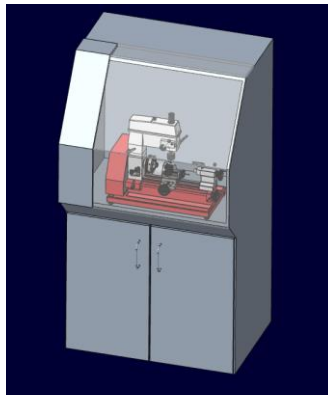

Figure 10. Notional CNC Machining Center

Future iterations may attempt to package the system in a volume more reminiscent of a CNC router table. It is also a forward trade to compare a traditional CNC system against laser or plasma cutters. A laser cutter is especially attractive as it would produce less FOD and offer high accuracy. It also may not need the vibration isolation system that a CNC will need. In the Common Habitat Architecture, the habitat receives power from a nuclear fission reactor in both the surface base camp [2] and Deep Space Exploration Vehicle, [4] so the higher power draw of the laser cutter may not be a significant issue.

VI. 3D Printing Facility

The 3D Printing Facility performs the functions of material handling; 3D printing; and dust, particle, and fume mitigation. Additive manufacturing is needed to complement subtractive processes and enable greater design freedom. Additive manufacturing encompasses a suite of processes which make possible rapid prototyping, light weighting of structures (as material can be deposited only where it is needed), manufacturing for design (rather than the traditional paradigm of design for manufacturing), and reduced production times for complex parts. The 3D Printing Facility, as envisioned in Figure 11, consists of six 3D printers: three fused filament fabrication (FFF) printers, which print thermoplastics, two metal FFF printers, and one double-sided, non-multilayered printed circuit board (PCB) printer. In 2014, the in-space manufacturing (ISM) project at NASA Marshall Space Flight Center (MSFC) first demonstrated 3D printing of thermoplastics in microgravity through a partnership with Made in Space. For the past few years ISM, in collaboration with Redwire, has pursued the development of a multi-material Fabrication Lab (FabLab) capable of printing with polymers, metals, and electronic materials within the same system. Additive manufacturing processes which are tested and matured on the International Space Station or future commercial low earth orbit platforms can be infused into the RMAF to enable greater capability. [11] Furthermore, the ISM project is studying crew 3D printing utilization within the Crew Health and Performance Exploration Analog (CHAPEA) Mars Dune Alpha habitat. [12]

While additive manufacturing offers unique advantages, subtractive manufacturing is still needed to machine many additive metallic parts to their final shape. For example, the net shape part produced with typical wire-fed metal processes may require finer resolution than can be achieved with the printing process alone (although the resolution/feature size required is part and application specific). Some parts manufactured in the 3D printing facility may thus require movement into the CNC machining center or glovebox for post-processing.

The printers are mounted in vibration isolation cages to prevent the vibrations of one printer from interfering with the performance of another. Feedstock spools are mounted above the six printers. The specific types and numbers of printers is notional at this stage and will be refined in forward work, but the general classes of plastic, metal, and PCB printers are all expected to be needed. The broader questions of what type of printing capabilities maximize quantitative benefits of ISM and the levels of reliability the systems must exhibit are subjects for further consideration. An additional question is the level of redundancy required. For example, if multiple identical printers are part of the habitat a failure in one printer (a systemic failure) may translate into loss of the other capabilities as well. This is a potential concern when manufacturing capabilities are being relied on for critical spares which are not manifested at levels needed to guarantee a high probability of sufficiency. [13]

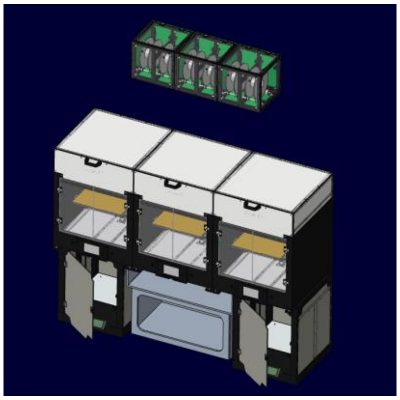

Figure 11. Notional 3D Printing Facility

VII. Welding Facility

The Welding Facility performs the functions of bonding metal, composite, and other surfaces; welding; and dust, particle, and fume mitigation.

Welding is needed for some fabrication operations where bolts, rivets, adhesives, or other fasteners lack sufficient strength. The initial concept for the RMAF Welding Facility, modeled in Figure 12, supports basic tungsten inert gas (TIG) welding with inert shielding gas collected by a directed fume extractor. The central structure of the facility is a fixture table to support parts being welded. Equipment stowed under the table includes the welding equipment, power supply, shielding gas tank, fixture equipment, and the fume extractor. Deployable welding curtains are stowed in the ceiling.

Electron beam welding was previously demonstrated in space by the Russians. A US flight experiment – the In-Space Welding Experiment (ISWE) – was planned for the space shuttle but was ultimately cancelled. The advantages of TIG welding relative to electron beam are lower power requirements, compatibility with Aluminum alloys commonly used in space structures, and versatility. Additionally, TIG does not produce ionizing radiation. . However, TIG-welding requires higher precision.

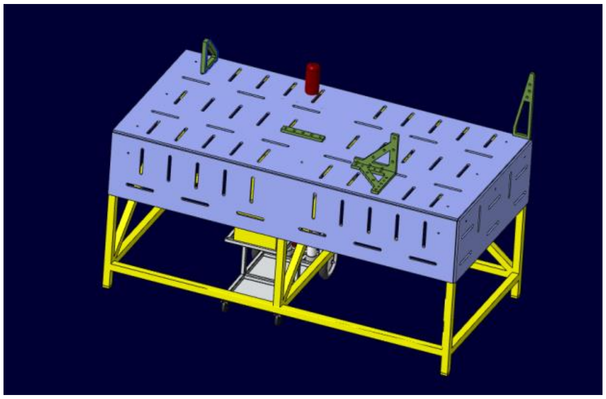

Figure 12. Notional Welding Facility

VIII. Glovebox Facility

The Glovebox Facility performs the functions of soldering; drilling; metal cutting and bending; metallurgical analysis; bonding metal, composite, and other surfaces; electronics analysis and repair; material handling; precision maintenance; and dust, particle, and fume mitigation.

The glovebox is used for RMAF operations that are associated with hazards that cannot be contained by the dust, particle, and fume mitigation capabilities of the other stations. The glovebox provides a sealed environment, isolated from the cabin atmosphere.

The initial configuration in Figure 13 depicts a glovebox modeled after the ISS microgravity science glovebox (MSG) [14] but the total number of units, the actual dimensions of each, and other specifications remain as forward work. Additionally, the eight mid-deck lockers surrounding the glovebox are only volume placeholders. The final solution may employ environmental control hardware, glovebox transfer locks, tool storage, or other capabilities within these volumes. At least one glovebox will also include an exterior transfer port, allowing components from elements outside the Common Habitat to be placed directly in the glovebox without bringing them into the cabin environment. This will be particularly important for maintenance or repair of equipment contaminated with hazardous chemicals, such as hydrazine or ammonia. This is something that could be encountered in the repair of an external thermal control system unit, a hypergolic thruster, or an auxiliary power unit.

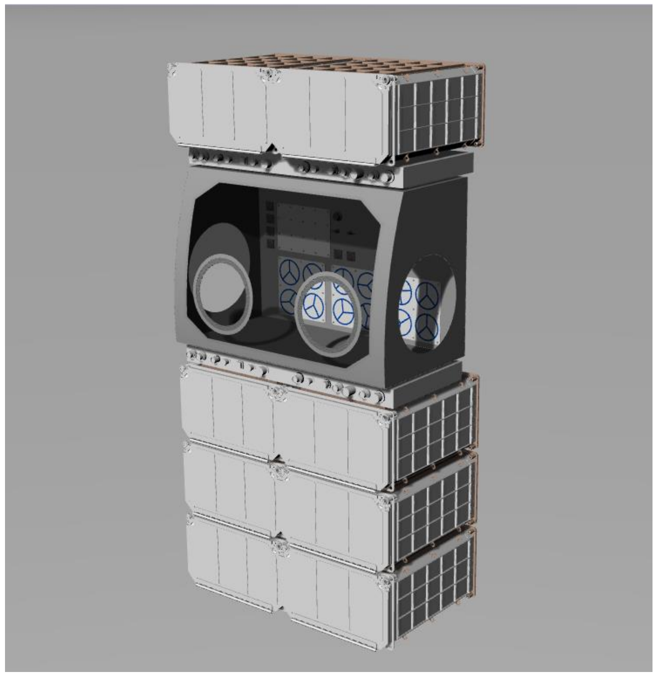

Figure 13. Notional Glovebox Facility

IX. Conclusions and Forward Work

As the second iteration of the Common Habitat's RMAF facility, the work encompassed in this paper represents a significant step forward over the visual images created by the University of Houston layout study in Figure 5 and Figure 8. This initial work only contained sufficient detail to indicate which portions of the mid-deck were allocated to RMAF, as opposed to exercise or science. The subsequent work detailed in this paper has actually tied specific functions to workstations and equipment. However, several areas of key forward work remain.

M. Additional Tool Systems

A drill press, band saw, chop saw / miter saw, pipe bender, and table saw stand out as machine shop tools that are missing from this initial configuration of the RMAF but may be needed to achieve the intended functionality. The next iteration of design will attempt to incorporate these missing items and other tools identified as adding value to the system in specific use scenarios.

N. Particle and Fume Collection

FOD mitigation, including dust, particles, and fumes is a critical function of every RMAF workstation, but it is only given a passing treatment in this paper. Forward work is needed to design a system that can contain, collect, and process the hazardous byproducts of RMAF operations. This will presumably include a pre-treatment of waste gases and fluids before they are processed by the closed loop life support system.

In the case of the glovebox, it is relatively straightforward that by definition of its nature a glovebox can contain generated FOD or other contaminants. However, what is less straightforward and requires some forward work, is how is the glovebox internal environment, including the component serviced within, then remediated to remove any solid, liquid, or gas contaminants or activity byproducts prior releasing the component from the glovebox and returning it to service or storing it as a spare.

For the remainder of the RMAF, the same remediation question applies, but containment must also be achieved. The leading concept is inspired from the HDU systems tested at Desert RATS. The HDU GMWS featured a deployable particle containment system that amounted to a flexible plastic barrier that deployed between the worktable surface and an overhead vent hood. This effectively transformed the worktable into a deployable glovebox. Something analogous to this was suggested for the Work Bench and Computer Station.

A larger concept could potentially encompass not only the work surface but the entire work area, effectively placing the working crew "inside" a deployable glovebox. This would, of course, necessitate personal protective equipment (PPE) to protect such a crew member and would invoke a need to not only remediate the item serviced but also the crew member, work area, and used PPE.

O. Variable Gravity Accommodation

Because the Common Habitat operates across the range of gravity environments from 0g to 1g there must be means to accommodate parts within the RMAF. During an assembly or disassembly operation a component could be broken down into dozens or even hundreds of pieces, both large and small. Escapement of these pieces into the cabin environment represents a major risk to crew health and safety. Additionally, multiple pieces may need to be held together during RMAF operations. Those operations involving high forces may call for significant material handling strength to hold pieces together.

P. CAD Incorporation

With the above work completed, the resulting RMAF facility will next be incorporated into the mid-deck of the Common Habitat CAD model. Human factors tabletop and virtual reality evaluations can then assess the acceptability of the facility from a usability perspective.

Q. Mass Estimation

A bottoms-up mass estimation exercise is currently in progress to determine the predicted mass of the Common Habitat. Thus, the RMAF components must be sufficiently identified and defined to estimate its contribution to the overall habitat.

R. Crew Time

An Artemis study for the lunar Surface Habitat predicted a corrective maintenance crew time at over 24 hours per 30-day mission. [15] Given that the subsystems of the Common Habitat are significantly different from the Surface Habitat, and that the RMAF is also responsible for maintaining additional spacecraft, it would be beneficial to conduct a similar study for all of the elements of the Common Habitat Architecture.

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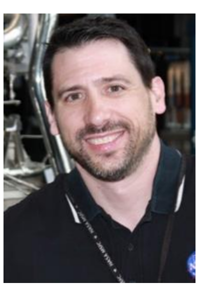
BIOGRAPHY

***Robert Howard** is the Habitability Domain Lead in the Habitability and Human Factors Branch and co-lead of the Center for Design and Space Architecture at Johnson Space Center in Houston, TX. He leads teams of architects, industrial designers, engineers, and usability experts to develop and evaluate concepts for spacecraft cabin and cockpit configurations. He has served on design teams for several NASA spacecraft programs, projects, and study teams including the Orion Multi-Purpose Crew Vehicle, Orion Capsule Parachute Assembly System, Altair Lunar Lander, Lunar Electric Rover / Multi-Mission Space Exploration Vehicle / Pressurized Rover, Lunar Terrain Vehicle, Deep Space Habitat, Waypoint Spacecraft, Exploration Augmentation Module, Asteroid Retrieval Utilization Mission, Mars Ascent Vehicle, Deep Space Gateway, Surface Habitat, Transit Habitat, and other human spaceflight studies mission studies. He received a B.S. in General Science from Morehouse College, a Bachelor of Aerospace Engineering from Georgia Tech, a Master of Science in Industrial Engineering with a focus in Human Factors from North Carolina A&T State University, and a Ph.D. in Aerospace Engineering with a focus in Spacecraft Engineering from the University of Tennessee Space Institute. He also holds a certificate in Human Systems Integration from the Naval Postgraduate School and is a graduate of the NASA Space Systems Engineering Development Program.*

***Tracie Prater** is in the habitation systems development office at NASA Marshall Space Flight Center, where she is a technical monitor for NextSTEP Habitat, supports habitation formulation activities and partnerships, and is engaged in the systems engineering and integration team for Mars Transit Habitat. She joined NASA in 2013 and was an engineer in the Materials and Processes Laboratory at NASA Marshall Space Flight Center from 2013-2021, where she supported advanced manufacturing research, in-space manufacturing, and the Centennial Challenges Program. She is a senior member of the American Institute of Aeronautics and Astronautics. She has a Ph.D. in mechanical engineering from Vanderbilt University.*



***James Stott** joined NASA's Marshall Space Flight Center in 2006 and currently serves as the Associate Manager for Space Vehicle Systems Office in the Human Landing System Program. He previously served as the In-Space Manufacturing Project Portfolio Manager as well as Project Manager for the Near Earth Asteroid Scout. Prior to his NASA career, Dr. Stott worked for the Department of Defense as an electronics engineer developing simulation and Guidance, Navigation, and Control (GNC) and Avionics software systems for the Systems Engineering Design and Integration branch of the Applied Sensors, Guidance, and Electronics Directorate of the Aviation and Missile Research and Development Center (AMRDEC). Dr. Stott holds advanced degrees in Physics, Mathematics, Electrical Engineering, and Mechanical Engineering earning his PhD in Electrical Engineering from the University of Alabama in Huntsville. He has received numerous awards, including Space Flight Awareness, a Silver Snoopy, and an*

Outstanding Leadership Medal among other recognitions. Dr. Stott currently resides in Huntsville, AL with his wife and three children.