

A mission concept to study multigenerational mammalian reproduction in partial gravity

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A team at NASA Langley Research Center conducted a study during which a conceptual space mission was designed. In this study, rodents are used as human analogs to gather biological and systems data in a relevant environment applicable to future settlements on Mars. The mission concept uniquely addresses the combined effects of long-durations (one-year or greater), autonomous and robotic operations, and biological responses to partial gravity with an emphasis on reproduction. The objectives of this study were to 1) understand challenges associated with designing an artificial gravity habitat that supports the reproduction and maturation of a large animal colony, 2) identify mission architectures and operational concepts to transport and maintain such a facility, and 3) identify fundamental science considerations for mammalian reproduction studies to inform vehicle design. A model demonstration unit was developed to visualize and test certain design concepts that resulted from these considerations. Three versions of this demonstration unit were built over the course of the study, each taking into account lessons learned from the previous version.

This paper presents the updated baseline mission and spacecraft design concepts to achieve these objectives, with a specific emphasis on updates since publication in previous works. Analyses of the integrated system trades among the elements which make up the conceptual vehicle are described to address overall feasibility and identify potential integrated design opportunities. The latest iteration of the habitat robotics design and a conceptual design example for autonomous care of crew and systems are also presented. Finally, the conclusion of this conceptual design study, necessary future analyses to enable such a facility, and comments upon other applications of a similar exploration-focused research facilities are addressed.

Nomenclature

ACS	Attitude Control System
AEON	Autonomous Entity Operations Network
AL	alert, log, and isolate
DDS	Data Distribution Service
DM	deceased mouse
DOF	degree of freedom

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DSN	Deep Space Network
EDDE	ElectroDynamic Debris Eliminator
EMC	Evolvable Mars Campaign
LaRC	Langley Research Center
LDRO	lunar distant retrograde orbit
LED	light emitting diode
LEO	Low Earth Orbit
GEO	Geostationary orbit
g	gravity
g/m	grams per meter
HD	high-definition
ISS	International Space Station
JPEG	Joint Photographic Experts Group
kg	kilo gram
kN	kilo Newton
kW	kilo Watt
kW-h	kilo Watt per hour
Mbps	Megabyte per second
MICEHAB	Multigenerational Independent Colony for Extraterrestrial Habitation, Autonomy, and Behavior health
m	meter
m/s	meters per second
mT	metric ton (1,000 kg)
Orbital ATK	Orbital Alliant Techsystems
QFD	Quality Function Deployment
RCS	Reaction Control System
RE	remove mouse and examine
RF	radio frequency
rpm	revolutions per minute
SACD	Systems Analysis and Concepts Directorate
SD	standard-definition
SLS	Space Launch System
SM	sick mouse
TA	thermal alert
TBD	to be determined
U	standard unit of measure for designating the usable space of racks
W	Watt

I. Introduction

The path to Mars requires exploration missions to be increasingly Earth-independent as the foundation is laid for a sustained human presence on Mars in the following decades.^{1,2} NASA is in the early stages of preparing to extend human presence beyond Low Earth Orbit (LEO) through missions conducted in cislunar space in the 2020s and planned missions to the Mars system in the mid-2030s.² These missions eventually culminate in extended-duration crewed missions on Mars' surface leading to a permanent Mars surface station.² NASA's current human exploration planning effort, the Evolvable Mars Campaign (EMC), follows this pioneering approach. The EMC designates the Proving Ground as a region in cislunar space where

missions beyond LEO will demonstrate increasing mission capabilities while reducing technical risks. This will provide valuable experience with deep space operations as missions transition from “Earth-dependent” to “Earth-independent”.² The EMC architecture serves as a framework to identify critical capabilities and technologies that need to be developed and tested in the Proving Ground in order to enable human exploration missions and eventually settlement on Mars.^{2,3}

In particular, autonomous and robotic system capabilities are required to operate long-duration habitation systems during crewed and non-crewed (dormant) times and to perform multiple functions including medical care for crew, integrated vehicle health management, spacecraft maintenance, and logistics management. Long-duration refers to durations of one-year or greater and autonomous refers to a combination of autonomy and automation.

These required autonomous and robotic capabilities are beyond the current state-of-the-art and are presently being analyzed within the EMC architecture.³ The International Space Station (ISS) maintains a permanent presence of crew, and its operations rely heavily on Earth-based mission control and crew involvement for both routine and specific operational activities. However, the current EMC architecture assumes habitation systems will be dormant on time scales of months to years due to the pre-deployment of exploration assets. Therefore, advanced autonomous mission capabilities are required to shift spacecraft operational control to both on-board systems and advanced robotic systems. These capabilities will minimize crew involvement in routine operational activities during intermittent occupation of a long-duration habitat and provide reliable architectures to maintain habitation systems during times of dormancy.

NASA’s pioneering of Mars will utilize these autonomous and robotic capabilities to expand the boundaries of human exploration, as a sustainable presence on the surface requires humans to successfully reproduce and mature in a partial gravity environment independent from Earth intervention. Before significant investment is made in capabilities leading to such pioneering efforts, the challenges of multigenerational mammalian reproduction in a partial gravity environment need to be investigated. Humans may encounter reproductive challenges in gravity environments different than Earth’s, as gravitational forces may disrupt mammalian life cycle processes and actively shape genomes in ways that are inheritable.⁴

To date, mammalian reproduction research efforts have focused on better understanding the effects of microgravity on rodent reproduction. This research provides insight into challenges associated with mammalian reproduction and maturation (breeding, birthing, nursing/weaning, and offspring development) in microgravity as compared to Earth’s gravity.⁴⁻¹⁰ For example, select short-duration (≈ 2 weeks) life cycle experiments conducted aboard the Space Shuttle indicated the mammalian maternal-offspring system is sensitive to changes in gravity, particularly during the early postnatal period when infants are dependent upon maternal care for their survival.^{4,8,9} Recent ground based simulated microgravity studies conducted using a clinostat showed a reduced birth rate in female mice that were implanted with healthy microgravity-fertilized and cultured embryos as compared to the Earth gravity control group.¹⁰

Long-duration (1-2 years) mammalian reproduction experiments are currently ongoing aboard the ISS. The Micro-10 investigation (P.I. Tash) is the first in-vitro study of mammalian sperm in microgravity that compares to Earth-based human in vitro clinical and research tests. The Space Pups experiment (P.I. Wakayama) is used to study the effects of space radiation on mammalian reproduction by storing freeze-dried mouse sperm aboard the ISS for up to two years, and then using the sperm to fertilize mouse eggs on Earth to produce mouse pups. Recently, Rodent Research-1 demonstrated specific hardware capability to support rodent research for long-duration experiments aboard the ISS.⁴ Please refer to the first subject paper published by this group of authors (Ref. 11 - hereafter referred to as Paper I) and cited publications for discussions of additional rodent based research focused on mammalian reproduction and maturation.

These highlighted short- and long-duration studies are experiments that evaluate specific steps within the mammalian life cycle, but do not evaluate the comprehensive mammalian life cycle. Understanding mammalian reproduction and maturation challenges require evaluation of the full life cycle. For this reason, the Rodent Research-1 experiment recently flown aboard the ISS is the first experiment in a series of experiments designed to study the full mammalian life cycle in microgravity.⁴ Research conducted on the reproductive challenges mammals may encounter in partial gravity is the next step toward a comprehensive understanding of the mammalian life cycle in multiple gravity environments.

A partial gravity mammalian reproduction experiment requires two things: 1) a long enough duration in which to study the full life cycle, and 2) a partial gravity environment in which to conduct the experiment. However, there is no testing platform for rodent research experiments in a partial gravity environment. Partial gravity mammalian reproduction research should be conducted prior to the late 2020s in order to

inform design decisions on future human Mars mission systems during Proving Ground evaluations and planning. Permanent surface settlements may be infeasible if partial gravity reproduction challenges are too great to overcome, leading to alternative strategies that focus on planet-orbiting facilities that simulate gravity more representative of Earth.

Therefore, a study was conducted at NASA Langley Research Center (LaRC) during which a conceptual, long-duration (one-year or greater), autonomous habitat was designed to house mice in a partial gravity environment. This study, the Multigenerational Independent Colony for Extraterrestrial Habitation, Autonomy, and Behavior health (MICEHAB), investigated the challenges associated with partial gravity mammalian reproduction. The objectives of the MICEHAB study were to 1) understand challenges associated with designing an artificial gravity habitat that supports the reproduction and maturation of a large animal colony, 2) identify mission architectures and operational concepts to transport and maintain such a facility, and 3) identify fundamental science considerations for mammalian reproduction studies to inform vehicle design.

Investigating these challenges provides an opportunity to design a mission concept and facility that uniquely address the combined effects of long-durations, partial gravity, and autonomous and robotic operations, while at the same time test biological responses to partial gravity with an emphasis on reproduction. The MICEHAB mission concept is designed to use rodents as human analogs to gather biological and systems data in a relevant environment applicable to future settlements on Mars. The MICEHAB mission concept is also designed to infuse a deep space, partial gravity testing platform into the EMC architecture in order to prove out human exploration class hardware.

A facility such as MICEHAB is capable of being delivered to the cislunar Proving Ground in the late 2020s and will employ advanced capabilities and technologies that are synergistic with human exploration. MICEHAB will enable future human exploration missions through 1) an improved understanding of mammalian reproduction in partial gravity and 2) demonstrations of advanced capabilities to live autonomously. Therefore, the scope of the MICEHAB study is defined to be consistent with Mars element design timelines and implementation, and to utilize existing or planned elements as much as possible. MICEHAB will provide strategic direction to inform whether Mars is a good candidate for human settlement, and lessons learned will guide development of current and future human exploration missions.

The MICEHAB concept study was funded through an Investment Award sponsored by the Systems Analysis and Concepts Directorate (SACD) of NASA LaRC. These awards are used to investigate novel ways of achieving NASA's missions while developing new capabilities and expertise within its workforce. The MICEHAB team is a multidisciplinary team of engineers, scientists, and students who worked over the course of one year to design and demonstrate key aspects of this concept. Kickoff of this activity began with a team brainstorming session, during which the following high-level study categories were identified: autonomy, fundamental science questions, vehicle considerations, biological science, and mission destinations. The team then attended a series of four self-facilitated sessions in the NASA LaRC Engineering Design Studio to rapidly advance design concepts within the high-level study categories.

These categories were used to formulate driving considerations that were then used to define the architectural trade space and potential mission strategies. Paper I describes in detail the MICEHAB trade space and mission strategies that are used to define the mission concept and baseline spacecraft design. Paper I also details the population and habitat sizing models, interior layout and radiation analysis, habitat layout, and animal enclosures that all make up the first version of the concept habitat. The two robotic systems housed within the habitat (one to perform maintenance and one to perform medical care) and the autonomous habitat functions are also described in Paper I. The first version of the integrated model habitat and robotics system created to demonstrate key aspects of the design round out the discussion in Paper I.

This paper begins in Section 2 with a review of the mission design. Highlighted are updates to the baseline mission and spacecraft design concepts following further analysis and trade studies. Section 3 provides analyses of the integrated system trades between the multiple elements which make up the MICEHAB vehicle to address overall feasibility and identify potential opportunities for a more integrated design. The latest iteration of the habitat robotics design and a conceptual design example for autonomous care of crew and systems is described in Section 4, and conclusions and future work are described in Section 5.

II. Mission Overview

Considerations were established in order to limit the applicable mission design space and identify the functionality of the MICEHAB facility, which is both an animal habitat and a space vehicle. These consid-

Table 1. MICEHAB driving considerations

Biological	Multigenerational	Spacecraft
<ul style="list-style-type: none"> • C57BL/6J mice selected as preferred species • Minimum of six breeding females per generation required for statistical significance • Experiment lasts three generations. Generation ≈ 90 days (Conception to mating maturity). Mission duration ≈ 300 days 	<ul style="list-style-type: none"> • Data-specific life cycle progression to confirm successive milestones • Microgravity, partial gravity, and full gravity test analogs to ensure partial gravity effects isolated • Routine animal observation by a veterinarian and animal health and well-being following defined protocol 	<ul style="list-style-type: none"> • Facility must carry all of the required observation and autonomous care • Telerobotic operations may be required to achieve desired medical and science data • Facility design must attempt to isolate the effects of partial gravity from other environmental factors
<ul style="list-style-type: none"> • Earth return of deceased and live animals (Crosscutting consideration) 		

erations were grouped into categories (biological, multigenerational, and spacecraft) and then were used to drive the formulation of three applicable mission strategies. Driving biological considerations were used to select an appropriate rodent species, to determine a statistically significant number of samples, and to determine experiment timelines based on species breeding practices. Driving multigenerational considerations regarding studies of the comprehensive mammalian life cycle were used to define habitat functionality and operational constraints, and driving spacecraft considerations were used to define vehicle specifications as well as additional habitat specifications. Table 1 lists all driving considerations.

One of the three missions strategies was selected as the baseline concept design because it balances feasibility and Earth independence with moderate in-situ science. Other options focused more on either science or Earth independence. Please refer to Paper I for detailed information regarding the driving considerations and mission strategy options. The baseline mission concept design is presented here.

A. Baseline Mission Concept Design and Concept of Operations

MICEHAB is designed to support a long-duration mission in a partial gravity environment analogous to planetary destinations. There are four elements which make up the MICEHAB vehicle: a habitat housing the rodents, a service module providing power and propulsive control of the vehicle, a boom/tether connecting the service module and habitat that enables artificial gravity, and a free-flying communications asset that provides accurate communications transmission/reception from Earth.

The vehicle will nominally launch as a co-manifested payload on the NASA Space Launch System (SLS) to a lunar distant retrograde orbit (LDRO), a stable lunar orbit, where the service module will insert the spacecraft into the desired orbit. The vehicle will then deploy using a boom or tether system attached to the service module at one end, and the habitat at the other end as shown in Figure 1.

Solar array panels are attached to a node located at the center of mass. The entire facility will spin up about the center of mass using a Reaction Control System (RCS) attached to the service module and the habitat spacecraft. The rotation will induce a Mars-like partial gravity ($3/8$ Earth gravity) with a spin rate analogous to acceptable limits for humans. This requires a 85.0 m minimum radius of rotation and a maximum angular velocity of approximately 2.0 revolutions per minute (rpm).¹²

After each year of operation, the vehicle will spin down and the boom/tether will retract both the habitat and the service module back toward the center of mass. The vehicle will then transfer to the planned EMC cislunar human habitat and dock, and the MICEHAB central robot will transfer samples to a caretaker robot aboard the human habitat (see Figure 1). The yearly rendezvous with the cislunar habitat will coincide with

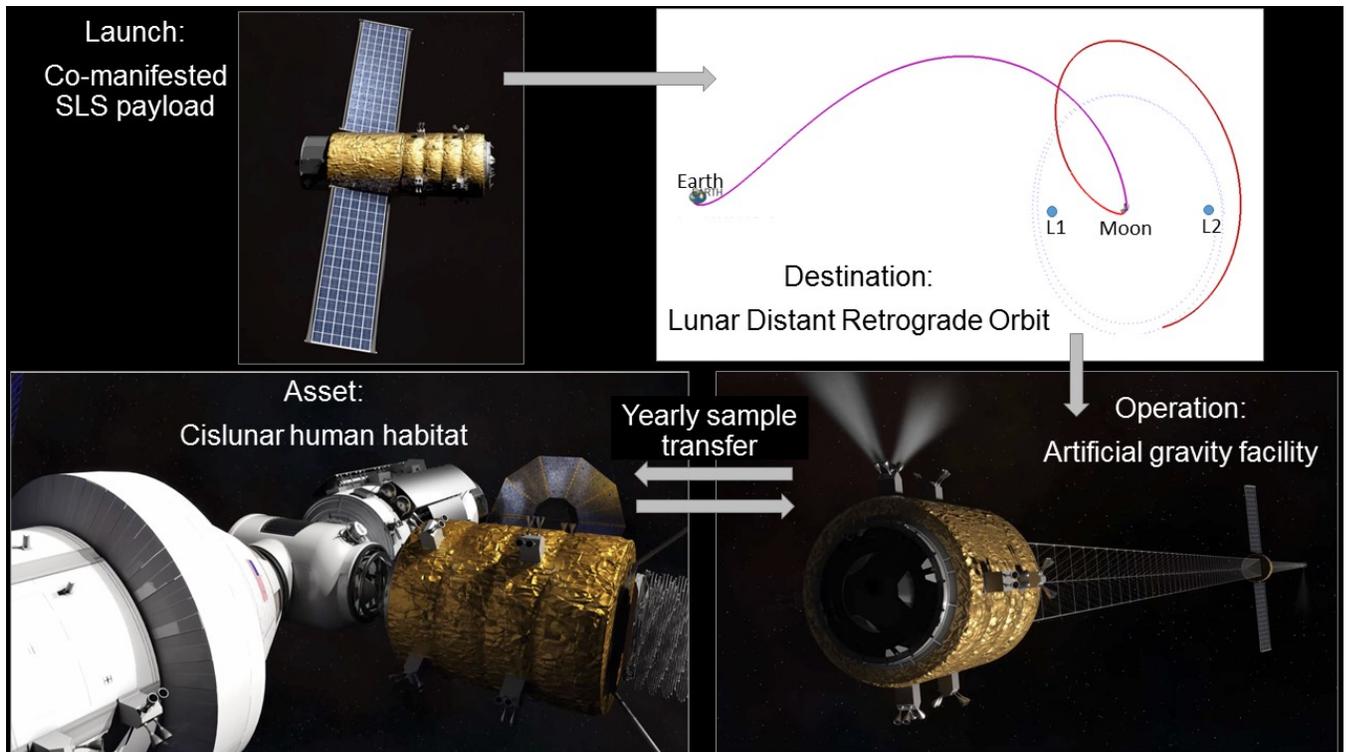


Figure 1. Concept of operations. Launch: MICEHAB vehicle with the boom in the stowed configuration. Destination: Service module inserts the spacecraft into the desired orbit. Operation: MICEHAB vehicle in the deployed configuration shown with the habitat on the near end, the service module on the far end, and the solar arrays attached to a node at the center of mass. Asset: MICEHAB vehicle docking to a notional planned cislunar human habitat. Image: NASA/LaRC 2015

planned human missions in order for the MICEHAB samples to be loaded onto the Orion capsule for Earth return with the crew. Maintenance on the MICEHAB will also be performed if required while docked. Additionally, logistics for habitat maintenance or animal care will be transferred from the human habitat to the MICEHAB during this time.

The MICEHAB vehicle will then undock and return to its orbit location, which trails the human habitat in a similar orbit. It is assumed that transfer time to and from the human habitat will be less than one week. The actual transfer time will depend on the designated human habitat keep out zone, which is a prohibited area near human habitats. The orbit phasing will be selected to ensure the shortest travel time from the MICEHAB orbit location to the human habitat. Once back to its original location, the MICEHAB facility will redeploy and resume its rotation and partial gravity operations. The yearly transfer to the initial cislunar habitat will continue for 10 years allowing for 10 full cycle experiments each based on a ≈ 300 day mission duration.

A communications asset will launch attached to the facility and will be inserted in the same orbit to trail the MICEHAB. The facility will spin with its solar panels continuously facing the sun to generate the power required to keep the habitat operational. The communications antenna attached to the habitat will point toward the communication asset, which acts as a communication relay for the habitat. Maximizing the communication capability of the MICEHAB is critical to its science mission.

Each of the four MICEHAB elements is designed to operate as an integrated system to provide a semi-autonomous platform to study biological responses to spaceflight environmental stimuli. The following descriptions of these elements assume one possible distribution of vehicle functions, but it is understood that alternate, more preferable, better performing distributions of functionality may exist and should be investigated in future concept designs.

A.1. Habitat

The habitat provides a pressurized environment and functionality to support a colony of up to 200 rodents for up to a year without resupply. This habitat must include life support and thermal management systems, vehicle subsystems, equipment necessary for autonomous care of the rodents, and equipment required for the primary scientific investigation. It must also include the functionality to operate semi-autonomously in cislunar space, including attitude and stack control. It must also provide a docking hatch for yearly visits to planned cislunar crewed habitats for sample collection, repair, and resupply. The initial design for this habitat was presented in Paper I and fundamental aspects are summarized here.

Individual Enclosures: The MICEHAB design consists of individual housing enclosures to allow for controlled breeding and to reduce aggression between males. This approach is different than current existing microgravity rodent habitat designs that employ behavior conditioning to mitigate animal aggression that occurs in colocated living spaces.^{4,13} The floor and volume sizing for the MICEHAB enclosures, 8 inches x 8 inches floor and 5 inches high, meet the space requirements for a female plus a litter set forth by the *Guide for the Care and Use of Laboratory Animals* for comfortable quarters for mice.¹⁴

Habitat Layout: Eighteen enclosures are arranged radially. The radial pattern of enclosures are stacked to 11 levels creating an open column in the center of the habitat where the maintenance robotic system is housed. This robotic system will move the enclosures in and out of bays to position the mice for mating and to take the mice to the medical suite where the medical robot will perform sensitive veterinary and science related functions. The mice are arranged in mating trios where a male mouse is housed between two female mice. Breeding is controlled by allowing the mice to interact using mating tunnels that connect adjacent enclosures.

Water, Food, Exercise, and Nesting: Inside the enclosures, lixit valves (connected to a centralized automated watering system), similar to those used in laboratory vivariums, and solid food bars are used to provide for the mice's hydration and nutrition.^{13,15} Each enclosure also has an exercise wheel to help maintain health in a partial gravity environment, as well as a nesting igloo available for the female and pups to huddle for temperature regulation and suckling.

Enclosure Surfaces: The interior surface area throughout the enclosure is almost entirely covered in a metal grid mesh similar to mouse enclosures on the ISS to allow easy maneuvering for the mice during microgravity. However, it is recommended to provide solid-bottomed caging with bedding for rodents as the rodents prefer to rest on a smooth surface.¹⁴ Evidence suggests that rodents show eliminative behavior and only deposit feces in specific locations to avoid soiling their resting location.¹⁶ For these reasons, the back half of the enclosure floor will be solid plastic and contain the nesting and eating areas.

Waste Removal: A disposable waste tray located below the front half of the metal grid mesh floor collects urine and feces and is removed by the maintenance robot on a monthly basis to reduce the ammonia levels from the urine. Used disposable waste trays can be stored and preserved for analysis upon sample return.

Ventilation and Lighting: The ventilation system will consist of a centralized air flow control system, which will distribute filtered air to each individual enclosure. This is necessary to prevent olfactory triggers which would induce aggressive or breeding behaviors in other mice. Air from the enclosures will be exhausted into the cabin of the habitat. Positive air pressure will be maintained in each enclosure to ensure that unfiltered cabin air does not enter an enclosure. The lighting system will consist of a series of light emitting diodes (LEDs) to illuminate the interior of the habitat and enclosures. These LEDs will be diffused across a surface to avoid point sources of light, and will limit the variance in light intensity to 20%.

Health and Science Observations: Visual observation is an important aspect of the mission. Optical and infrared cameras, located in each animal enclosure bay, will be utilized to obtain data required by the veterinarian and to obtain data desired for scientific purposes.

Medical Products: Specifications for the medical suite are determined by the veterinary and science return requirements provided in Paper I. Approximately 45 medical conditions similar or equivalent to those experienced by humans during spaceflight and ≈ 70 measurements for science and medical objectives are identified. These measurements and conditions combined with surveys of cryogenic storage and teleoperated surgical equipment were used to formulate an equipment list and habitat design considerations to include: veterinary visual observations; vitals measurements; waste collection and storage; food and water consumption measurements; physical exams for reproductive development; dissection and preservation; and sample return.

The combined MICEHAB vehicle (habitat + service module + boom/tether + communications asset) needs to be on the order of 10 metric tons (mT) in order to meet the projected mass requirement of

the SLS co-manifested cargo capacity. Therefore, it is critical to minimize the mass and size of the habitat. Integration analysis of the initially designed habitat with the other three elements resulted in the development of an updated habitat with performance shown in Table 2. Structural reductions combined with increased utilization masses for attitude control moment gyros to enhance sun pointing of spinning arrays and counter gravity-induced precession resulted in a mass increase of ≈ 300 kg. The performance in Table 2 represents a full capability habitat for year-long missions accruing 10 years of total operation, but scaled down versions are also acceptable.

Table 2. Updated habitat parameters and mass breakdown

Design Parameters		Mass Breakdown	Mass, kg
Pressurized Volume	18.9 m^3	Structure	1,080
Habitable Volume	6.1 m^3	Protection	60
Atmospheric Pressure	101.4 kPa	Power	480
Crew Capacity	200 mice	Control (ACS/RCS)	310
Crew Quarters (enclosure) ¹⁴	0.006 m^3	Avionics	330
Crewed Mission Duration	365 <i>days</i>	ECLSS	870
		• <i>Air Subsystem</i>	430
EOL Power Required	6 kW	• <i>Water Subsystem</i>	30
Total battery energy storage	18 $kW-h$	• <i>Other</i>	210
Number of Batteries	2	Thermal Control System	340
		Crew Equipment	400
ECLSS Closure - Water	Open	Utilization	750
ECLSS Closure - Air	Partially Closed	Growth	1,370
		DRY MASS SUBTOTAL	5,990
Habitat Structure	Rigid Cylinder	Logistics	590
Habitat Length	3.71 m	ECLSS Consumables (Nominal+Contingency)	500
Habitat Diameter	2.56 m	Reserve and Residual Propellant	70
		INERT MASS SUBTOTAL	7,150
Mass Growth Allocation	20%	Propellant	290
Project Manager's Reserve	10%	TOTAL WET MASS	7,440

A.2. Service Module

The service module is a commercially available propulsive spacecraft bus, modified to provide the necessary storable propellant to perform propulsive maneuvers. Assuming a 10 mT SLS co-manifested cargo capacity on a trajectory to LDRO, the insertion burns will be performed by a commercially available service module modified for MICEHAB operation. To minimize the system complexity and to improve the lifetime of the service module, storable propellants are chosen instead of cryogenic propellants for LDRO insertion, MICEHAB spin-up/spin-down, and rendezvous and phasing maneuvers. The service module serves as the counter mass for the MICEHAB for the duration of the artificial gravity mission. The RCS on the service module will be utilized in conjunction with RCS systems on the MICEHAB module to produce the thrust required for spin-up/spin-down.

A.3. Boom/Tether

As stated previously, to enable partial gravity environments for the MICEHAB facility, the habitat facility and a counter mass will both rotate about a common axis such that the mice experience a Mars-like artificial

gravity environment of 0.38 g. The counter mass and habitat have a deployable structural connection (e.g. boom or tether) that keeps the facility in a fixed rotational plane (akin to a dumbbell configuration) and also serves as a signal conduit for subsystems, such as power, guidance, navigation, and communications.

The acceleration due to the artificial gravity in a rotating reference frame is dependent upon the angular velocity and the radius of rotation (e.g. the distance from the MICEHAB facility to the system center of mass/axis of rotation). Previous research has investigated the neurovestibular effects of the fictional Coriolis force in rotating reference frames of humans for comfort and habitability in gravity environments, and several authors have agreed on a generally accepted comfort zone for humans.^{12,17} Accordingly, a minimum artificial gravity environment of 0.38 g can be achieved with a 85.0 m minimum radius of rotation and a maximum angular velocity of ≈ 2.0 rpm.¹² The purpose of the MICEHAB concept is to inform future crew health and performance of human habitat designs and missions; however, the Coriolis effects on mice in a partial gravity environment are currently unknown. Therefore, the baseline MICEHAB design follows the current limits and comfort zone for humans.

Paper I describes two preliminary concepts that were investigated from previous studies in the literature for the deployable structural member connecting the habitat facility and the counter mass in the MICEHAB design: flexible, rope-like tethers^{18,19} and rigidizable booms. In this research, a trade study for the boom and tether concepts was completed and included material parameters, as well as the complexity of packaging, deployment, and retraction mechanisms. In general, a flexible tether can only apply tension forces, cannot constrain the system in one dimension, and requires more complex propulsion and control. Rigidizable booms in general have greater lineal density and stiffness parameters than flexible tethers. A total of four concepts were examined for the trade study: three for flexible tethers and one for a boom concept, as shown in Table 3. The coilable rigidizable boom option is chosen as the model for further calculations and analysis, such as the integration of the boom with other elements and subsystems, the material performance in deep space environments, and the structured dynamic response during rendezvous and rotation of the facility, because it will require less propulsion to control, be easier to restow after deployment, and has more structural stiffness.

Table 3. Boom and tether concepts investigated for trade study

	Hoyt Tether ²⁰	Orbital ATK Coilable Boom ²¹	EDDE Tether ²²	LaRC Kevlar Straps ²³
Lineal density (g/m)	26.6	82.0	—	—
Material composition	Dyneema SK75	Graphite fiber / epoxy	Aluminum core with fiber composite layer	Kevlar or Vectran
Tensile strength	30.0 kN	Varies with diameter up to 400.0 kN	—	—
Deploy- ment/retractions mechanism	Orbital winch	Lanyard and motor	—	—
Notes	—	Deployed in flight missions	Operation limited to LEO	Creep at >50% of ultimate load

A.4. Communications Asset

The communication and navigation system aboard the MICEHAB spacecraft will be an integral aspect of the design for creating an autonomous partial gravity environment. The communication architecture must be able to both receive command uplink and effectively point at the Earth for data downlink, without impeding the spacecraft’s continuous rotation. The current concept utilizes a waypoint communications relay asset to receive transmissions from the spacecraft and to pass data and information to Earth. A relay is beneficial because accurately pointing to Earth from a continuously rotating facility in LDRO may be challenging if the spacecraft encounters high-rate motion disturbances. Pointing to a much closer target of

a relay satellite and allowing the relay satellite to then accurately point to the Earth is a more practical option. The spacecraft's relay antenna will be located along the axis of the spacecraft's rotation to provide a continuous communication link to the relay satellite (see Figure 2).

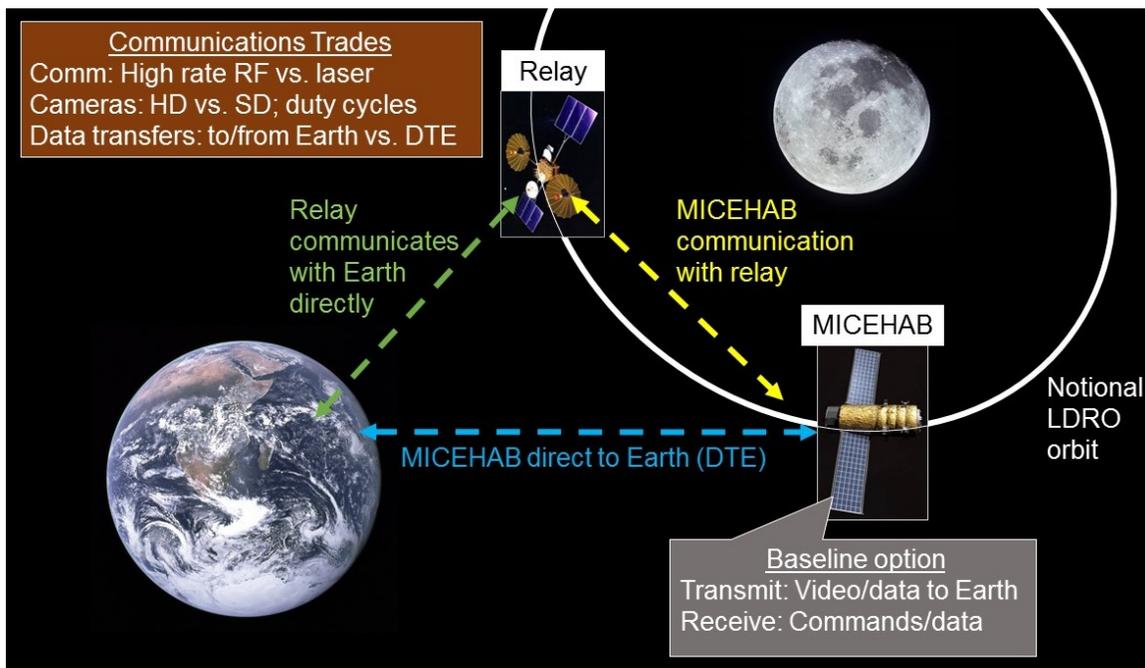


Figure 2. MICEHAB communications architecture (notional). Image: NASA/LaRC 2015

The MICEHAB spacecraft will also be outfitted with an additional antenna capable of receiving uplink directly from Earth. Since ground stations are relatively independent of sizing and power restrictions aboard interplanetary communication systems, the uplink signal will be powerful enough to bypass the waypoint relay and reach the spacecraft directly. Sending high-rate uplink directly to the spacecraft is common practice in order to send and receive emergency commands with a higher fidelity. The waypoint relay will be available to act as an auxiliary system for signal uplink if the Earth is unable to effectively contact the spacecraft. Additionally, if the high-rate antenna is blocked or the field of view disrupted between the relay or Earth ground stations during the yearly transfer of MICEHAB to the initial cislunar habitat, then high-rate communications may be paused while low-rate communications may still be enabled.

The communications relay waypoint will be equipped with a reception antenna pointed toward the MICEHAB and a transmission antenna focused on Earth. Additional trades will occur to determine the feasibility of using optical laser communications, which will dramatically increase the data transmission throughput to Earth. Refer to Table 4 to see the various communications technology options and capabilities.

MICEHAB will be equipped with at least 600 cameras for surveying the mice during mission duration. These cameras will be a mixture of high-definition (HD) cameras and standard-definition (SD). Telemetry data will be delivered at a rate of ≈ 100 megabits per second (Mbps) using a radio frequency (RF) communications relay. This assumes that only three HD and two SD cameras will be operating simultaneously at any given time. The rest of the camera data will be compressed with a lossy or lossless compression method and then sent via downlink afterwards. Please refer to Table 5 for camera data and compression trades.

All data processing occurs first aboard the MICEHAB spacecraft and allows the communications waypoint asset to act only as a point of continuing communication (bent-pipe relay). The 600 cameras will generate a large volume of data and will likely require the cameras to operate on duty cycles using compression techniques to reduce the data volumes for both storage and for telemetry communications with Earth. The remaining cameras will be assessed and assigned operating times, duty cycles, and compression selections prior to storage of the images and videos. Data from science experiments, sensors to monitor the mice, and health and status monitoring of the MICEHAB spacecraft and subsystems, can also be selected for telemetry transmission or for on-board data storage.

As seen in Table 5, the last row represents the baseline options selected to represent camera use and

Table 4. Telemetry communications trade options

	RF Comm	Optical Comm		Optical + RF Comm
Legacy Technology	X-band & Ka-band ^a	Lunar Laser space terminal ^b	Lunar cubsat	Optical laser to GEO relay; RF GEO-relay to Earth
Primary telemetry data rate (Mbps)	50-100	40-620	150-200 (Day/night dependence)	200-622 (laser); 150-300 (RF)
Component(s) mass	TBD	TBD	3 kg	TBD
Component(s) power & size constraints	TBD	TBD	10 W; 1 U	Both
Corresponding ground system	DSN 70m/34m antennas	Lunar laser ground terminal	1m ^c	1m aperture ^c ; GEO relay ^d

^asmall deep-space transponder

^bLunar Atmosphere and Dust Environment Explorer

^cOptical Communications Telescope Laboratory

^dLaser Communications Relay Demonstration

Table 5. Baseline Camera Data Rates and Compression Options

	No Compression	Lossy Compression (H.264) \approx 48:1	Lossless Compression (JPEG 200) \approx 24:1
High Definition Camera	\approx 1490 Mbps	31 Mbps	62 Mbps
Standard Definition Camera	\approx 180 Mbps	3.7 Mbps	7.4 Mbps
MICEHAB Operation Mode	N/A	\approx 100 Mbps	\approx 201 Mbps

telemetry communications. Two options exist: (a) \approx 100 Mbps is needed to operate five cameras while employing an industry standard lossy compression, or (b) \approx 201 Mbps is needed to operate five cameras while employing industry standard near lossless compression. The baseline telemetry from MICEHAB to the communications waypoint relay assumes a \approx 100 Mbps data throughput (additional margin will exist to handle instrumentation data). Depending on the communications technology available (RF versus optical laser), communications may be enhanced to handle additional cameras and/or science data as part of the telemetry. Future trade studies will involve camera(s) operational scenarios, duty cycles, and types of compression.

B. Mass Summary of MICEHAB Elements

Preliminary sizing estimates of the four described MICEHAB elements are used to perform a feasibility analysis. These sizing estimates provide the opportunity to calculate element masses based on the current mission concept design (see Table 6). The element masses total 11 mT, while the SLS co-manifested cargo mass capability is 10 mT. Refined element masses based on additional trade studies and integrated systems sensitivity analysis will likely lead to a design that meets the 10 mT limit. Therefore, it is assumed that the current architecture is reasonable for the MICEHAB conceptual design.

III. Integrated Elements Sensitivity Analysis

To better understand the relationships between the length and mass of a boom/tether system, the spinning facility propulsion requirements, and the crew comfort zone/Coriolis effects, a spreadsheet-based analytical tool was developed in which parameters of the MICEHAB system can be varied to size the boom

while maintaining system constraints. This sizing tool allows for quick design space exploration for changes to the mass, volume, and other subsystem properties of the MICEHAB vehicle.

Using the boom sizing tool, the impact of changes in different input parameters on the output parameter of interest can be determined. The input parameters (length of the counter mass, length of the boom, boom specific mass, length of the MICEHAB, mass of the MICEHAB, and time required to reach the operational rotational rate) were varied within defined ranges corresponding to the MICEHAB trade space. The boom length and specific mass and the center of mass length parameters were varied according to manufacturer expectations regarding the boom and packaging options, the MICEHAB length and mass parameters were varied according to launch vehicle constraints, and the spin time parameters were varied until asymptotic behavior was achieved. The resulting scatter matrix plot is shown in Figure 3 and shows the variation of the input parameter in each column and the output parameter of interest in each row. The vertical scatter in each plot is a result of variable multiple input parameters. The outputs are the thrust required at the MICEHAB and the counter mass to balance the rotational spin of the entire spacecraft, as well as the total ΔV required to achieve the rotational spin.

Table 6. Element mass summary

Element	Estimated Mass
Habitat	7.5 mT
Service module	2 mT
Boom/tether	<1 mT
Communications waypoint	1.5 mT
TOTAL	11 mT

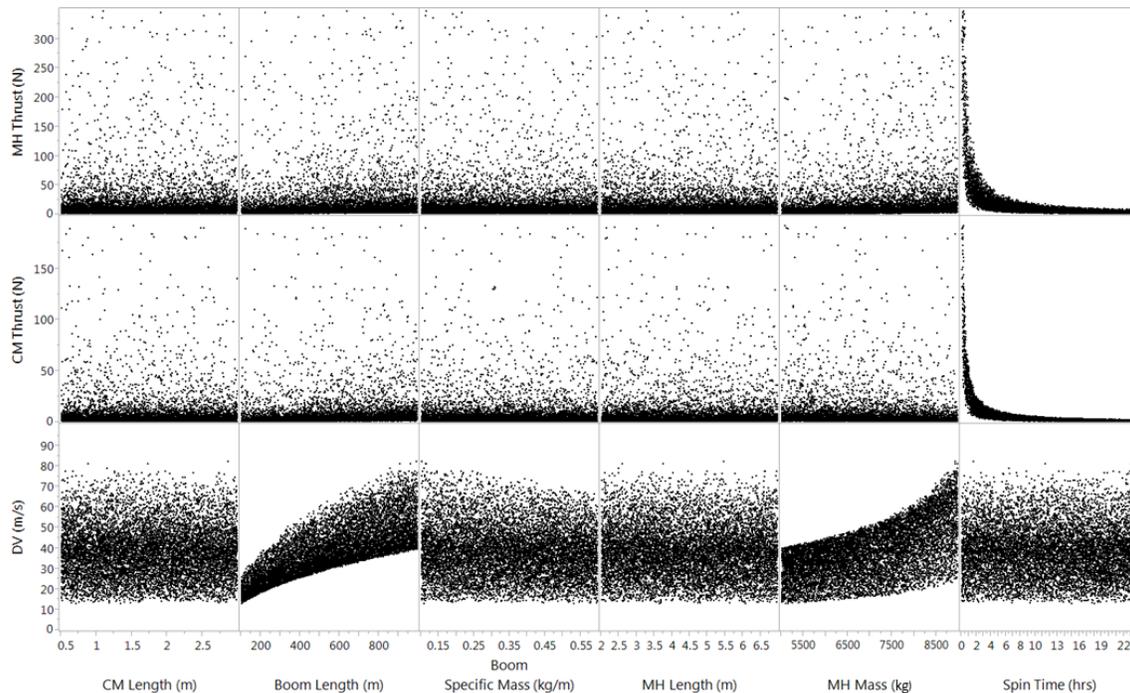


Figure 3. Varied input parameters and the resulting scatter matrix plots. Image: NASA/LaRC 2015

As Figure 3 shows, the thrust required at either location to achieve the desired rotation is only a function of the required spin time. The relationship between the thrust and time required is exponential in nature. As the spin time required to achieve the desired spin rate decreases, the thrust required increases exponentially. The knee of the curve for this exponential relationship resides around 2 hours of required spin time; thus, further increase to the spin time requirement does not reduce the thrust required significantly.

The total ΔV required to achieve the spin rate is correlated with both the length of the boom and the mass of the habitat. The relationship between the input and the output variable is non-linear in nature. Figure 4 shows the constant contour plot of the ΔV required as a function of both of these variables. The plots shows a range of ΔV between 15 and 70 m/s to achieve the desired spin rate for the experiment. The

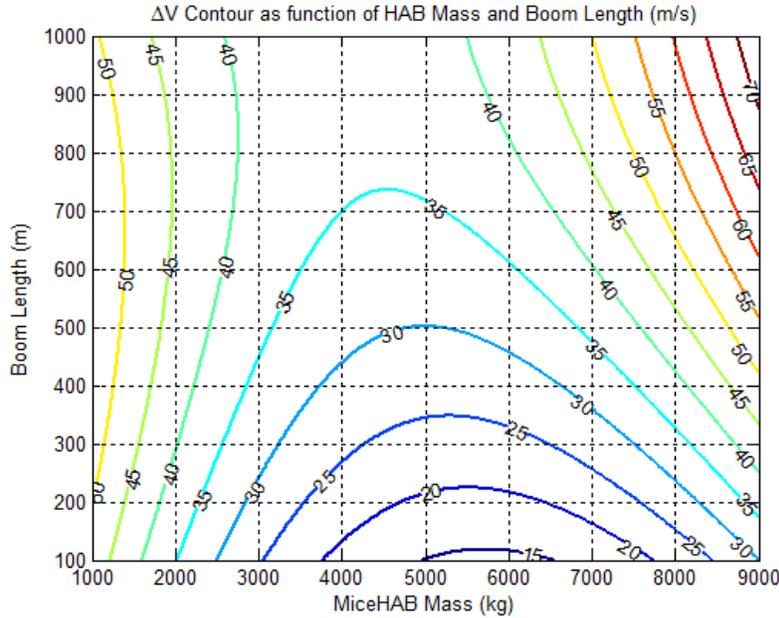


Figure 4. ΔV contour as function of the habitat mass and boom length (m/s). These ΔV s are only for spin up or spin down. Multiply the values by two for the total ΔV . Image: NASA/LaRC 2015

minimum ΔV required can be achieved with a habitat mass between 4,000 and 7,000 kg and total boom length less than 500 m.

For orbit insertion, the MICEHAB vehicle is assumed to be launched directly to trans-lunar-injection, where it will coast until a powered lunar flyby is performed to reorient the trajectory for LDRO insertion. Total propulsive cost for this maneuver is between 200 and 350 m/s depending on the duration of the total maneuver and the day of the month of the launch.²⁴ Transit time for this injection maneuver is between 8 and 13 days. While extending the duration from 8 to 13 days reduces the propulsive requirement by 20-30%, forcing the total injection time to longer than 13 days does not further reduce the propulsive requirements. Once the spacecraft is in LDRO, there is little to no propulsive requirement for orbital maintenance.

After one year of operation, MICEHAB will be required to de-spin and rendezvous with the prepositioned cis-lunar habitat to transfer samples and be resupplied for additional research. The phasing maneuver cost in LDRO depends on the separation distance of the target spacecraft and time required to achieve rendezvous. For phasing less than 20 days, the ΔV requirement can be upwards of 100 m/s if the target spacecraft is separated by 180 degrees of true anomaly.²⁴ The phasing ΔV can be reduced to 20 m/s if the phasing time is allowed to be more than 60 days. The service module needs to have enough ΔV capability to perform the insertion, spin-up/spin-down, and the phasing maneuver. For preliminary sizing purpose, the service module is required to have a minimum of 300 m/s of ΔV and a maximum of 500 m/s. Please refer to Paper I to learn more about the trajectory chosen for the baseline mission design.

IV. Robotics and Autonomous Systems

The latest iteration of the maintenance habitat robotics design is described in this section, as well as the updated corresponding demonstration unit. A conceptual design example for autonomous care of crew and systems is presented, along with a detailed description of the decision flow diagram of the integrated robot and autonomous systems. Please refer to Paper I for information about the first version of the maintenance robotics design (robotic arm attached to a platform structure) and about the baseline autonomous system architecture.

A. Robotics System

In order to better understand design requirements of the robotic system, a Quality Function Deployment (QFD) study was employed.²⁵ This study was used to identify the relative importance of all of the engineering

specifications based on a survey of an expert panel. This survey and subsequent rating system identified that reliability and arm capability were ranked very highly in the list with reliability being ranked the highest overall in importance.

The latest design iteration of the MICEHAB robotic system, using the information gathered from the QFD study, improves upon previous versions by simplifying the system and improving reliability. The overall design philosophy of this new version is to lean more heavily on the robotic arm capability rather than the platform. This new system utilizes a 7 degree-of-freedom (DOF) robotic arm that is fixed to a vertically translating platform. Previous versions had two additional degrees of freedom in which the platform rotated and the arm translated horizontally on the platform. These additional degrees of freedom were found to cause unnecessary complication, reduce reliability, and duplicate degrees of freedom in the arm.

Tables 7 and 8 identify the major design decisions considered for the robotics system. Option 1 is the design consideration chosen for both the platform and the arm. The arm is fixed to a platform and the platform is raised and lowered using ball screws. Ball screws were chosen for their high precision due to their zero backlash capability and are powered using DC brushless motors with position feedback control.

Table 7. Robotics platform design options

Design consideration	Option 1	Option 2	Option 3	Reasoning for option selection
Platform DOF	1	2	3	Lower DOF improves accuracy and reliability
Rotational to linear conversion	Ground ball screw	Rack and pinion	Acme lead screw	Zero backlash, high accuracy and high efficiency
Actuator	Servo motor (brushless)	Stepper motor	Brushless w/feedback	Closed loop, NASA-STD-5017A:A.2.4.1.3
Motor gearing configuration	Harmonic drive	Planetary drive	Parallel shafts	Zero backlash and compact design
Linear guidance	Linear triboplastic bearing	Linear shafting with recirculating ball bearings	Caged ball profile rail	Self-lubricating and reliable

Table 8. Robotic arm design options

Design consideration	Option 1	Option 2	Option 3	Reasoning for option selection
Arm DOF	7	6	5	Higher capability
Construction material	Aluminum	Steel	N/A	Lower mass
Enclosure interface	Quick-disconnect	Forklift	Gripper	Higher capability

The robotic arm uses an automatic tool changer interface in order to change end effectors for different tasks. This interface allows for electrical as well as pneumatic lines for the end effector to be connected and disconnected automatically by the robotic arm. This enables the use of complex end effectors such as a fully articulated robotic hand. By attaching a tool changer interface to the front of the animal enclosure, the enclosures can also be moved directly by the arm without the need for an end effector to pick up the enclosures. Figure 5 shows the computer aided design of this concept.

Once the preliminary design was completed, the second and the third versions of the demonstration unit were constructed as proofs of concept. The version 3 proof of concept is described here and aims to emulate, at a half scale, the preliminary robotic platform and arm design in function, although the hardware used is different. A comparison of the preliminary design to the version 3 demonstration is shown in Table 9. Please refer to Paper I for a description of the version 1 proof-of-concept demonstration. Version 2 was an intermediate design and is not discussed in this paper.



Figure 5. Cross-section of conceptual robotics design. Image: NASA/LaRC 2015; LBR iiwa 14 R82 Robotic arm image credit: KUKA Robotics

Table 9. Robotic platform and arm preliminary designs compared to the version 3 demonstration proof-of-concept.

Design consideration	Preliminary design	Proof-of-concept
Platform DOF	1	1
Rotational to linear conversion	Ground ball screw	Acme lead screw
Actuator	Servo motor (brushless)	Stepper motor
Motor gearing configuration	Harmonic drive	None
Linear guidance	Linear triboplastic bearing	None
Arm DOF	7	5
Arm construction material	Aluminum	Aluminum
Arm-enclosure	Quick-disconnect	Quick-disconnect

Figure 6 shows how the proof-of-concept can demonstrate the ability to move animal enclosures around the entire interior volume of the habitat. It also demonstrates the concept of using a quick-disconnect system as the arm-enclosure interface, thus causing the enclosure to become the end effector of the robotic arm. Automatic end effector changing of the robotic end effector was also demonstrated.

Future work involves integration of the autonomous control system into the proof-of-concept demonstration in order to determine feasibility of a fully autonomous system. Additional future feasibility studies involve design and integration of major habitat systems such as the water system, food system, and camera system with the robotic system.

B. Autonomous Systems

Autonomy is accomplished by automating vehicle functions and by transitioning responsibilities from the Earth to the spacecraft. Work on the MICEHAB autonomous system design since Paper I focused on two areas: understanding the viability of automating the care of animals with minimal reliance on Earth-based control, and describing the probability of various system states that dictate appropriate system responses. Certain environmental operations centered on crew care, by nature, require varied levels of autonomy and automation. The distinction between autonomy and automation lies in how a system can manage and continue normal operation in the presence of uncertainty given off-normal operating conditions. A system that is automated can robustly handle erroneous system states given a fully-defined decision tree, with specific error sets and remedy actions scripted which are fully deterministic.

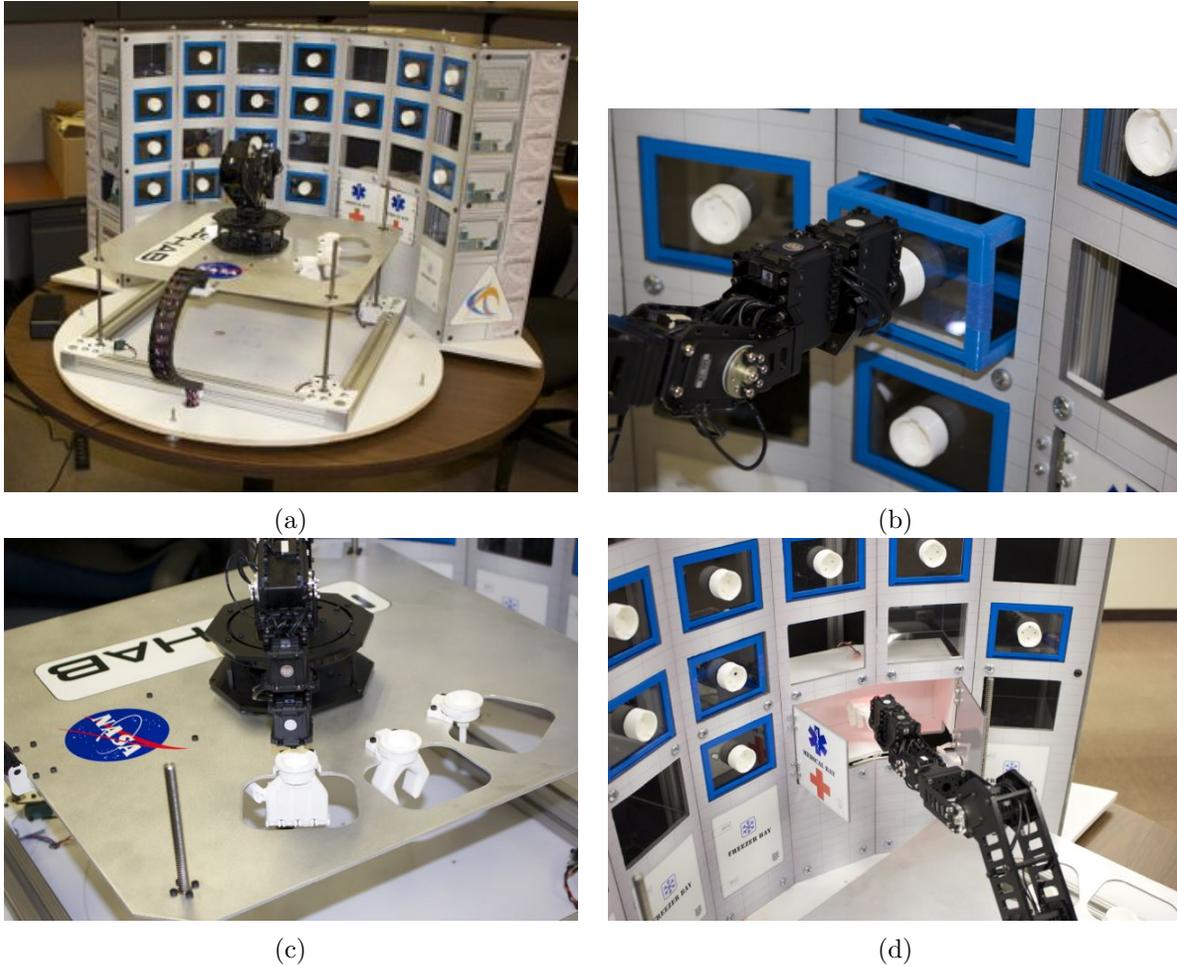


Figure 6. MICEHAB version 3 proof-of-concept demonstration: (a) Half scale model full view. (b) Quick-disconnect system for the arm-enclosure interface. (c) Automatic end effector changing. (d) Interactions with medical bay. Image: NASA/LaRC 2015

Behavior based systems require a hybrid approach because they are defined generally as systems that rely on learned behavior patterns and prior experience and handle unscripted off-normal events with no immediate clear path to resolution. Various architectures exist for encapsulating robotic system behaviors and many more are hybrid designs that effectively enable robust autonomous decision making.

These architectures, summarized here, can be categorized as: deliberative, reactive, and adaptive.^{26,27} A deliberative architecture is an architecture that has a structured, hierarchical design and relies heavily on planning prior to execution of scripted behaviors. Reactive architectures are designs that are concerned with the immediate response to surrounding stimulus in the problem space. Adaptive architectures deliberate internally in order to make the best decision given detected components of the workspace. Please refer to Ref. 26,27 for an in-depth exploration of behavior based systems architectures.

Advanced software architectures for robotic systems are required to achieve the desired level of autonomy on MICEHAB. Such an architecture is integrated into the habitat and vehicle design beginning in the conceptual phase and is implemented through a sophisticated framework. A hybrid deliberative/reactive adaptive system is chosen for MICEHAB, because this system capitalizes on the benefits of a fully scripted decision tree learning capability that allows for robust decision making in the presence of uncertainty. The primary robotic software framework, Autonomous Entity Operations Network (AEON),²⁸ is depicted in Figure 7, which highlights the primary operations and examples for the MICEHAB crew care system. For a description of AEON and its development at the NASA LaRC Autonomy Incubator, please refer to Paper I and the references within.

The framework enables two distinct and parallel modes, encompassing automated operations and autonomous operations in a single implementation. The automation branch handles the day-to-day components of the habitat, running scripted and scheduled tasks on both the maintenance and medical robotic arms.

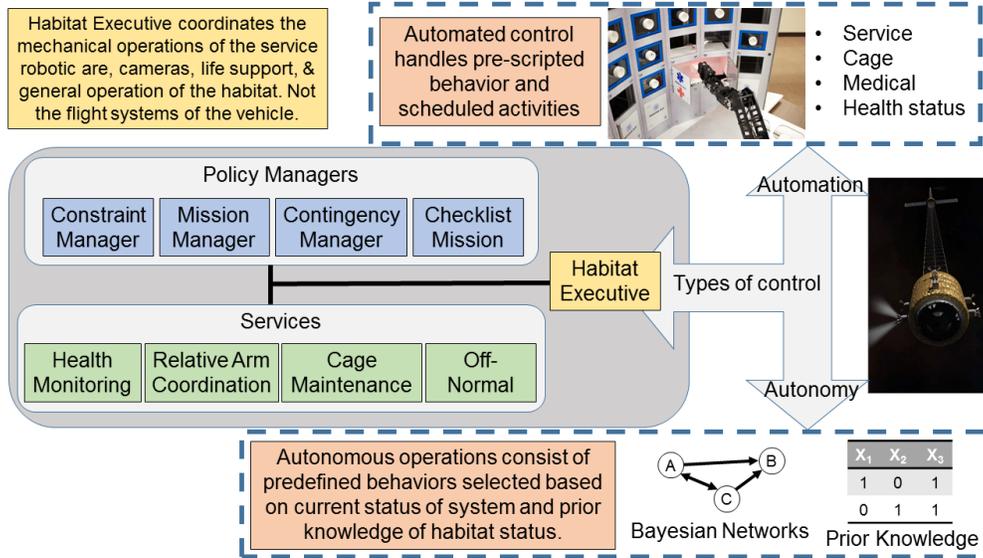


Figure 7. AEON Architecture depicts both Automation and Autonomy control branches. Image: NASA/LaRC 2015

Habitat enclosure cleaning, mice feeding, and medical scheduled operations are carried out as pre-planned by remote operators or scientists.

An example layout for MICEHAB operations (presented in Paper I) illustrates how independent programs run in a distributed and parallel manner while using a Data Distribution Service (DDS) protocol to send and receive messages throughout the network.²⁸ DDS is a standard for publish-subscribe middleware that brings new features and abstractions while guaranteeing inclusion of distributed software systems and systems of systems. Many vendors have implemented middleware suites that fulfill the requirements of the standard and provide other extended functionality and tooling on an individual basis. All of the implementations of DDS middleware are guaranteed to be interoperable at the wire-protocol level, so there is generally no risk of vendor lock-in when choosing an implementation. MICEHAB will be able to leverage these implementations of DDS and further tailor the standard to specific conditions.

Work since Paper I also focused on describing various system states that dictate appropriate system responses through definition of example decision flows for autonomous care of crew and systems (Figure 8).

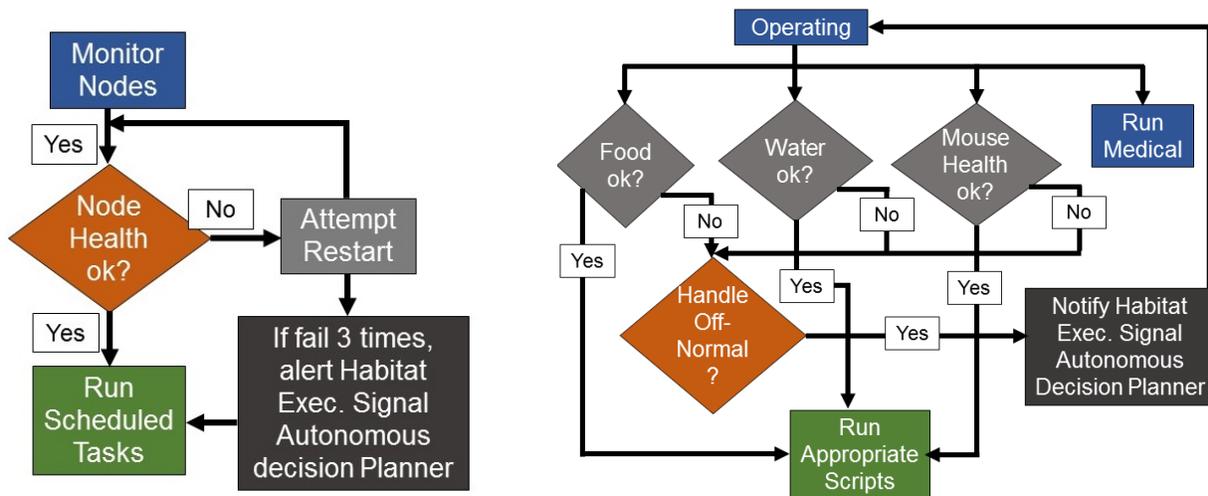


Figure 8. Decision flow examples of [left] node health and [right] general operations. Image: NASA/LaRC 2015

The MICEHAB architecture emphasizes: independent nodal execution, program encapsulation, specific system control and monitoring design, publishing and subscription to data structures using the DDS protocol,

and node publishing of health data for system maintenance and monitoring. In addition, feedback from sensors and robotic arm status/health nodes trigger scripted actions for preplanned operations and initiate decision tree recursion for unexpected off-normal conditions.

Each decision tree is fully scripted with all desired nominal and off-nominal behaviors that operators wish to be handled specifically. During off-normal conditions that have not been accounted for, the decision trees defer handling to the autonomous decision planner, which analyzes all data inputs and conditions and checks across a database of prior experience to best decide the appropriate action to take. The best decision is made and action is taken. All actions are then reported to the ground control system/human monitor.

The autonomy decision planner can also take the place of the scripted decision tree components given sufficient training. Machine learning and decision strategies, such as Bayesian Networks, use Bayesian inference to calculate posterior probabilities on actions to take given prior knowledge of actions taken under the same or similar system conditions. See Ref. 29 for a detailed description of Bayesian probability statistics.

For MICEHAB, an example is an off-normal mouse condition within the habitat enclosure. Figure 9 depicts a thermal alert condition based on a change in the animal's temperature as measured by an infrared camera. Possible conditions for inputs trigger the alert and possible actions to be taken given what the autonomous decision planner decides is the correct action based on prior information on similar alerts and inputs. The conditions are shown in blue, the alert is shown in orange, and the actions are shown in green. Figure 10 depicts the Bayesian analysis for the priors, and Equations (1) and (2) depict the corresponding posterior calculations for the final planner handling of the thermal alert condition.

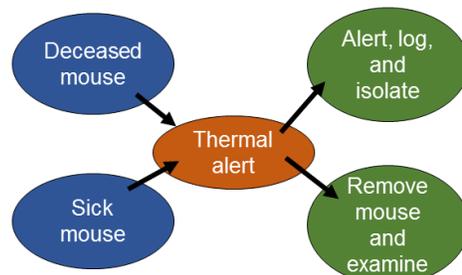


Figure 9. Thermal alert condition. Image: NASA/LaRC 2015



Figure 10. Bayesian analysis using notional prior information: DM = deceased mouse; SM = sick mouse, TA = thermal alert; AL = alert, log, and isolate; RE = remove mouse and examine. Image: NASA/LaRC 2015

$$P(DM|TA) = \frac{P(TA|DM) * P(DM)}{P(TA|DM) * P(DM) + P(TA|SM)P(SM)} \quad (1)$$

$$P(SM|TA) = \frac{P(TA|SM) * P(SM)}{P(TA|SM) * P(SM) + P(TA|DM)P(DM)} \quad (2)$$

Equations (1) and (2) report the system probability of a deceased mouse (DM) or sick mouse (SM) causing the thermal alert (TA). The system will then compare the probabilities of a deceased mouse, $P(DM|TA)$,

versus the sick mouse, $P(SM|TA)$, and choose the most likely probability as the actual situation and then execute the appropriate action based on the information given. The probability of the mouse being deceased or sick can be determined using Bayesian analysis to select the higher probability given prior thermal alerts from the enclosure.

The result will also be logged to help the system strengthen its decision capability. This can be done by continually tracking the performance output using either performance or confusion matrices, and then using these matrices to calculate the prior situation given the current system status.

V. Conclusions and Forward Work

Future human exploration missions require the development of capabilities to live independently from Earth. This requires an improved understanding of how the human body reacts to different environments and the development of capabilities to live autonomously (i.e. Earth-independent). MICEHAB will demonstrate both of these facets of human exploration. MICEHAB will demonstrate the robotic capabilities to perform preventative and corrective maintenance tasks usually performed by crew aboard the ISS. This is enabled by robotics available in the 2020s that will likely allow real-time processing to collect data and respond accordingly to perform a task. MICEHAB will take advantage of such advanced robotic and autonomy capabilities to operate and maintain an artificial partial gravity rotation facility in cis-lunar space in order to study the effects of partial gravity on mammalian reproduction and maturation over multiple generations. MICEHAB offers a platform to test exploration-class systems designed to feed forward to human missions to Mars. The facility will be delivered in the mid-2020s as a co-manifested payload on the SLS and will be located near the planned long-duration human habitat so that samples can be transferred to the human habitat for return to Earth.

Paper I provided an initial feasibility assessment of the MICEHAB concept, and analysis indicated that the MICEHAB facility will likely meet the approximate 10 mT mass requirement. The continued work described in this paper addresses refinements of the element designs. These refinements did not reduce the element masses but added substantial credibility to the operational feasibility of the MICEHAB concept including: robustness of the communications and data transfer architecture, robustness of both the robotic platform and robotic arm concept design, and a design example for autonomous care of crew and systems. Attaining the defined baseline communications architecture may be challenging considering industry standard data compression rates, thus requiring a modified concept design for monitoring the animals. The latest iteration of the robotic system design relies on more capability in the arm and less capability in the platform, resulting in a more reliable system. Autonomous system example decision flows for autonomous care of crew and systems provide feasible design examples for automating the care of animals with minimal reliance on Earth-based control. Integrated element analyses presented in this paper indicate there are additional considerations that need to be investigated, such as optimization within the trade space that may lead to designs that reduce the mass to conform to a 10 mT launch mass constraint.

Forward work involves applications of similar exploration-focused research facilities. Work is ongoing to assess utilization of the MICEHAB facility for other biological science purposes such as a deep space radiation testing platform for large animal colonies. Forward work to investigate the extensibility to other destinations to enable additional biological phenomenon such as interactions with dust is highly desirable and will be considered. Rework of launch and trajectory analyses may become necessary if a SLS co-manifested launch is not available due to higher priority payloads. In this case, work would begin to design a mission that is launched on commercially available launch vehicles.

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