A Methodology for the Systematic Review of Space Architecture Concepts

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The vast majority of space vehicles and habitats have been launched and operated by nations for scientific and exploratory purposes. Consequently, their form has been shaped by the constraints posed by the scientific and diplomatic needs of the mission as well as the physical limitations of their launch and operation. These constraints have resulted in a homogenous appearance of space architecture, with either a single monolithic hull or a central, cylindrical axis with branching, pressure-cylinder modules. Recently, an influx of private investment in space has resulted in low-cost access to orbit and an emerging space services economy that has in turn led to a surge of interest in commercial space habitat design. With an increasingly diverse pool of spaceflight participants, the design of these future space habitats must evolve past the 'orbital laboratory' to instead accommodate a wide range of participants and reasons for spaceflight.

This work presents a space habitat assessment methodology and systematically reviews space habitat concepts throughout modern history, including flight-proven spacecraft, ideas from NASA competitions over four decades, technical workshops, industry concepts, terrestrial analogues, and notable, credible designs from science fiction. Ninety concepts were collected and characterized based on figures of merit such as pressurized volume, occupancy, location, structural geometries, and purpose. From this broad search, gaps between current capabilities and future-leaning designs are identified for research and development. Broad categories of trends and opportunities are identified for the space architecture community–namely, determining the technologies needed to enable the next generation of space habitats. This paper presents the foundation of a space architecture database collected from concepts across the field, analyzes the resultant technology gap, and proposes R&D workstreams for meaningfully democratizing access to space via in-space infrastructure that can scale up habitat occupancy.

I. Introduction

Low-cost access to orbit, technology advancement, and tremendous private investment have created an emerging space services economy, in which companies, goods, and services are created entirely to supply space-bound customers.[1] As access to space grows, so will the opportunities and reasons for spaceflight. This is already evident with emerging fields such as space tourism, which have contributed to a surge of new space habitat concepts, with additional support from NASA for a commercial replacement for the International Space Station (ISS).[2,3]

To date, the majority of space habitats have been primarily launched and operated by nations for scientific and exploratory purposes, designed under constraints set by operational parameters, designer knowledge, funding, and the physical limits of available launch vehicles. Generally, there was little room for creative freedom in space habitat design, with engineers instead focused on achieving the minimum functionality required to meet mission objectives and ensure survival, with any additional design work focused on margins of safety and operability.[4] The design of future space habitats must evolve past the 'orbital laboratory' to instead accommodate the wide range of participants and reasons for spaceflight using a multidisciplinary approach to space architecture.

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Ideas for space destinations are not new; space architecture concepts can be traced back to the 1880s in Konstantin E. Tsiolkovsky's spherical habitat depicted in *Free Space* and to the 1920s in Herman Potočnik's *Problem of Space Travel*, in which ideas for early space stations are sketched.[5,6] In 1967, Hilton Hotels proposed an idea for a 'hotel on the moon' that would cater to tourists.[7] The idea for the space hotel has been mirrored in film and media, such as the Hilton Hotel in *2001: A Space Odyssey*, which depicted a Low Earth Orbit (LEO) destination on a rotating space station. Although these ideas never came to fruition, the space race would catalyze the imagination of designers across NASA, commercial companies, and artists in film and media to envision the future of space habitation.

This paper summarizes a trade study from across the field of advanced space architecture in order to better understand its current state, gaps, and opportunities for development. Established ideas from concept studies, proposals, film, media, history, and the state of the art are characterized through select figures of merit, which include the functional purpose of each architecture, with a focus on designs that deviated from the traditional axial design of contemporary space stations. From this search, key gaps and areas for technological development are identified in order to enable future concepts of space habitation.

II. Methodology

An initial search is performed across historical and state-of-the-art concepts in human spaceflight, sourced as expansively as possible based on their established renown, references in space architecture literature, or from new discovery of unique contributions with credible design ideas. This study includes both concepts from terrestrial analogues, science fiction, and architecture design contests, and concepts from more traditional sources such as NASA studies and flight heritage. Key figures of merit are defined and recorded for each design whenever possible; in some cases, concepts come with fragmented supporting material and we have chosen not to speculate, and rather only report figures of merit where originally conceived. In total, 90 designs are cataloged, and from this collection of designs, common themes and gaps are assessed in order to highlight directions for future research. It should be noted that this effort is ongoing, and concepts will be continuously added to this database as they arise, along with any updates to existing concepts. Concepts can be viewed and suggested at the URL included in the paper's conclusion.

III. Focus

The focus of this work is on characterizing emergent designs that are a major departure from traditional space habitat design. Previous space architecture trade studies have focused on exploring a set trade space given known state-of-the-art design assumptions or constraints. These include comparing engineering solutions, such as the utilization of rocket upper stages toward common habitat designs, the tradeoffs between crew and volume for a traditional cylinder design, or the use of inflatables as additional ISS modules.[8,9,10] Other studies have examined the intersection between psychology and the design of space habitat interiors for ergonomic value and comfort.[11,12] While these previous studies are valuable for modern designers, most are limited to the cylindrical, axial structure that has been the standard of space habitat design for the past 50 years. Future stations proposed by Axiom and Orbital Reef, although commercially designed and operated, would also fall into this category.[13] Although these emergent designs are included in the search, an emphasis is placed on novel designs that will require significant technological development to achieve, with a large focus placed on scalability, new functionality, and architectural merit. The scope is limited to designs that showed a baseline level of feasibility with known technology.

IV. Background

A. Definitions

In order to discuss the results of the trade study, several key definitions are provided to align terminology. These definitions are summarized in table 1.

Table 1: Relevant space architecture terms and working definitions.

Term	Definition
Space Habitat	An environment capable of sustaining human life in the inhospitable environment of space[9]

Space Station	A spacecraft meant for long-term in-space operations, research, and tourism, often in orbit around a celestial body
Habitability	A set of qualities and characteristics that allow the support of life[14]
Space Architecture	The theory and practice of designing and building inhabited environments in outer space;[15] specifically, an approach to designing for life in space that combines engineering thinking with criteria related to habitability and human factors, such as considered in architecture and industrial design, plus other disciplines such as medicine and science[16]
Low Earth Orbit	Geocentric orbits that are typically less than 2,400 km (1,491 mi) in altitude[17]
Cislunar Space	The volume of space influenced by the Earth and/or the Moon[18]
Deep Space	Environments in space beyond the Moon's orbit
Transporter/Space Tug	A spacecraft that moves crew or payloads from one location in space to another
Artificial Gravity	The simulation of gravity in a microgravity environment by acceleration or centrifugal forces

B. Designing for Space

Building for the microgravity environment poses a unique set of design challenges not only for the design and construction of space habitats, but also for the physiology and psychology of the humans onboard. A high-level discussion of some of these challenges will be provided in this section.

At the time of writing, the cost to launch a kilogram of material to LEO onboard a SpaceX Falcon Heavy rocket is approximately $1,500/kg.[19] While this is a historic low, it nevertheless remains expensive to launch and construct large, heavy structures in space. The ISS required over 40 assembly launches to achieve a final station mass of nearly 410,000 kg.[20] Additionally, its construction required over 1000 hours of Extravehicular Activity (EVA) over ten years, with additional years spent developing the procedures, training, and skills required for the construction and maintenance of its modules.[21] The operation of modern-day space stations such as the ISS requires hundreds of flight controllers that aid in writing procedures, scheduling, advising crew, and diagnosing problems onboard the vehicle. This ground support is critical for all maintenance, repair, and science operations that occur onboard the ISS, although design qualities such as operability, maintainability, and reliability can potentially reduce this reliance on Earth.[22]

Once in orbit, there are several aspects of the environment that present challenges for the design, construction, and operation of space habitats. These include the microgravity environment, vacuum, and extreme temperature swings resulting from intermittent sun exposure. Other challenges include radiation, micrometeoroids and orbital debris (MMOD), which present acute and long-term hazards for those living in space.

The microgravity environment requires significant physiological adaptation. The first 24 hours of spaceflight results in a variety of changes, including a redistribution of body fluids that can lead to facial swelling, reduction in total blood volume, and motion sickness. Additional long-term effects begin after several days, including a decrease in muscle strength, a 60-70% increase in calcium loss, and a gradual loss of bone density of 1-2% per month.[23] Although these adaptations depend on the length of flight, they affect all spaceflight participants to some degree and may be better mitigated in the future through advanced habitat design (e.g., artificial gravity).

Psychological effects of spaceflight are less widely understood. Challenges include feelings of isolation, anxiety caused by the high-stress environment, and boredom during long-duration spaceflight.[24] However, there has also been widespread documented evidence of a phenomena known as 'the overview effect,' in which astronauts and spaceflight participants report overwhelming emotion about the fragility of the planet Earth and feeling of identification with humanity as a whole.[25] This idea is often cited as a key motivating factor for participation in spaceflight, although all psychological factors should be considered in the design of space habitats.

The unique space environment can also provide designers with opportunities to create architecture that would be otherwise impossible under Earth gravity. Creative use of microgravity, three-dimensional space, and orbital mechanics can provide designers with new opportunities to play with form and function. However, additional concerns such as MMOD create new challenges for the structural design and maneuverability of orbital habits. Space architects must cultivate a baseline understanding of the space environment in order to fully understand all design constraints, challenges, and opportunities.

C. Evolution of Space Architecture
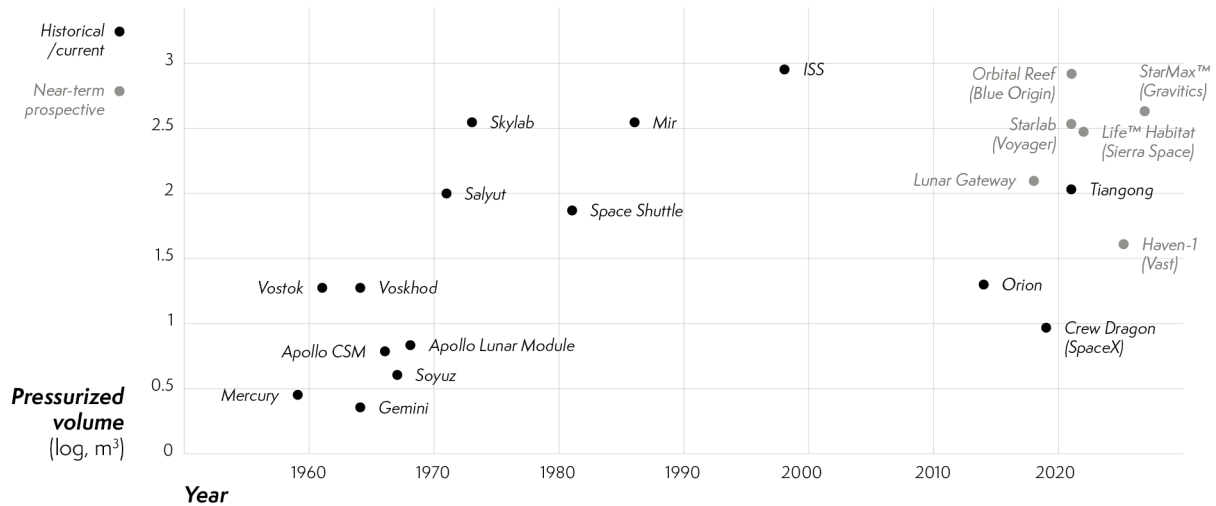
Figure 1: Pressurized volume of historical and near-term prospective space habitats over time.[26-31] A notable exception is the Axiom Hab One design, which is currently in development but does not have publicly available information on pressurized volume.

Early spaceflight vehicles were primarily limited to capsule-based designs such as Vostok, Mercury, and Gemini, in which a limited crew of one or two people would launch to LEO to perform scientific experiments and technology demonstrations. During the Apollo missions, the basic capsule—the Command Module—was extended to also include the Service Module, which would provide propulsion, electrical power and storage for various consumables required during the mission. This joint Command and Service Module would be connected with the Apollo Lunar Module, which provided additional habitable volume during transit to the Moon and would allow two of the crew to descend to and return from the Lunar surface.

In 1971, the Soviet Union began the Salyut Programme, during which four crewed scientific research space stations and two crewed military reconnaissance stations flew from 1971-1986. Each of these employed the use of modules, where multiple spacecraft were connected post-launch to form the final station, including a separate crew transfer vehicle. Salyut marked the beginning of long-duration human habitation of space with the addition of multiple docking ports and the ability to perform crew handovers.

The first American space station was Skylab, a laboratory built from a repurposed Saturn S-IVB upper stage linked with an Apollo Command and Service Module. Skylab was operational from 1973-1974, and was habited for a total of 24 weeks across three crewed missions. Notably, Skylab did not rely on resupply, and instead was launched fully provisioned.

The Soviet space station Mir was the first habitat to truly test the limits of human endurance in space. Mir operated in LEO from 1986-2001, and was host to over one hundred visitors from twelve nations. Unlike Skylab, Mir relied on continuous cargo resupply from Earth. Valeri Polyakov set the record aboard Mir for a single, continuous on-orbit stay of 437 days, 17 hours and 38 minutes.[32] The long-duration flight experience and international cooperation enabled by Mir paved the way for the ISS, which began construction in 1998.

The ISS has been continuously occupied since 2000, and like Mir, has benefited from several leaps in habitat technology. Improvements in crew quarters, workspaces, air revitalization, and water reclamation technology has led to both a higher quality of life for the astronauts aboard the ISS and an increase in life support sustainability.[33-35]

Since the construction of the ISS, the China National Space Administration (CNSA) has constructed three space stations, including prototypes Tiangong-1 and Tiangong-2, as well as Tiangong, which is currently crewed. Although these stations—along with future plans for NASA's Lunar Gateway—represent more recent designs than the ISS, few details are known about their design, and so the ISS will represent the state of the art for the purposes of discussion.
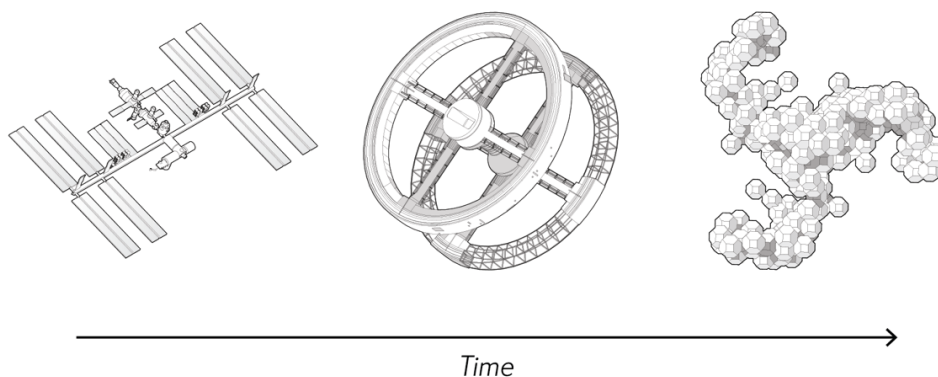
D. Architectural Categories

With the goal of departing from traditional axial space station design used in both Mir and the ISS, four categories of interest have been formulated based on their architectural merit and contribution to the human spaceflight experience.

Table 2: A description of each architectural category.

Category	Description/Key Traits
Artificial Gravity	A spinning structure capable of generating an artificial gravitational force for long-duration life in space.
Modular/Reconfigurable	A structure capable of forward deployment that is easily and autonomously reconfigured (including ISS-like models, but advancing beyond) to meet changing mission needs in deep space.
Polylithic	A decentralized structure with an organic 'accretion' of nodes. Could serve as an architectural basis for space cities, or at a smaller scale, apartment-style buildings. May use plesiohedron geometry for dense, space-filling packing.
Monolithic	A structure conceived or built to achieve a single, often monumental, open chamber or geometry. Often (though not always) definable by a globally convex topology.

These four options have been selected as categories of interest for the initial trade search based on their functional merit, occupancy and volume scalability, and potential to enable transformative new habitat concepts through technological innovation. Although they are defined separately, a given architecture may represent some combination of several categories, such as a modular artificial gravity habitat. Looking forward to future case studies and technology roadmap development, a down selection of these categories will be chosen based on current technology gaps, feasibility with launch and operation, and projected return on investment.
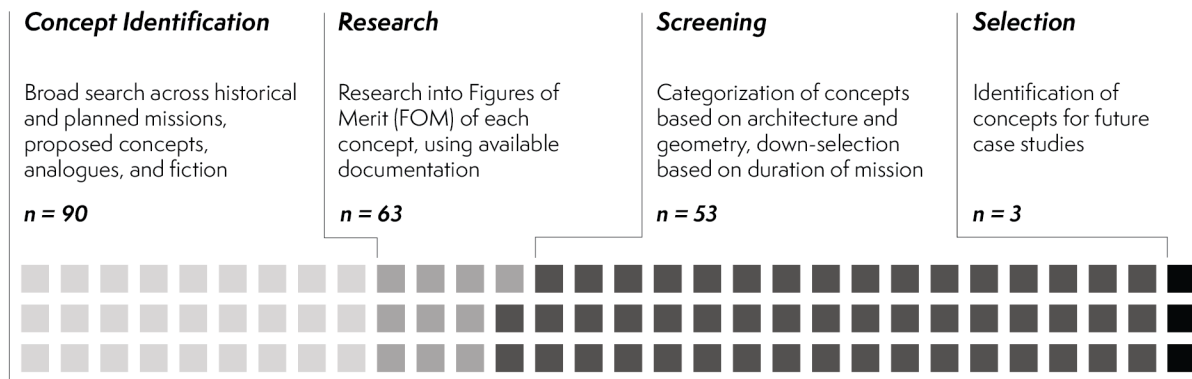

Time

Figure 2: Examples of orbital habitats across three different architectural categories: current modular design (ISS), an artificial gravity design, and a polylithic, organic structure.

Examples of an artificial gravity habitat design, a current modular design (ISS), and a polylithic, organic structure are illustrated in figure 2.

V. Trade Study

A. Selected Designs

Of the 90 designs under consideration, 23 have flown or are currently flying. Another 14 are currently in development, with the majority stemming from private companies such as Axiom, Blue Origin, Sierra Space, and Bigelow. The majority of the final concepts included in the study arose from proposals and contests. The designs ranged in occupancy from 1-100000 people, with planned volumes from 2 m^3 to 6×10^7 m^3. Following the broad search of concepts, each design has been categorized by select figures of merit, which are discussed below. Future work will perform a detailed case study of three select designs from the architectural categories that show the most return on investment for future space habitation.

Concept Identification	Research	Screening	Selection
Broad search across historical and planned missions, proposed concepts, analogues, and fiction	Research into Figures of Merit (FOM) of each concept, using available documentation	Categorization of concepts based on architecture and geometry, down-selection based on duration of mission	Identification of concepts for future case studies
n = 90	*n = 63*	*n = 53*	*n = 3*

Figure 3: An illustration of the review and down-selection process towards future case studies.

B. Figures of Merit

A list of key figures of merit was created to aid in the characterization of the space habitat trade space. These figures encompass a wide range of descriptive variables pertaining to the launch, construction, maintenance, location, form, function, and purpose of the space habitat in question. Some figures, such as crew size and pressurized volume, should inform one another. Others, such as mass, number of launches, materials, and ongoing maintenance are directly related to the overall cost of the habitat; however, these exact specifications are often unknown in early concept studies. Although many more figures of merit exist, the following have been chosen based on their general availability for designs across the trade study.

Table 3: Descriptions of each figure of merit used to characterize concepts in the space architecture study.

Figure of Merit	Description/Justification
Purpose	What is the designated purpose of the habitat? Research, tourism?
Functional Category	Is this a habitat for short duration crew transfer? Capable of reentry? Long-duration surface stay?
Architecture Category	Which of the aforementioned architectural categories can the habitat be classified as?
Location	Where is the habitat located? Microgravity, or surface? Near Earth, or in deep space?
Occupancy	How many people can live, work, or visit this habitat?

| Pressurized Volume	The total space inside the habitat that is kept at a habitable pressure.

Exact values for each design are taken from company websites, engineering documents, concept descriptions, and press releases. In many cases, and particularly for fictional concepts, values are unavailable or are not disclosed.

1. Purpose and Functional Category

The purpose of each design varied widely depending on the era of human space exploration. Initially, the majority of crewed spacecraft were capsules capable of sustaining a crew of 1-3 people in Low Earth Orbit, or in the case of the Apollo program, to the surface of the Moon and back with the addition of a lander. The capsule design is unique for its ability to both support a crew in space for a limited period of time and return them to Earth through entry, descent, and landing. Historically, landers are distinct from capsules, and rely instead on retropropulsion to provide a controlled descent onto the Moon. Future landers for locations such as Mars will require a blended design due to the presence of the Martian atmosphere.

To date, all long-duration space habitats have taken the form of microgravity stations, and have been primarily used for scientific research. As previously mentioned, these designs rely on cylindrical modules arranged in an axial configuration, with multiple docking ports for crew and cargo capsules. Although dedicated long-duration surface habitats are still in the conceptual design phase, several notable concepts are detailed in NASA architectural design challenges. Many of these designs make use of additive manufacturing techniques, Martian regolith, and unique modularity in their design in order to enable low-cost building and autonomous assembly.[36]

Although these functional categories are discussed individually within this section, many designs perform multiple functions. For example, the Apollo Lunar Excursion Module (LEM) can be described as a lander, although it served as a surface habitat for the crews during the duration of their stay on the Lunar surface. Likewise, although capsules are primarily used for crew transport and atmospheric reentry, many designs are capable of sustaining a crew for upwards of a week. Rather than provide definitive categories, this terminology is used to discuss the *primary* purpose of a design. The terms 'habitat' and 'settlement' have been distinguished in order to denote scale and permanence, although this terminology is subject to change as the taxonomy of space architecture evolves.
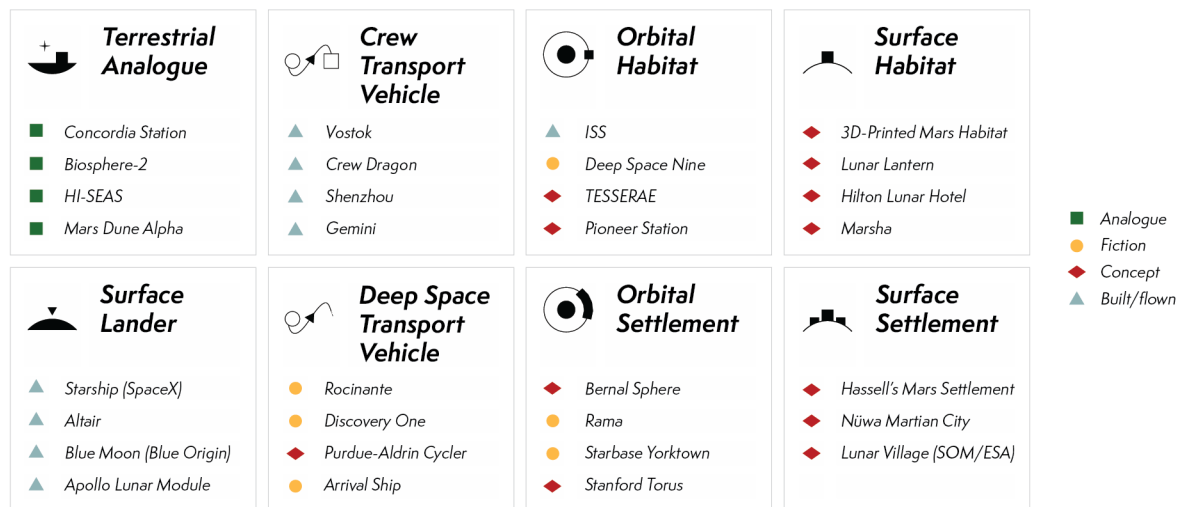

Figure 4: Selection of sample space architecture concepts grouped according to functional category (expanded list in Trade Study database).

2. Architectural Category

The architectural category describes the form factor, inspiration, and shape of the habitat design, according to the predefined categories of interest, noted in Table 3. Of the concepts studied, 18 could be classified as artificial gravity designs, 4 as polylithic, 6 as monolithic, and 20 as modular. Crew capsules, Earth analogues, lifting bodies, and landers are not included in the architectural breakout due to their indeterminant geometric classification according to

the preselected categories, but these are captured in the project database. This group represented an additional 23 designs.
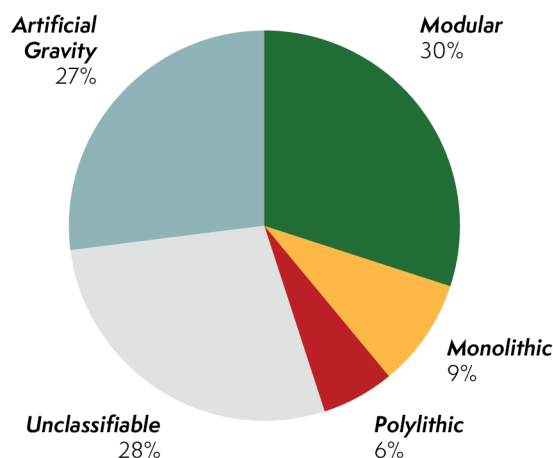
Figure 5: A breakout of designs in the trade study by architectural category.

Several designs represent combinations of multiple architectural categories. The most common combinations observed are monolithic/artificial gravity designs and modular/artificial gravity combinations. Of the concepts under development for NASA's Commercial Destinations in Low-Earth Orbit program, none depart from the axial, modular design of historical space stations. However, notably, Sierra Space has developed an inflatable Life™ Habitat module that will be integrated into the joint Blue Origin/Sierra Space Orbital Reef design. This design is similar to the Transhab/BEAM design developed by NASA and Bigelow Aerospace, although it does not directly stem from that research and design.

3. Location

Of the designs under consideration, 39 are designed for LEO, 13 explicitly for the lunar surface, 3 for cislunar space, 10 for the Martian surface, and 18 for general deep space. All real, flown designs under consideration have been limited to the Earth-Moon sphere of influence. Newer designs proposed by commercial space companies are generally planned for LEO, with exceptions for multi-use crew transport vehicles planned for missions to the Moon or Mars. Designs for deep space vary from Martian transit vehicles to deep space long-duration habitats, such as concepts such as the Bernal Sphere, O'Neill Cylinders, the Stanford Torus, and Rama.

The locations of space analogues are most often located in remote, scientifically relevant locations such as Utah, Antarctica, or the Australian desert. Fictional spacecraft are generally located in deep space locations, while those from NASA design competitions tended to be located on the Lunar or Martian surface to make use of raw building materials such as regolith.
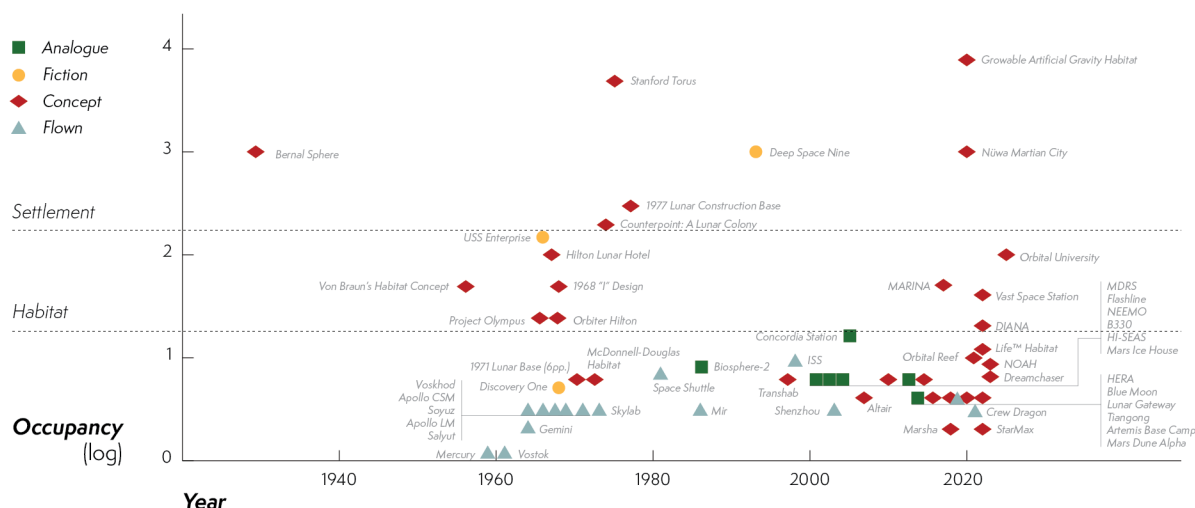
4. Occupancy

The occupancy of space habitats is coupled to their pressurized volume through a relationship most commonly described through the curve established by Celentano.[37] For the purposes of this work, the state of the art can be taken as the ISS, which generally hosts a crew of 6-9 astronauts in a volume of 916 m^3. Across the designs considered in the study, occupancy ranged widely, from one person in crew capsules to thousands in notional space settlements. However, there is a notable concentration of designs in the 6-12 person range, and a lack of designs that accommodate several dozen occupants. There is another small concentration of designs envisioned for the far future, in which thousands or hundreds of thousands of occupants live together in large space settlements.

The primary gap in the space architecture design space can be seen in the size and occupancy of current space habitats and those envisioned in the far future. This gap—between a crew of ten and a settlement of thousands—is populated only by designs such as MARINA (MAnaged, Reconfigurable, In-space Nodal Assembly), semi-permanent lunar dwellings such as the Counterpoint Lunar Colony and the Hilton Lunar Hotel, the Orbital

University concept, and Werner von Braun's artificial gravity toroid concept. These gaps will be discussed in greater detail in the following section.

Figure 6: Plot of select space habitat concepts' occupancy over time, including prospective future dates (provided by the concept, no endorsement of timeline feasibility implied).

5. Pressurized Volume

The pressurized volume of the concepts ranges from 2.8 m³ for the Mercury capsule, capable of sustaining a crew of one, to 6.9x10⁷ m³ for the Stanford Torus, an orbital settlement concept developed by a team of researchers in 1975. Historically, the pressurized volume of flown designs has been limited by available launch vehicles and the ability to construct large structures in orbit. These constraints highlight the necessity of modularity in space habitat design and novel in-space construction techniques.

The pressurized volume of a habitat should increase in accordance with the number of occupants and the duration of habitat. However, certain features such as crew quarters may increase in size as the demographics of spaceflight evolve along with expectations of amenities, personal space, and activities. Likewise, areas for leisure or evolving in-space activities onboard microgravity habitats may increase demand for different volumes or form factors on orbit, changing the standard ratio of pressurized volume to occupancy. Self-assembling structures and reconfiguration may become enabling for this changing landscape.

VI.   Discussion

A. Gap Analysis

Across the landscape of space architecture, there are several near-term gaps that can be addressed through dedicated research and development. On an architectural level, there is the aforementioned gap between current habitat designs that follow the established cylindrical, axial design, and the more future-leaning designs explored in science fiction media.

Architectures capable of generating artificial gravity and utilizing true modularity have the potential to enable a new era of space habitation. The use of artificial gravity would mitigate both the short- and long-term effects of microgravity exposure, which is particularly enabling for missions of exploration. These architectures, potentially combined with non-rotating segments, could allow for both the microgravity experience for tourists and science as well as for the mitigation of effects such as bone density loss, cardiovascular deconditioning, and muscle atrophy.

This ongoing search effort unearthed many artificial gravity habitat concepts, although to date none have been built or flown. Limits in human comfort—both due to gravity gradients and motion sickness induced from high spin rates—require a large radius of rotation, and a subsequently large space structure.[38] Dedicated research into large space structures and their subsequent attitude determination and control at sustained spin rates will be key to enabling artificial gravity habitats. Likewise, in the emerging field of space tourism, a primary driver of space travel for participants may be to experience microgravity. In this case, designs should maintain either a non-rotating

segment or central volumes allowing for the microgravity environment. For short spaceflight duration on the order of weeks, artificial gravity may not be necessary.

Modular architectures allow for the construction of large structures and their reconfiguration as the needs of the mission or habitat change. Although modular space habitats have existed in theory for decades, they are very rarely utilized in a truly modular form. Rather, the term 'modularity' generally refers to the launch of separate components that are then used to construct a larger habitat structure once in orbit, such as the ISS. In order to enable truly multipurpose habitats, future designs must utilize modularity as an active tool to enable adaptive reconfiguration. Modularity will also be key to constructing large space structures capable of generating artificial gravity and hosting a large number of occupants.

As previously mentioned, historical space habitats have been designed to sustain crew sizes from 1-12 people for durations of several months without resupply. Many future designs and concepts in the study depict humanity as a multi-planet species or large-scale orbital settlements. However, there are few designs that bridge the gap between the far future and state of the art. Mid-sized structures capable of sustaining dozens of occupants in correspondence with a space services industry will necessitate the assembly, maintenance, and support of large-scale space structures. The launch of these structures, station-keeping, power, and onboard life support systems will all need to be tested with larger, complex architectures. Although many ideas from film and media depict crew transport vehicles capable of traversing large swaths of space at or exceeding the speed of light, for the purposes of this study, interstellar and faster-than-light propulsion such as that described in far-future science fiction ideas are out of scope. Discussion of propulsion will be limited to station-keeping and the guidance, navigation, and control of large, potentially spinning structures. The specifics of enabling technologies will be discussed in greater detail below.

B. Enabling Technologies

In order to bridge the gap between the state of the art and the future designs found throughout the trade study, several key enabling technologies will require significant research and development. In some cases, this will simply be an adaptation or improvement of existing technologies to support larger structures, a higher number of occupants, or evolving habitat purposes. In other cases, new technology will need to be created where no solutions exist or have yet to be flown in space. This list is not exhaustive, although it is meant to highlight clear needs revealed from trends in the collected designs.

At a high level, the enabling technologies fall into two primary gaps: support of large-scale space structures and higher occupancy. These are further broken out into specific functions, which will be described in this section.

Table 4: A description of the identified gaps between state-of-the-art space architecture and the future-leaning concepts analyzed in this review.

Gap	Function	Candidate Technology Solution	Rationale
Large-Scale Space Structures	Construction	Autonomous In-Space Assembly	Construction of the ISS took hundreds of hours of highly trained, scheduled astronaut EVA. Self-assembly will allow for more affordable, fast construction of larger space structures with fewer overall launches.
	Guidance, Navigation, and Control (GNC)	Attitude and spin control for artificial gravity habitats	Although GNC is well-established for architectures such as the ISS, it is yet untested for the generation of artificial gravity in large space structures, which may have to contend significant gravity gradient and solar radiation pressure effects while maintaining a consistent spin plane.
	Reconfiguration	Autonomous Reconfiguration	The space services economy may require that habitats adapt to changing demand or evolve for new purposes as they arise.
	Environmental Control and Life	Enabling reliable and adequate temperature, circulation and consistently habitable	New form factors will introduce challenges to the ECLSS approaches previously employed. As the demographics of spaceflight evolve,

Higher Occupancy	Support Systems (ECLSS)	atmosphere for large, spacious structures; handling recycling of waste across multiple streams	there will be an increase in participants who are not necessarily trained to service, maintain, and repair all subsystems.
	Bioregenerative Life Support (BLS)	Integrating organic matter to aid in ECLSS loop closure and provide fresh produce for occupants	BLS is one element of sustainability, in accordance with NASA's goal of transitioning from the ISS to a long-term, sustainable commercial human spaceflight economy in LEO.
Improved Interior Environments	Novel habitat interaction design, industrial design & programmatic design	Human-centered design methodologies for 'life in space' artifacts and larger habitat environments; best-in-class responsive space habitats (e.g., integration of Internet of Things, AI assistance, health monitoring, and other modern convenience tools)	A new approach to 'design' for space architecture must combine the prior focus on human performance engineering (or 'human factors'), with the more user-centered-delight and thriving considerations that modern citizens have come to expect in their living environments, particularly when expanding access to a broader pool of individuals and requiring less training.

1. Large-Scale Space Structures: Construction and Assembly

In some cases, such as for construction and assembly, multiple technologies may be capable of meeting the functional gap. There are numerous methods of in-space assembly, including robotic arms and electromagnets.[39,40] Companies such as MDA, Altius, Maxar, Redwire, and Honeybee are leading development of in-space robotics and on-orbit servicing, manufacturing, and assembly capabilities. These technologies will be enabling for all architectural categories, but in particular for modular and polylithic designs that are built from multiple structures with the potential for reconfiguration. Some modular designs, such as TESSERAE and Orb2, are capable of being launched in a compact, stacked configuration and assembled on-orbit, enabling volumes that would otherwise require multiple launches.[41,42] Other technologies, such as additive manufacturing, may aid in the creation of specific parts or other supplementary architecture components.

2. Large-Scale Space Structures: GNC

Guidance, navigation, and control of space habitats is well established. The ISS relies on a combination of control moment gyroscopes (CMGs) that utilize electric power from the solar cells onboard, in conjunction with thrusters for more powerful attitude control capabilities and station-keeping. However, the spin-up and stabilization of a large space habitat structure is yet untested in the space environment. Uncrewed spacecraft such as Juno, Pioneer 10, Pioneer 11, and the Mars 2020 cruise stage have been spin stabilized, but not for the purposes of generating artificial gravity. This technology, along with the appropriate interior design to accommodate variability gravities, is an area for research and development.

In order to effectively generate artificial gravity in a habitat, a constant spin rate must be achieved through an applied torque. To date, spin stabilization has been performed primarily through the use of reaction control system (RCS) thrusters which eliminate the need for the complexity and additional mass of CMGs and reaction wheels.[43,44] Additional torques, such as the coning maneuver, can be applied to alter the angular momentum of the spinning spacecraft and subsequently alter its attitude and plane of rotation.[45] Recent work has investigated the use of distributed magnetic torque rods for the attitude control in comparison to large centralized torques, which can ensure rigid body motion for large scale structures that would otherwise flex or bend in undesirable ways.[46] The use of electromagnets or other smart material techniques could help ensure rotational stability in large, spinning structures, and may be further proven in scale flight demonstrations.[47] However, some of the additional considerations, such as the effects of gravity gradients and solar radiation pressure, may only be observed in large scale structures. The development of high-fidelity physics modeling and simulation will be key to understanding these interactions and for identifying optimal attitude control systems for different habitat designs.

3. Large-Scale Space Structures: Reconfiguration

Similar to in-space construction and assembly, reconfiguration of habitat modules can be accomplished through various methods. Robotic arm manipulation or autonomous flight, rendezvous, and docking could allow for the

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rearrangement and ongoing expansion of microgravity habitats. Likewise, depending on the functional needs of the habitat, it may be beneficial to be able to rearrange the interior volume for different purposes, such as science or leisure. Adaptive architecture and autonomous reconfiguration are key technologies for this capability, and they should be integrated during the design phase.

4. *Higher Occupancy: Reliable Environmental Control and Life Support Systems (ECLSS)*

Although environmental control and life support technologies are well-established, they have placed a higher-than-expected demand on crew time for maintenance and repair onboard the ISS,[50] and are yet untested in larger volumes depicted in many advanced orbital concepts. Air revitalization, temperature, and humidity control must be adjusted for increases in habitat size and occupancy. Likewise, habitats built for space tourism or other non-scientific purposes may necessitate lower maintenance requirements to accommodate inexperienced occupants.

On the ISS, air revitalization systems such as the Carbon Dioxide Removal Assembly (CDRA) have experienced high downtime which has in turn led to the crew experiencing symptoms such as headaches.[49] Other systems, such as the active thermal control system (ATCS) require external maintenance through extravehicular activity (EVA), which necessitates a highly-skilled crew.[50] However, the ISS has also shown significant loop closure through the processing and recycling of water through the Water Recovery and Brine Processing Systems,[51,35] which in turn have had a notable effect on the required number of resupply flights over time.[52] Despite these mass savings, the ISS water system has exhibited high ongoing maintenance requirements. Advances in reliability, maintainability, and the ability to repair these regenerative life support systems in-situ will be key to the longevity of future space habitats.

While increasing reliability can reduce maintenance time and logistics mass requirements, there are limits to the benefits of increasing reliability alone, and future missions should also consider a combination of sparing, redundancy, and in-situ resource utilization to reduce mass requirements and mitigate risk.[53,54] Previous work on self-aware self-assembly of large space structures has identified modularity in ECLSS systems as a potential way to enhance reliability, reduce costs, and provide greater flexibility in meeting mission objectives.[55]

Finally, there is ongoing work into the use of digital twins and other simulation models to enhance spacecraft autonomy and self-awareness, particularly for ECLSS.[56] While these systems are still in development, they have the potential to increase onboard autonomy through the ability to simulate, diagnose, and manage faults onboard the spacecraft. The ability to model component degradation and subsystem health in real-time will be key to increasing habitat self-sufficiency.[57] Comprehensive, distributed sensor suites, a key component of digital twins, will allow for active monitoring of onboard environmental parameters such as atmosphere composition, temperature, humidity, and trace contaminants throughout the habitat.

5. *Higher Occupancy: Bioregenerative Life Support (BLS)*

Bioregenerative life support refers to the use of an ecological system (potentially in accordance with traditional ECLSS) for atmosphere management, water management, waste processing, and crew nutrition. This aligns with NASA's aim of creating a sustainable LEO economy, as in the limit of a closed system, the need for ongoing ECLSS consumable resupply would approach zero. However, the inclusion of plants and biophilic design for purely aesthetic reasons has shown to improve mood and mental state in the design of crew quarters,[12] and would be beneficial even if full loop closure is not reached. The cultivation of fresh produce is desirable for long-duration spaceflight and would offer an improvement over the state of the art, in which fresh produce is only available in the weeks after resupply. Research into plant cultivation in space has been done onboard the ISS, notably with the VEGGIE system,[58] though in-space demonstrations of the use of plants for oxygen production have not been performed. Earth-based analogues such as Biosphere-2 and the Lunar Palace 1 have been host to numerous bioregenerative loop closure experiments with crop sufficiency, water recycling, and atmosphere revitalization as key areas of study.[59,60] Additional work has examined optimal crop combinations for long-duration exploration missions that meet crew nutritional needs as well as packing requirements.[62]

Previous work has identified Membrane Biological Reactors (MBRs) as a modular ECLSS method of removing water that could increase flexibility in ECLSS for large-scale space structures.[55] This technology is under investigation at NASA JSC and could serve as a redundant system to other water processing methods.[62] The modular integration of bioregenerative ECLSS alongside other advances in physiochemical processes may enable higher reliability and further advances toward total loop closure.

6. Improved Interior Environments: Novel Habitat Interaction Design, Industrial Design & Programmatic Design

Explainable artificial intelligence,[63] robotic repair capabilities,[64] human-autonomy teaming support and workload estimation[65,66] are currently under development through the NASA HOME Space Technology Research Institute, which aims to develop autonomous and 'smart' systems that could enable future self-aware and self-sufficient space habitation. While these capabilities could be potentially mission-enabling in deep space, where communication latency and long transit times will introduce novel mission constraints, this use of digital twins and other autonomous, 'smart' systems could also enable near-Earth space habitats capable of supporting occupants from a variety of different backgrounds, training, and experience levels.

Work underway at the MIT Space Exploration Initiative has explored novel interior design and artifact industrial design for habitats[67,68] and 'responsive' spaces that autonomously update interior conditions (lighting, projection, temperature, sound, and smell) based on biosignal inputs from occupants.[69] Furthermore, we expect tools like ChatGPT[70] to revolutionize human interaction with space stations in coming years, as the digital and physical environments of a space station are able to be mediated through human voice and AI agent exchange (finally achieving the grand computer agent assistants associated with many of the trade study's science fiction entries). Overall, a new approach to 'design' for space architecture must combine the prior focus on human performance engineering (or 'human factors'), with the more user-centered-delight and thriving considerations that modern citizens have come to expect in their living environments, particularly when expanding access to a broader pool of individuals and requiring less training.

C. Technology Transfer

Many of the technologies capable of sustaining a long-term human presence in space have additional applications for life here on Earth. Self-assembling structures in resource-constrained environments could enable rapid construction of affordable housing in remote locations and areas affected by natural disasters.[71]

Likewise, low-cost, highly reliable ECLSS has applications in both military and disaster relief scenarios. The ability to reliably filter air in high-volume, high-occupancy structures is increasingly relevant for locations affected by seasonal wildfires and other emerging climate change challenges. Ensuring circulation and air quality within large structures such as office buildings, schools, and hospitals is beneficial both to reduce the risk of disease transmission and to protect inhabitants from other pollutants.[72,73]

With an increasing percentage of the world's population living in cities, the cultivation and growth of produce in indoor settings or gardens has applications in urban areas and other space-constrained environments. Beyond an increase in the availability of nutritious and affordable food, the inclusion of home and community gardens in neighborhoods leads to higher social connectivity and civic engagement,[74] and may help to combat increasing food prices and insecurity due to the effects of climate change.

D. Expanding Space Architecture Purposes and Programs

While this study presents key technology gaps between state-of-the-art and novel space architectures, additional non-technical considerations must be accounted for to accommodate the wide range of participants and potential reasons for human spaceflight. For instance, a better understanding of how habitat purposes and programs may evolve over time is key to successfully utilizing both existing and enabling technologies, in order to support the development and adoption of novel space architectures. Habitat accessibility—who will be supported by the habitat and how—will also play an important role in the selection of novel space architectures as well as their environmental and interactive designs, with research already underway by companies such as AstroAccess.[75]

This trade study indicates a focus on exploration and research as key activities current space architecture concepts support, with a small sample accounting for tourism, a relatively new activity for humans in space contexts. These three activities, however, are only a small selection of what humans may do in space now and in the future, which in turn will be mediated through the architectures they inhabit. This suggests that future work in this space should incorporate human-centered frameworks to help evaluate high impact space architecture concepts that move beyond a focus on crew health and performance towards accommodating a more diverse set of spaceflight participants, mission objectives, and user experiences.

VII. Conclusion

This study conducted a broad literature search across NASA design competitions, commercial space companies, contracts, historical missions, film, and media in order to characterize the current landscape of space architecture. From this broad search, designs were further cataloged based on select figures of merit, including their location,

pressurized volume, occupancy, and architecture type. Gaps between the state of the art and future designs were discussed, along with technologies that show the most promise in enabling those future designs.

Future work will identify high-value habitat concepts for next-generation research and development. These concepts will be chosen from representative architectural categories with the highest merit for addressing the gaps between the state-of-the-art and proposed space habitat designs. In addition, these concepts will also be examined through human-centered and programmatic lenses, to uncover how these novel technologies may impact proposed habitat purposes, mission objectives, crew needs, and human-station interaction. From here, 3 concepts will be chosen for small-scale prototyping and ISS technology demonstration missions ("build, test, fly"), such as the scale test flight of the TESSERAE tiles on the Axion-1 mission, to advance proof of concepts for several of the technologies identified in our gap analysis. We also intend to expand the database and make this available as an ongoing, open-source tool as additional concepts arise within the space architecture community. We welcome any additions to the database, a current snapshot of which can be found at: https://www.aureliainstitute.org/trade-study.

Acknowledgments

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