H.O.P.E.
Humanity's Orbital Presence Endeavour

A next generation human rated space station program to be leveraged as an interplanetary communications network is proposed, following a conceptual approach to designing the system architecture to the system level. Systems engineering studies will be conducted to propose a possible solution for such a system, comparison studies will be conducted on different viable solutions throughout the project and development of the proposed architecture. An orbital analysis study is being conducted to be completed later this year. Different solutions will be investigated and contingencies for each will also be explored. This study is being conducted as a response to the impending interplanetary role human beings are striving towards.

Keywords: *Spacecraft design, interplanetary exploration, system architecture, systems engineering, orbit analysis*

Introduction

Motivation

In the last few decades, humankind has been pushing the envelope in space exploration consistently, continuously, and exponentially with no signs of stopping. This pattern of progression yields increased knowledge of the universe; advancements in science and engineering; the continued commercialization of the space industry; and technological innovations that have benefited those on Earth; as seen for the human race.

These benefits and advancements are the primary enablers for increasing technological capabilities with respect to space exploration as a whole. With plans for a lunar gateway, striving towards a colonized Mars, and countless opportunities for innovative ideas to establish themselves in the current space economy, organizations/companies like NASA, Lockheed Martin, SpaceX, Blue Origin, and more are now able to push even harder in the human space race.

With these increased capabilities, researchers still rely on the current communications infrastructure that has been used since the 1970s, a solution that can be improved and should be to meet the impending change in space exploration as shown in NASA's 2015 Audit of the DSN [1]. To match the technological advancements, a sustained human presence at adjacent bodies of interest to the Earth and beyond is an inevitable future that will slowly become more and more feasible as time passes. As humans begin participating in longer duration missions in space, at destinations further and further away, a communications and gateway infrastructure throughout the universe will be an immeasurable asset to the explorers of the new frontier.

Figure 1. *NASA Lunar Gateway Illustration*

Source: NASA 2023 [2]

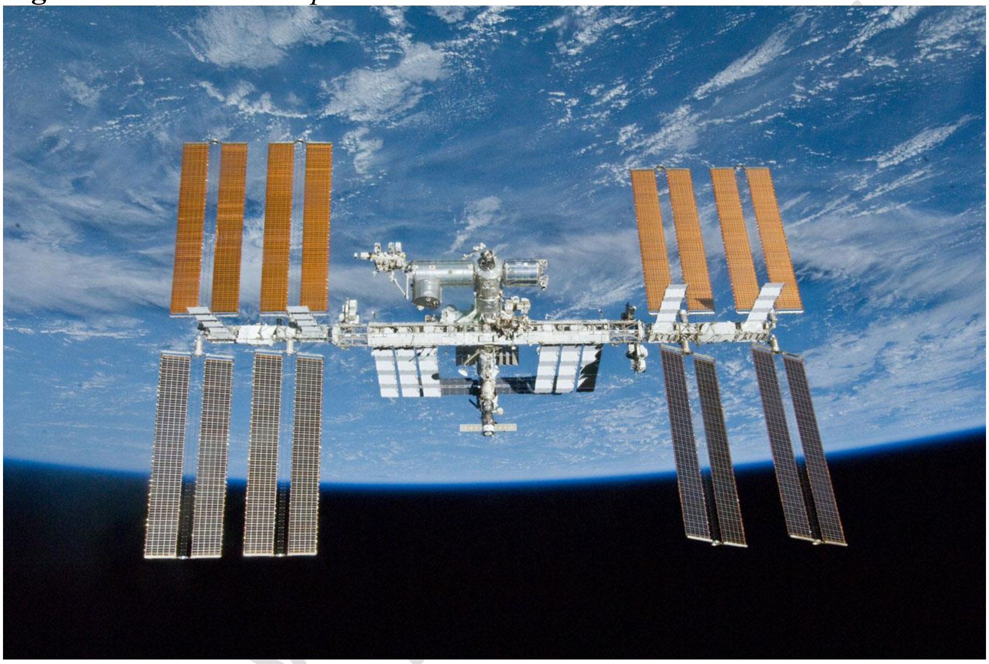
Literature Review

As this is a highly complex, multifaceted design problem, this review will explore the different areas of research that are considered critical or of importance to the implementation of the proposed design solution. Although they are not directly researching the proposed problem, they are highly relevant for the problem field. This literature review will attempt to cover the relevant challenges that have been identified and tackled by other researchers in their respective fields. It is important to note there are only a handful of existing systems that could be considered similar, the Lunar Gateway and the International Space Station and the ISS is a only system that is currently in operation.

International Space Station as a Steppingstone

The International Space Station is just that, an international collaboration of a manned Earth based space station to carry out science and exploration that is not possible on Earth. The ISS program holds decades of knowledge and is the first steppingstone in the pursuit of an interplanetary human presence. Containing an indispensable number of lessons learned that will carry forward with the Artemis program, Mars habitation, and in extension any other interplanetary exploration efforts as discussed in Planetary Surface Operations and Utilization [3]. NASA is implementing processes to leverage lessons learned from ISS missions and operation to directly reduce risk and uncertainty for future Mars missions. Current operations and activities are deliberately aligned with enterprise level blueprint objectives as outlined by the administration. Some key considerations for a successor system to be aware of are discussed in [4]. As with any system that has been in operation for a significant amount of time, new considerations will arise that were not explicitly considered in the initial design. These uncertain characteristics are key to understanding long term reliability and robustness of a manned space station. [5] is the safety requirements document of the ISS, it is imperative to understand the key requirements that have led to the successful deployment and operation of the ISS to be able to understand how the next steps may be taken. A photo of the ISS is included in figure 2 for reference.

Figure 2. *International Space Station*

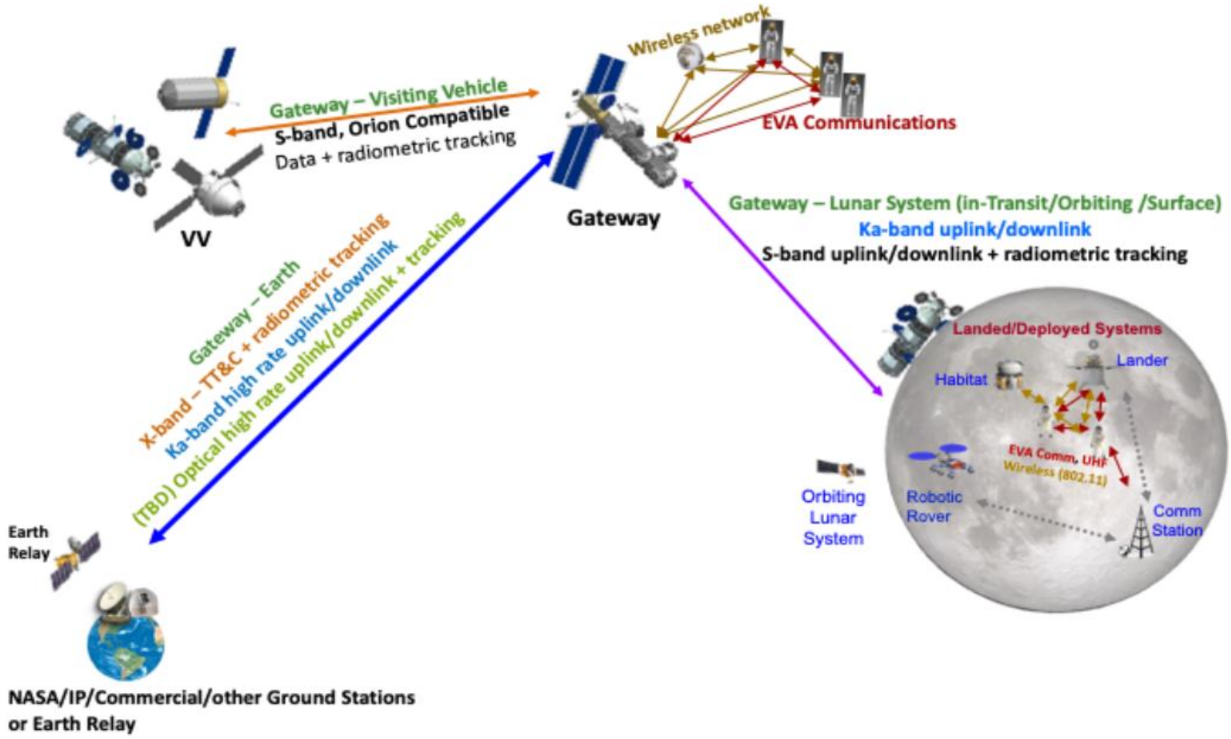


Source: NASA 2020 [6]

Lunar Gateway as a Point of Departure

As part of the Artemis program, a lunar gateway is being developed. This gateway will act as a communications relay from the moon to Earth and will serve as a pit stop for certain missions to recollect themselves before heading to the moon and/or other bodies of interest. The gateway is not a system that is in place yet and is still undergoing development, but it will act as the exact point of departure for other interplanetary manned outposts. The gateway will function as a direct line to the moon, being able to communicate with missions taking place on or about the moon and relaying data or precious information back to the Earth [7]. This will serve as the first step to an interplanetary communications network, containing communications subsystems to enable S-band, X-band, and Ka-band uplink and downlink through NASA's DSN and NSN. The communications architecture is depicted in figure 3 below.

Figure 3. *Gateway Communications Architecture*



Source: International Communications Satellite Systems Conference 2021 [7]

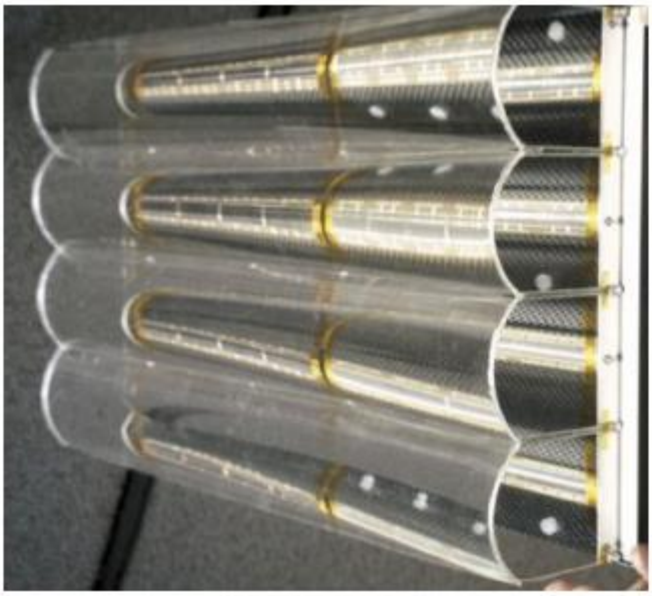
This approach to incremental advancement of capabilities allows the gateway to serve as a building block for future space technologies. The Gateway will serve as a scientific lunar hub for missions and exploration but will be a precursor for Mars exploration and beyond [8-10]. Through the collaboration with international partners, and private industry, operation of the Gateway will foster further innovations to be applied in the future on larger scale efforts. The PPE module will house the main communications systems onboard, it will also provide power and propulsion to the Gateway. As the predecessor system, the requirements found in [11], will lend a hand to establishing the exact point of departure of the current state of the art and how that may be extended to future systems.

Interplanetary Mission Design Considerations

Interplanetary science and exploration have been studied since the very early days of possibility, [12-14] are a series of references that have been chosen from three very different eras. Each reference has a focus on the possibilities of interplanetary science, manned and unmanned, starting with environmental considerations to the different possible science that could be conducted. [14] addresses the photovoltaic concerns any system in the deep space regime would need to consider, diving into what is possible and necessary for outer planetary missions in terms of power generation and radiation concerns for Jupiter. A proposed photovoltaic solution is shown in figure 4 for deep space applications. These considerations may be compared across all three time periods found in [12-

13] to ensure a proper understanding of interplanetary mission design is established.

Figure 4. *Demonstration Unit, Stretched Lens Array for Deep Space Applications*

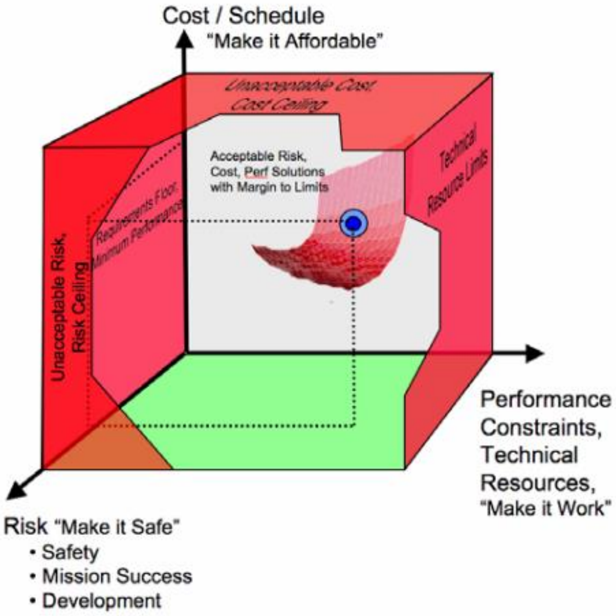


Source: IEEE Photovaltic Specialists Conference 2015 [14]

Human Rated Space Systems

Unmanned spacecrafts have come a long way and are incredibly versatile, however there is no replacement for human intelligence and adaptability, which is why manned space stations has been a topic of research that continuously sees advancements in the limits of capability continuously. [15-19] are key areas of interest for the research conducted in this design study. [17] provides insight into the human error aspect of these manned space stations, and the analysis necessary to create a safe reliable solution, these solutions help mitigate problems at the system level rather than focusing on individuals, which is not something that can be designed for with ease. [18-19] cover some of the non-conventional forays into space structures and artificial gravity. Some key areas of research that did not seem to be as prevalent were interplanetary manned space stations, however these references have information relevant to any manned space system. As seen in figure 5, a project constraints box from [15] is shown and is an example of one of the higher level balancing methodologies to consider for human rated space systems.

Figure 5. *Human Rated System Project Constraint Box Diagram*

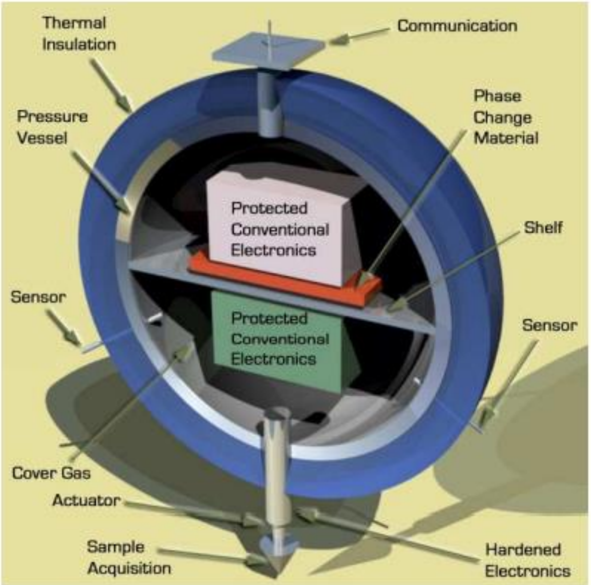


Source: NASA 2008 [15]

In-situ Resource Utilization

The references found in [20-26] delve into the research of in-situ resource utilization, spanning the ages since the early days of space flight. Although these are not the exact situations being proposed in this report, these papers lend considerable lessons to apply to any long term deep space presence. [20,25] explores Saturn's moon Titan and the different considerations that should be taken when in-situ resource utilization is required in a deep space environment. These considerations lend their way to other bodies of interest and what may need to be investigated to leverage the environment for a sustained presence. [21-24] describe different proposed methods of large-scale manufacturing systems in space, these papers describe system concepts that are scalable and applicable to the state of the art available and how these large-scale programs may come to fruition. Figure 6 shows a depiction of one of the technologies proposed in [25], to be used for in-situ resource utilization, these kinds of technologies may be leveraged for other locations.

Figure 6. *Venus In-situ Mission Pressure Vessel*



Source: International Astronautical Congress 2006 [25]

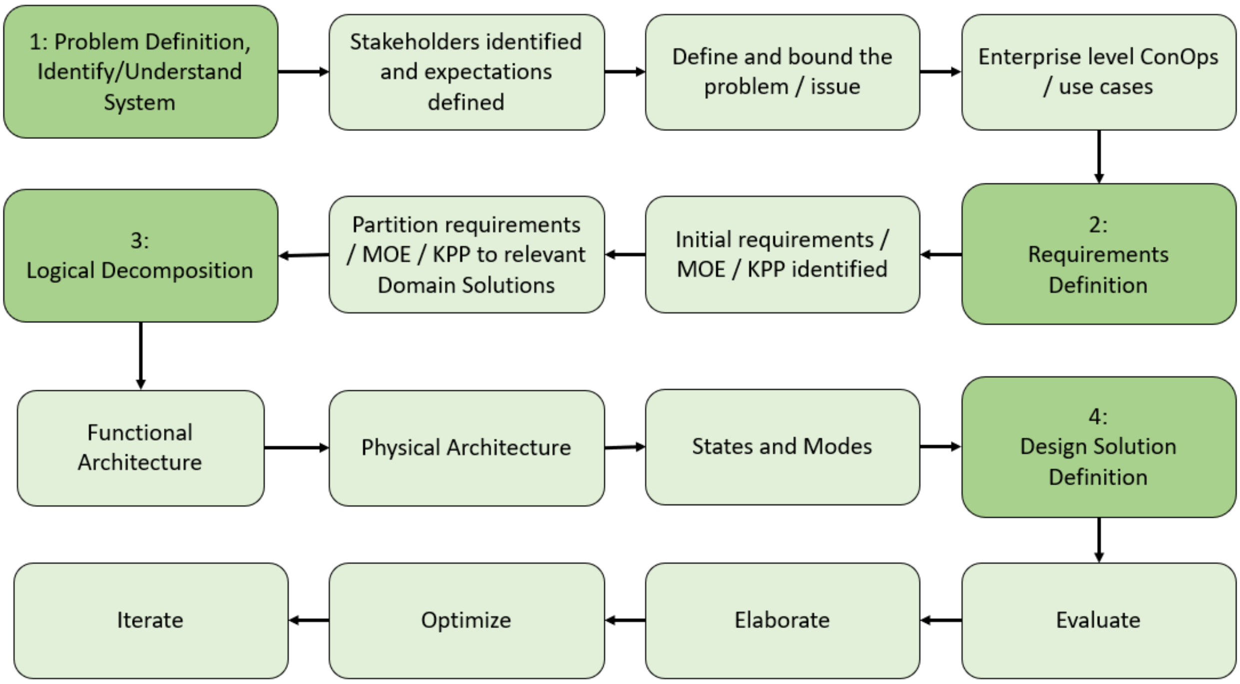
Methodology

Using systems engineering methodologies taught in SJSU and from outside references, a system architecture design study will be carried out to the system level of a future space station to be used as a multiplanetary human presence in the solar system. Digital engineering will be leveraged where possible, defining key features of this system and how the system will interact with its environment through the use of model-based systems engineering methodologies. Although it is important to note that a tailored approach to SysML conventions will be used in some of the diagrams, SysML convention will not be followed exactly as these graphics will be used to plainly demonstrate the concepts rather than demonstrate sysML conventions.

This project will adopt a set of tailored systems engineering methodologies to approach the system architecture development: from what is taught at SJSU, concepts from Wasson's System Engineering Process [27], Wiley's Systems Engineering Principles and Practice [28], and NASA's Systems Engineering Handbook [29] will serve as the primary resources utilized. Relevant trade studies will be conducted, and the architecture will be explored at the system level, defining key features of the system and how it will interact with its environment. The orbital mechanics and behavior will be modeled using NASA's Mission analysis tool GMAT, in conjunction with analytical hand calculations. Orbital analysis methodologies as taught in the advanced orbital mechanics course in SJSU coupled with the aid of outside references will be implemented.

The methodology can be described as a tailorable, modular approach that leads to extension and reduction in the architecture. As shown in figure 7 below, a general flow of the adopted methodology has been modeled. The key to any successful architecture is translating desires and needs of the prospective system stakeholders into a solution where the system artifacts will satisfy the original needs. Architecting is an iterative and recursive process that is just one part of the development of a system.

Figure 7. *Tailored Methodology*



Source: Author

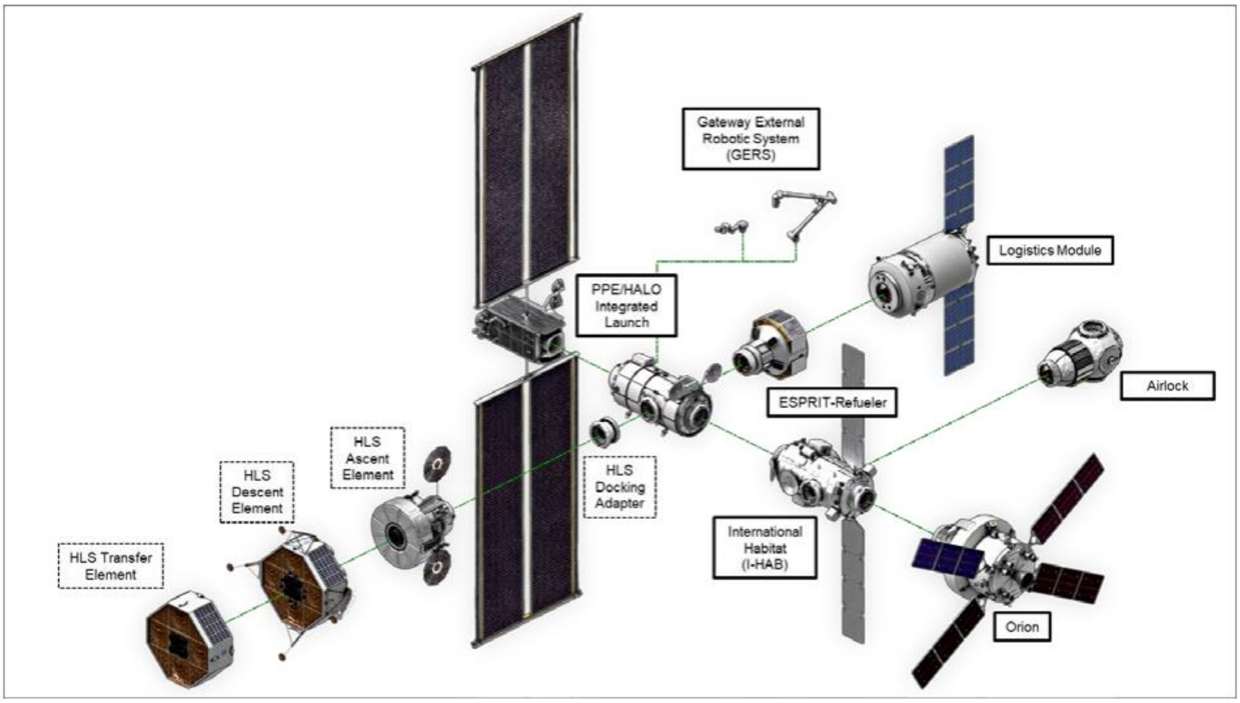
Problem Definition

<u>Points of Departure</u>

Lunar Gateway

The Lunar Gateway reflects what will be considered a direct steppingstone for HOPE, the gateway is a lunar orbiting outpost station that will serve as a communications and explorations hub for humans in the near-Earth system and beyond. Allowing for ease of communications and enabling higher fidelity for immediate Moon and Mars science objectives. The Gateway will serve as a human rated habitat to support manned missions, science, and research objectives. These objectives include establishing a sustained human presence on the lunar surface, enabling Mars exploration, and pushing the envelope even further on what was built by the International Space Station.

Figure 8. *Expanded View of the Lunar Gateway with Optional Configurations*

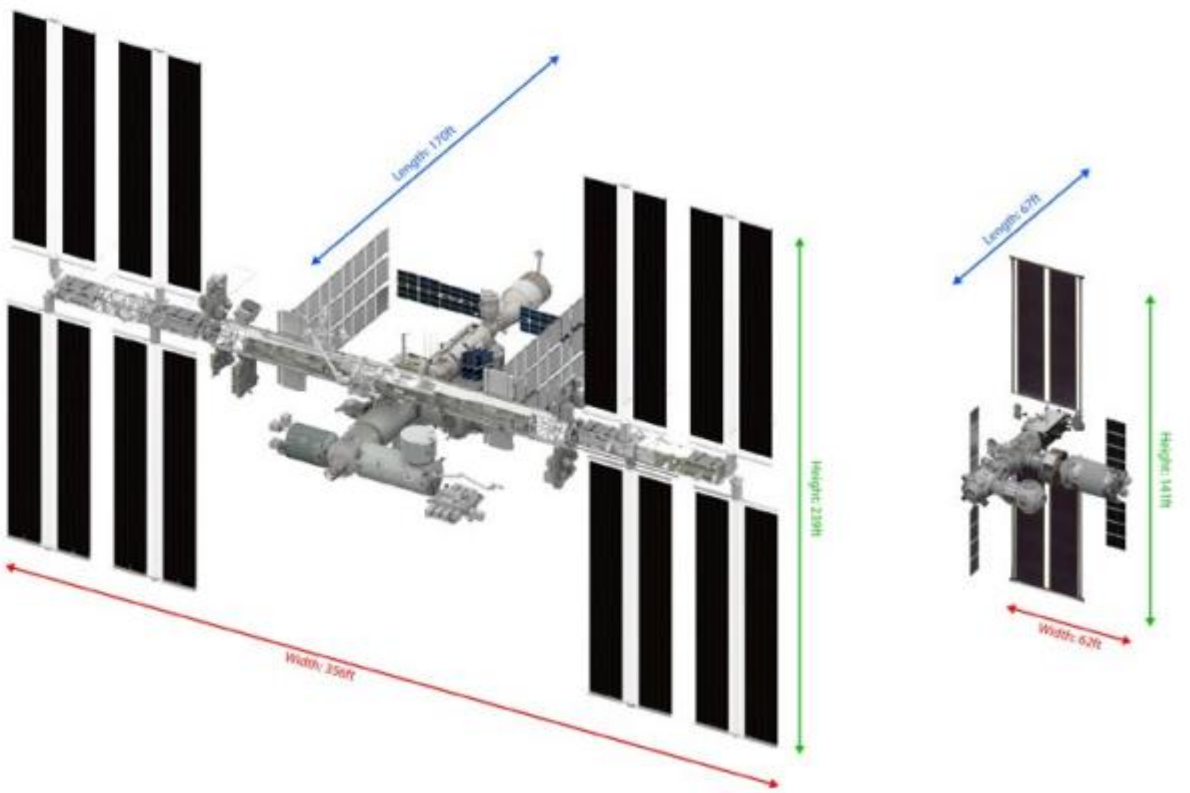


Source: International Astronautical Congress 2021 [30]

The Lunar Gateway will initially be composed of two major subsystems that in turn will be complex systems in their own right. The first element is the Power and Propulsion Element, referred to as the PPE, this can be seen in figure 8 above. The second element, also shown above, is the Habitation and Logistics Outpost also known as the HALO. The PPE will be responsible for housing a Solar Electric Propulsion system (SEP) for orbital maneuvers and a bi-propellant chemical propulsion system for attitude control; the primary components for Earth communications, containing multiple X-band and Ka-band links; and will handle attitude control, orbit maintenance, and transfer capabilities. The PPE spacecraft will be built by Maxar technologies of Colorado [30], contracted by NASA Glenn research Center. The HALO will handle the habitation, research, and command control aspects of the gateway. The HALO will have modular docking stations for visitor spacecraft, with NASA's Artemis program components being the first expected with a targeted launch date no earlier than November 2024. NASA's Artemis spacecraft includes the Orion spacecraft, the Human Landing System (HLS) and the logistics resupply spacecraft as shown in figure 8.

The Gateway will leverage key lessons learned from the ISS, major lessons include acceptable risk and human rated safety concerns. Another key lesson learned from previous space endeavors has led to the evolution of how humankind conducts state of the art space program developments, from international competition to now international cooperation. The gateway, just like the ISS will be an international effort, with partners, contractors, and subcontractors from all over the world contributing to the development of and execution of the Artemis program as a whole. This evolution comes from the benefits seen from collaboration, as was done during the earliest days of the ISS to the present-day logistics and activities concerning the ISS. Figure 9 below shows a size comparison between the Lunar Gateway and the ISS. The positioning of the gateway and size constraints will lead to different safety concerns for humans aboard for sustained periods of time, invaluable experience onboard the ISS will serve as a baseline for the gateway in terms of the technology required and where advancements must be pushed.

Figure 9. *ISS (Left), Gateway (Right), Size Comparison*



Source: International Astronautical Congress 2021 [30]

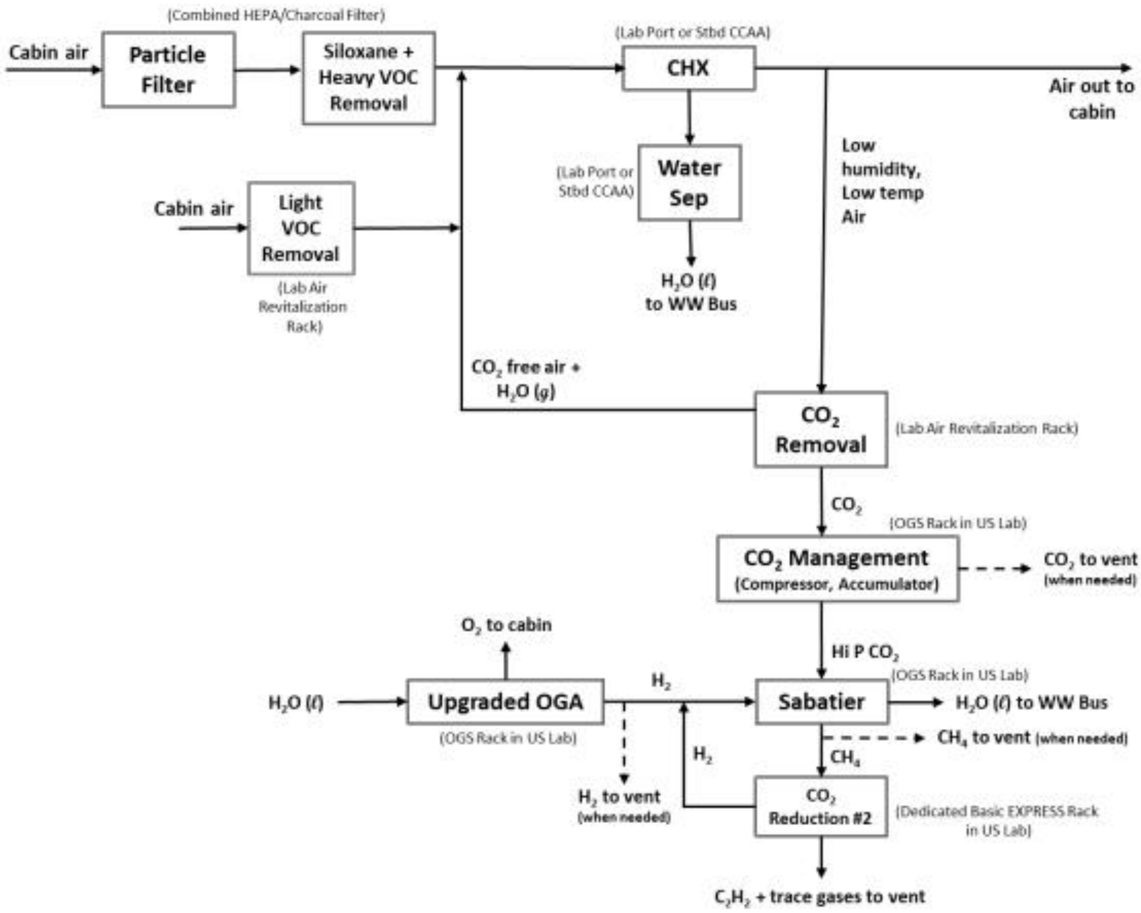
It is important to note that a major intention of the Lunar Gateway is to enable technologies that will serve to raise the baseline of what is possible and expand upon the maturation of the state of the art available. NASA plans to leverage the gateway for unique research concerned with lunar and heliophysics, space biology, life sciences including human health, and materials to name a few. This will enable and pave the way for Mars centric manned and unmanned missions, ultimately pushing towards a manned intragalactic presence.

International Space Station

The International Space Station represents the first international human effort for a long term, manned presence onboard a spacecraft. Starting with a presidential directive in 1984 from Reagan, the ISS has maintained a manned crew for over 20 years. The ISS is a space station that resides in low Earth orbit (LEO) supporting international government research and in recent years has supported many private industry experiments, research, and technology. The ISS was built over the course of a decade before becoming fully functional through international efforts and utilization of NASA's Space Transportation System (STS). The ISS was intended to be an in space laboratory platform for microgravity experiments, a deployment hub for in space LEO missions such as CubeSats, and was thought to serve as an outpost for lunar and earth based missions. For these reasons it can be considered as the major system in service that HOPE can be traced to.

Over the course of its service life, the ISS has seen its share of human related challenges and solutions that come about to address these challenges. Some of these challenges include extravehicular activity (EVA), resource management, resource recycling, radiation, and more. These experiences are essential for the development of any future human rated space station, the Lunar gateway, and HOPE. The development of life support systems will be essential not just for HOP, but for the Artemis program that is set to operate within the decade. Systems such as the Air String and Water String, which will be tested by the ISS are examples of the kinds of systems that will be leveraged for future space outpost missions [31]. An operational concept diagram is shown in figure 10 below.

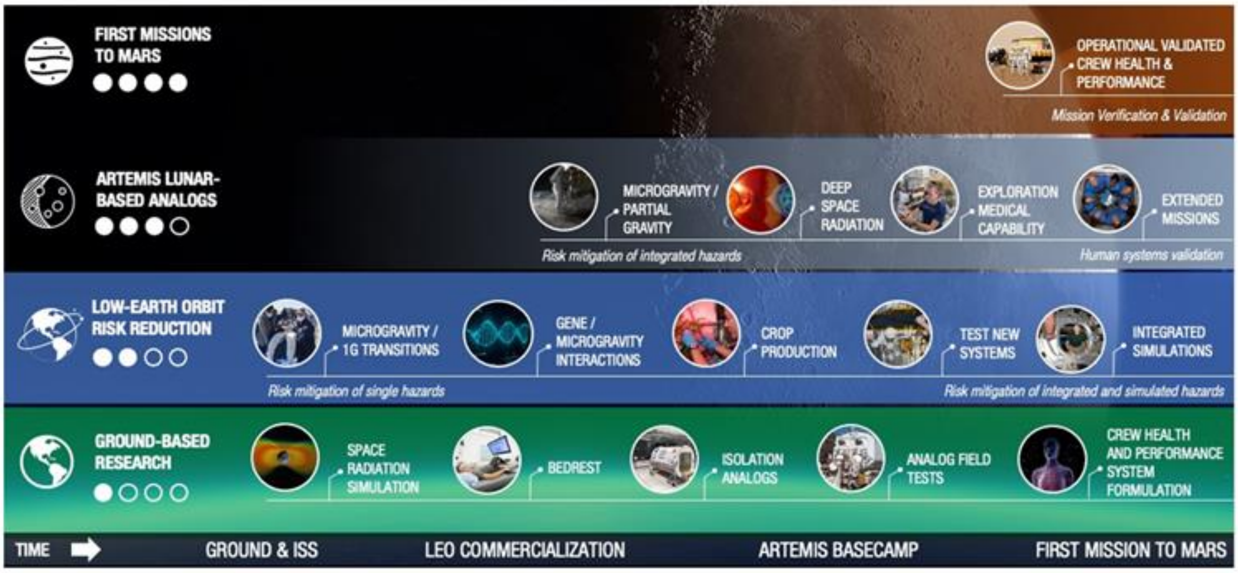
Figure 10. *ISS Air String Operational Concept*



Source: International Conference on Environmental Systems 2022 [31]

Risk reduction and acceptance by the ISS will be a critical component of lessons learned to incorporate and build on for future systems. Over the decades, the ISS has seen many things impossible to predict in the design phase and could only be addressed through experience in operation. Initially many design requirements were deemed adequate and through its service life has seen revisions due to unforeseen circumstances causing these requirements to become inadequate. Many areas where risks were underestimated have since been reassessed and mitigated with understanding only found through operational use [4]. New processes have been put in place by NASA to leverage these lessons learned from the ISS, mature them through the Artemis program and extend them to Mars and beyond. These activities and the process to achieve them are outlined at a high level in figure 11, the deliberate coordination between NASA programs have been designed to gain a closer understanding of maintaining a human presence in space.

Figure 11. *Notional Human Spaceflight Strategy to Achieve Mars Mission Readiness*



Source: International Astronautical Congress 2022 [32]

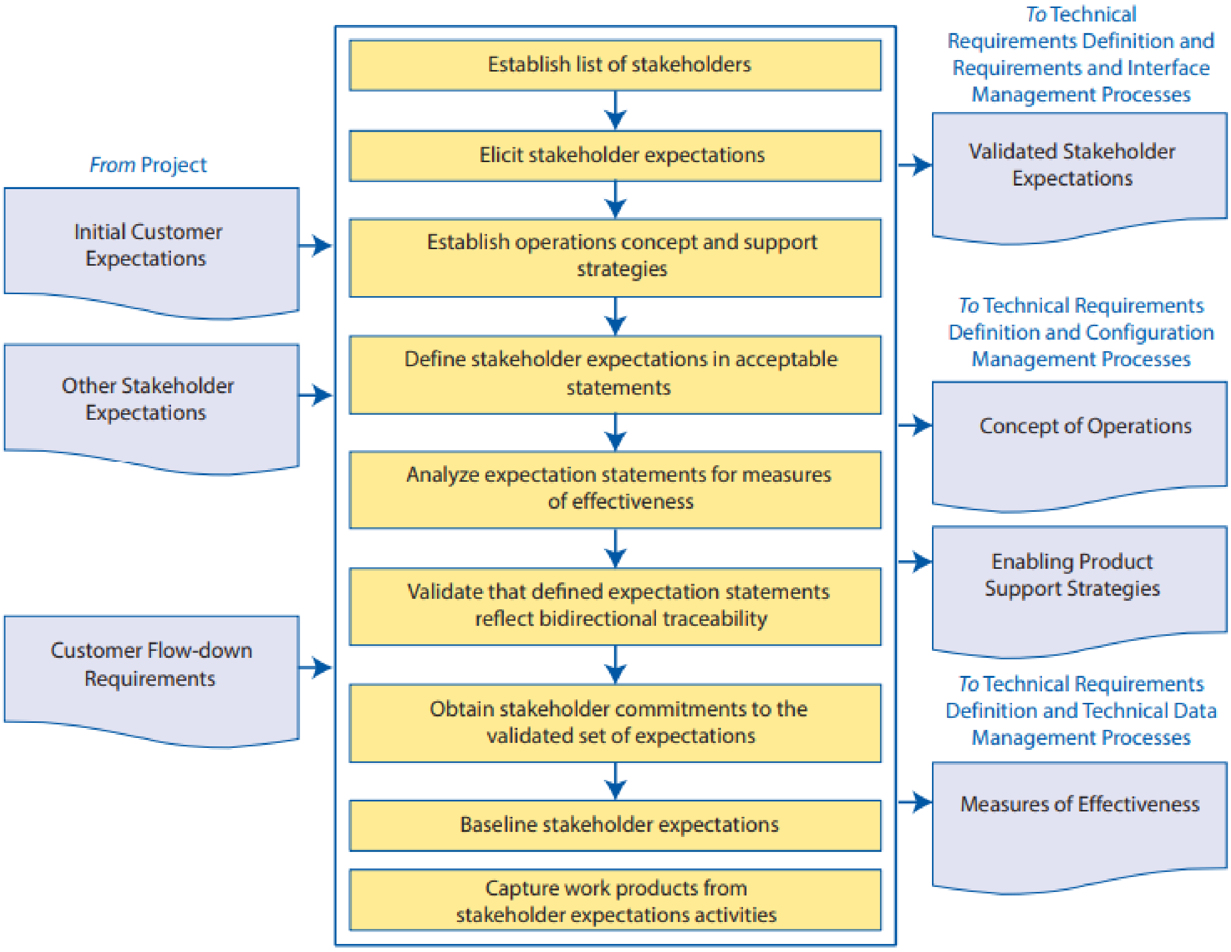
The active and deliberate usage of the ISS to extend to future missions has established this space station as the ground zero steppingstone for all future manned space outposts. The gateway will leverage all lessons learned and mature the solutions that rise from them, while these solutions will in turn lend a hand to future outpost systems like HOPE.

Results

Stakeholder Analysis

The HOPE program will leverage existing systems as a point of departure and potential stakeholders will be derived as such. The stakeholder definition process from NASA's Systems Engineering Handbook [29] will be tailored and leveraged as the methodology applied to the HOPE program.

Figure 12. *Stakeholder Expectations Definitions Process*



Source: NASA 2016 [29]

<u>Stakeholder Definition</u>

Active stakeholders for the HOPE system shall be defined as stakeholders that play an active role with the system when it is operational and in use. Passive stakeholders for the HOPE system shall be defined as stakeholders that do not play an active role with the system when it is in operation, rather these stakeholders will influence the system. It is important to note that the list of stakeholders may change for a given system depending on the phase of the program lifecycle, this notional list will be considering stakeholders during the time of operation. A preliminary list of stakeholders for the HOPE program is shown below in table 2.1.

Table 1. *Notional Stakeholders*

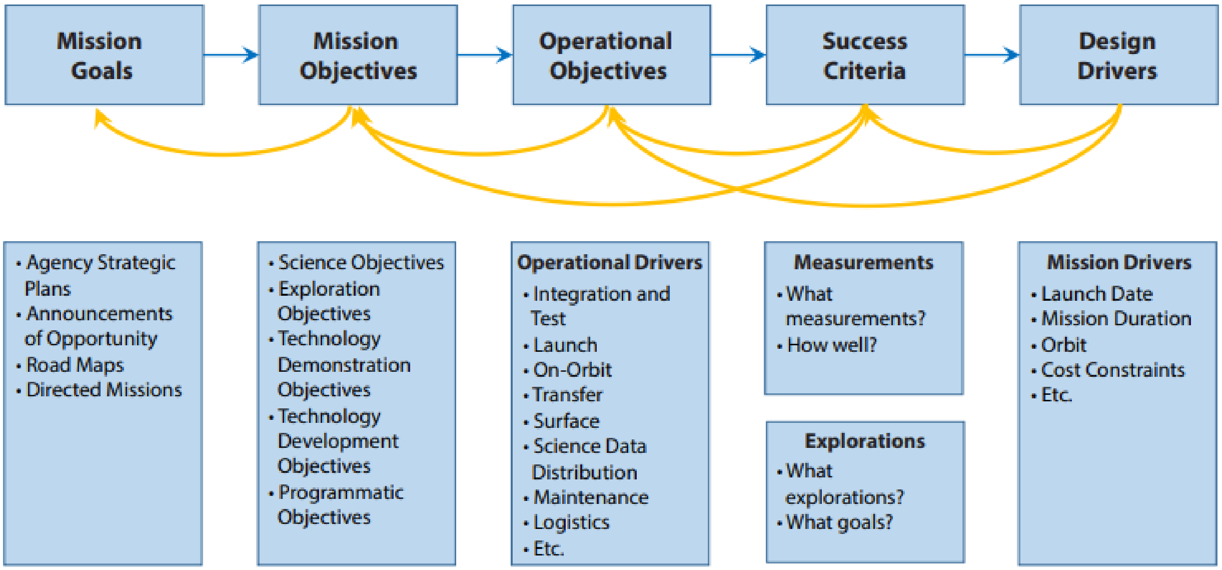
Name	Role	Description
	Active Stakeholders	
NASA	Owner / Maintainer	Government Space Agency
International Collaborators	Owner / Maintainer	Federal Government
Private Industry / Technology Development	User / Maintainer	N/A
Science / Research and Exploration	User	N/A
Public	User	N/A
	Passive Stakeholders	
United States Government	N/A	Federal Government
Internal / External Program Advisory Board	N/A	Advisory Team
Public	Beneficiaries	N/A

Source: Author

Expectations

Leveraging legacy systems, and the stakeholders outlined in table 1, preliminary stakeholder expectations may be derived for HOPE. These expectations may be derived using the methodology laid out in [29]. This thought process is shown in the figure below.

Figure 13. *Information Flow for Stakeholder Expectations*



Source: NASA 2016 [29]

These stakeholder expectations will be captured in the following sections, as we follow through on the flowchart shown in figure 13, a tailored methodology will be adopted to define the elements within stakeholder expectations.

<u>Constraints</u>

As with any highly complex system with key stakeholders, constraints will be driven into the system and will influence the overall design approach and requirements. These constraints will flow into the system from both active and passive stakeholders of the system.

Mission Definition

<u>Needs</u>

This is the single statement that will drive everything else, a singular statement that does not relate at all to the solution but is fully addressing the problem at hand [29]. In other words, the need to be addressed exists regardless of the solution. The HOPE program will be developed to create a means for having manned outpost stations throughout the galaxy at different bodies or locations of interest. There is no current system that achieves this, and the legacy systems chosen will take the first steps to reach the point of departure that HOPE is addressing. This singular statement encompasses the ultimate problem being addressed by the proposed program designed in this study.

<u>Goals</u>

The goals will be defined as an extension of our program's need statement. These goals will constitute a specific set of expectations for the system to be developed and will address critical issues identified in the initial problem assessment. It is imperative that goals do not need to be a measurable metric, rather they should allow for the assessment of if these metrics can be achieved.

<u>Objectives</u>

The objectives of the HOPE system will, while ignoring any potential solutions, specify levels of different targets or parameters HOPE must achieve to be considered a successful system. These objectives will be traced to various relevant goals as outlined in the section above.

<u>Constraints</u>

Constraints will be imposed on the system, from external interfaces and entities. These constraints will assist in establishing the design boundaries of the system.

The two major constraints that will be considered for this design study will be the natural space environment and the induced environment expected to be experienced by the system. The natural space environment will place constraints on the system and influence system requirements at a functional and physical level. The induced load environments expected for the system capture any self-imposed loading conditions and load conditions that may occur from non-space environments experienced throughout the lifecycle of the system.

Mission Defined

The high-level mission definition is achieved through the methodologies and definitions laid out in the sections above. The stakeholder assessment has resulted in the following table.

Table 2. *Mission Definition*

Mission Need: To establish an intragalactic, interplanetary human presence.	
Goals	**Objectives**
1. Provide sustainable human presence onboard outpost stations in deep space.	1.1 Enable deep space crew habitation for a minimum of 8 months.
	1.2 Develop a system that can be extended to multiple bodies of interest in deep space.
2. Provide an intragalactic communications network.	2.1 Provide a means of communication between bodies of interest.
	2.2 Reduce the average time of communications between major deep space locations and Earth by 40% as compared to conventional deep space communications methods of 2023.
3. Provide a research and exploration hub for locations of interest.	3.1 Provide a platform to enable deep space science missions
	3.2 Provide a platform to enable deep space exploration missions
	3.3 Provide a platform to enable technology maturation missions
	3.4 Provide these capabilities at multiple bodies of interest
4. Reduce the risk of sustained human presence in deep space.	4.1 Reduce the risk of environmental effects on crew by 50%
	4.2 Provide life support for deep space missions with adverse conditions
	4.3 Provide life support for deep space missions with off nominal conditions

Concept of Operations

Now that the stakeholder expectation study has come to an initial conclusion, notional high-level concept of operations will be proposed here. These concepts of operations will tie to various enterprise level scenarios of the completed system. These scenarios may be referred to as design reference missions and will encompass all known operational uses including off nominal events. These events will be considered a walkthrough of the lifecycle of the program at the highest level and are intended to be very broad at the current state of development.

Table 3. *Operational Concepts*

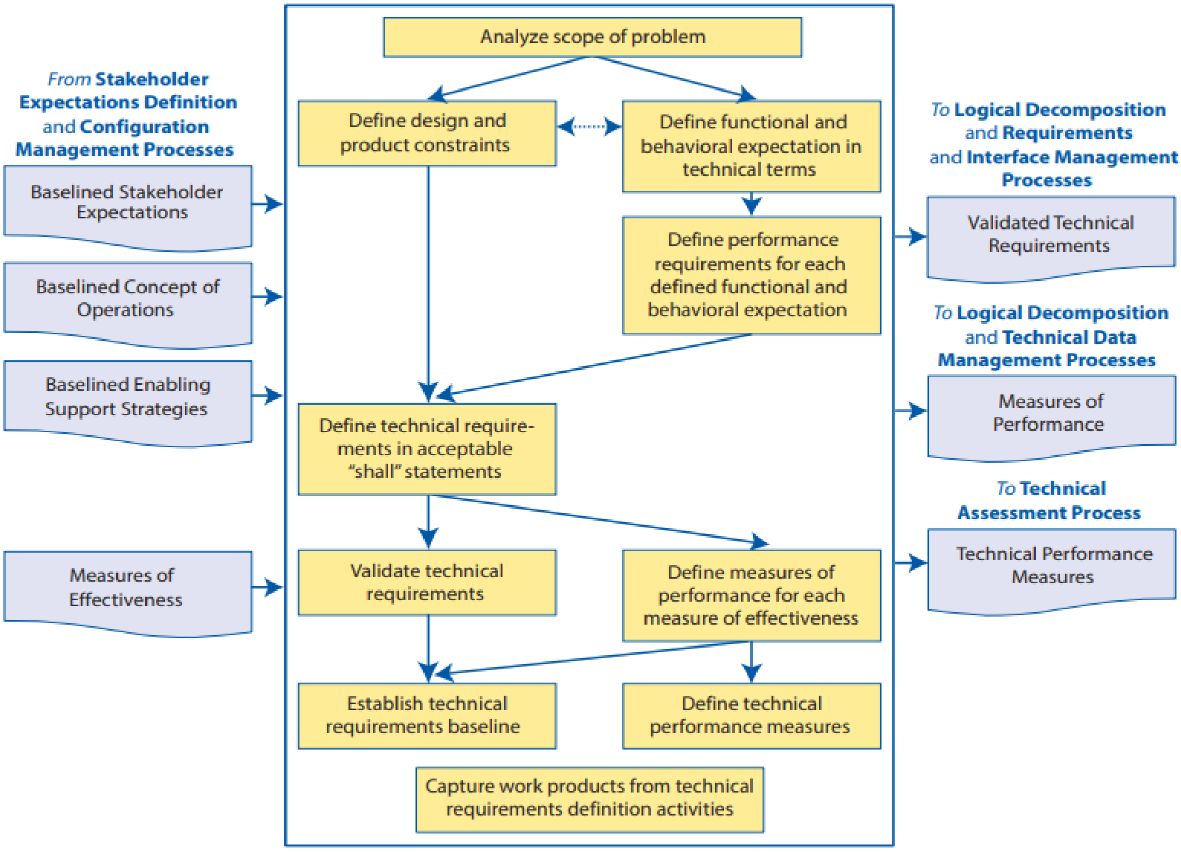
Program Level Operational Concepts		
Scenario Name	**Pre-condition / post condition**	**Description** This operational concept describes all the activities or scenarios that…
System Deployment	End of manufacturing / System emplacement	Encompass the system and its interactions immediately after manufacturing all the way up to orbit emplacement by the launch vehicle.
Nominal Operations	System deployed / End of mission	Describe the system activities once it is deployed at the location of interest, all the way up to the nominal end of mission.
Off Nominal Operations	Off nominal event / Reset and Recover	Captures all the off nominal or unintended events that may occur and the operations that take the system from the off-nominal event to a reset and recover protocol.
System Disposal	End of mission / System disposed	Will handle the responsible disposal of the system, starting with the end of mission nominal or off-nominal to the disposal.

System Level Requirements

<u>Initial Requirements</u>

NASA's Systems Engineering Handbook leads the previously defined stakeholder expectations and transforms them into a set of technical requirements. These requirements will encompass the system's inputs, outputs, relationships, constraints, performance, etc. Figure 14 below outlines this process.

Figure 14. *Requirements Definition Process*



Source: NASA 2016 [29]

System level requirements at the highest level will be derived from the initial stakeholder expectations defined in the stakeholder definition section. These system level requirements will be revisited throughout the course of this design study and will capture only what is necessary for the scope of the study. The vernacular used within the requirements will follow standard NASA verb implementations as seen below [11].

- "Shall" statements will be used to denote requirements that are non-negotiable contractually obligated for the system.
- "Should" statements will be used to denote requirements that are considered best practices that are desired, but not necessary for the success of the system.

Table 4. *System Level Requirements*

Requirement ID	Description
SYS-01-001	The HOPE system shall support a crew of 6 for a minimum of 8 months.
SYS-01-002	The HOPE system shall have a presence at each major planet or nearby body of interest adjacent to major planet within the galaxy.
SYS-01-003	The HOPE system should support a crew of 6 for a maximum of 13 months.
SYS-01-004	The HOPE system shall support crew sizes of 1 – 6.
SYS-02-001	The HOPE system shall provide a communications network between at least 6 locations of interest within the galaxy.
SYS-02-002	The HOPE system should reduce the link budget losses as seen in current DSN communications by 50%.
SYS-02-003	The HOPE system shall comply with all FCC regulations and guidance.
SYS-02-004	The HOPE system should support encrypted and unencrypted communication pathways.
SYS-03-001	The HOPE system shall utilize a modular docking interface.
SYS-03-002	The HOPE System shall provide federal and private entities with testbed capabilities at various locations in the galaxy.
SYS-04-001	The HOPE system shall mitigate radiation exposure to crew.
SYS-04-002	The HOPE system shall contain mitigation procedures in the event of an off-nominal radiation event.
SYS-04-003	The HOPE system shall provide necessary life support for crew for a minimum of 6 months without resupply.
SYS-04-004	The HOPE system should reduce radiation exposure to crew by 50% as compared to heritage systems in similar environments.
SYS-05-001	The HOPE system shall have modular LRUs in the event of corrective maintenance.
SYS-05-002	The HOPE system should have a minimum operational service life of 30 years in orbit.
SYS-05-003	The HOPE system shall support a minimum of 3 significant orbit transfers per mission duration.
SYS-05-004	The HOPE system shall maintain sufficient functionality for end of mission disposal.
SYS-06-001	The HOPE outposts shall have accommodations for autonomous logistics resupply
SYS-06-002	The HOPE outposts shall have accommodations for autonomous docking and undocking
SYS-06-003	The HOPE outposts shall have accommodations for in orbit refueling

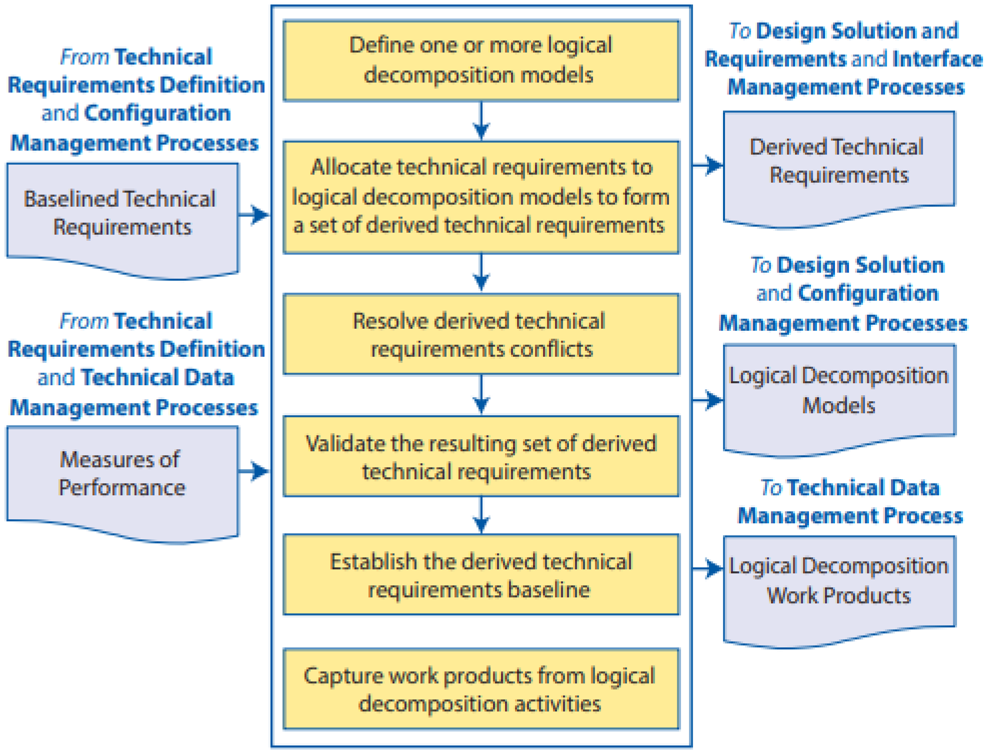
Source: Author

Logical Decomposition

<u>Functional Architecture</u>

The functional architecture of the system is designed as follows to fulfill the top-level requirements and stipulations found in chapter 2's stakeholder analysis exercise. NASA's logical decomposition process will be utilized to decompose from the high-level requirements into technical and functional requirements for each element of the system. This decomposition process will also allow for the formulation of the various solution domains. The illustration in figure 15 is a representation of the general flow of activities.

Figure 15. *Logical Decomposition Process*



Source: NASA 2016 [29]

The requirements seen in table 4 establish what is desired to fulfill the basic needs of the stakeholders. Using these baselined requirements, functionality will be assigned to subsystems from the functional perspective and lower-level requirements will emerge from these allocations. This will allow for a purely functional view of the HOPE architecture and will allow for clear traceability of the functional decomposition. The table below shows the traceability from top level requirements to functions of the system.

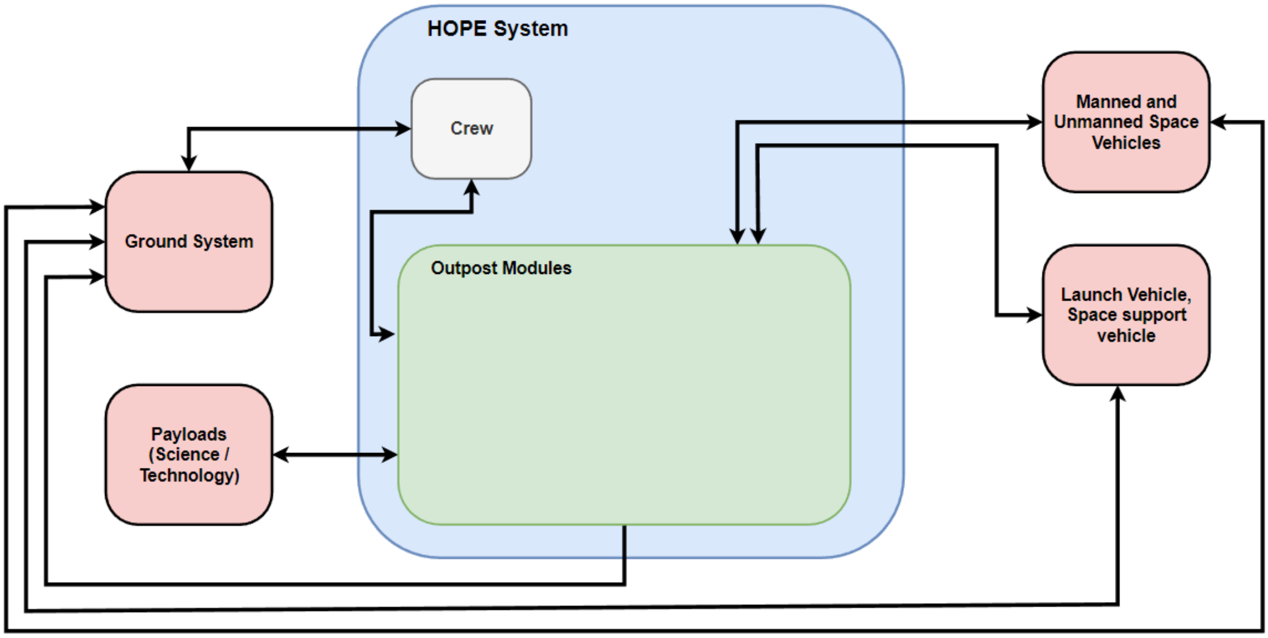
Table 5. *Functional Allocation*

Functional Allocations	
Function	Requirement ID
Sustain Crew	SYS-01-001
	SYS-01-003
	SYS-01-004
	SYS-04-003
Protect Crew	SYS-04-001
	SYS-04-002
	SYS-04-004
Sustainment	SYS-05-002
	SYS-05-004
Provide Intragalactic Communications	SYS-01-002
	SYS-02-001
	SYS-02-002
	SYS-02-003
	SYS-02-004
Provide Science / Exploration Hub	SYS-03-002
	SYS-05-003
In-space Maintenance Activities	SYS-03-001
	SYS-05-001
	SYS-06-001
	SYS-06-002
	SYS-06-003

Source: Author

These traces are then used to identify key functions desired from the HOPE system. Once these functions are identified, the common grouping allows for functional group allocations to begin. These groupings can be used to begin the process of interface definition and physical decomposition. This notional grouping of requirements also helps to begin defining the operations solution domain of our system. Once the operations domain begins to present itself, the behavioral domain can begin development. The high-level behavior of the HOPE system can be seen in figure 16 below.

Figure 16. *HOPE Functional Diagram*



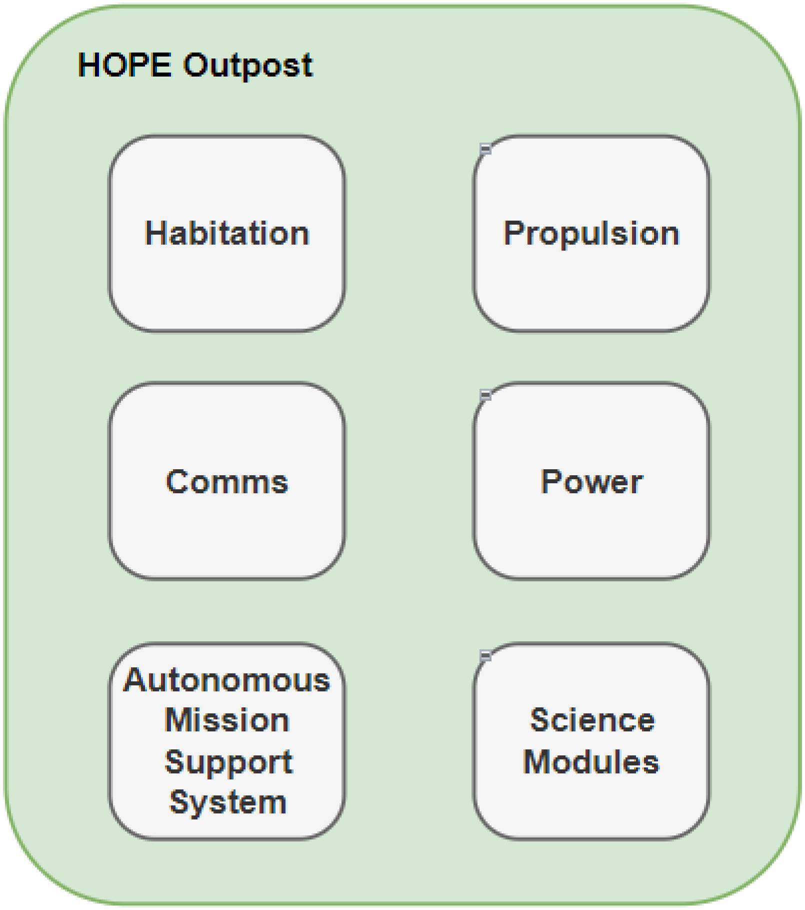
Source: Author

This notional functional diagram depicts the HOPE system and how it interacts with its environment. This notional behavioral depiction coupled with the previously defined solution domains allow for the physical solution domain to begin formulating as discussed. The derivation of the various solution domains as presented in preceding sub sections follows the logical decomposition process laid out in NASA's systems engineering handbook and methods from Wasson's systems engineering method. These steps set the system definition up for the physical architecture to be defined.

Physical Architecture

The proposed physical architecture is derived from the various points of departure discussed in previous sections and from the various solution domains as defined in Wasson's approach to problem solving [27]. The notional physical architecture can be seen in figure 17 below, this is a notional architecture and is subject to trade studies of each proposed element.

Figure 17. *HOPE Outpost Physical Architecture*



Source: Author

The various proposed elements from figure 17 above will be discussed in the following sections. The outpost elements will place an emphasis on leveraging state of the art technologies that either currently exist in a premature fashion to some degree or technologies that are on the cusp of a breakthrough. These elements will also place human and system safety as a top priority, although establishing an intragalactic communications network is a key theme of the system, safely advancing human exploration capabilities will be imperative for creating a sustainable approach to interplanetary travel.

Habitation

The habitation module will house the onboard crew during the various missions possible for each outpost, the associated functional allocations can be seen in table 5. The habitation module will support long term manned deep space efforts for various purposes.

Propulsion

Depending on the specific location, a different final solution may be necessary with the propulsion system of each outpost. In general, the various propulsion systems used will have a high specific impulse, be capable of station keeping, and allow for the outpost to make a few significant orbital maneuvers in the case that an orbit transfer is required to support a specific mission or payload. Electronic and chemical propulsion systems will be utilized where possible for significant maneuvers and for attitude control respectively. The Gateway program will be utilizing a similar configuration, the HOPE outposts should build on the technology that will be matured and developed through the Artemis program.

Communications

A robust communications system will be an inherent characteristic of any HOPE outpost placed throughout the solar system. One of the driving needs being addressed by the HOPE program is to establish an intragalactic communications network, this will be established by having multiple HOPE outposts at various bodies of interest. These outposts will communicate with one another to relay messages back and forth, allowing for incredibly deep space missions to have an infrastructure in place to communicate with the Earth through a well established network rather than having to broadcast from the spacecraft directly to Earth. This will increase the types and size of data being collected by various missions from distant locations as there will be less dependency on the system's ability to transmit long distance and nearby outposts will be able to receive and transmit on behalf of the spacecraft.

The general communications architecture will vary depending on location, however the overall approach and hardware should be relatively similar across each outpost. There will be multiband capability for receiving and transmission including, along with leveraging optical communication technologies for specialized purposes depending on the maturity level at the time. S, X, and Ka band will be supported along with the various other forms of communications that may appear. The Lunar Gateway currently under development is the first step to having this infrastructure in place, as it will serve as a communications relay from the Moon to Earth and eventually deep space to the Earth. The notional concept of operations is depicted in figure 3. The hope is to have a multiplanetary solution for what is being demonstrated by the Gateway.

Power

The power module of each HOPE outpost will vary between one another. Each location will have different solar availability, environmental constraints, and power budgets. This will cause each system to vary, although it would be ideal to keep every outpost as similar to one another as possible, this is highly unlikely due to the reasons mentioned.

Highly robust and advanced solar arrays are currently in development for deep space applications, eventually these will be utilized on systems such as the HOPE outposts. Another solution for power would be leveraging nuclear power systems, such as fission or radioactive decay systems where it is possible to lessen the dependency on the Sun at locations of interest where there is very little sunlight.

Autonomous Mission Support System

The Autonomous Mission Support System, AMSS, is the module of each HOPE outpost that will leverage machine learning and AI technologies to carry out tasks autonomously without or with minimal human input. These tasks may include, but are not limited to unmanned logistics management, manned tasks that would require crew to spend significant time on such as certain LRU replacement procedures or maintenance activities, communications encryption/decryption priority rating, and any other relevant tasks that may be taken on depending on the location and mission.

The main purpose of the AMSS would be to leverage emerging AI technologies for unmanned operations that would generally require crew to be onboard an outpost. This will allow for sustained uncrewed operations at each HOPE outpost as needed. This system will be able to make low and mid priority decisions ranked based on effects to the system.

Science Modules

The science modules in figure 17 represent any scientific module that may be a part of that specific HOPE outpost. The science modules will differ for each outpost as each body of interest will have specific science objectives in mind that will cause the modular design to be tailored to the deployment location.

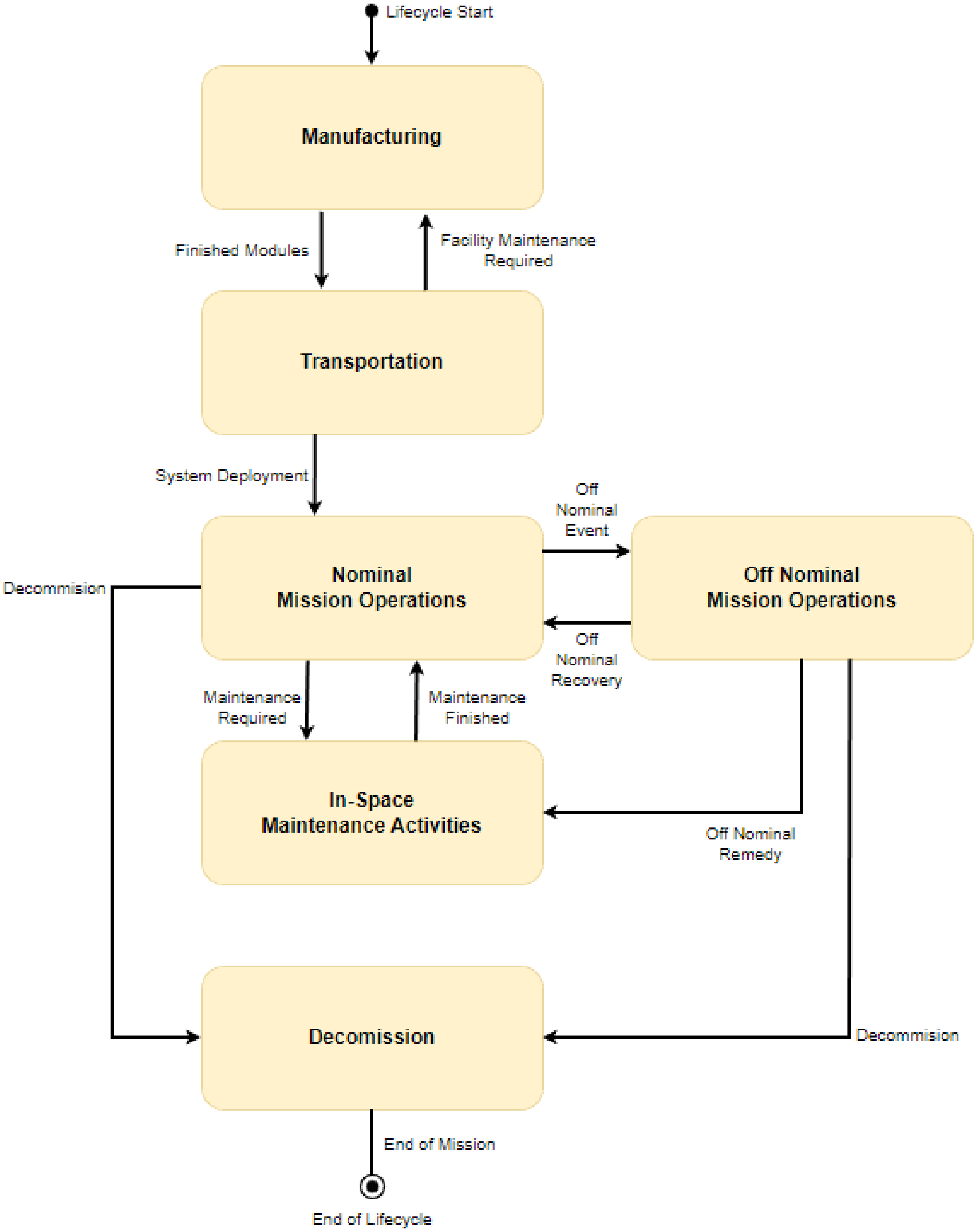
Each HOPE outpost will have standard modules to support scientific experiments and science instruments for general use that would be applicable to retain at any location. The modular design aspect of the outposts will allow for the addition of modules designed specifically for each location of interest as needed or tailoring the exact configuration.

<u>States and modes</u>

The following graphic represents the different state changes and triggers associated that our system would experience through various phases of an outpost's ConOps. Defining the various states and modes of the outpost system allows for further decomposition of the overall ConOps and allows for specific operations to be defined and traced to the lowest level.

These states describe the various points of the program level behavior and the specific triggers associated with each transition. These states are derived from the operational concept outlined in table 3 and the functional allocations found in table 5.

Figure 18. *HOPE Program Level State Machine Diagram*



Source: Author

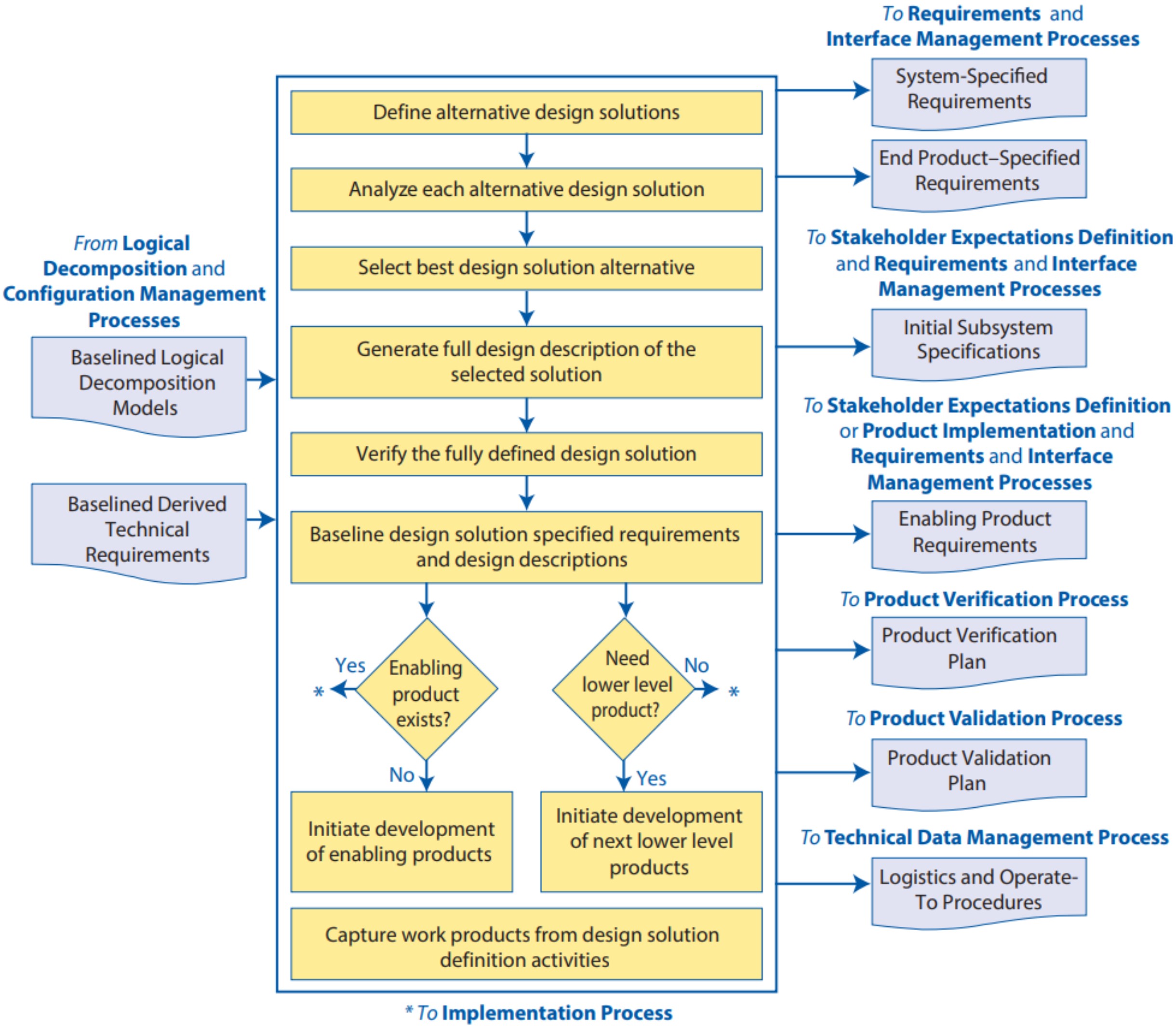
The state machine diagram shown in figure 18 above depicts the few states expected for the outpost to go through its lifecycle. The diagram shows the various triggers required to move through the states found in the lifecycle. An example walk through the nominal lifecycle starts from being in a state of manufacturing where the various outpost components are being manufactured, to exit manufacturing a completed signal is required. Afterwards it is expected to go through some sort of transit stage, including ground transportation, air transportation, and space transportation for the outpost to reach the deployment site. A deployment trigger then takes the system from a transportation state to a nominal mission operations state, this encompasses all activities that may be encountered in a typical mission duration. From the nominal operations state, depending on the trigger, the outpost may enter an off nominal state or a maintenance state. Eventually, the system will receive a decommission trigger that takes it to the decommission state where the system will be responsibly disposed of and then transition to the end of its lifecycle.

Discussion

Design Solution

With the physical and logical architecture both defined at a high level, the actual design solution may now be discussed. Taking the functional architecture that was derived from the stakeholder analysis, a notional physical architecture is decided, from which further decomposition may occur. This decomposition of the higher-level architectures is what will be addressed in this chapter. NASA's design solution process can be seen in figure 19 below, this method will be coupled with tenets from Wasson's problem-solving process.

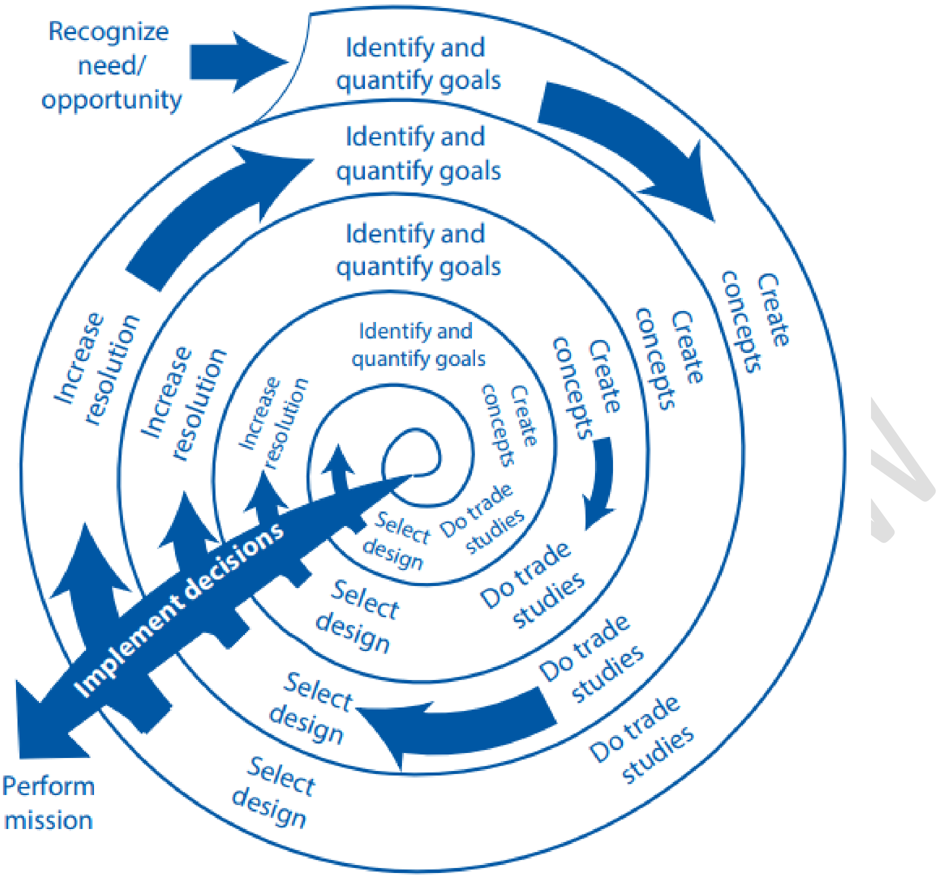
Figure 19. *Design Solution Definition Process*



Source: NASA 2016 [29]

Although we have defined our system architecture to a baselined notional state, a key aspect of any architecture design process is to investigate alternative design solutions at every level. This is important to fully understand the choices being made for the proposed solutions and the tradeoffs associated with every decision, this understanding will allow for the decision-making process to have as much confidence as possible. Figure 20 below depicts a recursive and iterative process that may be used at a high level for any project or program.

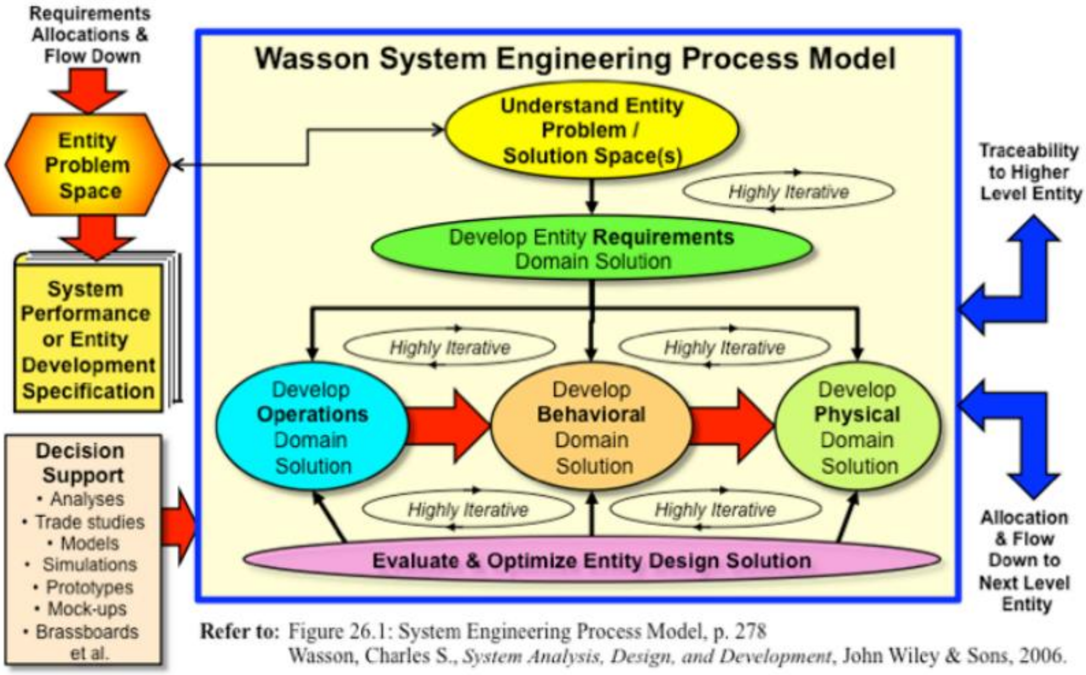
Figure 20. *The Doctrine of Successive Refinement*



Source: NASA 2016 [29]

This doctrine illustrated above is also present in Wasson's process, although Wasson emphasizes iterating at every step of the way. In figure 21 below, the design solution definition step is encompassed by the separate domain solution iterations and the final optimization step.

Figure 21. *Wasson System Engineering Process Model Representation*



Source: American Society for Engineering Education Conference 2012 [27]

Alternatives

Space Station Approach

The current architecture proposes multiple long-term optionally manned space stations throughout the known galaxy to serve as communications and exploration hubs. This current architecture lends the way for HOPE to be leveraged for science and technology demonstration missions.

Although one of the core themes of the current architecture is to have as much human involvement as possible, another way to approach this problem would be to have much shorter duration or completely autonomous outposts to eliminate the need to have complex life support systems. These stations could support a human presence for less than a month and would essentially serve as a temporary stop along the way to a different outpost or serve as a simple auxiliary station for manned spacecraft to dock onto for resources and rehabilitation, not to use as a habitation platform.

By minimizing human presence onboard this alternative approach would allow for the outposts to become less complex, as they would just serve as an auxiliary input for the manned visiting spacecraft. This could reduce risk significantly for locations such as Jupiter where the radiation environment in orbit is significantly difficult to navigate if a human presence is necessary.

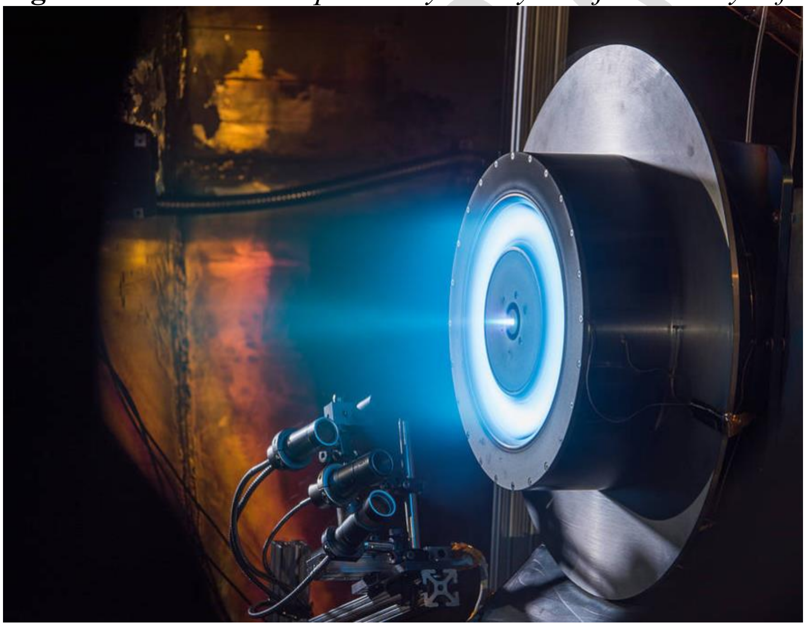
Although there are clear benefits to this approach, a hybrid approach may also be adopted. Based on location and significance, the outpost may support a long- or short-term human presence. This hybrid approach would be ideal for tailoring the overarching modular system for each mission and location; however, this would increase complexity and would cause a need to arise for an adjacent long-term outpost in nominal and off-nominal scenarios.

Propulsion Systems

The propulsion systems of each HOPE outpost may be different from one another based on location, although in the current architecture an electronic propulsion system is proposed. This technology is in the current architecture as that is what is being used by the lunar gateway and by the time humankind is at the point where something like HOPE is achievable, that electronic propulsion system has matured to where it is a viable option for all locations of interest.

On the other hand, there is no shortage of propulsion systems that may be utilized for these outpost stations, from cold gas thrusters, liquid propellant rocket engines, and solid propellant rocket engines to name a few. These options were not considered for the current architecture to reduce the number of consumables necessary for nominal operations of each outpost. Solid and liquid rocket engines would be an ideal option if many significant orbital maneuvers that require high thrust must be performed in as short a time as possible were expected, so these may be an option if the mission demands it. Cold gas thrusters could also be an option, although, would not be as applicable as a main propulsion system for an outpost with the current state of the art.

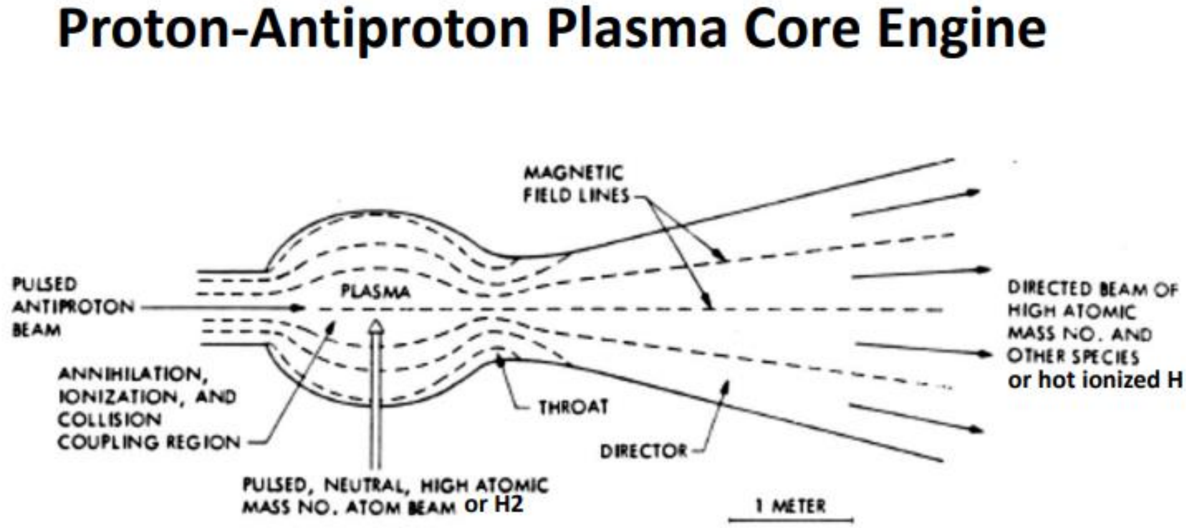
Figure 22. *Electronic Propulsion System by Aerojet Rocketdyne for Lunar Gateway*



Source: NASA 2023 [33]

There may also be different solutions in the future such as viable solar propulsion, nuclear propulsion, laser, or antimatter propulsion systems that are either not viable now or are very early in development. One antimatter concept illustration from a 1985 article is shown in figure 23 below. The main importance that the electric propulsion system is being used is that the only consumable each outpost would be relying on is electricity generated by solar arrays or by nuclear means. These technologies should be utilized where possible when available.

Figure 23. *Proton-antiproton Antimatter Engine Concept*



Source: NASA 2023 [34]

<u>Communications System Approach</u>

The current architecture builds upon the scope and capabilities that are being developed for the lunar gateway. The proposed solution uses current state of the art RF methods of communications. Another direction to go with the HOPE communications network would be heavily leveraging optical communications, each outpost would be equipped with a receiver and transmitter for optical capabilities. By having optics as the primary form of communication, the network would be able to leverage state of the art technologies all throughout from the communication systems onboard each outpost to new optical communications based ground stations.

Figure 24. *NASA's Laser Communications Relay Demonstration Illustration*

Source: NASA 2021 [35]

Figure 24 above depicts NASA's recent foray into optical communications, when this technology has matured it can be utilized by future systems such as HOPE outposts. By utilizing optical communications, much higher data rates can be achieved. This will allow the outposts to communicate with one another and send messages long distances in much shorter times than if a conventional RF solution is used.

Conclusion

Next Steps

With the conclusion of this design study, the system has only been partially developed. Regarding the system architecture, design has been conducted to the system level with a conceptual approach to each element. The orbital study only analyzes a single proposed implementation of the HOPE outpost system, there are many ways one could expand upon this design study to bring it to the next steps.

The fundamental elements of a high-level system architecture and the necessary background work have been conducted in the first half of this design report. A few suggestions to expand upon this research may include further decomposition to the subsystem levels and below; continuing the current scope carried out in a recursive and iterative nature; Refinement of the various solution domains; and Continuing trade studies to narrow down on solution domain choices to name a few. There are many paths to take the system architecture down, it has been left intentionally open ended to accommodate for future technologies and other architects to take over as their own.

Any program like HOPE can be designed at the architecture level with many different design choices, however the backbone of taking these concepts into conception will rely heavily on expansive analyses on lots of different parts of the system. This design study decided to begin work that is required to consider what may be necessary at a high level for a Jupiter implementation. With the current system architecture, further analysis can be done on investigating a Jupiter implementation of the program. Alternatively, other bodies of interest may be investigated for feasibility and to see what may be required for such an implementation. The current architecture also supports notional amounts of mechanical design, one may begin to visual what such an implementation of HOPE may look like and the manufacturing concerns. Another possible route to investigate with the current architecture would be an in-depth investigation on communications between bodies of interest and the infrastructure or specific considerations that would be necessary to support a multibody communications network such as link budgets or synchronized orbits. These suggestions are just a few ways that someone could take the work started in this design study and expand upon it.

Larger undertakings could include a full system architecture decomposed to levels below the subsystems in a full digital model, this would reflect where many larger programs and designs are heading in the current state of the industry, leveraging model-based systems engineering tools. This undertaking would include traceability from the highest level of the system to the lowest, from requirements, to behaviors, physical and logical representations, and more. The benefits of designing a system digitally with these strong traceable linkages allow for as much risk reduction as possible as early as possible among many other core benefits of the digital engineering landscape.

Concluding Statement

The HOPE program is an intragalactic space station program that will be leveraged as a communications network for relaying messages from any point in the galaxy to another without having to rely on a direct line of sight. Messages will be transmitted from one station to another until the destination is reached, this will allow for more opportunities of communication throughout the galaxy. The modular space stations will allow for tailoring each respective body of interest's station to that body's scientific objectives and environmental requirements resulting in a science and exploration hub at key locations in the galaxy.

A notional system architecture has been designed to the system level, with the relevant systems engineering trade studies being conducted to lead to the decisions made to result in the proposed design solution. This design is not the be-all and end-all solution that may exist for the HOPE program and it should not be, this is simply the initial take at attempting to define a possibility within the solution space of the proposed problem.

An orbital analysis will be conducted jointly with the architecture design as part of the authors graduate research to be completed by August of 2023, to study and model a single implementation of the outpost system and how it may behave in this instance. This simulation follows one of the proposed operational concepts within the system level use cases to demonstrate the viability of one such instance.

These elements can be considered the first attempt at defining Humanity's Orbital Presence Endeavour.

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