

Impacts of In-Space Assembly as Applied to Human Exploration Architectures

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Human missions to Mars present several major challenges that must be overcome, including delivering multiple large mass and volume elements, keeping the crew safe and productive, meeting cost constraints, and ensuring a sustainable campaign. Traditional methods for executing human Mars missions minimize or eliminate in-space assembly (iSA), which provides a narrow range of options for addressing these challenges and limits the types of missions that can be performed. This paper discusses recent work to evaluate how the inclusion of in-space assembly in space mission architectural concepts could provide novel solutions to address these challenges by increasing operational flexibility, robustness, risk reduction, crew health and safety, and sustainability. Several assembly focus areas identified through previous work were developed and evaluated to identify high-potential iSA applications that can have meaningful impacts on the challenges facing Mars missions. Architecture trade options were developed and assessed through sensitivity analyses, resulting in identification of six iSA-based architecture solutions that could be incorporated into Mars mission architectures with moderate levels of assembly. Assembly agent and infrastructure concepts were also developed that would be necessary to enable or facilitate the iSA operations. Several observations developed through the study are presented to inform future human mission architecture and campaign developments.

I. Nomenclature

$C3$ = Characteristic energy
 t = metric ton, 1000 kg

II. Introduction

Humanity continues to reach into space with increasingly ambitious missions to expand our knowledge of the universe and to extend our presence throughout the solar system. Missions to Mars are a long held goal for human exploration. Human missions to Mars, however, present several major challenges that must be overcome. The delivery of multiple large mass and volume elements, keeping the crew safe and productive, meeting cost constraints, and ensuring a sustainable campaign are examples of a few of the major challenges. Innovative methods will be necessary to address these challenges, as traditional methods of launching integrated, fully-functioning systems cannot meet the demands of most Mars mission architectures. Particularly challenging are missions proposing long-duration surface stays or a sustained presence that require hundreds to thousands of tons of mass in low Earth orbit or cis-lunar space to enable the missions.

In-space assembly (iSA) is a new approach with potential to expand the trade space of architecture options and provide greater mission flexibility, enabling solutions to some of these exploration challenges. Recent and ongoing developments in assembly, and closely-related servicing, capabilities are advancing the state of the art, making it practical to incorporate iSA into system design and architecture concepts. The In-Space Assembly System Study

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(ISASS) investigated the potential benefits and risks of incorporating iSA applications for human exploration missions and identify necessary capabilities to inform technology investment decisions. The background and foundation of the analysis discussed in this paper is based on results from Reference 1. This previous work investigated potential iSA applications for human exploration missions and identified their potential benefits, drawbacks, and implementation considerations based on how and where in the architecture iSA is incorporated. Through this process, several focus areas were identified where applications of in-space assembly could affect multiple Mars mission challenges. Each focus area was developed to identify functions, potential assembly solutions and operations, key architectural trades, and potential considerations and implications of implementation. The previous work also revealed how iSA implementation decisions are highly coupled with, and affect, many other mission system and architecture design decisions. A better understanding of these linkages and interdependencies is needed in order to effectively build and assess iSA-enabled architectures and campaigns.

In a continuation of the previous work, the analysis discussed in this paper investigated specific iSA applications for several iSA-based architecture options to develop architectural relationships and provide data that could inform future architecture and campaign development and assessments. To accomplish this, a series of sensitivities were evaluated to investigate key parts of the architecture where iSA is expected to have the greatest impact, and two representative architectures were developed to investigate comparisons against a more traditional, minimal assembly architecture. The sensitivities and representative architectures were then used to develop a series of six potential iSA-based solutions specifically geared to address challenges with launch capacity and cadence, element sizing, entry descent and landing (EDL) capacity, and human health. This paper describes the sensitivity analyses performed and how they are applied to support architecture development, examines the architectures and potential iSA solutions that were then developed, and discusses the observed interrelations among assembly strategy and mission design decisions. Additionally, this paper examines assembly agent options for implementing the solutions, including hosted robotics, free-flyers, and assembly platforms, and discusses considerations for early incorporation and paths to expand assembly agent capabilities over time. Finally, several key observations from the work and proposed areas for future investigation are discussed.

III. Analysis

Previous work [1] identified and developed iSA application focus areas relevant to human Mars missions. These areas included three assembly regions: Earth vicinity, Mars orbital, and Mars surface, and three system areas: the Mars transit vehicle; entry, descent, landing, and ascent; and communications and navigation infrastructure. The primary objective for the current analysis was to use those focus areas to identify and evaluate high-potential iSA solutions for addressing Mars mission challenges and frame the architectural options for future campaign analyses. To facilitate these assessments, a series of sensitivity analyses were performed to investigate the relationships between key architectural factors and mission systems. Additionally, representative assembly-based architectures options were developed. Combined, the sensitivities and representative architecture options were used to identify and develop potential high-value assembly-based solutions for addressing the challenges with executing human missions to Mars.

A. Sensitivity Analyses

The sensitivities performed for this study were based on the Evolvable Mars Campaign (EMC) point of reference architecture and mission systems [2], and focus on sensitivities associated with launch, transfer stages, landers, and assembly location. These sensitivity analyses provide insight to help architecture and campaign developers understand how incorporation of different iSA strategies can affect architecture options, and also how architecture decisions and constraints may drive different iSA approaches. When combined, the sensitivities also allow for examining the implications of trade decisions on the overall campaign and assembly needs, as trade decisions for one part of the architecture ripple through to others.

1. Launch Sensitivity

The launch sensitivity analysis investigated the options for launching large Mars elements on the known (or expected) insertion capabilities of currently available and planned launch vehicles. The major elements assessed included the hybrid propulsion stage (HPS), the deep-space habitat (DSH), the combined deep space transport (DST) that consists of the HPS and DSH, and a lander with a 20t payload delivery capacity. Basic definition for these elements was taken from NASA's EMC [2]. Figure 1 depicts the basic options space for each of these elements against the launch capability of the different launch vehicles.

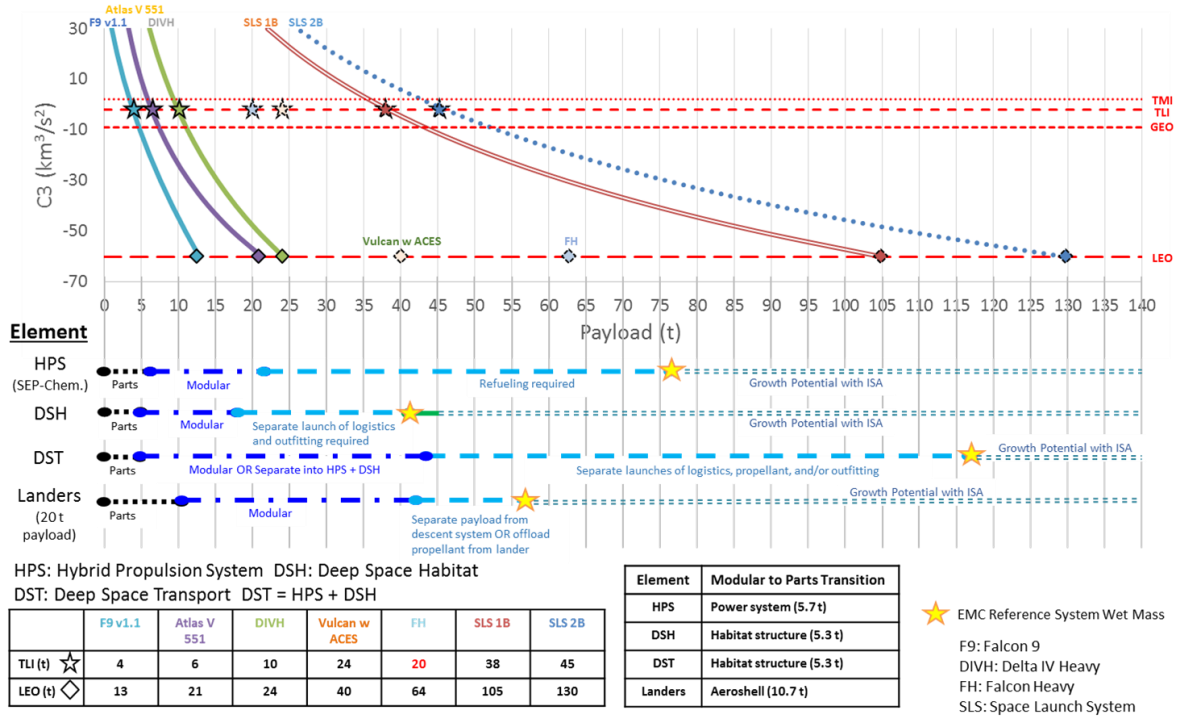


Fig. 1 Sensitivity depicting launch vehicle selection as relates to offloading and assembly options for mission elements [3-5].

As evidenced in Fig. 1, these elements, when launched fully loaded and fueled, approach or exceed the capabilities of even the largest launch vehicles. In a minimal assembly architecture, fuel, supplies, and some internal equipment would be removed from these elements, thus requiring refueling, additional logistics flights, and time to outfit the spacecraft. A fully fueled and outfitted DST requires separate launches of the HPS and DSH, with at minimum docking or berthing assembly to join the two elements.

Adding limited assembly capabilities such as robotic manipulators opens options for separately launching payloads and landers and loading the payloads in space, which can reduce the launch burden of the lander, and for external outfitting of systems. While beneficial for element launch mass reduction, these options still rely primarily on the heaviest launch capabilities, although smaller launch vehicles can be used to deliver logistics, outfitting, and lander payloads.

Incorporating modular assembly into designs will be needed to enable the use of smaller launch vehicles to deliver spacecraft elements components and provide maximum architecture flexibility. In this and all sensitivity analyses, the mass range depicted by the modular lines in the graphics were derived by determining the mass of individual subsystem units for each element that can reasonably be assembled with moderate assembly capabilities and leveraging standard interfaces and plug-and-play assembly techniques. Examples include solar array/radiator booms and panels, propulsion modules, propellant or consumable tank modules, and small habitat modules that comprise the full habitat element.

2. Transfer Stage Sensitivity

The transfer stage sensitivity focused on the stage mass, wet and dry, as the transported payload mass increases. Both the HPS [6], which travels round trip, and the EMC cryogenic methane chemical stage [7], which travels one way, were evaluated. These sensitivities in Fig. 2 show the effects of adding mass to the payload are significant for the transit fuel load required, but the impacts on stage dry mass are much less severe. This highlights a need for on-orbit fueling or fuel tank module installation, especially as the expected mass of assembled and outfitted systems and payloads grows. The ability to provide this additional propulsion capability also facilitates aggregation of payloads and assembly of larger transit habitats, which can benefit the crew and includes artificial gravity options and larger landers, which allows for delivery of larger, fully functional surface elements and reduces the need for more extensive surface assembly capabilities.

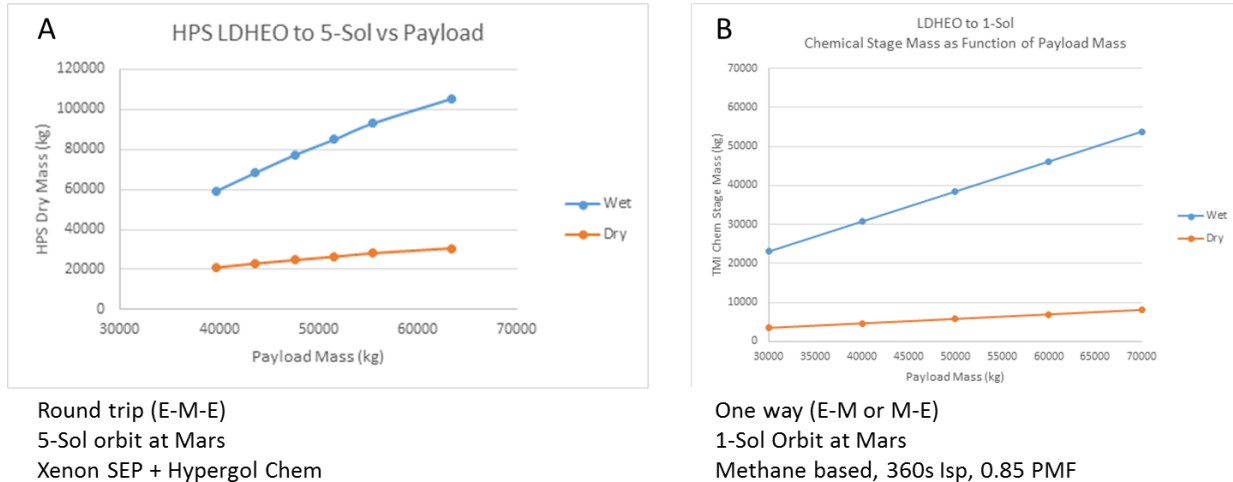


Fig. 2 Impact of increased payload mass on transit stage wet and dry mass.

3. Lander Sensitivity

The lander sensitivity analysis investigated the impact of the lander payload delivery capability on the need to assemble surface assets. Landers with greater capacity could be used to land larger payloads, but would need advanced EDL capabilities and possibly iSA of the lander. Alternatively, smaller landers can be used, which requires assembly of surface assets on the surface, but alleviates the difficulty of advancing EDL capability.

The major surface elements that must be delivered to the surface are the habitat [8], Mars Ascent Vehicle (MAV) [9], in-situ resource utilization (ISRU) system, power system, mobility systems, and logistics [10]. The elements that are most impacted by a reduced lander capacity are the MAV and the habitat (outfitted and loaded with logistics). This sensitivity analysis considers multiple options for these two elements. The MAV trade space includes 2- and 4-crew variants, different parking orbits, and different propellant options. The 2-crew MAV requires two vehicles to deliver the four crewmembers to orbit. The habitat trade space includes a monolithic habitat or modular habitats (both 2- and 3-module configurations).

These elements can be delivered fully assembled, or can be assembled on the surface. Figure 3 presents the impact of lander payload delivery capability on the level of surface assembly for the MAV and habitat elements. Along the top of the figure, the lander payload capability is presented from the current state of the art of approximately 1 t up to 50 t. Each line (red for MAVs and blue for habitats) represents the required level of surface assembly for each element at the lander payload capability defined along the top. The blue region below each line defines the number of individual landers that are needed to deliver the element to the surface. The habitat section includes the number of separate logistics landers that would be required after offloading logistics from the habitat.

From the figure, a 4-crew MAV (similar to those proposed in Mars Design Reference Architecture 5.0 (DRA 5.0) [11]) needs a lander capable of delivering more than 40 t to the surface without offloading propellant. Allowing propellant offload with ISRU propellant could reduce the required lander capability to 10 t. Further reduction in lander capability would require assembly of the MAV subsystems on the surface. Going to low Mars orbit instead of an elliptical orbit also reduces the required lander capability to approximately 20 t before propellant offload is needed. Delivering two, fully-fueled, 2-crew MAVs to the surface would require a pair of 18 t landers similar to those used the EMC.

While a lander capable of delivering approximately 30 t to the surface is required for a monolithic habitat including the associated logistics and outfitting, the logistics and outfitting can be delivered separately. This would reduce the requirement to two landers capable of delivering approximately 15 t. Modular habitats could also be delivered completely outfitted (connection of the modules on the surface is still required) on two 20 t landers. Although the two scenarios would require the same number of landers, from a setup time, risk, and complexity perspective, delivering two fully outfitted modules may be favorable over offloading logistics and outfitting from a monolithic habitat.

The lander payload delivery capability will have a significant impact on the amount of surface assembly required in a Mars architecture. If a >40 t lander is available, it's possible that fully integrated, functional modules can be delivered to the surface ready to use by the crew. However, if 10 t is all that is available, offloading propellant on the

MAV and using offloaded modular habitats that are assembled, outfitted, and fueled on the surface is still a viable architecture.

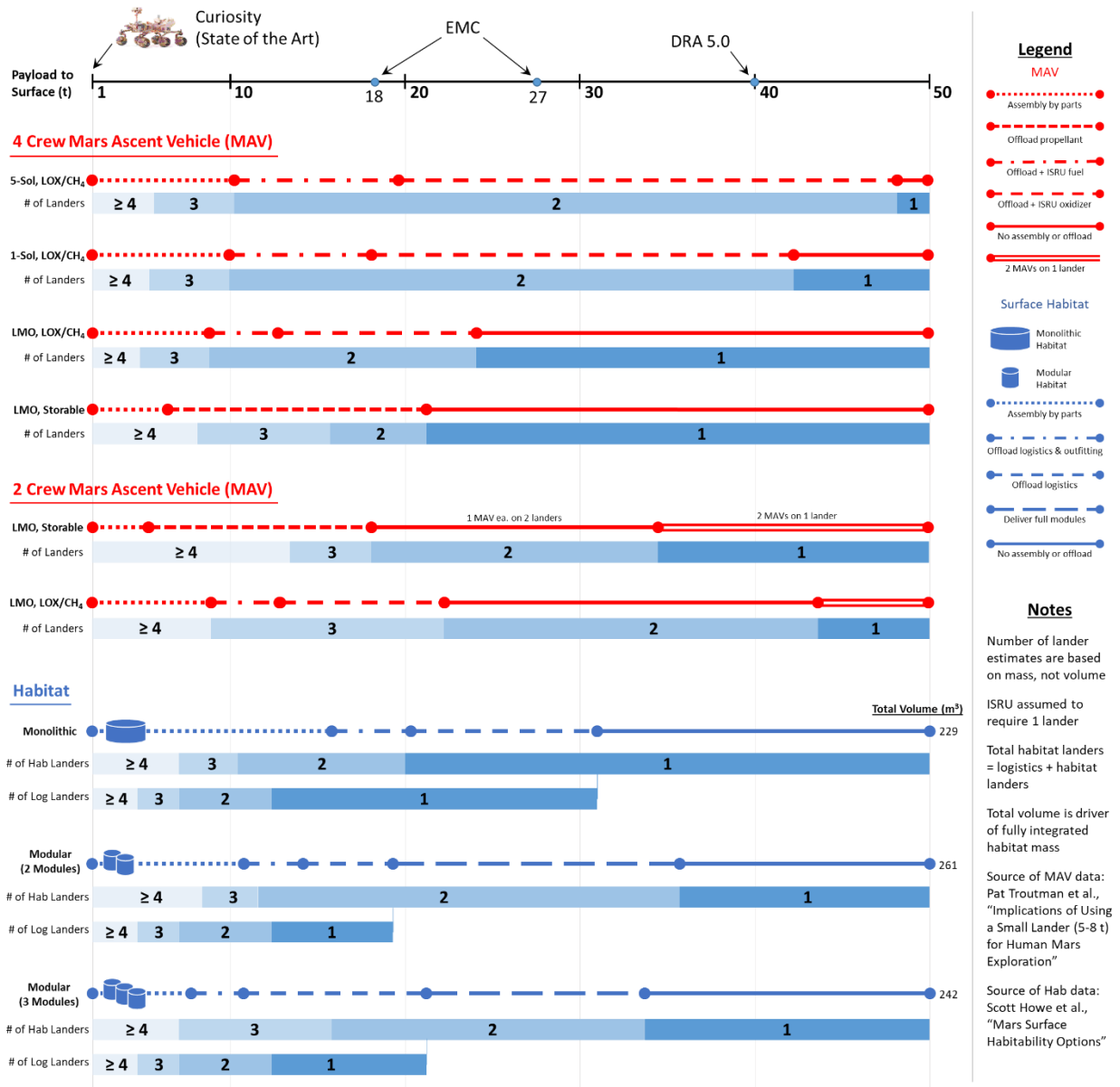


Fig. 3 The lander sensitivity analysis presents the impact of lander payload delivery capability on the level of assembly required on the Mars surface.

4. Assembly Location Sensitivity

The assembly location sensitivity investigated several key factors affecting assembly that are impacted by assembly location, including communication, micrometeoroid and orbital debris, radiation environment, trans-Mars injection mass, and leveraged infrastructure. The intent of the sensitivity is to help inform decisions on where to perform assembly operations based on a selected assembly strategy, mission architecture, or other campaign objectives. Key considerations for each assembly location and a relative comparison (best to worst) of each factor among assembly locations is depicted in Fig. 4. A further assessment of particular considerations affecting assembly of each major mission element in Earth vicinity or Mars vicinity is summarized in Fig. 5.

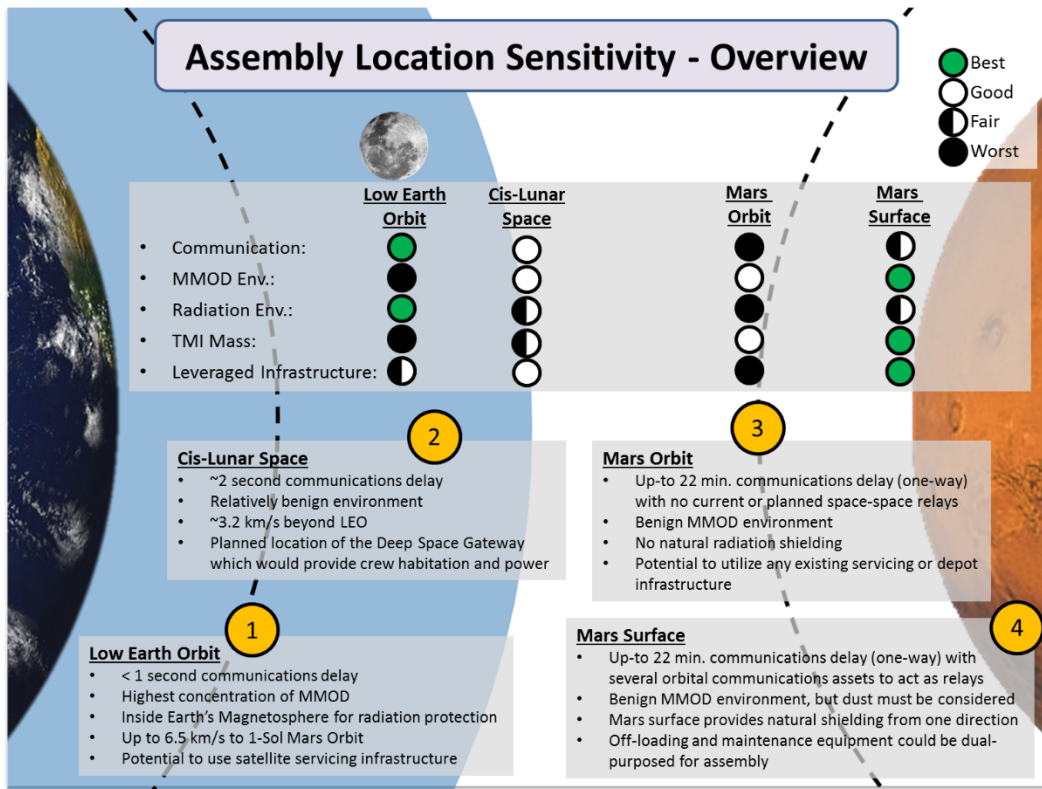


Fig. 4 Relative comparison of factor impacts by assembly location and key considerations for each location.

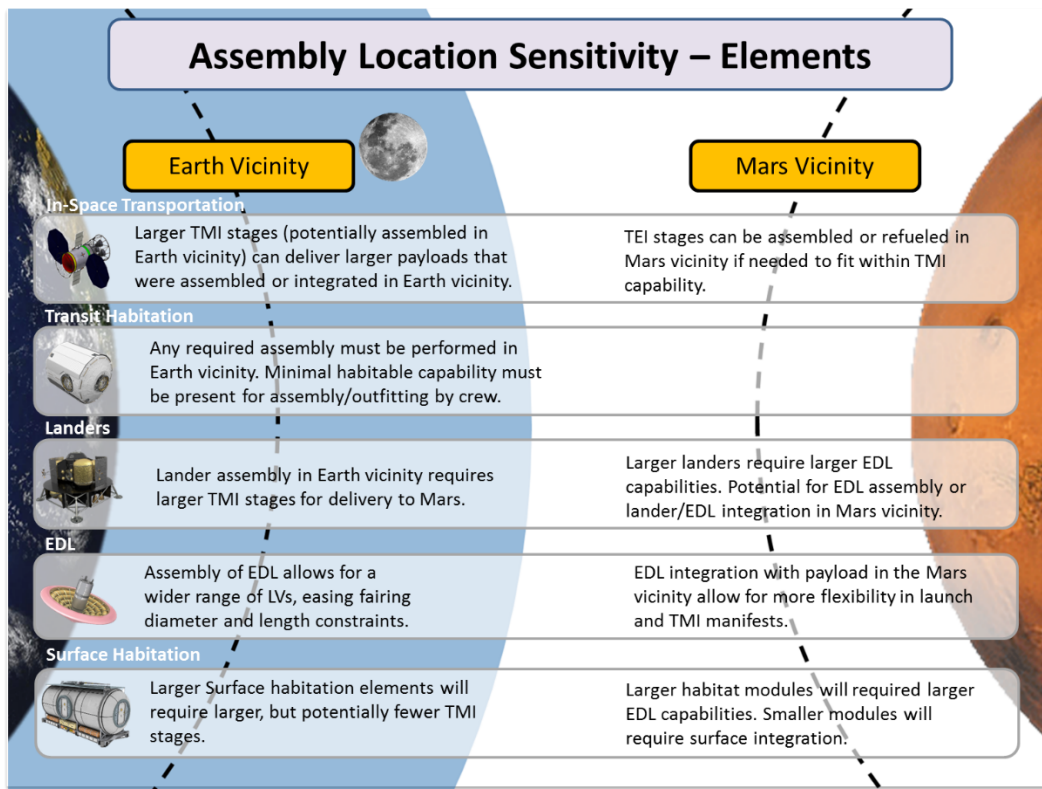


Fig. 5 Key considerations for selecting Earth-vicinity or Mars-vicinity assembly for Mars mission elements.

B. Representative Architectures

Using information derived from the sensitivity studies, two representative architectures were generated that incorporate moderate and pervasive levels of assembly, respectively. The representative architectures help to exemplify the architecture and mission system relationships identified through the sensitivity analyses, and provide points of comparison against a more traditional, minimal assembly architecture represented by the EMC. General descriptions of each assembly scenario follow.

1. Minimal Assembly

Virtually all human and robotic space missions, with the notable exception of the International Space Station (ISS), follow a minimal assembly strategy where the mission systems are launched as integrated, fully functional spacecraft, and the only “assembly” performed is the docking or berthing of two or more of these spacecraft together via a mating mechanism that connects necessary shared services. The EMC follows this pattern, with docking used as the means to aggregate elements when necessary, and refueling and logistics deliveries used to make up for any shortfall in propellant, supplies, or outfitting resulting from element mass reduction to fit within launch vehicle capabilities.

2. Moderate assembly

Moderate assembly approaches focus on incorporating iSA for the larger mission systems to mitigate launch mass limitations or provide additional flexibility and robustness to the campaign. The modules that comprise the completed system are typically either fully integrated elements in their own right (e.g., a propulsion stage, habitat, or loaded cargo pods), or modules with one or more integrated subsystems (e.g., a propulsion module with tanks and engines, a command and control module, or a module with integrated power and thermal subsystems). Moderate assembly primarily uses element-to-element mating and modular assembly of components strategies [1] for system assembly, and leverages assembly capabilities that are either already available or nearing completion of development. Moderate assembly can be incorporated into architectures with minimal additions such as the inclusion of robotic arms and tugs to deliver the modules. While assembly infrastructure such as platforms could be used to support moderate assembly operations and agents, they generally would not be necessary.

3. Pervasive assembly

Pervasive assembly approaches leverage more advanced iSA capabilities to assemble components and smaller modules into large modules and subsystem assemblies that are then assembled into a complete system. A greater number of large and small mission systems are assembled in space either in Earth or Mars orbit, or on the surface of Mars. Assemblies may increasingly take advantage of in-space manufactured components and in-situ resources. A more robust and expansive suite of assembly agents and infrastructure is needed to enable a pervasive assembly architecture, with pervasive assembly providing a greater amount of flexibility for the mission systems and architecture as a whole. Pervasive assembly provides numerous opportunities for commercial providers to supply needed services. Smaller launch packages enable greater participation by more commercial companies to provide launch services. Additionally, the rate of iSA provides a stronger market case for commercial provision of assembly agents, infrastructure, and services. Finally, support elements like tugs will most likely be common in a pervasive assembly architecture, opening opportunities for delivering component payloads and cargo to the assembly location.

C. High-Potential Solutions

The sensitivities and representative architectures were used to develop a series of six potential iSA-based solutions specifically geared to address challenges with launch capacity and cadence, element sizing, EDL capacity, and human health. The discussion for each proposed solution covers the challenges addressed, a description of the assembly approaches, and specific application of the sensitivity analysis to explore the assembly approaches. Additionally, the architecture pros and cons, risk mitigations and additional risk introduced, enabling capability developments needed, and systems that can be leveraged from the exploration architecture to support assembly are investigated. Examples for key systems from each architecture scenario are also provided.

1. Docking/berthing assembly of Mars crewed transport and cargo spacecraft

Docking or berthing assembly of major elements in space, such as Mars transfer vehicles for crew or cargo, provides the most accessible and least complex option for addressing challenges with launch capacity and packaging, lander size and packaging, and crew health and safety. A closer look at the launch sensitivity for these elements reveals the challenges for even the most powerful launch vehicles to launch a mission-ready DST or lander (Fig. 6). In all cases, some degree of refueling and/or on-orbit outfitting will be necessary, and as system masses grow, some pre-integrated crew and cargo transport designs may not be able to be launched at all. However, by incorporating iSA via docking or berthing and launching the habitat or lander separately from the propulsion stage, the habitat can be launched fully integrated with no on-orbit assembly or outfitting required, landers can be and launched with more pre-

integrated payload and fuel, and the propulsion stage can be launched with as much propellant as the launch vehicle (LV) capacity allows, reducing the on-orbit refueling demands.

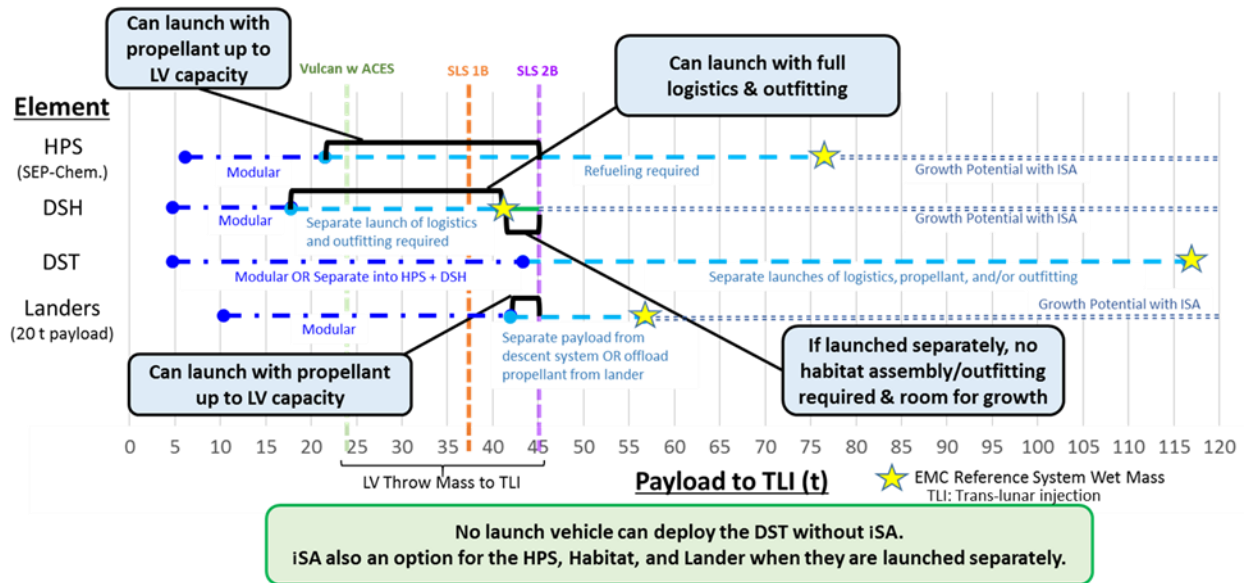


Fig. 6 Launch sensitivity for key Mars mission systems incorporating options for assembly, post-launch outfitting and fueling, and pre-integrated, monolithic launch.

Architecture and Campaign impacts

Incorporation of the docking or berthing assembly solution has both positive and negative impacts on the architecture and campaign that need to be considered when evaluating the potential benefits of the options. The impacts for this solution are summarized in Table 1.

Table 1. Architecture and campaign impacts from implementing the docking/berthing assembly solution.

Architecture and Campaign Impacts	
Positive	Negative
<ul style="list-style-type: none"> • Can reduce launch mass for each flight, thus reducing required LV capacity and/or providing launch margin (mass and volume) • Reduces on-orbit refueling needs (fewer launches, fewer tankers, reduce schedule needed for on-orbit fuel transfer) • Reduces logistics deliveries for habitat outfitting (fewer launches, fewer logistics vehicles, reduced schedule for outfitting and preparation) • Allows for full pre-integrated testing of habitat on ground • Enables accommodation of additional habitation capabilities to improve crew performance and safety • Facilitates future replacement/upgrade of individual DST elements • Eliminates need for elements to support stacked elements through launch, reducing launch loads and structures mass • Reduces stacked launch loads and parasitic payload adapter mass 	<ul style="list-style-type: none"> • More launches of large elements • Additional schedule for launch manifesting, on-orbit integration, and checkout • Additional element mass for integration hardware • Need for propulsion and power to deliver and provide keep-alive support for non-propulsive elements

Risk discussion

In addition to the operational impacts on the architecture and campaign, iSA solutions bring new risks and risk mitigations that can affect the crew or mission. While mating elements of the mission system together requires more launches to deliver all the elements, which increases the risk that one of those launches will fail, no single launch loss can destroy the full mission system, thus mitigating the impact of the loss. The ability to launch the elements separately reduces the risk that mission system mass will increase and launch performance will decrease to the point where the system cannot be launched and delivered. Additionally, as each element can be launched without needing to offload equipment, the element can be pre-integrated, tested on the ground, and launched fully integrated, which reduces the risk of subsystem failures on orbit. However, on-orbit mating and integration of the elements to each other introduces the risks of rendezvous, proximity operations, and docking (RPOD) failures, damage during assembly, failure of the inter-element connections, including fluid leakage, signal short circuits, and power short circuits, as well as risks from space exposure due to longer loiter times.

Assembly capability development

The solution of docking or berthing assembly requires several assembly capability developments to enable or facilitate incorporation into an architecture. These include:

- Automated RPOD of spacecraft elements
- Robotic manipulator(s) for berthing
- Interconnects and automated joining of connections
 - Fluid pass through
 - High-pressure gas pass through
 - Data/command & control pass through
 - Power pass through
 - Structural connections
- Remote In-space Testing & Verification of Spacecraft

Representative Architecture Components

Examples of key architecture elements for implementing docking/berthing assembly are shown in Table 2. If docking/berthing assembly is the only iSA implemented, the pervasive assembly scenario is not applicable.

Table 2. Representative architecture elements for different assemble scenarios when implementing the docking/berthing assembly scenario.

	Minimal Assembly	Moderate Assembly	Pervasive Assembly
Launch Vehicle	Large launch mass and volume required	Large launch mass and volume required	NA
Crew Transit Vehicle	Habitat and Propulsion System pre-integrated for launch, need outfitting and refueling on orbit	Outfitted Habitat and Fueled Propulsion System launched separately and mated on orbit	
Cargo Transit Vehicle	Lander and Propulsion System pre-integrated for launch, need refueling on orbit	Fueled Lander and Fueled Propulsion System launched separately and mated on orbit	

2. In-space assembly of propulsion stages

In the iSA of propulsion stages solution, propulsion systems for Mars transit vehicles are built up from multiple, independently-launched modules. Representative modules include a core, propellant tanks or tank modules, power systems such as solar arrays, engine and thruster pods, etc. In a moderate assembly scenario, system assemblies would consist of a few larger modules housing one of more pre-integrated subsystems that connect to other modules with minimally complex connections and interfaces similar to berthing. An example would be adding SEP tanks and components to a chemical propulsion vehicle. More pervasive assembly scenarios could see the build-up of the propulsion system from individual engines, tank modules, solar arrays, and other subsystems mounted to a core structure, which can expand to meet the propulsive needs of the mission. Adding components and joining connections

could be via plug-and-play type interfaces or more complex interfaces, and the performance characteristics for robotic capabilities and on-orbit verification and validation will be more demanding. Adding the ability to refuel the tanks on orbit provides additional flexibility for the mission.

The iSA of propulsion stages can help address the challenges with launch capacity and element sizing, Space Launch System (SLS) capacity and launch schedule, and human health. As seen in the sensitivity in Fig. 7, an HPS used to transfer crew or cargo to Mars cannot be launched on any LV without offloading fuel and refueling tanks in space. While refueling the tanks is a viable option, the moderate assembly approach of separately launching the SEP and chemical components of the propulsion system and assembling them together in space provides additional flexibility and allows both the SEP and chemical modules to be launched with a full load of fuel. The smaller component modules can also fit on more LV options, providing flexibility in manifesting. Combining assembly with on-orbit refueling would also enable the launch of larger SEP or chemical stages, which would increase the propulsion system’s performance and enable faster transits or greater payload capacity.

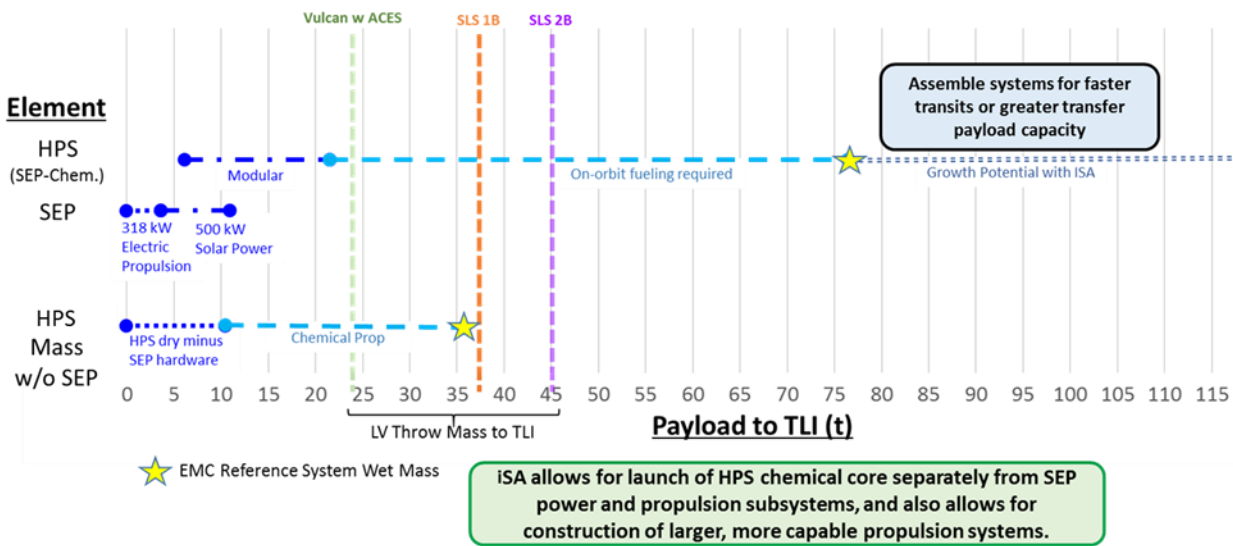


Fig. 7 Launch sensitivity of hybrid propulsion system assembly options

Architecture and Campaign impacts

Incorporation of the iSA of propulsion stages solution has both positive and negative impacts on the architecture and campaign that need to be considered when evaluating the potential benefits of the options. The impacts for this solution are summarized in Table 3.

Table 3. Architecture and campaign impacts from implementing the iSA of propulsion systems solution.

Architecture and Campaign Impacts	
Positive	Negative
<ul style="list-style-type: none"> • Launch and delivery of smaller launch packages, which can reduce needed LV capacity and allow for use of alternate LVs • Can build larger stages to make faster transits or deliver increases payload mass • Separate launch of tanks/propellant reduces structural mass of the core • Enables selective component or full module replacement without losing entire propellant system 	<ul style="list-style-type: none"> • More launches • Additional schedule for integration and check-out • Increased total propulsion system dry mass from added connections and structure • More complex plumbing and control due to distributed systems • May need additional bus/delivery vehicles to keep non-propulsive modules/components alive and deliver to assembly location

Risk discussion

Many of the new risks and risk mitigations for assembling the propulsion stage in space are similar to those for separately launching and mating vehicle elements in space, including the risks and benefits of launching components

on multiple launch vehicles, added margin against mass growth, and the risks associated RPOD, assembly, and long loiter times. One particular risk mitigation provided by the ability to assemble propulsion stages with increased performance is the potential to reduce crew transit times, thus reducing the crew’s exposure to the microgravity and radiation environments of deep space.

Assembly capability development

The solution of iSA of propulsion stages requires several assembly capability developments to enable or facilitate incorporation into an architecture. These include:

- Autonomous/teleoperated robotic assembly with ISS-level dexterity and precision
- Advanced proximity operations (autonomous/teleoperated)
- Interconnects and automated joining for propellant, power, thermal, fluid, command & control
- Remote in-space testing & verification
- Propellant Transfer (if incorporating refuel)
 - Transferable propellant tanks/tank modules
 - Propellant transfer

Representative Architecture Components

Examples of key architecture elements for implementing iSA of propulsion stages are shown in Table 4.

Table 4. Representative architecture elements for different assemble scenarios when implementing the iSA of propulsion systems scenario.

	Minimal Assembly	Moderate Assembly	Pervasive Assembly
Launch Vehicles	Large launch mass and volume required	Mix of large and small LVs depending on module mass and volume, but generally still dependent on larger LVs.	Mix of large and small LVs, with greater opportunities for small LVs.
Propulsion System	Monolithic, pre-integrated at launch. May need to be refueled.	Pre-integrated, highly functional modules (e.g. chemical modules, SEP modules, power/thermal modules, etc.) mated together to form full propulsion system	Building propulsion systems from constituent components like engine/tank pods, solar array booms and wings, command and control modules, etc.

3. In-space assembly of habitats

In the iSA of habitats solution, habitats for Mars transit vehicles are built up from multiple, independently-launched modules and components. Representative modules include habitable volumes, airlocks, docking nodes, consumables modules, power generation systems, and additional radiation shielding. Moderate assembly approaches would focus on connecting some number of modules with pre-integrated functionality which, together, provide all the needed functionality for the habitat. More pervasive assembly scenarios expand on the habitat modules with assembly and attachment of external components such as solar array booms and panels, externally mounted consumables tanks, and augmented shielding. The modularity enabled by iSA allows for habitat concepts and configurations that exceed the limitations of LV fairings, which can address challenges with launch capability and element sizing, as well as SLS launch capacity and schedule. Incorporating iSA also allows for augmentation and growth of the habitat over time, which can address crew health and safety challenges. As seen in the sensitivity below (Fig. 8), monolithic, pre-outfitted habitats of the class considered for the EMC strain the launch capabilities of even the largest launch vehicles, but iSA can provide flexibility to overcome limitations and allow for growth. Additional architecture elements needed to enable iSA of habitats include assembly agents and additional propulsion stages or tugs to deliver the habitat modules to the assembly location. Larger iSA facilities such as assembly platforms can facilitate assembly of larger, more advanced habitat designs.

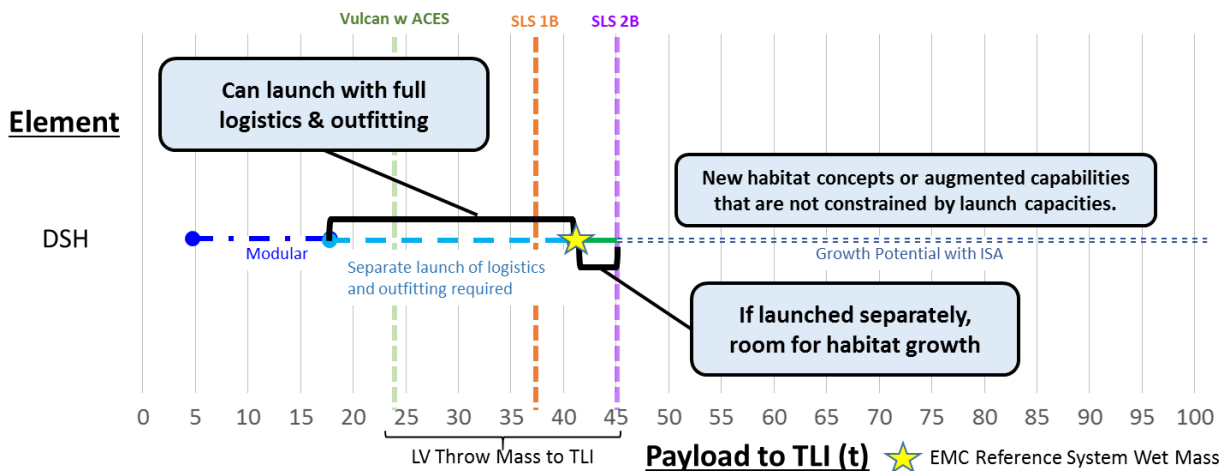


Fig. 8 Launch sensitivity of transit habitat assembly options

Architecture and Campaign impacts

Incorporation of the iSA of habitats has both positive and negative impacts on the architecture and campaign that need to be considered when evaluating the potential benefits of the options. The impacts for this solution are summarized in Table 5.

Table 5. Architecture and campaign impacts from implementing the iSA of habitats solution.

Architecture and Campaign Impacts	
Positive	Negative
<ul style="list-style-type: none"> Delivering a habitat in modular elements decreases the delivered mass of the Hab. Reduces limits by launch fairing on habitat configuration (increased volume, artificial gravity) Multiple habitat elements provide redundancy for crew in case of emergencies. Modular habitats provide a path to upgrade/augment capabilities Multiple elements provide added safe haven capabilities Enables selective component or full module replacement without losing entire habitat 	<ul style="list-style-type: none"> More launches Additional schedule for integration and check-out Increased total habitat dry mass from added connections and structure May <i>require</i> redundant capabilities in Habitation modules Additional activities to relocate/assemble modules

Risk discussion

Many of the new risks and risk mitigations for assembling the habitat in space are similar to those for separately launching and mating vehicle elements in space, including the risks and benefits of launching components on multiple launch vehicles, added margin against mass growth, and the risks associated RPOD, assembly, and long loiter times. Particular risk mitigations provided by the ability to assemble habitats in space are the ability to provide redundant habitat volumes and systems to provide safe haven and the ability to incorporate alternative habitat concepts and configurations (e.g., artificial gravity or embedded habitats) that can reduce crew health risk. Additional risks include integration problems from distributed systems and failure of pressurized interconnects.

Assembly capability development

The solution of iSA of habitats requires several assembly capability developments to enable or facilitate incorporation into an architecture. These include:

- Autonomous/teleoperated robotic assembly with ISS-level dexterity and precision
- Advanced proximity operations (autonomous/teleoperated)

- Interconnects and automated joining for propellant, power, thermal, fluid, command & control
- Structural connections Remote in-space testing & verification

Representative Architecture Components

Examples of key architecture elements for implementing iSA of habitats are shown in Table 6.

Table 6. Representative architecture elements for different assemble scenarios when implementing the iSA of habitats scenario.

	Minimal Assembly	Moderate Assembly	Pervasive Assembly
Launch Vehicles	Large launch mass and volume required	Mix of large and small LVs depending on module mass and volume, but generally still dependent on larger LVs.	Mix of large and small LVs, with greater opportunities for small LVs.
Habitat	Monolithic, pre-integrated at launch.	Pre-integrated, highly functional modules mated together to form full habitat	Multi-module habs artificial gravity habs, hab modules built from subsystem component modules (e.g., power, radiators, comm., external consumables tanks, etc.)

4. In-space assembly of landers

In the iSA of Mars landers solution, Mars landers are launched separately from the cargo to be delivered, and the landers themselves can be built up from components. Moderate assembly scenarios would have a cargo package loaded onto a lander in space, either in Earth vicinity or Mars orbit, and could incorporate plug-and-play assembly of landing gear or solar array modules or installation of a modular landing package, with an aero-entry device and landing gear, to a core lander module. More pervasive assembly scenarios could individually mount payloads and install a backshell or other thermal protection, and assemble the lander from subsystem modules such as core structure, propellant tanks, engines, power generation, and thermal protection.

As seen in the sensitivity below (Fig. 9), which considers a ~20t-class EMC lander, no launch vehicle can launch a fully loaded lander with the maximum payload. The ~20t-class lander design was derived by a requirement to land pre-integrated ascent vehicles and habitats that need no assembly on the surface of Mars. In order to launch, some combination of payload offloading, reduced propellant loading, and lander assembly is needed. The ability to load cargo and assemble landers in space addresses challenges with launch capacity and element sizing, SLS capacity and launch schedule, and EDL capacity. On-orbit installation of the aero-entry device to the lander has a high potential option for addressing these challenges. Fairing limits on LVs place significant constraints on lander size and cargo arrangements, and can limit aero-entry options [12], but iSA offers flexibility in both lander size and payload arrangements. By assembling aero-entry devices onto the lander in space, larger devices that enable the lander to safely land with more cargo mass can be installed.

In addition to iSA’s ability to address mission challenges, iSA also opens new architecture options that are otherwise unavailable. The ability to load cargo and replace expendable components such as the aero-entry device and landing gear on the landers enables architectures with reusable landers, which can significantly reduce the mass that needs to be delivered to Mars for each mission. iSA also opens opportunities to combine two or more landers together at Earth for transit to Mars (e.g., to rideshare on a propulsion stage), and then separate them at Mars for landing. Additional architecture elements needed to assemble landers in Earth vicinity are similar to those needed for habitats and propulsion stages. Some assembly capability will be needed in the Mars vicinity for loading payloads onto landers and enabling reusable lander architectures. Although this capability may initially be provided by a robotic arm on the transfer vehicle that delivers the payload, reusable lander architectures can be greatly facilitated by the addition of an infrastructure node in Mars orbit.

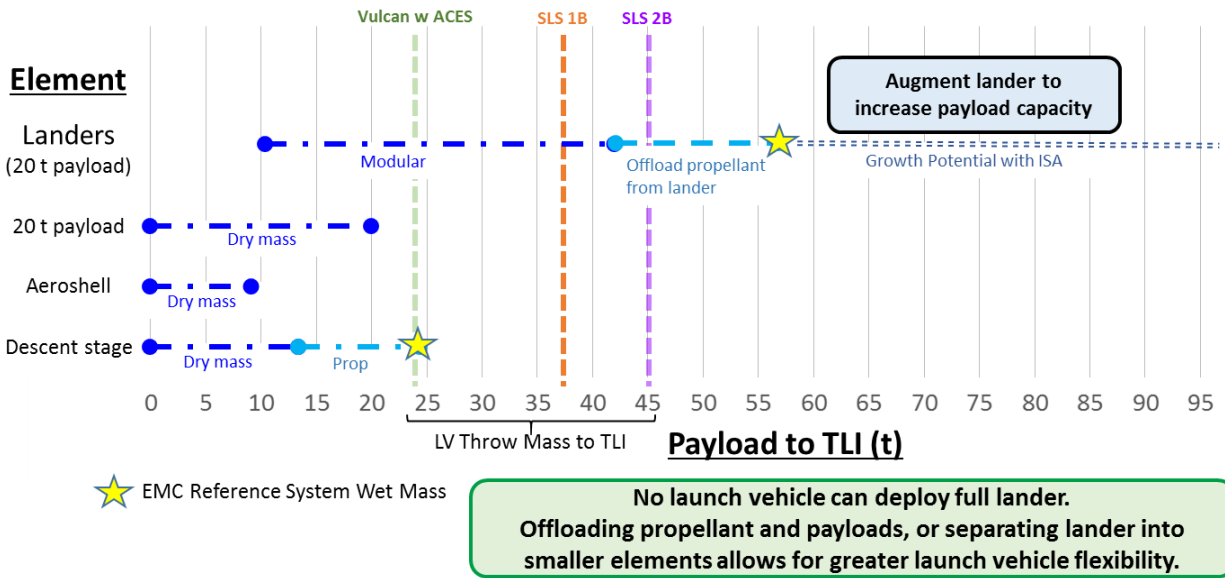


Fig. 9 Launch sensitivity of lander assembly options

Architecture and Campaign impacts

Incorporation of the iSA of landers has both positive and negative impacts on the architecture and campaign that need to be considered when evaluating the potential benefits of the options. The impacts for this solution are summarized in Table 7.

Table 7. Architecture and campaign impacts from implementing the iSA of landers solution.

Architecture and Campaign Impacts	
Positive	Negative
<ul style="list-style-type: none"> • Launch and delivery of smaller launch packages, which can reduce needed LV capacity and allow for use of alternate LVs • Separate delivery of payloads and on-orbit refueling allow for alternate LVs to deliver cargo/prop • Improve lander packaging in the Launch Vehicle • Can increase lander capacity/range via additional lander capabilities 	<ul style="list-style-type: none"> • More launches • Additional schedule for integration and check-out • Increased total lander dry mass from added connections and structure • Longer loiter periods at Earth or Mars to aggregate lander modules • Required coordination of orbital arrival and assembly schedules may reduce flexibility in launch schedule

Risk discussion

Many of the new risks and risk mitigations for assembling the lander in space are similar to those for separately launching and mating vehicle elements in space, including the risks and benefits of launching components on multiple launch vehicles, added margin against mass growth, and the risks associated RPOD, assembly, and long loiter times. Particular risk mitigations provided by the ability to assemble landers in space includes the ability to increase performance and propellant margin to address contingencies during EDL.

Assembly capability development

The solution of iSA of landers requires several assembly capability developments to enable or facilitate incorporation into an architecture. These include:

- Autonomous/teleoperated robotic assembly with ISS-level dexterity and precision
- Advanced proximity operations (autonomous/teleoperated)
- Interconnects and automated joining for propellant, power, thermal, command & control
- Remote in-space testing & verification

- Propellant Transfer (if incorporating refuel)
 - Transferable propellant tanks/tank modules
 - Propellant transfer

Representative Architecture Components

Examples of key architecture elements for implementing iSA of landers are shown in Table 8.

Table 8. Representative architecture elements for different assemble scenarios when implementing the iSA of landers scenario.

	Minimal Assembly	Moderate Assembly	Pervasive Assembly
Launch Vehicles	Large launch mass and volume required	Mix of large and small LVs depending on module/cargo pod mass and volume, but generally still dependent on larger LVs.	Mix of large and small LVs, with greater opportunities for small LVs.
Lander	Monolithic, pre-integrated with cargo and transfer propulsion system at launch. May need fueling on orbit.	Monolithic. Cargo loaded and mated to transfer propulsion stage on orbit. May include attachment of landing gear and aero-entry device. May be reusable with cargo loading and assembly for refurbishment in Mars orbit.	Assembled from multiple modules, including propulsion/tanks, entry and landing devices, power modules, etc. May include mating multiple lander modules together to form a larger lander for transit and separating those lander modules in Mars orbit for landing.

5. Surface assembly of the Mars ascent vehicle

In the surface assembly of the MAV solution, elements of the MAV are delivered separately and assembled on the surface to reduce the minimum landed mass, thus addressing challenges with EDL capacity. A “ready-for-ascent” vehicle has a total estimated mass of ~20-40 t, depending on crew size, target orbit, and engines. A representative MAV design from EMC consists of two propulsive stages and a crew cabin. In addition to surface fueling the MAV, which is a common component of many Mars architectures, surface assembly would enable separate delivery of the propulsion stages and crew cabin. In a moderate assembly scenario these components could be pre-integrated modules that are connected together on the surface. The crew cabin may also be repurposed from other elements, such as the descent cabin or pressurized rover cabin. More pervasive assembly would include installation of component subsystems such as solar power, radiators, and tank/engine modules.

The sensitivity below (Fig. 10) shows how a range of options from modular assembly, through offloading and surface fueling, to no assembly required affect landed mass and number of landers for different target ascent orbits and propellant types. Delivered payload capabilities for current state of the art (Curiosity), EMC, and Mars DRA 5.0 lander concepts are also annotated for reference. The sensitivity can be used to inform architecture decisions that include not only lander and surface system sizes and assembly needs, but also transit stage designs and LV capability needs.

Architecture elements needed to enable surface assembly of the MAV include unloading and mobility assets to deliver modules to the assembly area and robotic assembly agents to connect and test the assembled vehicle. Additional architecture elements that facilitate surface fueling include ISRU equipment to produce and maintain propellants and tankers to transfer the propellants and load the MAV tanks. This ISRU and fueling hardware would be needed for any architecture with surface fueling of the MAV, regardless of additional assembly. Assembly capabilities in Mars orbit also facilitate architectures with reusable ascent vehicles, which can then also serve as landers, enabling a single architecture element to provide both functions. The combined lander/ascent vehicle not only supports crew access to and from the surface, but can also be used to transfer cargo from orbit to the surface and also transfer propellant and other commodities from the surface to orbit for use by Mars orbital elements [13].

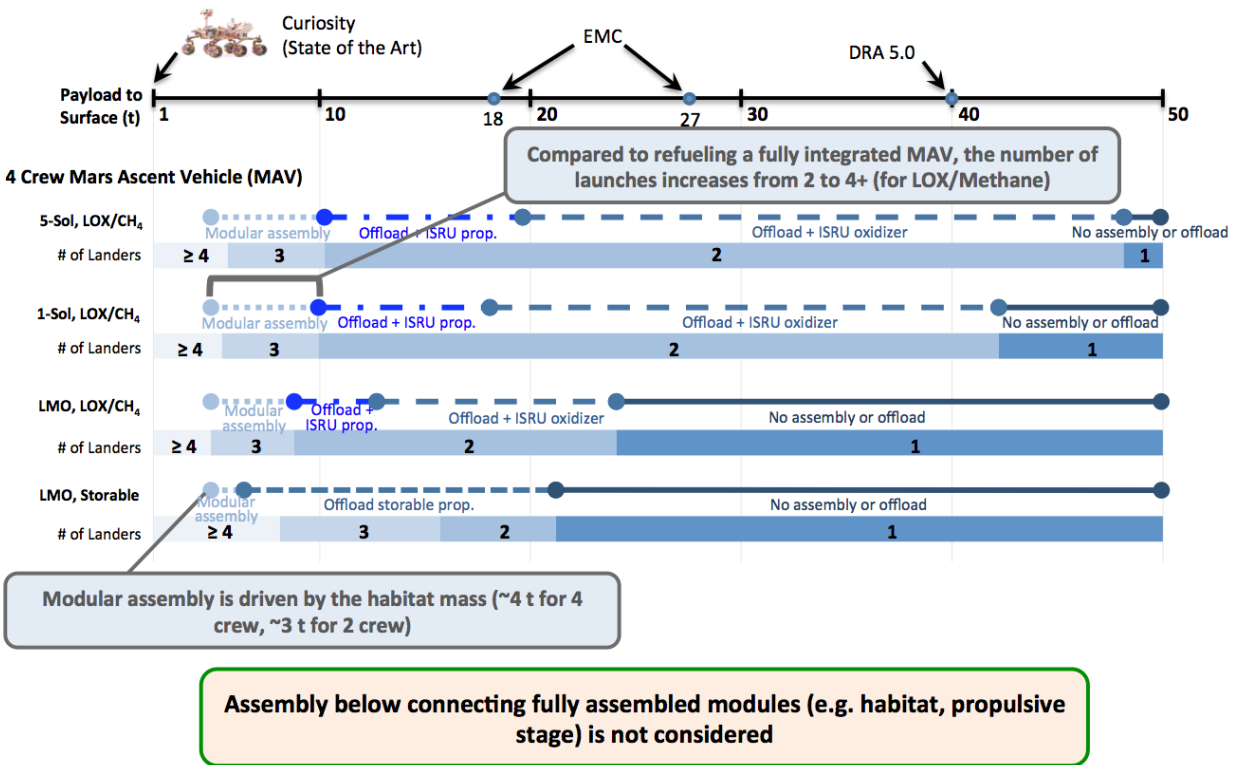


Fig. 10 Lander sensitivity to MAV assembly options

Architecture and Campaign impacts

Incorporation of the surface assembly of the MAV has both positive and negative impacts on the architecture and campaign that need to be considered when evaluating the potential benefits of the options. The impacts for this solution are summarized in Table 9.

Table 9. Architecture and campaign impacts from implementing the surface assembly of the MAV solution.

Architecture and Campaign Impacts	
Positive	Negative
<ul style="list-style-type: none"> Independent delivery of MAV cabin and stages, with assembly on surface, decreases the minimal lander capacity required to deliver the MAV. Smaller modules improves packaging on the Mars lander Ascent stage can be sized to provide additional crew habitation or to provide descent/ascent abort Delivering a partially fueled (fuel only – no oxidizer) or unfueled lander substantially decreases the delivered mass of the MAV. Use of ISRU reduces the total required landed mass. 	<ul style="list-style-type: none"> Smaller lander capacity requires additional landers (and in-space propulsion & launches) to deliver the same level of capability. Total element mass increases due to added connections/structure Additional elements required for to unload, move, and assemble modules More complex plumbing and control due to distributed systems

Risk discussion

Surface assembly of the MAV shares the risks and benefits associated with launching modules or components on multiple launch vehicles as discussed for the iSA solutions. Similarly, using multiple landers to deliver modules and components to the surface increases the risk of a failed landing, but reduces the impact of the loss if a landing fails. As with iSA, surface assembly reduces the risk that mass growth of the MAV will limit ability to launch or land the vehicle. Like iSA, surface assembly also has the risks associated with damage during assembly, inability to integrate

components, and failure of connections, including leakage. New risks particular to surface assembly include the need for additional critical EDL activities such as precision landing, exposure of critical interfaces to dust, and damage or failures during unloading and transfer of components. Particular risks for surface assembly of the MAV include failure of power or signal connections, propellant tank or refueling connections, and the potential that the MAV will not be ready when the crew arrives. Particular risk mitigations provided by the ability to assemble the MAV include the ability to increase performance and propellant margin to address contingencies during ascent.

Assembly capability development

The solution of surface assembly of the MAV requires several assembly capability developments to enable or facilitate incorporation into an architecture. These include:

- Lander unloading system and mobility
- Precision entry, descent, and landing
- Autonomous navigation around site
- Robotic assembly system
- Remote on-surface integration, verification, and testing
- Fuel delivery and transfer system (tanker or transferable tanks)
- ISRU generation, liquefaction, thermal control, and power

Representative Architecture Components

Examples of key architecture elements for implementing surface assembly of MAV are shown in Table 10.

Table 10. Representative architecture elements for different assemble scenarios when implementing the surface assembly of the MAV scenario.

	Minimal Assembly	Moderate Assembly	Pervasive Assembly
Delivery	MAV delivered on a single large-capacity (~20 t +) lander.	Modules delivered on separate smaller landers (~10-20 t).	Open to large and small LVs and landers. Mix of delivery via transfer vehicle and direct launch to Mars surface.
Ascent Vehicle	Monolithic, pre-integrated systems integrated with lander for launch. May need fueling on surface.	Mating of pre-integrated highly functional modules (e.g. mounting a pressurized rover cabin onto a propulsion base to make the ascent vehicle). May need fueling on surface. May be reusable with refurbishment at Mars.	Assembly from constituent components on the surface and fueled via ISRU.

6. Surface assembly of Mars infrastructure and elements

In the surface assembly of Mars infrastructure and elements solution, all surface elements except the MAV, which was discussed in the previous solution, are candidates for assembly on the surface. As the largest single element after the MAV, the habitat was used in the sensitivity analysis shown below (Fig. 11) to investigate options that include modular assembly, offloading outfitting and supplies, and delivering full, pre-integrated habitats. Other large elements include science labs and greenhouses, pressurized rovers, and fission power systems. For visual clarity, only moderate assembly approaches with the connection of habitat modules are displayed in the sensitivity graph, but more pervasive assembly that includes installation of external components such as consumables tankage, radiators, and radiation protection, could also be considered.

Surface assembly of Mars infrastructure and elements addresses challenges with EDL. By delivering surface habitats and other surface infrastructure elements in multiple pieces, the mass of any single landed component can be reduced, which allows for smaller landers and reduces the EDL requirements. Launching smaller modules and assembling them together also facilitates operational readiness, since the modules can be landed with all outfitting already installed, integrated, and tested. Larger modules that offload outfitting to meet lander constraints need additional setup time and may require crew time to complete. Additionally, assembly facilitates build-up and augmentation of the base over time, which can help to address crew health and safety challenges on the surface.

Surface assembly of Mars infrastructure and elements can utilize the same unloading, mobility, and robotic assembly assets as those used to assemble the MAV. Any Mars mission that unloads payloads from a lander and moves them will likely already include many of the mobility and robotic assets that can be leveraged for surface assembly operations, particularly for connection of element modules. Additional capabilities may be needed as more pervasive assembly operations are incorporated. A more in depth assessment of autonomous surface assembly needs to ensure a mission site is safe a ready for crew arrival is provided in Reference 14.

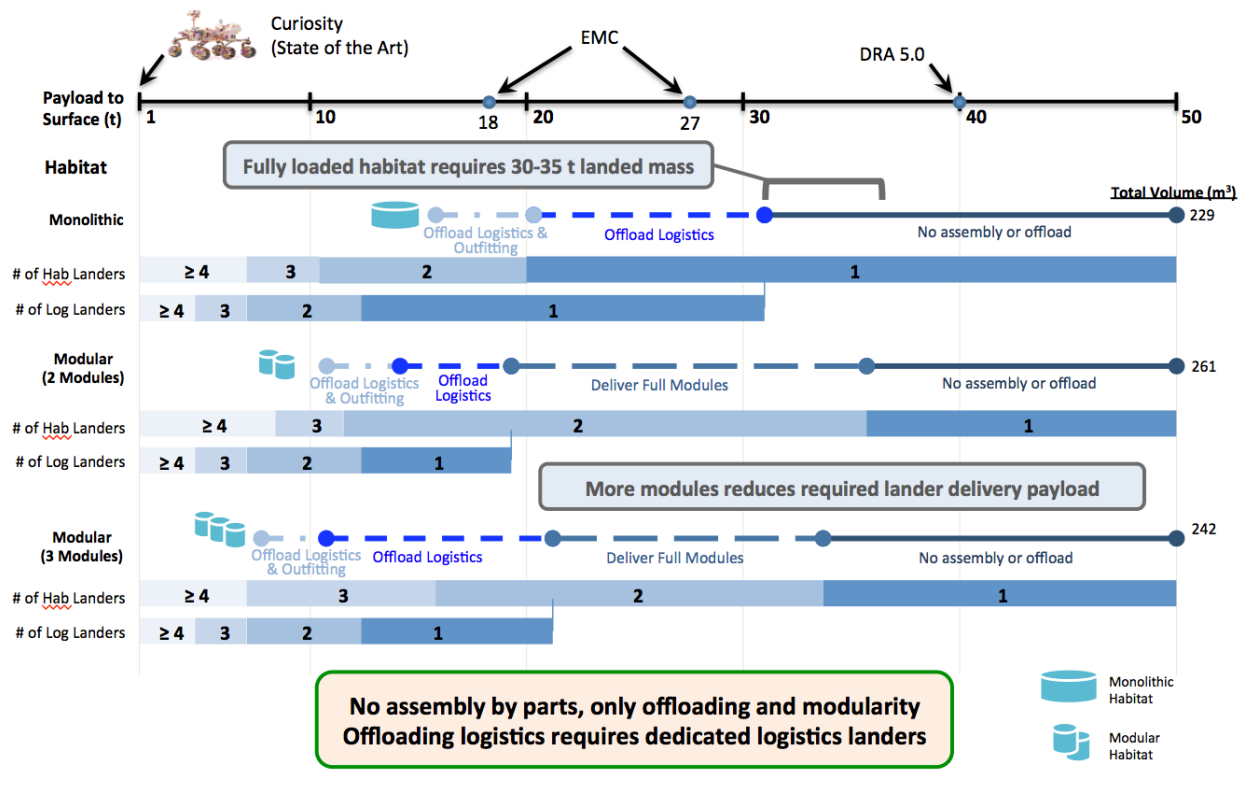


Fig. 11 Lander sensitivity to surface infrastructure and element assembly options

Architecture and Campaign impacts

Incorporation of the surface assembly of the Mars infrastructure and elements has both positive and negative impacts on the architecture and campaign that need to be considered when evaluating the potential benefits of the options. The impacts for this solution are summarized in Table 11.

Table 11. Architecture and campaign impacts from implementing the surface assembly of Mars infrastructure and elements solution.

Architecture and Campaign Impacts	
Positive	Negative
<ul style="list-style-type: none"> Delivering a habitat in modular elements decreases the delivered mass of each single Hab. Multiple habitat elements provide redundancy for crew in case of emergencies. Modular habitats provide a path for evolutionary increase in surface duration over crew exploration campaign Reduced size of propulsion stages to deliver landers to Mars Opens architecture for direct delivery of payload to Mars 	<ul style="list-style-type: none"> Smaller lander capacity requires additional landers (and in-space propulsion & launches) to deliver the same level of capability. Total element mass increases due to added connections/structure Additional elements required for to unload, move, and assemble modules More complex connections and control due to distributed systems

Architecture and Campaign Impacts	
Positive	Negative
<ul style="list-style-type: none"> • Added Safe Haven Capabilities • Allows for Progressive Build Up of Surface Duration • Improve element packaging on lander 	

Risk discussion

Surface assembly of Mars infrastructure and elements shares many of the risks and mitigations as described for the MAV. Particular risk mitigations include the ability to have redundant habitat volumes and systems to provide safe haven in an emergency, the ability to build up greater radiation protection around the habitats for crew safety, and the ability to build up infrastructure to add capacity and redundancy for Mars base systems. Additional risks particular to surface assembly of infrastructure and elements include failure of pressurized interconnects and the potential that the habitat may not be ready for crew arrival.

Assembly capability development

The solution of surface assembly of the Mars infrastructure and elements requires several assembly capability developments to enable or facilitate incorporation into an architecture. These include:

- Precision landing
- Lander offloading system
- Mobility systems to reposition elements
- Surface preparation
- Autonomous/teleoperated robotic assembly with ISS-level dexterity and precision
- Advanced proximity operations (autonomous/teleoperated)
- Interconnects and automated joining for consumables, propellant, power, command & control
- Remote on-surface integration, verification, and testing

Representative Architecture Components

Examples of key architecture elements for implementing surface assembly of Mars infrastructure and elements are shown in Table 12.

Table 12. Representative architecture elements for different assemble scenarios when implementing the surface assembly of Mars infrastructure and elements scenario.

	Minimal Assembly	Moderate Assembly	Pervasive Assembly
Delivery	One or more systems delivered on a large-capacity (~20 t +) lander	Modules and components delivered on separate smaller landers (~10-20 t).	Open to large and small landers. Mix of delivery via transfer vehicle and direct launch to Mars surface.
Surface systems	Monolithic, pre-integrated systems integrated with lander for launch. Self-contained operation on the surface	Large surface systems launched as modules assembled on surface. Smaller systems launched pre-integrated. Surface connections between systems. Some ISRU-based surface construction/preparation	Both large and small systems assemble or expanded from component modules.

IV. Assembly Agents to Support Operations

D. Assembly Agent Classes

Each of the solutions will require assembly agents to carry out the assembly operations, and the capabilities provided by these assembly agents will depend on the selected assembly strategy and the mission system design. Assembly agents used for iSA can vary greatly in size, complexity, level of capability, and scope of operations performed. This variability provides a pathway for a build-up of capabilities over time as iSA technologies mature, and the tailoring of assembly agents as appropriate for a given mission or operational need. Three classes of assembly agents (Fig. 12) were identified that could support varying degrees of assembly, including onboard robotics, free-flying assembly agents, and persistent assembly platforms. There are several existing or proposed concepts for onboard robotics and free-flying systems that can be applied to in-space assembly.



Fig. 12 Representations of the classes of assembly agents.

These concepts were assessed in the context of the proposed solutions to better understand realistic near-term assembly application implementations and identify development paths to advance assembly capabilities for more complex assembly operations over time. By incorporating modular assembly into spacecraft designs and leveraging modest assembly capabilities that either already exist or are in active development, significant opportunities for early application of iSA for human exploration missions can be achieved. Modular packages that can attach to the mission system via standard interfaces (e.g., booms, arrays, and antennas; lander payloads; extension modules like airlocks; and propellant pods) can address the immediate mass and volume-related challenges associated with Mars mission systems while delaying the development of highly dexterous and precise assembly capabilities needed for more complex assembly. On-board robotics for these early applications can be installed on the mission system or hosted on the Gateway NASA plans to establish in cis-lunar space [15]. Free-flying assembly agents derived from ongoing servicing demonstration missions (i.e., NASA's Restore-L [16], Defense Advanced Research Projects Agency/Space system Loral's Robotic Servicing of Geosynchronous Satellites [17], and Orbital ATK's* Mission Extension Vehicle [18]) could also be leveraged to support iSA these early operations in low-Earth orbit or cis-lunar space.

A particular assessment of the proposed Gateway was conducted to evaluate how it could be used to support iSA for human exploration and other missions. Additionally, concepts for independent persistent platforms both in cis-lunar space and in Mars orbit were developed to investigate their potential application within a Mars architecture.

* Now Northrop Grumman Innovation Systems

E. Gateway as an Assembly Platform

NASA's Gateway provides an ideal opportunity for executing early assembly operations to support exploration missions. As planned, Gateway will be established in time to support lunar and Mars missions, includes robotic assets, and is already nominally intended to support preparation of the lunar landers and the DST [2]. Gateway provides a platform for crewed teleoperation of assembly assets, crew oversight, and EVA support if needed. With multiple ports and external attachment fittings, Gateway could potentially host multiple assembly agents, including temporary docking of free-flying agents, and provides an opportunity to demonstrate a variety of assembly capabilities, which could pave the way for future assembly operations. Additionally, Gateway could provide support and oversight for mission system assembly and servicing activities that are co-located in the Gateway vicinity, such as propellant refueling or tank module exchange for landers or deep-space transport propulsion stages.

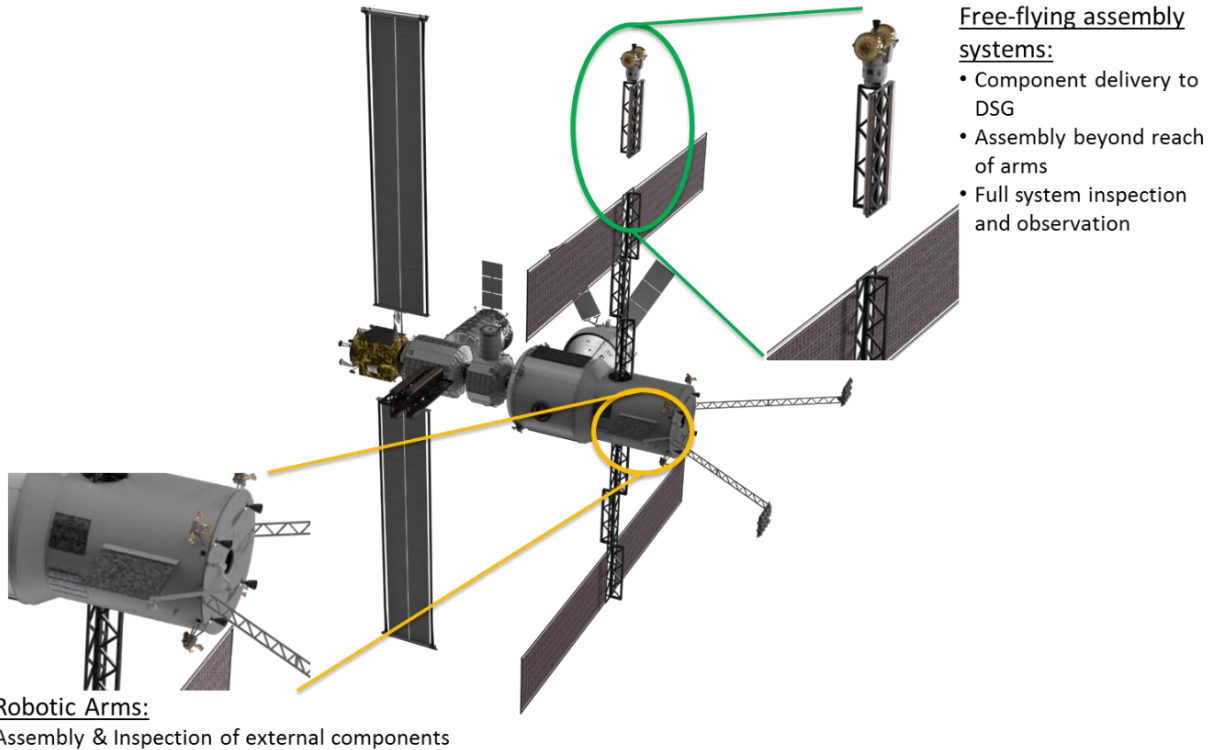


Fig. 13 ISA opportunities at the cis-lunar Gateway.

F. Persistent Assembly Platforms for Mars Missions

Beyond Gateway, independent persistent assembly platforms in cis-lunar space and Mars orbit could provide additional architecture opportunities that benefit execution of Mars surface missions.

1. Cis-lunar platform

The sheer number of Mars cargo transports and lander systems needed to carry out a crewed surface mission on Mars make relying solely on Gateway as an assembly and servicing platform impractical and risky. Use of a co-located independent platform in cis-lunar space enables higher assembly throughput and reduces the risk of damage to the Gateway from assembly operations, while still allowing for crew oversight and teleoperation of assembly agents. It provides a staging area for prepositioned cargo and refuel tankers to reduce requirements on those systems (e.g. years-long loiter times between operations). Free-flying assembly agents can base from the independent platform to reduce the support burden on the Gateway, while still remaining near enough to support assembly operation at both the Gateway and the platform. An independent cis-lunar platform will likely require dedicated launches for delivery, which could compete with launch of the mission systems. Also, some amount of assembly itself to become operational, but if modularly designed it can be expanded over time to build up capability as need and budget dictate. A cis-lunar platform provides opportunities for commercial and international partners to provide platform component delivery and assembly, payload deliveries, and assembly and servicing operations at the platform.

2. Mars Orbital Node

A Mars orbital platform, or node, provides an intermediary staging and aggregation point for architecture elements in the Mars sphere of influence. Mars nodes enable reusable system architectures, in particular reusable landers, and facilitate architectures that rely on cyclers or high-orbit transportation systems that avoid the deep gravity well at Mars. High potential applications for the node include payload transfer to landers; in-space refueling for transfer tugs, crew taxis, and landers; crew transfer and abort safe haven; and crew lander checkout prior to descent. A facility with some robotic arms and docking/berthing ports can support staging for systems (e.g., reducing those systems' orbital maintenance requirements), payload handling, and a variety of assembly and servicing functions. Adding features such as fuel tankage, lighting, and imaging systems can expand capabilities to include refueling and inspection. By including a pressurized tunnel or module, the facility can support crew transfer between Earth-Mars transportation stages or tugs and the lander or ascent vehicle, and could potentially serve as a safe haven. In more ambitious assembly scenarios, the Mars node can support lander assembly and replacement/refurbishment of EDL systems. Depending on the node design, node components may be able to rideshare to Mars with another payload. Otherwise a dedicated transport would be needed. As with the cis-lunar platform, the Mars node could be expanded to build up capabilities over time. To take best advantage of a Mars node, the architecture will need to include tugs to transfer crew and payloads, and may also need augmented communications and navigation support.

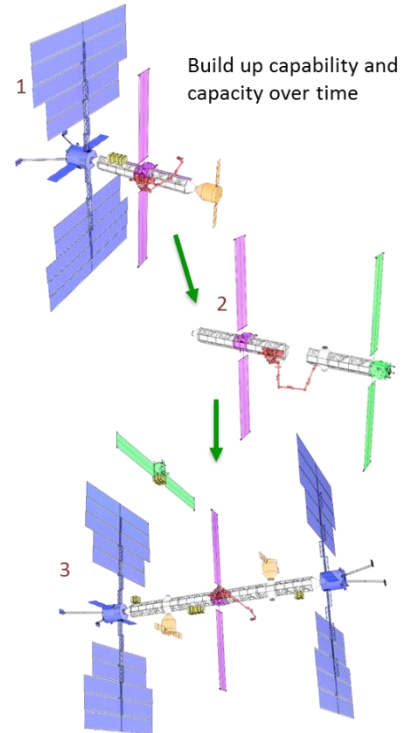


Fig. 14 Concept for a cis-lunar platform and its expansion over time.

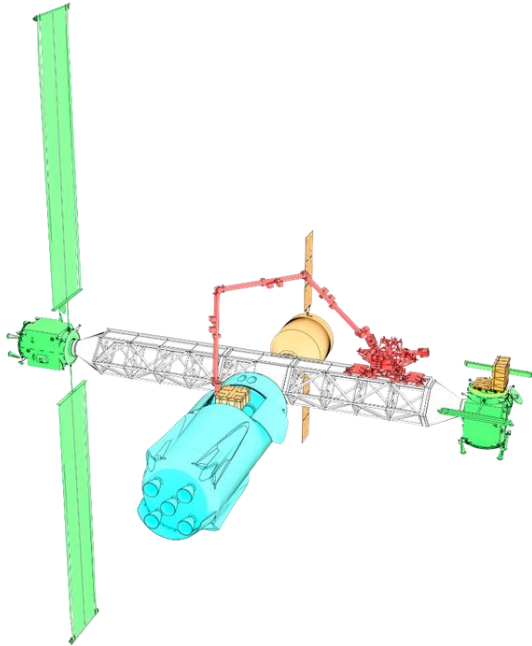


Fig. 15 Concept for a Mars orbital node loading cargo onto a lander.

V. Observations

Throughout these analyses, several observations were made regarding the use and applicability of iSA to human exploration, early architecture benefits that can be achieved with existing assembly capabilities, and the importance of designing for assembly from the outset and concurrent design of assembly agents if iSA is to be applied in the architecture.

1) **Some degree of iSA is required for any human Mars architecture**

Recent assessment of launch capacity vs. planned systems (e.g., Deep Space Transport, Gateway, Mars Lander) show that ‘Element-Element mating’ iSA is required to enable a human Mars architecture based on an SLS launch platform, and at least ‘modular-level’ iSA will be required if element sizing and LV capacity trends continue. Many of these operations will take place without the presence of crew, leading to a need for more autonomous assembly capabilities. Development of critical iSA capabilities must be conducted in conjunction with Mars mission planning and development.

2) **Use of iSA can provide flexibility in selection of launch vehicles and in the launch campaign**

Incorporating assembly allows for smaller launch packages, which increases margin for larger elements to be launched on SLS, opens opportunities for more launch providers to participate, and provides robustness to launch losses and delays. Cis-lunar space provides a favorable location for iSA supporting human exploration missions due to being outside of the Earth’s gravity well and the LEO debris environment, while still having near real-time communications and potential support from the Gateway or other exploration infrastructure. Additionally, assembly operations, provision of assembly assets, component delivery, and providing and running assembly platforms are all opportunities that can be provided by commercial providers.

3) **ISA can reduce risk and provide robustness to the exploration architecture**

By its nature, iSA is a modular approach, which provides a level of redundancy and robustness to failures; while each subsystem may become less reliable (e.g. failures at connections), the overall system has a higher availability and improved ability to recover from failures. In many cases, there is built-in redundancy between elements, and in the case of failure, only the failed module(s) need to be replaced. Additionally, significant synergy exists between assembly capabilities and servicing capabilities, so the ability to assemble a modular system inherently provides the ability to service it.

4) ISA can provide flexibility to the architecture

ISA opens architecture options that are not possible without assembly and allows for campaigns in which capabilities are built up over time. This can help address affordability and sustainability challenges, and also allow for earlier execution of meaningful missions. Mission capabilities and infrastructure can be built up over time, expanding the number and complexity of in-space elements, and mission systems can initially be deployed with current technology and later upgraded with advanced capabilities when development allows. Examples of new architecture options that become available with iSA include reusable landers, high-capacity landers, artificial gravity, larger habitats, and faster transits that are not possible without assembly.

5) Use of iSA enables a robust Mars landing and surface architecture

ISA capabilities are required on the Mars surface for the establishment of long-stay infrastructure. Any long-stay surface architecture requires some sort of set up, even if it is just connecting power cables and mating elements. As these capabilities will already be present, it opens the opportunity for performing more assembly operations on the surface with minimal additional development costs. For example, these capabilities also provide benefits for the delivery and assembly of large payloads. Increased assembly on the surface allows for the use of smaller landers and thus smaller required lander EDL capabilities, resulting in an optimal convergence of lander size vs. number of landers.

6) iSA must be designed into the architecture

Use of iSA must be designed into the architecture from the start and iSA capabilities must be developed in conjunction with the architecture. Mission system designs will be different if designed for assembly, but as those designs are not yet generated, impacts to development costs should be minimal. Early design for assembly is facilitated by advances in modular assembly of systems, which are likely achievable with near-term investments in capabilities such as standard interfaces and connections that facilitate modular assembly of components and elements, sufficient autonomy and situational awareness to enable these operations over time delays or without nearby human intervention, and in-space inspection and verification and validation of the assembled systems.

7) Early benefits can be realized with modest assembly capabilities

Relevant assembly capabilities that already exist or are under current development (e.g. for servicing) provide early opportunities for incorporating assembly that can provide benefits for exploration architectures. Robotic capabilities, tele-robotic operations, autonomous rendezvous and proximity operations, interfaces, and sensing and imagery systems can support sufficient levels of assembly to reduce payload sizes to meet LV capabilities, add robustness and increased flexibility to the mission, and reduce risk of total loss with a launch or system failure. Additional investment for advances in autonomy/autonomous operations; sensing; spatial orientation; common interfaces and standards to facilitate modular assembly; and in-space inspection, verification, and validation are needed to improve safety, efficiency, and operational timelines, and reduce reliance on local crew presence.

While this study focused primarily on Mars missions, the solutions explored and observations made can be applied to any human exploration mission that rely on large mission systems for transporting and delivering crew and cargo.

VI. Conclusion

Through the solutions developed in this study, several potential applications for incorporating iSA into human spaceflight architectures have been examined. Each solution presents opportunities for early adoption of moderate levels of iSA into architecture concepts using capabilities that are currently available or expected to be ready in the next few years. While each solution focused on one particular aspect of a Mars architecture, the benefits from iSA can multiply when options from multiple solutions are incorporated together and common assembly capabilities are leveraged throughout. The sensitivities presented show relationships between LVs, landers, and mission system assembly options, which can facilitate development of iSA architectures that efficiently tie assembly operations together across the missions and campaign.

Given the breadth covered during this study, the architecture options analyzed herein were at a relatively high level of detail, but also provide tools for more in-depth investigations. The team identified several areas as potential next steps for future investigations.

1) **Modular Deep Space Habitat Design & Assembly Capabilities**

Explore the trade space of DSH design options that become available when not limited by launch vehicle mass and volume constraints. Include an evaluation of modular habitat designs with increased mass and volume, and assess options for radiation protection, artificial gravity, and enhanced crew systems.

2) **Modular Hybrid Propulsion Stage Design & Assembly Capabilities**

Explore the trade space of hybrid propulsion design options that become available when not limited by launch vehicle mass and volume constraints. Evaluate modular hybrid propulsion stage designs with increased mass and volume, including their ability to enable alternate trajectories, and assess options for increased thrust systems, transferable tanks, refueling, and repositioned propulsion stages.

3) **Deep Space Gateway Assembly Capabilities**

Evaluate different potential capabilities at or near the Deep Space Gateway to facilitate assembly of Mars mission systems. Include assessments of assisted docking and berthing capabilities, habitat assembly and outfitting capabilities, propulsion stage assembly and fueling capabilities. Similar capabilities for servicing the Mars mission systems at or near the Gateway between missions should also be included in the assessment.

4) **Mars Vicinity Assembly Capabilities**

Evaluate different potential capabilities in Mars orbit to facilitate assembly of Mars mission systems. Include assessments of lander assembly and outfitting; propulsion stage/tank module swap or refueling options for deep-space propulsion systems, orbital tugs, and reusable landers; and habitat resupply and re-outfitting options. Investigations should also consider the potential for crew support during transfer to and from landers and safe haven during an abort.

Opportunities exist now for incorporating iSA into human exploration missions that can begin to address some of the challenges facing human missions to Mars. Over time, the development of advanced assembly capabilities and mission system concepts designed to take advantage of those capabilities could facilitate safer, more robust, yet also more ambitious missions of the future.

Acknowledgments

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