

The Case for Architecting Space Nuclear Propulsion Missions and Vehicles That Incorporate In-Space Servicing, Assembly and Manufacturing Principles

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Concepts for Space Nuclear Propulsion (SNP) vehicles are currently being matured for crewed and cargo missions to Mars and deep space. SNP vehicles are large and massive systems that cannot be orbited by a single launch or packaged in a single launch vehicle fairing. Thus, the vehicle must be aggregated and assembled on orbit. Technologies for In-space Servicing, Assembly, and Manufacturing (ISAM) are maturing at a rapid rate and can provide significant benefits to SNP mission and vehicle architectures. However, incorporating ISAM into SNP architectures has not been explored in great detail as of late. In this work, we propose conducting a comprehensive architecture study that assesses using ISAM capabilities from the onset of both SNP mission and vehicle design to realize benefits and identify technology gaps.

I. INTRODUCTION

NASA and partners are exploring the use of SNP vehicles for crewed, cargo, and science missions to Mars and deep space. Propulsion concepts of interest include nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) (Fig. 1), as well as hybrid configurations of NEP-chemical propulsion, and NEP-NTP. Each nuclear propulsion option provides respective benefits depending on mission goals. NASA is working primarily to advance reactor-based and reactor-adjacent components to meet propulsion performance goals for various mission architectures.

Considering the SNP spacecraft as a complete system, gives insight into the number of different subsystems, components, and structures that must be aggregated to assemble the full spacecraft. Initial estimates of vehicle size (100 m to 150 m in length) results in a vehicle length of similar magnitude to that of the International Space Station (ISS), which is comprised of 17 different modulesⁱ that were assembled on orbit. Due to length, a SNP vehicle is classified as a large structure/system and cannot be assembled entirely on Earth and packaged for launch in a single vehicle. Thus,

the SNP vehicles will require multiple launches of components/modules that are then assembled on-orbit.

Each module for the ISS was designed to fit within the launch vehicle payload bay (mainly the Space Transportation System (STS)) and designed to withstand the launch loads experienced during transport to the ISS. Both the Shuttle Remote Manipulator System (SRMS) or Canadarmⁱⁱ (Fig. 2) and the Space Station Remote Manipulator system (SSRMS) were primarily used to berth new modules to the existing structure. Also, Russian modules have used the Igluⁱⁱⁱ and Kurs^{iv} systems to dock and berth modules with the ISS.



Fig. 1. An artist's rendition of NTP (left) and NEP (right) spacecraft envisioned for deep space exploration.



Fig. 2. Berthing of the Unity and Zarya modules started the construction of the ISS in 1998.

Current ConOps^v call for the SNP vehicle components to be fully integrated on Earth and docked together in a nuclear safe orbit, meaning each component would have to be an independent spacecraft. Additionally, the current standard launch vehicle fairing diameter is approximately 5 m (SpaceX Falcon 9^{vi}, United Launch Alliance Vulcan^{vii}), potentially growing to anticipated sizes of 9 m (SpaceX Starship^{viii}) to 10 m (Space Launch System [SLS] Block 2^{ix}) in the future. Launch fairing size limits the design space for vehicle components which can also lead to imposing limitations on missions. Further, reliance on a single launch platform poses additional risk to programs if the launch platform is unavailable due to vehicle availability, grounding or program cancelation.

ISS assembly relied heavily on astronaut intravehicular activity (IVA) to teleoperate the SRMS or SSRMS to deploy solar arrays, and connect elements, etc. NASA and partners are planning to follow a similar strategy for assembling the Lunar Gateway^x with the anticipated seven modules being assembled primarily by autonomous robots with some EVA support. SNP vehicle assembly is unlikely to involve EVA due to potential hazards to astronauts and should rely on remotely operated or autonomous robotic agents to perform assembly operations.

In this paper, we propose that SNP architectures and vehicles be designed using ISAM principles from the onset to enable reusability and relieve design constraints imposed by launch vehicle size. A strategy for a comprehensive architecture study is discussed and potential benefits are reviewed.

II. IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

ISAM^{xi} is a paradigm-shifting capability for space operations, supported by NASA, DOD, other government agencies, and commercial partners. Past and current strategies for achieving large structures in space have relied largely on two strategies; the first is to launch monolithic structures (designed to meet launch vehicle requirements for payload size, mass and launch loads) that are docked or berthed to other monolithic structures on-orbit to form a larger structure (e.g., the ISS¹); the second is folding and packaging large structures to fit inside a payload fairing and deploying the full-sized structure (unaided) once on-orbit (e.g., the James Webb Space Telescope [JWST]^{xii}). ISAM on the other hand, and in particular assembly, considers on-orbit construction of space systems using discrete modules and components. Designing a spacecraft for assembly from the outset also results in a serviceable spacecraft that can be inspected, repaired, altered, evolved, or extended after initial launch. Serviceable spacecrafts are inherently reusable and become capable of executing multiple missions.

A comprehensive ISAM approach establishes an ecosystem concept that has all the capabilities (assembly, maintenance, repair, etc.) that should be considered during architecture and spacecraft conceptualization and design. Designs relying on a high degree of component modularity can leverage existing technologies to realize their architectures in a more time- and cost-efficient manner. Broad interest in these emerging technologies from multiple US government agencies, coupled with the expediency of commercial technology development, is already accelerating the technology readiness level (TRL) of ISAM technologies in the near term (e.g., availability of space robotic manipulators in Fig. 3).

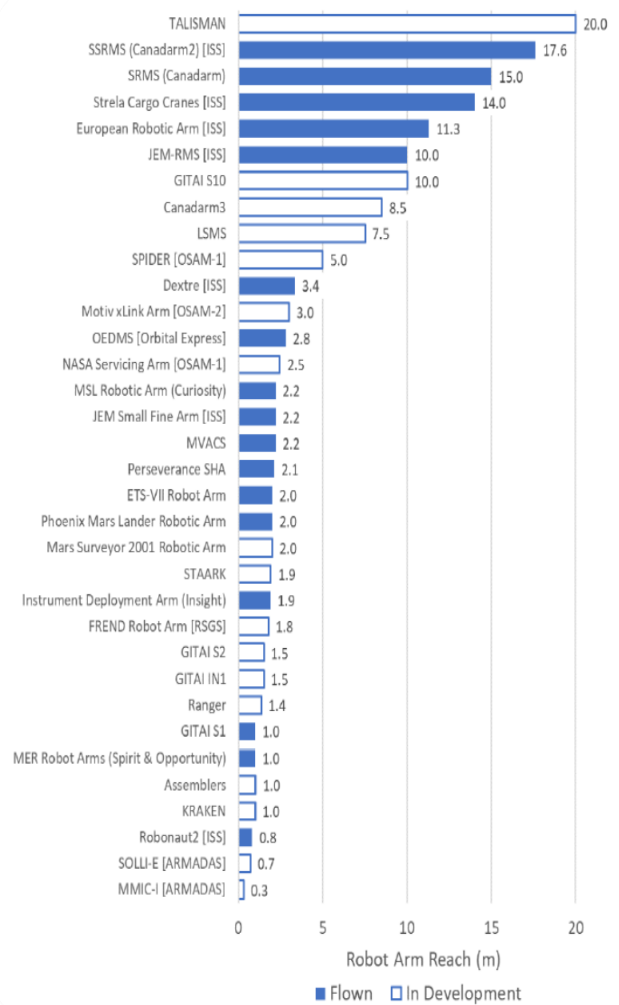


Fig. 3. Available space robotic manipulators categorized based on reach from the ISAM State of Play in 2023.

ISAM technologies are rapidly maturing. NASA Langley Research Center (LaRC) maintains the ISAM State of Play^{xiii} for the aerospace community: an annual review and update of 11 different capability areas. The ISAM State of Play is envisioned to “inform architecture studies, mission formulation, and pathfinding options to establish an economic ISAM ecosystem^{xiii}.” For example, a relevant technology for an architecture study considering the assembly of an SNP vehicle, would be available robotic manipulators (categorized by reach and flight-heritage) as shown in Fig. 3. Similarly, capability assessments of rendezvous and proximity operations, docking, mating, planned and unplanned repair and refueling and fluid transfer are likely relevant.

III. PERCEIVED RISK OF INCORPORATING ISAM

ISAM has been studied for decades^{xiv} but struggles to be adopted by missions due to perceived cost, schedule, and technical risk concerns. Two recent reports^{xv, xvi} demonstrate the reluctance to consider ISAM in SNP architectures because of concerns for complexity, reliability, and risk. A fundamental flaw in approach occurs when attempting to apply ISAM to an already existing mission or vehicle architecture. To realize its benefits, ISAM should be considered from the onset of mission and vehicle architecture definition, not as an afterthought or a consideration that is ignored. One goal of NASA’s recently canceled On-orbit Servicing, Assembly, and Manufacturing -1 (OSAM-1) mission^{xvii} was to refuel the Landsat-7 satellite, which was not designed to be serviced. The refueling operation required developing unique and specialized robotic tools to access the fill and drain valves. Using ISAM, spacecraft refueling capability would have been incorporated from the start allowing the spacecraft to rely on commercially available refueling capabilities, like the Northrop Grumman Mission Extension Vehicle^{xviii}, to service the spacecraft instead of a specialized mission.

A 2019 study^{xix} of an in-space assembled telescope (iSAT) (shown in Fig. 4) was commissioned to investigate the feasibility of ISAM for achieving large aperture space telescopes and when it would make sense (main aperture diameter) to assemble a telescope on-orbit rather than on Earth (like JWST). A study team was assembled involving multiple NASA centers, industry partners, other government agencies, and academic partners that spanned the numerous disciplines necessary for taking a holistic approach to telescope design. The cross-disciplinary nature of the study team helped facilitate knowledge transfer between respective disciplines on the state-of-the-art for all areas required for the telescope system. Previous existing barriers to

incorporating ISAM into the telescope architecture were essentially eliminated by ensuring a baseline understanding of technology maturity for ISAM capabilities (especially among the science community) across all of system disciplines. This education also led to ISAM being incorporated into all of the subsystem designs. Trade studies were then performed to optimize the design and address all concerns.

The study resulted in several outcomes including: ISAM required for aperture size greater than 15 meters but having significant benefits even for aperture sizes greater than or equal to 5 meters; agreement that servicing, repair and upgrading are a natural and beneficial byproduct of designing with ISAM; and that ISAM results in a potentially more manageable risk posture than the single-launch approach. Most importantly, technology gaps were identified which allowed gap-closure technology development efforts to be pursued. One of the gaps identified was whether a precision structure for supporting a 20-meter primary mirror surface could be assembled using autonomous robotic agents. LaRC addressed closing this gap through a Space Technology Mission Directorate (STMD) funded Game Changing Development (GCD) project called Precision Assembled Space Structures (PASS)^{xx}. The PASS project successfully developed and has demonstrated the capability to autonomously assemble multiple TriTruss structural modules together to form the support truss for the aperture using an industrial scale robot in a 1-g laboratory demonstration. Fig. 5a and Fig. 5b show the simulation of the 20-m truss structure with mirrors and the assembled first-ring structure (central green section in Fig. 5a) from the laboratory demonstration.

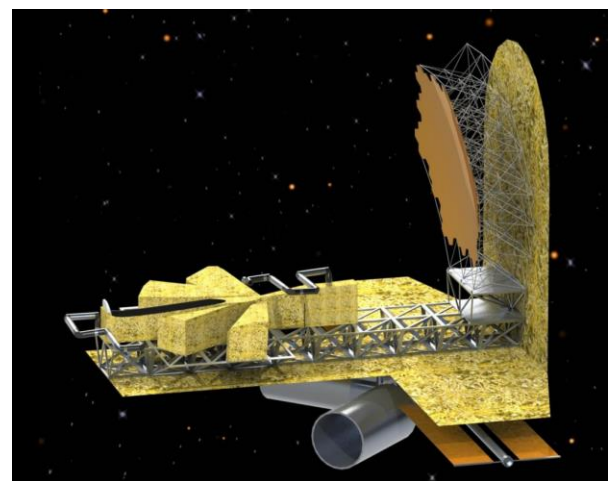
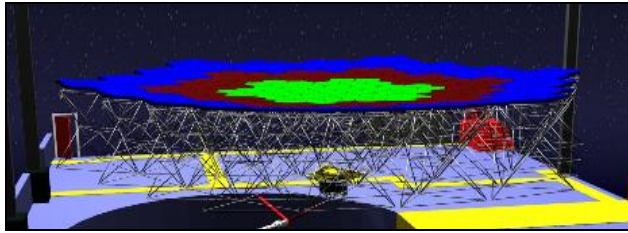
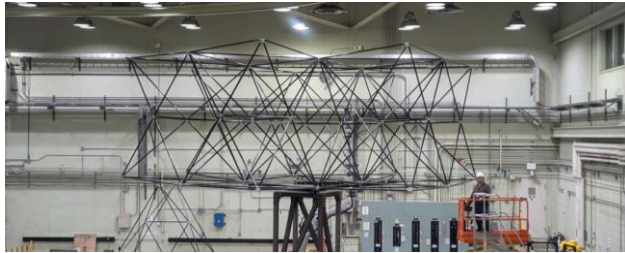


Fig. 4. An in-space assembled telescope.



(a)



(b)

Fig. 5. (a) Simulation and (b) laboratory demonstration of the assembly of the primary aperture support truss. The demonstration assembled the first ring (central green section in [a]).

III. AN ARCHITECTURE STUDY FOR SNP

Identifying existing technology gaps for an ISAM-designed SNP vehicle is a critical first step that would result from incorporating ISAM into the mission and vehicle architectures. A study, modeled after the iSAT study, could be commissioned to investigate NTP, NEP, and hybrid configurations to identify common gaps that need closing to realize the vehicle architectures. The study should include all disciplines related to the vehicle including mission reusability, nuclear reactors, structures, assembly, robotics, autonomy, habitation, rendezvous and proximity operations, verification and validation, launch vehicles, orbital dynamics, radiators, and propulsion. The study should also draw from a variety of partners including DOD, DOE, industry, and academia. Similar cross-disciplinary knowledge transfer on the state-of-the-art in related fields would occur as did during the iSAT trade study.

The study should start from mission objectives (considering reusability), requirements and desired outcomes to develop a ConOps for crewed and cargo Mars missions. The ConOps development should include ISAM capabilities that can enhance the architecture like assembly operations, planned servicing, repair (in transit) and refueling. As part of the study, the team should identify the different modular units that the vehicle components are to be assembled from (e.g., strategy for assembly/deployment of backbone truss structure, radiator

panels for NEP vehicle, etc.). An initial assumption for the study should include current as well as projected launch vehicle capabilities to be used such that modular units can be designed to package in the associated fairings. The ISAM State of Play can be used to guide ISAM capability availability. The study should make recommendations on a path forward and technology gaps needing to be closed. Then the community can work to close gaps to ensure the technology is ready to on-ramp when required for the mission. Identifying the capabilities needed will also drive commercial industry to invest in relevant areas.

The Modular Assembled Radiators for NEP VehicLes (MARVL) is a new start project that commenced at LaRC in October 2024. MARVL is starting to investigate using ISAM principles for NEP vehicles by focusing on the primary heat rejection system (PHRS). The PHRS assembly is identified in the NEP Technology Maturation Plan (TMP)^{xxi} as benefiting from ISAM capabilities since the radiator system is likely the largest structure conceived thus far for in-space use. While the MARVL studies are a start at investigating the use of ISAM for NEP vehicles, a thorough study should be conducted for all variants of SNP.

IV. BENEFITS OF ISAM FOR SNP

Architecting SNP missions and vehicles with ISAM principles will bring benefits to the architecture^{xxii}. Incorporating ISAM would likely expand the design space for mission and vehicle architectures leading to reduced technical challenges and expanded functionality. For NEP, a bi-wing radiator structure (shown in Fig. 1) is achievable using ISAM^{xxi}. Compared to an x-wing radiator architecture, the bi-wing will likely result in a reduced radiator mass and effects from solar heat flux as the radiator orientation is edge-on to the sun, instead of also having panel-on to the sun components.

As was found in the iSAT trade study, servicing is a natural byproduct of designing with ISAM. SNP vehicles likely will benefit from servicing activities during a long duration mission if, for example, one or more NEP radiator panels becomes inoperable during transit to Mars. With a traditional approach, the radiator system would need to have sufficient redundancy to meet mission requirements given a certain number of panels being inoperable during the mission duration, which likely increases system mass and cost. However, if ISAM is incorporated, the radiator system can be designed to be serviced during operation, where the impacted panel can be isolated, and a spare replacement panel installed using the same on-board robotic agents used to assemble the original system.

If the SNP vehicle can be serviced during its lifetime, the vehicle can be reused for multiple missions which should result in significant cost savings to a permanent Mars presence. In addition to any servicing that happens during a single mission, the vehicle can go to overhaul maintenance to be refurbished for future missions. This could include inspection of all subsystems for damage, repair of damaged components, upgrading instruments, and refueling consumable components. ISAM also offers increased versatility to readily evolve systems and make changes late in the design cycle or for subsequent missions that cannot be accommodated efficiently using traditional means. Reusability will be key to having a cost-effective vehicle and continuous crewed and cargo missions to Mars.

By developing an architecture and vehicle design that incorporates ISAM techniques and capabilities, the program can have a greater degree of flexibility in launch vehicle options and drastically reduce program risk. Relying on a fairing size that is readily available from multiple launch vehicle providers provides flexibility and competitive pricing whereas a vehicle with a larger proposed fairing size, such as the SLS, may be limited in availability depending on other mission priorities. For example, currently, there may be only one SLS launch per year under an optimistic scenario; and those launches may be dedicated exclusively to Artemis/Lunar missions. In this situation, a Mars mission may have to compete with lunar missions and/or planetary science missions for launch vehicles. The frequency of launch may also not ensure a timely assembly of a nuclear vehicle. The emergence of SpaceX Starship may positively impact the availability of frequent launches with a larger fairing size. Regardless of launch vehicle capabilities, incorporating ISAM can reduce design complexity required to package the structure ‘origami’ style into the launch fairing and thus mitigate the associated increased program schedule, risk, and cost to validate packaging and deployment before launch. An example of incorporating this complexity is the significant effort (schedule and budget) spent on validating the folding, packaging, and deployment approach for the JWST^{xxiii} primary mirror so that it would fit inside the Ariane 5 launch vehicle payload fairing for launch. By taking advantage of modularity and ISAM, SNP can leverage current and future technology development for persistent platforms and reduce complexity of the SNP modules. For example, the largest single systems of the NEP vehicle are the radiators, which could be redesigned using an ISAM approach rather than being packaged as a monolithic, deployable structure.

V. CONCLUDING REMARKS

ISAM is game changing for SNP mission architectures and vehicle designs because of the expanded versatility it offers across all capabilities and technologies. ISAM technologies are rapidly maturing, and increased capabilities will likely be more readily available when SNP vehicles are being readied for Mars missions. The need for capabilities will also drive commercial industry to mature technologies to meet schedules. However, to realize the benefits of ISAM, SNP architectures and vehicles should be designed considering ISAM from the outset. To identify existing technology gaps that need to be closed to incorporate ISAM, we recommend that the community undertake a comprehensive trade study like the astrophysics community did with the iSAT study. Identifying critical gaps now would allow government, academia, and industry time to close those gaps and ensure the technology is ready when needed to incorporate into NASA missions.

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