IDEAS FOR INFUSING IN-SPACE SERVICING, ASSEMBLY AND MANUFACTURING CONCEPTS INTO NUCLEAR ELECTRIC PROPULSION ARCHITECTURES

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ABSTRACT

NASA is currently investigating nuclear electric propulsion (NEP) for human Mars transport within the space nuclear propulsion portfolio. NEP spacecraft have the following characteristics, they: 1) include very large structures (~100-meter length); 2) are comprised of many components/modules; and 3) have very long lifetimes (e.g., 50 years for fuel rods). Thus, NEP spacecraft can be classified as a "persistent asset," which is any zero-g or planetary surface system that benefits from in-space assembly (ISA) or multiple visits for servicing, repairs, and upgrades. NEP spacecraft will benefit from taking advantage of, and incorporating, in-space servicing, assembly, and manufacturing (ISAM) capabilities in the spacecraft architecture from the onset, enabling system maintenance, repair, and evolution. ISA has a long history of being proposed for, and studied as, a means for achieving large systems in space. More recently, the benefits of ISA have been recognized by NASA, the Department of Defense (DOD), other government agencies, and commercial space companies, and thus, ISAM is being actively pursued at a national level. 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 and mass) that are docked or berthed to other monolithic structures on-orbit to form a larger structure (e.g., the International Space Station [ISS]); 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]). To date, conceptual architecture studies performed for NEP spacecraft capable of human-rated Mars transport have only included a combination of the two previously mentioned strategies. In this paper, ideas will be proposed for infusing ISAM strategies into NEP vehicle architectures that leverage existing and near future technologies and enable the resulting NEP systems to be realized in a more time- and cost-efficient manner.

INTRODUCTION

Nuclear electric propulsion (NEP) spacecraft are persistent assets generally having the following characteristics: 1) they include very large structures (~100-meter length); 2) are comprised of many components/modules, and 3) have very long lifetimes (e.g., 50 years for fuel rods). Thus, SNP spacecraft will likely benefit from servicing, repairs, and upgrades to maintain and expand their capabilities by embracing the persistent asset paradigm and taking advantage of and incorporating in-space servicing, assembly, and manufacturing (ISAM) capabilities in the spacecraft architecture from the onset[1]. In-space assembly (ISA) has been proposed for and studied as a means for achieving large systems in space for decades.[2] More recently, in-space operations have been recognized by NASA, the Department of Defense (DOD), other government agencies and commercial space companies as providing significant impact and benefit to mission design and operations, and thus, ISAM is being actively pursued at a national level.[3]

Conceptual architectural studies of the NEP spacecraft take a modular approach[4] to achieving the final configuration on-orbit. Given the significant advancements in ISAM in the past few decades, the architectures should be reviewed through an ISAM lens, to assess: 1) the state-of-the art (SOA) in assembly

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and integration strategies for large space structures; 2) ISA and ISAM capabilities and technologies that might be applied to a NEP vehicle; 3) the current and projected future work in ISAM and identify options that might be relevant and incorporated into the NEP vehicle, and, to 4) broaden the NEP vehicle architecture and trade space to include options that embrace the increased launch frequency and reduced costs of the rapidly advancing commercial launch market. Although the contents of this paper focuses on technologies for NEP systems, the recommendations for ISAM capabilities/technologies are also applicable to, and provide benefits for, nuclear thermal propulsion (NTP) systems. Thus, ISA/ISAM technologies and capabilities should be included in further research and technology development based on their relevance to SNP.

There are five sections in this paper that focus on: 1) a review of SOA large space structure assembly and deployable structures; 2) ISA technology developments at the NASA Langley Research Center (LaRC); 3) current ISAM capability developments and demonstrations; 4) opportunities for ISAM technology insertion into SNP architectures, and 5) a recommended path forward.

STATE-OF-THE-ART LARGE SPACE STRUCTURES

Past and current strategies for achieving large structures on-orbit have relied largely on two strategies: 1) launching monolithic structures designed to meet launch vehicle requirements for size and mass, that are docked or berthed to other monolithic structures on-orbit to form a larger structure (e.g., the International Space Station [ISS] shown in Fig. 1(a), and; 2) 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] shown in Fig. 1(b) to (e)). Conceptual studies[iv,5] for NEP architectures up until now have only included a combination of the two previously mentioned strategies to achieve an NEP spacecraft capable of human-rated Mars transport. An example for each strategy along with a summary of NEP architecture studies is reviewed in the next section to provide a baseline understanding of the SOA in large, monolithic and deployable space structures.

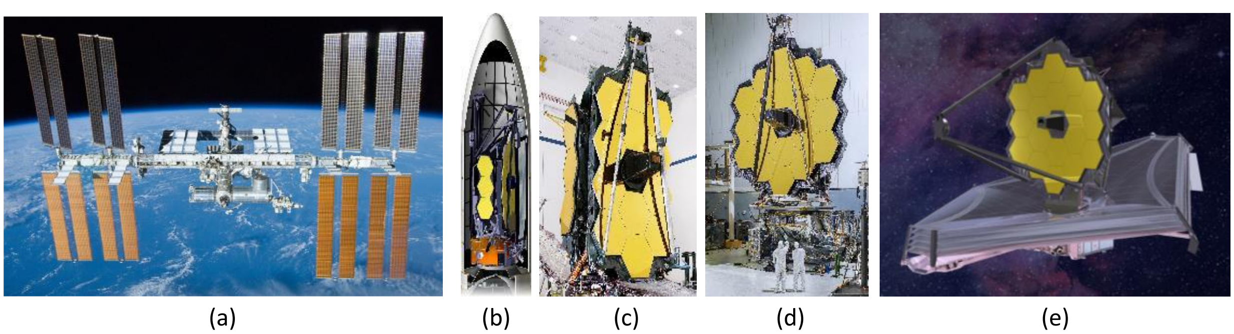

Figure 1. (a) The International Space Station, and the James Webb Space Telescope: (b) packaged for launch in the Ariane V rocket fairing, (c) with the primary mirror folded for launch, (d) with the primary mirror fully deployed, and (e) as envisioned fully deployed on-orbit.

The only technology readiness level (TRL)[6] 9 analog to a NEP system is the ISS.[7] The ISS is an orbiting laboratory assembled from 17 pressurized modules, having four solar panel arrays and measures 109 m in longest dimension (comparable to the NEP system size). The first modules were launched in the late 1990s, and the most recent upgrade occurred in July 2021, when the 17th module (the Multipurpose Laboratory Module-Upgrade (MLM-U or Nauka[8]) docked with the ISS Russian Orbital Segment. In total, over 40 launches were required to transport ISS components and assemble the ISS achieved primarily

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through use of the Space Transportation System (STS) or Space Shuttle, several flights of the Russian Soyuz-U and Proton rockets, and the SpaceX Falcon 9[1]. Over the lifetime of the ISS, the estimated (as of 2010) costs have accrued to approximately $160B[9] and constructing the ISS required dedicated, regular launch services to transport modules, replacement hardware, experiments, and logistics.

Each ISS module was designed to fit within the launch vehicle payload bay (predominantly the STS), built and tested entirely on the ground, and designed to withstand the launch loads experienced during transport to the ISS. The Shuttle Remote Manipulator System (SRMS) or Canadarm[10] was primarily used to berth modules to the existing structure. Russian modules have used the Igla[11] and Kurs[12] systems to dock with the ISS. The ISS assembly relied heavily on astronaut extravehicular activity (EVA) to tele-operate the SRMS, deploy solar arrays, and connect elements. NASA and partners are planning to follow a similar strategy for assembling the Lunar Gateway with the anticipated seven modules being assembled primarily by autonomous robots with some EVA support. Targeted launch of the initial Power and Propulsion Element (PPE) and Habitation and Logistics Outpost (HALO) is no earlier than November 2024.[13]

Deployable structures are another strategy for achieving large structures on orbit. Examples of deployable structures,[14] folded origami-style for launch, include antennas, solar arrays, reflectors, instrument masts, and gossamer sails. The JWST[15] represents the current SOA in single-launch, deployable structures, with a 6.5-m diameter primary mirror and a five-layer, kite-shaped deployable sunshield measuring 22 m by 10 m. The JWST launched in 2021, and successfully demonstrated deployment of a complex structure on-orbit. The telescope was designed to fit inside the 5.4-m diameter fairing of an Ariane V launch vehicle. A total of 178 release mechanisms all had to deploy successfully to realize the operational JWST, highlighting the incredibly complex deployment sequence required. The deployment period was often referred to as “two to three weeks of terror” due to the high number of single-point failure opportunities. Approximately $10 billion dollars[16] has been invested in the JWST (including design, build, test, launch, commission, and five years of operation) since development started in 1996. The project had numerous schedule delays, cost overruns, and went through a major redesign in 2005. A significant portion of development time was dedicated to the packaging of the JWST for launch and designing and testing of reliable deployment mechanisms to achieve the precise structural stability requirements for an optical instrument.

The Mars Transportation Assessment Study (MTAS)[iv, v] completed by the Compass Team at NASA Glenn Research Center (GRC) in 2012 evaluated the design of advanced SNP systems including a NEP-chemical propulsion system for human Mars transport. The study assumed the launch of multiple single large elements (including the nuclear power/electric propulsion module, xenon interstage, habitat, and chemical stage) as well as a deployable radiator system which would all be assembled to complete the full spacecraft. The resulting complete NEP/chemical vehicle is approximately 100 m in length (similar size to the ISS). To transport elements to the nuclear-safe low Earth orbit (1100 km) for assembly, this configuration relies on two space launch system (SLS) launches, two Starship launches and five Super Heavy Falcon 9 launches. All elements are independent, free-flying spacecraft that can dock and undock as needed, using autonomous rendezvous and docking. Deployable structures would be used for the radiators and boom to provide approximately 50 m of separation between the reactor element and electronics. Element aggregation requires making power connections (low power, <10 kW) as well as Xenon fluid connections across the docking interface. Many different interface types (electrical / fluid / gas / mechanical) are required for NEP vehicle integration, which presents challenges for assembly. Verification and maintenance of interface connections are key to credible mission reliability.

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[1]Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the test hardware. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified equipment is the best available.

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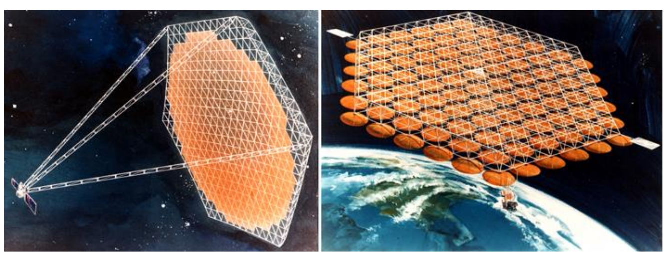
The strategies described in this section have been the standard during the past 30+ years for achieving large structures in space, including NEP vehicle architectures. New NEP vehicle architectures that embrace and leverage ISAM/ISA capabilities and technologies have the potential to increase the vehicle performance while reducing program schedule, cost, and risk.

DEVELOPMENT OF IN-SPACE ASSEMBLY TECHNOLOGY AT LARC

In this section, a brief summary is provided of the extensive set of integrated ISA and ISAM technologies and expertise that have been developed and is resident at LaRC.[17] Complementary capabilities in robotic servicing and automation/robotics are being developed at other NASA Centers, other government agencies and commercial space companies which will be summarized in the next section.

MODULAR STRUCTURES AND STRUCTURAL ASSEMBLY OPERATIONS

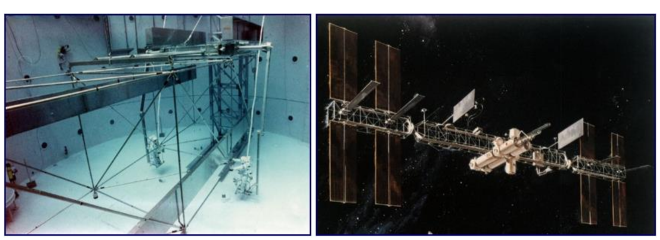
Since the 1960s, NASA has investigated space missions which require structures that are considerably larger than what can fit inside available launch vehicle payload shrouds and, thus, can only be achieved using ISA. These space structures include large support trusses for orbiting space stations, reflectors for deep-space science and earth environmental studies, and large spacecraft for manned missions to Mars and the Moon. Two early examples are shown in Figure 2.



(a) (b)

Figure 2. Early NASA Concept for a (a) large space reflector and (b) communication satellite.

LaRC ISA efforts began in the early 1980s investigating Space Station Freedom (SSF) assembly using astronaut extra vehicular activity (EVA) (Fig. 3). Extensive research and development resulted in validated structural and assembly infrastructure hardware as well as efficient assembly operations concepts. Two other important outcomes validated by the work were: 1) the ability to accurately predict the final (as-built) structural performance, and 2) the assembly efficiency achieved by co-designing the



(a) (b)

Figure 3. Five-meter SSF cubic truss (a) during ground demonstrations at the zero-g facility at Marshall Space Flight Center and (b) as envisioned as the SSF backbone.

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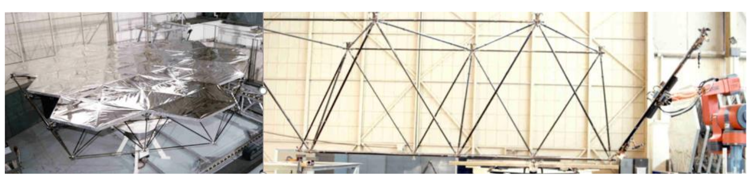
structural concept and assembly approach while including the capabilities of the agents and infrastructure involved in the assembly.

The LaRC SSF truss hardware versatility was demonstrated by successfully scaling the 5-cm diameter hardware down to 2.54-cm diameter and using that hardware for two ISA telescope aperture support truss applications. The first application involved designing, fabricating, and assembling a 14-m diameter offset parabolic radiometer (Fig. 4) reflector support truss (and associated assembly tools) that was based on a telescope concept developed during the Large Deployable Reflector program.[18] The assembled truss accurately matched the offset parabolic geometry of the 20-m mirror surface. In the second application, a 2-ring curved tetrahedral truss, 4 m in diameter was assembled, with the assembled structure achieving a measured root-mean-square (RMS) surface precision of ~ 0.0719 mm.

The LaRC Automated Structures Assembly Laboratory (ASAL) developed automated approaches for truss structure assembly[19] in the mid-1990s. A planar tetrahedral truss structure, consisting of 102 structural elements, and covered with 12 simulated telescope reflector panels, was assembled using a supervised autonomy approach (Fig. 5). The same system and hardware were also used to assemble a linear beam, illustrating the versatility of the hardware and software system. Thus, with a small set of common elements, building a variety of structural geometries is possible. While the primary focus of the research was on automated assembly, the resulting 102-member structure achieved an RMS surface accuracy of ~0.14 mm.[20]

Figure 4. Astronaut assembled 14-m precision segmented reflector truss.



(a) (b)

Figure 5. Truss structures assembled in the ASAL: (a) a primary reflector and (b) the backbone truss.

For large space telescopes, one of the most challenging components to assemble is the large primary aperture, which must provide a stable wave front to the instruments with nanometer precision over 10's of hours of observation.[21] LaRC recently developed the TriTruss[22] structural module (Fig. 6) to enable efficient robotic ISA, high structural efficiency, and high precision for hexagonal topologies including aperture support and metering structures. The TriTruss is a generic modular component relevant to multiple persistent platform applications.

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Astronauts and robots are two types of agents typically used to perform ISAM operations. The Assembly Concept for Construction of Erectable Space Structures (ACCESS, Fig. 7) experiment was launched on the Orbiter Atlantis in 1985.[23] The objectives of ACCESS were to: 1) evaluate an assembly line technique for effective use of astronauts as space construction workers; 2) provide on-orbit data to correlate with assembly rates and techniques developed in neutral buoyancy simulations; 3) gain on-orbit EVA construction experience, and 4) evaluate assembly, handling, repair, and maintenance of a large space structure in support of SSF development. All of these objectives were successfully accomplished on the flight.

Figure 6. Assembly of TriTruss collapsible modules.

A Mobile Transporter (MT) concept, based on previous work-station construction fixtures, was developed as an EVA aid for SSF assembly. The SSF truss was to be assembled out of the Space Shuttle cargo bay using the MT as a construction base. To demonstrate this concept, LaRC developed a 1-g version of the MT and evaluated 1-g and simulated 0-g assembly of the 5-m bay SSF truss structure in 1988 (Fig. 8).

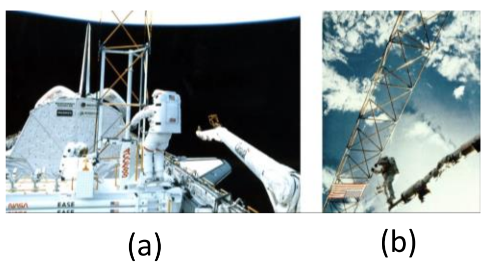

Figure 7. ACCESS Shuttle flight experiment showing two views of EVA Assembly: (a) an astronaut assembling the truss and (b) the assembled structure.

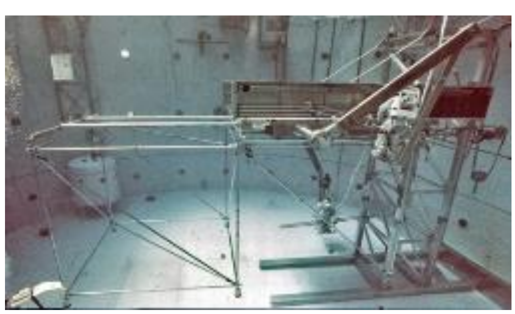

Figure 8. MT used for astronaut positioning in neutral buoyancy testing.

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The Tendon-Actuated Lightweight In-Space MANipulator[24] (TALISMAN) is a new robotic agent for performing long-reach operations. This long-reach arm uses a series of tension members (nominally cables) for both structural stiffening as well as joint actuation. The TALISMAN arm is depicted in Figure 9 grappling a spacecraft and maneuvering the spacecraft within reach of small dexterous robotic arms. Compared to state-of-the-art in-space manipulators, such as the SRMS and the Space Station Remote Manipulator System (SSRMS), a TALISMAN with equivalent stiffness in the plane of the cables provides an order of magnitude reduction in mass and nearly an order-of-magnitude reduction in packaging volume.

(a) (b) (c)

Figure 9. TALISMAN: (a) depiction in space, (b) ground test on a flat floor, and (c) manipulated back on itself.

The most recent ISAM activity at LaRC, Precision Assembled Space Structures (PASS),[25] will develop and demonstrate (in the laboratory) the technologies required to autonomously assemble modular, high-precision and high-stiffness structural modules to achieve a 20-meter diameter offset parabolic primary aperture (Fig. 10). PASS will use TriTruss structural modules (Fig. 6) that support compact packaging and can be deployed from their packaged state autonomously using a robotic arm. Then two robotic arms will cooperatively and autonomously position and assemble the TriTruss modules to complete a three-ring aperture. Integrated modeling and simulation will be used to plan the sequence of operations and then receive sensor data feedback to validate successful assembly.

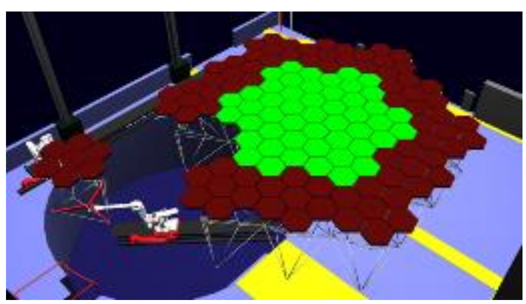

Figure 10. Twenty-meter diameter primary aperture assembly simulation for the PASS project.

AUTONOMY AND ROBOTICS RESEARCH

NASA LaRC has a long and rich history of developing, launching, and operating complex automated systems. Applying this extensive knowledge and experience will be critical for achieving an integrated ISAM capability. Autonomy often involves a multi-objective decision-making problem that has uncertain or incomplete information. Complex decision-making in real-world systems is often intractable because it requires repeated expensive high-fidelity function evaluations. Alternatively, optimization with

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low-fidelity surrogates may not yield practical results. LaRC has developed rigorous optimization methods using variable-fidelity models that yield high-fidelity results with reduced computational cost. Quantifying complex system trustworthiness requires practical system operational risk estimation at all scales. Risk estimation, in turn, is a function of system uncertainties. LaRC is developing comprehensive methods to synthesize and quantify uncertainties during system operations.

Assembly agents must know their own position and orientation (their state) with respect to a global coordinate system as well as the relative position and orientation of local objects, such as assembly components and other assembly agents. Successful solutions to state estimation require metrology, sensing, and situational awareness (SA). Perception is a foundational component of SA: perception is the ability to recognize and classify objects of interest such as structural modules, assembly joints/nodes, or other agents. LaRC has theoretical and practical expertise with image recognition systems, convolutional neural networks (CNN), fiducial markers, and radio frequency identification (RFID). A technique developed at LaRC to detect a TriTruss from point cloud data coming from a three-dimensional (3-D) camera is illustrated in Figure 11 by comparing data with known geometric models. In addition to awareness of the world around them, assembly agents must be able to monitor their health and status to reduce the reliance on human operators. LaRC has developed anomaly detection for flight system telemetry streams that could be used to provide this capability.

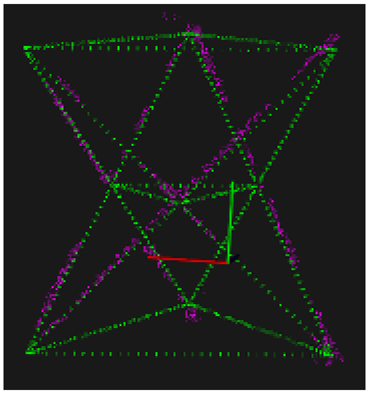

Figure 11. A LaRC developed technique enables TriTruss detection from point cloud data. The green points are a discretized computer aided design (CAD) model of the TriTruss, and the pink points are point cloud data from a depth camera. The point cloud data is compared to the CAD model to detect the TriTruss in the environment.

Validation and verification (V&V) can be used to reduce mission risk by providing high-fidelity simulation of assembly operations. V&V for autonomous systems is an unsolved research problem, but will likely combine formal methods, stability margins, and Monte Carlo methods, followed by software- and hardware-in-the-loop testing and evaluation (T&E). LaRC has in-house mixed-reality modeling and simulation testbed experience that enables these methods and approaches to be implemented in a multi-agent distributed framework. An example of a distributed simulation is shown in Figure 12, where hardware is located in one LaRC facility and the space environment is generated in a simulation in a different facility across the Center.

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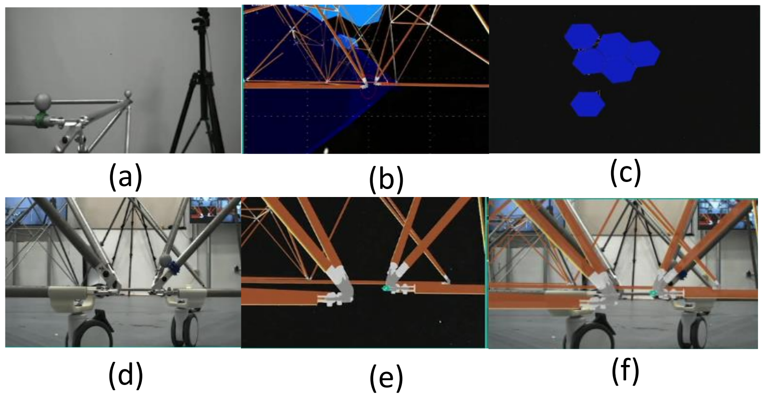

Figure 12. Mixed-reality hardware-in-the-loop simulation for in-space assembly test and evaluation: (a) TriTruss hardware, (b) simulation of joining of two TriTruss modules, (c) top view of primary mirror truss assembly, (d) laboratory test of joining two TriTruss modules, (e) simulation view of two TriTruss modules, and (f) simulation view overlaid over laboratory test view.

CURRENT AND FUTURE DEMONSTRATIONS OF ISAM CAPABILITIES

Space operations are at the brink of a paradigm shift enabled by ISAM, and backed by strong interest from NASA, DOD, other government agencies, and commercial partners. In the near-term (next 5 to 10 years), there are planned in-space demonstrations of autonomous ISAM capabilities. The in-space demonstrations will build confidence and further validate the benefits of embracing the persistent asset paradigm for future space operations.

The most well-known in-space assembled structure, the ISS, consists of modular components that were designed and tested on Earth and assembled on-orbit using a combination of tele-operated robotic agents and astronaut EVA, as described in the first section. A similar assembly strategy is proposed for the Lunar Gateway.[26]

In-space manufacturing (ISM) and ISA technology demonstrations are an integral part of the on-orbit servicing, assembly, and manufacturing (OSAM) 1 and 2 missions. OSAM-2,[27] launching no earlier than 2024, will use the Redwire Archinaut One, a versatile, in-space, robotic, precision manufacturing and assembly system, to autonomously 3-D print a backbone truss and assemble solar arrays for a small satellite (smallsat) (Fig. 13(a)). OSAM-1,[28] launching in 2024, is planned to first refuel Landsat-7 (Fig. 13(b)) and then demonstrate the Tethers Unlimited ISM of a 10-meter lightweight composite beam. In addition, the Space Infrastructure Dexterous Robot (SPIDER) payload will assemble a functional, 3-meter Ka-band communications antenna from seven modular elements (Fig. 13(c)). Coupled with the ISM demonstration, SPIDER will verify the ability to construct large space structures on-orbit.

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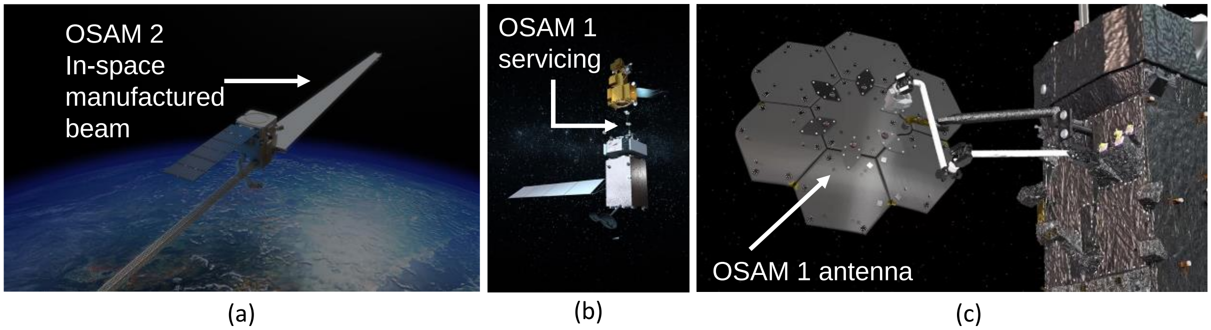

Figure 13. (a) OSAM-2 demonstrates in-space manufacturing of a beam. OSAM-1 demonstrates (b) servicing of a satellite and (c) assembly of an antenna.

Satellite servicing, mission extension tugs, and relocation services can be used to transport spacecraft components to assembly orbits. Northrop Grumman has several commercial servicing vehicles,[29] including the Mission Extension Vehicle (MEV), and the Mission Robotic Vehicle (MRV), provide life extension and evolution to existing satellites. MEV-1 (February 2020) and MEV-2 (April 2021) demonstrated successful docking with two Intelsat geostationary Earth orbit (GEO) communication satellites, respectively. MEV-1 also demonstrated relocating the target satellite from GEO to a graveyard orbit, where the docking occurred, and back to GEO to continue its mission. DARPA and Northrop Grumman have partnered to use the MRV[30] as part of the Robotic Servicing of Geosynchronous Satellites (RSGS) program, which will offer servicing, augmentation, assembly, inspection and relocation services to clients. Astroscale entered the satellite servicing arena with the acquisition of Effective Space Solutions[31] in June 2020 and intends to offer GEO services by 2024. With the significant number of commercial entities currently offering satellite servicing and relocation options, it is not unreasonable to assume that commercial relocation tugs will be readily available during the assembly of a NEP system.

At the heart of all ISAM capabilities is autonomous operations of robotic agents. Focused projects like Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS),[32] Assemblers,[33] and the Multi-Agent Clusters for Persistent Observations from Space (MACPOS)[34] are developing the autonomous agents that will execute ISAM operations. ARMADAS focuses on developing hardware and software for “builder robots” which will autonomously assemble large structures such as habitats, large antenna arrays and spaceports, and will also develop a small satellite-sized payload that autonomously unpackages and assembles into a functioning system. The Assemblers project focused on developing modular robots by stacking Stewart platforms in a variety of configurations resulting in autonomous ISA of modular components. MACPOS is focusing on creating and demonstrating proof-of-concept multi-agent dynamic formation management for a fleet of rovers and will advance multi-agent teaming capabilities needed for assembly operations and hand-offs.

A comprehensive ISAM approach establishes an ecosystem concept that has all the capabilities (ISA, maintenance, repair, etc.) that should be considered during 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, will certainly accelerate the TRL of ISAM technologies in the near term. NEP systems will have multiple opportunities to leverage these developments.

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OPPORTUNITIES FOR TECHNOLOGY MISSION INFUSION OF ISAM CONCEPTS INTO SNP ARCHITECTURES

The NEP vehicle architecture has the potential to take advantage of new and innovative ideas that would be supported by ISAM technologies, approaches, and operations concepts. Many ISAM capabilities are currently being developed by commercial space companies and these also can be leveraged to reduce the time and cost of system development. Examples of commercial ISAM capabilities currently being developed, and described previously in this report, include spacecraft life extension (MEV, etc.); spacecraft orbital transfer (from low Earth orbit [LEO] insertion to GEO, etc.); space logistics and transfer (including robotic capabilities); and, spacecraft refueling, among others. Given the long lead time before the first potential NEP mission to Mars might take place (late 2030s), it would be appropriate to take advantage of these commercial investments and propose new spacecraft and mission architectures, ideas and solutions that incorporate projected capabilities that are likely to exist 15 years from now. This section will discuss several aspects of current NEP architectures that might be addressed and improved upon with an approach that emphasizes/maximizes ISAM capabilities, and/or ISAM technologies.

The presented NEP architectures rely heavily on using multiple launches of the Space Launch System (SLS) for implementation. There are several risks in assuming use of the SLS. First, there will likely be heavy competition for limited launches. 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. Second, the frequency of launch may not ensure timely assembly of an NEP vehicle on orbit. Even if the Mars mission gets exclusive use of SLS, at one launch per year, a NEP vehicle that requires four (or more) launches to place systems in orbit would result in at least a four-year period to assemble the vehicle. Spacecraft systems on the first launch would have to add four years to their lifetimes to accommodate this build up. Additionally, there are cost and risk aspects to consider. The SLS will be expensive even if only recurring costs are considered in the NEP mission budget. Reliance on a single launch platform poses additional risk to the program. By developing an architecture and vehicle design that incorporates ISAM techniques and capabilities, like those that follow, the program can have a greater degree of flexibility in launch vehicle options and drastically reduce program risk associated with SLS not being available and/or the risk of not being cost competitive.

Designing monolithic large space structures inevitably results in spacecraft that exceed the volume available with current, as well as projected, launch vehicles. The result is increased design complexity to package the structure ‘origami’ style into the launch fairing and 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[35] primary mirror so that it would fit inside the Ariane 5 launch vehicle payload shroud for launch. Given the proposed size of SNP systems and the schedule requiring multiple launches, significant development time will be required to validate the packaging and deployment operations for any large vehicle structures. 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.

NEP architectures use large modules as the basic building blocks (size maximized to fit within an SLS payload shroud). From the architecture descriptions, these modules are independent/self-contained

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free-flying spacecraft which use active docking to assemble themselves into the final vehicle. By incorporating a long-reach robotic manipulator, such as the TALISMAN, into the architecture, the primary means of assembly for these large modules can become berthing (grapple assisted) instead of docking (unassisted). If the module can be berthed, the mass, cost, and complexity of systems such as: propulsion; guidance, navigation and control; attitude control; etc. can be eliminated. Additionally, berthing eliminates potential issues associated with assembly-bots firing maneuvering thrusters near components being assembled. Thus, berthing may lead to less expensive and less complicated modules.

NEP architectures have very complex assembly sequences with some assembly and fueling done in LEO, then transfer to lunar distant high Earth orbit (LDHEO) for more fueling/tank disposal, then a final transfer to near-rectilinear halo orbit (NRHO) with more fueling/disposal and acquisition of the habitation module. In addition, there are chemical stages, nuclear stages, Gateway stops for vehicle checkout, Orion crew and logistics flights; all before departing for Mars. Given that the ISAM capability for orbital transfer is now a reality in the commercial world (at a small scale currently), an architecture could be developed that assumed commercial orbital transfer services are available by 2039 that can accommodate the size and mass of vehicle components making up the NEP spacecraft. This architecture would hire out all orbital transfers, eliminate any LEO assembly, and transport all components to a single assembly location (which would also be the departure location for the Mars mission). Upon return, the spacecraft would arrive at the same departure location, where logistics/transfer services would be hired and waiting to refurbish and refuel the spacecraft.

The current architectures assume that fuel tanks are launched filled and transported to the various assembly orbits. Many launches are required to emplace the necessary fuels for the chemical and NEP elements. Given that the ISAM capability for in-space refueling is rapidly becoming a reality in the commercial world (gas stations in space), an architecture could be developed that assumed commercial in-space fuel tankers are available by 2039 and could be hired to fuel the NEP at its single assembly/departure location. In this case, the architecture could incorporate and use ISAM inflatable pressure vessel (could be habitats or fuel tanks for example) technology and transport all the fuel tanks dry and collapsed to the assembly site. Once integrated with the NEP vehicle, the fuel tankers could be hired and scheduled to arrive and fill all the tanks right before Mars departure. Upon return, fuel tankers could once again be hired to refuel the vehicle for its next flight to Mars.

Proposed NEP architectures exclusively incorporate large components that are in-line and require docking and undocking at various stages of the mission to add or eliminate modules. (The potential advantage of berthing versus docking has been discussed previously). Many spacecraft architectures can benefit from adopting the ISAM/persistent platform layout that incorporates a backbone truss as the main vehicle structure. This backbone truss can be deployed, constructed, or manufactured on site. Mature technologies for large deployable and erectable space structures and robotic in-space assembly have been developed and discussed earlier in this paper. The backbone truss would incorporate standard modular connectors for mechanical, electrical, data and fluid attachments. Utilities are routed through the truss interior, as was done for the STRM truss that was flown twice on the space shuttle. All vehicle subsystems, such as tanks, solar arrays, radiators, etc. are connected to a face of the backbone truss. By including a long-reach TALISMAN in this architecture, all the components can be berthed instead of docked. This approach also eliminates all in-line connections needed in the current architectures to separate linear components (which then become free flyers) at various stages of the mission to allow for removing or adding components.

Current architectures focus on nuclear propulsion technology being developed exclusively for the Mars Mission application. NEP (and/or NTP) should be considered and developed as an independent module/capability for the ISAM system that could be used as soon as they are available. In that sense, NEP

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has many uses and applications besides the Mars exploration mission/vehicle. For example, NEP could be incorporated into planetary science missions thereby decreasing the time the spacecraft takes to reach their destinations; perhaps direct trajectories could replace those that require many planetary fly-bys and build flight heritage in NEP systems prior to human flights. Other government agencies are becoming very interested in persistence, maneuverability, and long duration operations in cis-lunar space. By incorporating nuclear propulsion into the spacecraft and taking advantage of commercially available in-space refueling, nuclear-based, cis-lunar space capabilities could be fielded by other government agencies many years before the Mars mission takes place.

ISAM is recognized at the national level as a priority amongst US government agencies and commercial industry. The ISAM national initiative team, a NASA headquarters led group of researchers and policy makers in ISAM, has developed and recently released Version 1 of the OSAM "State-of-play" database[36] to track SOA OSAM (now ISAM) capabilities and which became available in November 2021. Additionally, Space Technology Mission Directorate (STMD) at NASA is undergoing a road-mapping activity to identify key technology development activities that support the mission and are linked to technology demonstrations, with SNP systems specifically identified under assembly of structures.

POTENTIAL PATHS FORWARD FOR AN IN-SPACE ASSEMBLED NEP SYSTEM

ISAM offers many capabilities and technologies that could lead to new NEP/Mars vehicle architectures that have significant advantages over current concepts. The ideas offered here need to be traded in a study of future NEP vehicle concepts, but architecting a vehicle that maximizes ISAM and leverages the advantages will likely lead to some new configurations and operations concepts that improve on the current state of the art. For example, high thrust/high specific impulse (Isp) systems coupled with gas stations in space[37] yield unlimited mobility for a long duration persistent platform.

An architecture study should be commissioned for the SNP systems that incorporates ISAM principles and evaluates a persistent platform structural design and assembly co-design process from the onset. A similar, high-level study[38] was chartered for an in-space assembled telescope in 2018-2019 to answer the question "when is it worth assembling telescopes in space rather than building them on Earth and deploying them autonomously from a single launch vehicle?" The study showed that for telescopes with primary mirrors larger than 15 m in diameter that ISA is the only feasible option. A similar question could be proposed for SNP systems. In this study, traditional monolithic spacecraft could be compared and evaluated against those developed using in-space assembled/ISAM architectures. Techniques that optimize the nuclear and non-nuclear spacecraft components for a modular architecture and in-space assembly potentially could result in a more versatile and cost-efficient SNP system.

Future projects should include an assessment to determine which components and operations are most beneficial for providing relevant technology demonstrations. Ground demonstrations that leverage existing infrastructure can provide confidence and inform the development of requirements for SNP system assembly. For example, the currently existing autonomy and robotics infrastructure at NASA LaRC, developed for the assembly of a 20-m diameter mirror support truss for an in-space assembled telescope, can be leveraged to assemble a simulated reactor to a backbone truss and radiator assembly for a SNP system. Challenges like fluid line connections and routing can be investigated in the laboratory. High-fidelity simulations of the assembly environment (Fig. 10) can rapidly investigate assembly concept of operations (ConOps). A technology demonstration mission (TDM) could be used to demonstrate and validate autonomous in-space assembly technologies needed for SNP systems.

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Designing the SNP system as a modular ISAM element that could be tested and validated before needed for the Mars mission may also be advantageous. This design would allow the SNP module to be incorporated into a space force or planetary science mission, thus validating the technology for Mars missions while supporting national security and accelerating the cis-lunar economy. Cargo will likely arrive at Mars prior to humans; the cargo spacecraft can be assembled without habitat/crew modules and later augmented. ISAM offers increased versatility to readily evolve systems and make changes late in the design cycle that cannot be accommodated efficiently using traditional means.

CONCUDING REMARKS

In this paper, the opportunities for ISAM technology insertion in SNP architectures, and a recommended path forward are presented as motivated by ISA technology developments at LaRC and current ISAM capability developments and demonstrations. A notional discussion of infusion of ISAM into currently proposed architectures (MTAS) is presented as part of the discussion. Revisiting NEP architectures through an ISAM design lens will improve SOA for nuclear-based spacecraft by reducing design complexity, increasing flexibility in choice of launch vehicle and assembly location, and leveraging current (and future) commercial industry capabilities with the potential to reduce cost, schedule, and risk. Current and past work in large space structure assembly and autonomous systems can be applied to the assembly of large SNP vehicles. Specific to NEP, a radiator module can be designed (like the TriTruss modular unit for the PASS in-space assembled telescope (iSAT) assembly) to be autonomously assembled into the full radiator assembly by robotic agents. This activity would leverage current research work from the PASS project on precision joining techniques, alignment, and autonomous path and motion planning, while addressing challenges specific to the NEP radiator architecture (e.g., autonomous fluid connections and leak checks). Architecture studies can leverage currently occurring and upcoming technology demonstrations by commercial industry (e.g., gas stations in space, ISAM demonstrations, orbital tugs, etc.) to generate new architectural concepts for SNP vehicles. ISAM is a paradigm shifting strategy for space operations that will provide additional flexibility, reduced cost, and complexity to SNP vehicles. Further, taking an ISAM approach to SNP vehicles will ensure reusability of the spacecraft because the onboard robotics used to assemble the vehicles can be used to service and evolve during the lifetime. Considering the estimated cost of SNP vehicles exceeds several billion dollars, reusability should be included in the mission ConOps from the onset.

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REFERENCES

[1] Doggett, W. R., et. al., “Persistent Assets in Zero-G and on Planetary Surfaces: Enabled by Modular Technology and Robotic Operations,” 2018 AIAA SPACE and Astronautics Forum and Exposition, Orlando, FL, 17 – 19 September 2018, https://doi.org/10.2514/6.2018-5305.
[2] Belvin, W. Keith, Dorsey, John T., and Watson, Judith J., “Technology Challenges and Opportunities for Very Large In-Space Structural Systems,” International Symposium on Solar Energy from Space, Toronto, Canada, 8-10 September 2009.
[3] Arney, D., et. al., “Space Science and Technology Partnership Forum: In-Space Assembly Data Collection and Analysis,” 2018 AIAA SPACE and Astronautics Forum and Exposition, Orlando, FL, 17 – 19 September 2018, https://doi.org/10.2514/6.2018-5308.
[4] Mason, L., et. al., “Nuclear Power concepts and Development Strategies for High-Power Electric Propulsion Missions to Mars,” Nuclear Technology, 2022, pp. 1-15, https://doi.org/10.1080/00295450.2022.2045180.
[5] Oleson, S.R., et. al., “Compass Final Report: Nuclear Electric Propulsion (NEP)-Chemical Vehicle 1.2,” NASA Technical Memo No. CD-2020-181, September 2021.
[6] Tzinis, I., “Technology Readiness Level,” https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level, Published: October 28, 2012. Accessed: October 24, 2022.
[7] Anon., “International Space Station,” https://www.nasa.gov/mission_pages/station/main/index.html, Accessed: October 5, 2022.
[8] David, L., “Russia’s New Nauka Module Readied for Launch to International Space Station,” https://www.space.com/russia-nauka-space-station-module-readied-for-launch, Published: July 12, 2021. Accessed: October 5, 2022.
[9] Anon., “How much does it cost?” https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/How_much_does_it_cost Published: November 6, 2010. Accessed: October 5, 2022.
[10] Anon., “About Canadarm,” https://www.asc-csa.gc.ca/eng/canadarm/about.asp, Accessed: October 5, 2022.
[11] Grahn, S., “The IGLA Radio System for Rendez-vous and Docking,” http://www.svengrahn.pp.se/histind/RvDRadar/IGLA.htm, Accessed: October 5, 2022.
[12] Askins, B., and Card, M., "NASA Automated Rendezvous and Capture Review: Executive Summary," NASA, TM-108597, November 1991.
[13] Anon., “NASA, Northrop Grumman Finalize Moon Outpost Living Quarters Contract,” https://www.nasa.gov/press-release/nasa-northrop-grumman-finalize-moon-outpost-living-quarters-contract, Published: July 9, 2021. Accessed: October 5, 2022.
[14] Kiper, G., and Soylemez, E., "Deployable Space Structures," 2009 4th International Conference on Recent Advances in Space Technologies,” IEEE, 11-13 June 2009, https://10.1109/RAST.2009.5158183.
[15] Anon., “James Webb Space Telescope,” https://jwst.nasa.gov/content/webbLaunch/index.html, Accessed: October 5, 2022.
[16] Feinberg, L., et al., "Breaking the Cost Curve: Applying Lessons Learned from the James Webb Space Telescope Development," Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave. Vol. 10698. International Society for Optics and Photonics, https://doi.org/10.1117/12.2309661.
[17] Watson, J. J., et. al., “A History of Astronaut Construction of Large Space Structures at NASA Langley Research Center,” IEEE Aerospace Conference Proceedings, Vol. 7, 2002, https://10.1109/AERO.2002.1035334.
[18] Bush, Harold G., et al., “Design and Fabrication of an Erectable Truss for Precision Segmented Reflector Application,” Journal of Spacecraft and Rockets, Vol. 28. No. 2., 1991, pp. 251-257, https://doi.org/10.2514/3.26238.
[19] Doggett, W.R., “A Guidance Scheme for Automated Tetrahedral Truss Structure Assembly Based on Machine Vision,” NASA TP-3601, November 1996.
[20] Wu, K. C. et.al., “Analytical and Photogrammetric Characterization of a Planar Tetrahedral Truss,” NASA Technical Memorandum 4231 (1990).

[21] Edberg, Stephen J., et. al., "SIM PlanetQuest Science and Technology: A Status Report," Techniques and Instrumentation for Detection of Exoplanets III, Vol. 6693, International Society for Optics and Photonics, 2007, https://doi.org/10.1117/12.732728.
[22] Doggett, W.R., et al., "TriTruss: a New and Novel Structural Concept Enabling Modular Space Telescopes and Space Platforms," 70th International Astronautical Congress (IAC), Washington D.C., USA, 21-25 October 2019.
[23] Heard, JR, W., et. al., "Results of the ACCESS Space Construction Shuttle Flight Experiment," 2nd Aerospace Maintenance Conference. 1986, https://doi.org/10.2514/6.1986-1186.
[24] Doggett, W. R., et. al., "Development of a Tendon-Actuated Lightweight In-Space Manipulator (TALISMAN)," Presented at the 42nd Aerospace Mechanisms Symposium, NASA Goddard Space Flight Center, 14-16 May 2014.
[25] Doggett, W. R. et. al., "Supervised Autonomous Assembly to Create and Evolve Persistent Assets," Presented at the AIAA SCITECH 2022 Forum, San Diego, CA & Virtual, 3-7 January 2022, https://doi.org/10.2514/6.2022-2076.
[26] Clark, S., "NASA's Lunar Gateway: The Plans for a Permanent Space Station that will Orbit the Moon," https://www.sciencefocus.com/space/nasa-lunar-gateway/ Published: February 26, 2022. Accessed: October 5, 2022.
[27] Anon., "On-Orbit Servicing, Assembly, and Manufacturing 2 (OSAM-2)," https://www.nasa.gov/mission_pages/tdm/osam-2.html, Accessed: October 5, 2022.
[28] Anon., "OSAM-1: Robotic Servicing Mission," https://nexis.gsfc.nasa.gov/osam-1.html, Accessed: October 5, 200.
[29] Anon., "Space Logistics," https://www.northropgrumman.com/space/space-logistics-services/, Accessed: October 5, 2022.
[30] Anon., "DARPA Picks Northrop Grumman as its Commercial Partner for Satellite Servicing Program," https://spacenews.com/darpa-picks-northrop-grumman-as-its-commercial-partner-for-satellite-servicing-program/, Published: March 4, 2020. Accessed: October 5, 2022.
[31] Anon., "Astroscale U.S. Enters the GEO Satellite Life Extension Market," https://astroscale.com/astroscale-u-s-enters-the-geo-satellite-life-extension-market/, Published: June 3, 2020. Accessed: October 5, 2022.
[32] Costa, A., et. al., "Algorithmic Approaches to Reconfigurable Assembly Systems," 2019 IEEE Aerospace Conference, Big Sky, MT, 2-9 March 2019, https://10.1109/AERO.2019.8741572.
[33] Cooper. J. R., Neilan, J.H., Mahlin, M.K., and White, L.M., "Assemblers: A Modular, Reconfigurable Manipulator for Autonomous In-Space Assembly," AIAA ASCEND 2020, Virtual, 16-18 November 2020, https://doi.org/10.2514/6.2020-4132.
[34] Vaughan, M.P., et. al., "Towards Persistent Space Observations through Autonomous Multi-Agent Formations," AIAA SCITECH Forum, San Diego, CA & Virtual, 3-7 January 2022, https://doi.org/10.2514/6.2022-2074.
[35] Anon., "NASA's James Webb Space Telescope Full Mirror Deployment a Success," https://www.nasa.gov/feature/goddard/2020/nasa-s-james-webb-space-telescope-full-mirror-deployment-a-success, Published: March 31, 2020. Accessed: October 5, 2022.
[36] Arney, D., et al., "On-orbit Servicing, Assembly, and Manufacturing (OSAM) State of Play," 2021.
[37] Anon., "Gas Stations in Space," https://www.orbitfab.com/ Accessed: October 5, 2022.
[38] Anon., "NASA in-Space Assembled Telescope (iSAT) Study," https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/, Published: August 31, 2020. Accessed: October 5, 2022.