State of the Profession Considerations: NASA Langley Research Center Capabilities and Technologies for Large Space Structures, In-Space Assembly and Modular Persistent Assets

William (Bill) R. Doggett, John T. Dorsey
Structural Mechanics and Concepts Branch
NASA Langley Research Center, Hampton, VA, 23681, USA

David S. Kang
Analytical Mechanics Associates, Inc, Hampton, VA 23666

1. Introduction

The astrophysics community is now at a tipping point where they can conceive of the next space-based observatory sharing key characteristics of Earth-based observatories:

1) Very large apertures (greater than 15 meters),
2) Very long life times (greater than 50 years), and
3) Cost efficiency (instrument upgrades, expanding observatory capabilities, servicing and repairs).

These characteristics will be made possible by embracing the Persistent Asset (PA)[1] paradigm when architecting the next astrophysics space-based observatory. In order to increase performance, and greatly reduce the risk, cost and implementation schedule for future astrophysics observatories, concepts that embrace the PA attributes and use the capabilities of Orbital Servicing, Assembly and Manufacturing (OSAM) are being studied.[2] A study that developed and assessed an in-Space Assembled Telescope (iSAT) architecture has recently been completed and is being submitted to the Astrophysics Decadal Survey.[3] Members of the iSAT study team included subject matter experts in all aspects of telescope science and instruments, spacecraft subsystems, in-space assembly, robotics and spacecraft design: the participants represented many NASA Centers and commercial space companies. The iSAT study established the attributes and extensive benefits associated with architecting a large-diameter in-space assembled observatory and the feasibility for implementation in the next decade.

In-Space Assembly (ISA) has been proposed for and studied as a means for achieving large systems in space for decades.[4] More recently, additional benefits of in-space operations have been recognized by NASA, other government agencies and commercial space companies and thus, OSAM is being actively pursued at a national level.[5] As a result, space operations are on the cusp of a revolutionary new operational paradigm that leverages modular systems and repeated robotic visits to “Persistent Assets”, where these visits can be used for assembly, expansion, servicing, repairs, reconfiguration, and upgrades of those assets.[6] A new in-space observatory architecture and design that embraces the PA paradigm will benefit from major changes to traditional single-launch deployable spacecraft requirements[7], some of which include:

1) with frequent and inexpensive launches, minimum mass will no longer be the primary driver and system mass increases (to enhance robustness for example) can be traded to reduce mission cost (design, development and fabrication), risk (increased structural margins, carry spares) and testing.
2) by modularizing the observatory to package for a specific launch vehicle class, the launch volume and payload shroud dimensions will no longer be a primary driver because multiple launches (from potentially different launch providers) can be economically procured.
3) components may be arranged to optimize packaging over multiple launches with few operational constraints limiting their final location on the observatory.
4) by modularizing the observatory, more efficient launch packaging schemes can be used that minimize the impact of launch loads on individual module designs so that launch loads are no longer a significant driver. The observatory can thus be designed and optimized for in-service (zero-g) loads reducing mass. The mass saved by the additional design freedom may be greater than any mass increase associated with modularizing the system.
5) with regular and multiple visits to the observatory, it can be serviced, repaired, have instruments enhanced, upgraded or reconfigured as new technology becomes available or mission needs change, enabling not only a pay-as-you-go approach, but also an in-space observatory with lifetime and scientific impact measured in decades.

The purpose of this white paper is to provide the Astrophysics Decadal Survey community a brief summary of the extensive technology and expertise that has been developed at the NASA Langley Research Center (LaRC) in the areas of Large Space Structures (LSS) and ISA.[8] With this background, it is hoped that the astrophysics community will become confident enough to embrace and consider ISA and servicing as a viable option for architecting the next observatory and include LaRC in that partnership. Although this paper will focus on the extensive set of LaRC capabilities and technologies, note that extensive complementary capabilities in robotic servicing and automation/robotics are being developed at other NASA centers, other government agencies and commercial space companies.

2. Structural Concepts for Telescopes: Past Efforts and Significant Achievements

Since the 1960s NASA has considered space missions which require structures that are considerably larger than what can fit inside available launch vehicle payload shrouds. These space structures include large support trusses for orbiting space stations, reflectors for deep-space science studies, reflectors for earth environmental studies, and large spacecraft for manned missions to Mars and the Moon. Two examples of early science spacecraft architectures are shown in Figure 1; a concept for a large space reflector, and a communications satellite. With recent advances in lightweight structures, assembly technologies and robotics, and with experience gained from assembling the International Space Station (ISS) and servicing missions to Hubble Space Telescope (HST), NASA is again evaluating in-space assembly and construction techniques for large space structures.

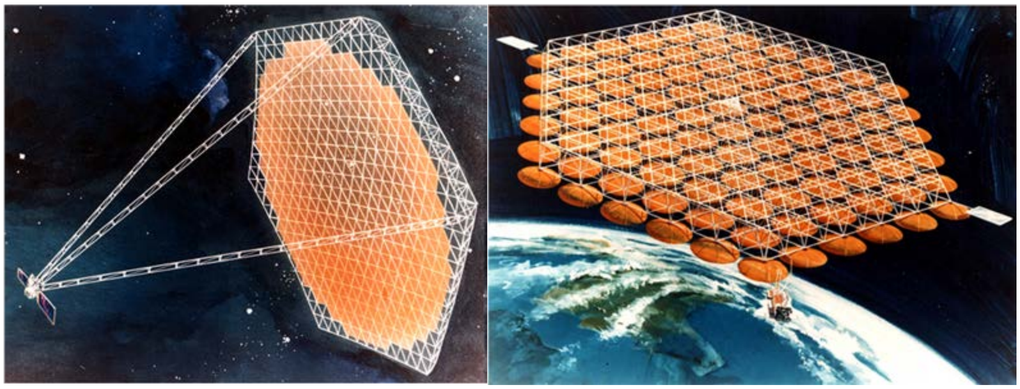

Figure 1. Early NASA Concept for a Large Space Reflector and Communications Satellite.

5-meter Space Station Cubic Truss – Metering/Instrument Support truss

Efforts in ISA began within LaRC in the early 1980s investigating assembly of the Space Station Freedom (SSF), Figure 2, using astronaut Extra Vehicular Activity (EVA). Two important outcomes validated by the work were: 1) the ability to accurately predict the final (as-built) structural performance a priori, and 2) the assembly efficiency achieved by co-designing the structural concept and assembly approach while including the capabilities of the agents and infrastructure involved in the assembly[9]. The SSF effort resulted in detailed design, fabrication and testing for several unique and significant components including: 1) an erectable truss node and joint (connector) system used for ISA of the large (5-meter bay size) SSF backbone truss; 2) a mobile transporter, capable of transporting agents around all 4 sides of the SSF using an efficient system that engaged guides on the SSF backbone truss; 3) efficient rotary joints (called the alpha joint) capable of orienting large solar arrays; and 4) a unique approach to installing cable harnesses during assembly.

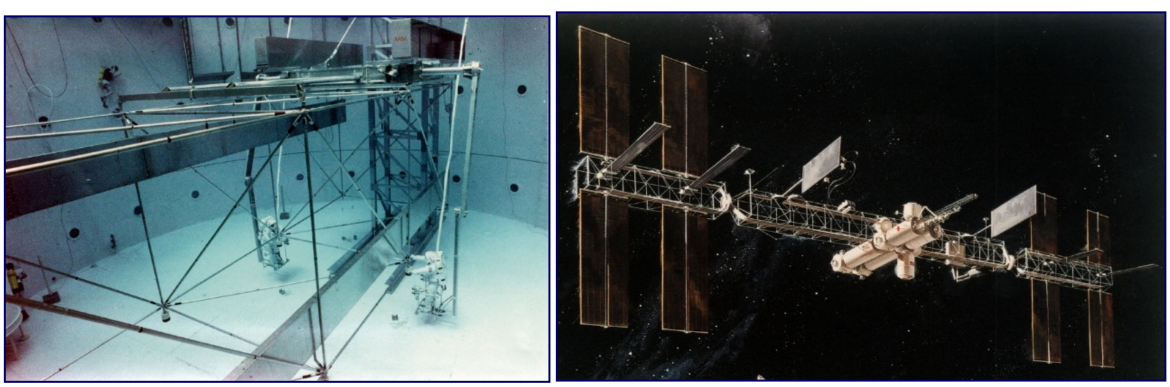

Figure 2. 5-meter Space Station Cubic Truss.

Precision Segmented Reflector (PSR) Tetrahedral Truss

The versatility of the LaRC truss hardware was demonstrated by scaling the 2-inch diameter SSF truss hardware down to 1-inch diameter hardware for application to telescope aperture support trusses. In addition to SSF, a series of significant EVA assembly activities were undertaken using this one-inch diameter joint system. Two of these activities are highlighted here. The first involved the design, fabrication and assembly of a 14-meter diameter offset parabolic radiometer (Figure 3) reflector support truss (and associated assembly tools) that was based on a telescope concept developed during the Large Deployable Reflector program[10]. The assembled truss geometry successfully matched the offset parabolic shape of the 20-meter mirror surface. An erectable ISA approach was selected because the critical performance requirements for diameter and stiffness could not be met using a deployable. Second, the precision segmented reflector, a 2-ring curved tetrahedral truss, 4 meters in diameter was assembled and tested. The assembled structure achieved a measured surface precision of ~ 0.0719 mm (0.00283 inches) root-mean-square (RMS).[10, 11] This assembly precision is nearly independent of diameter if the same number of truss rings are used. Thus, using 3-meter long structural elements instead of 1-meter elements results in a 12-meter diameter structure with similar accuracy and precision.

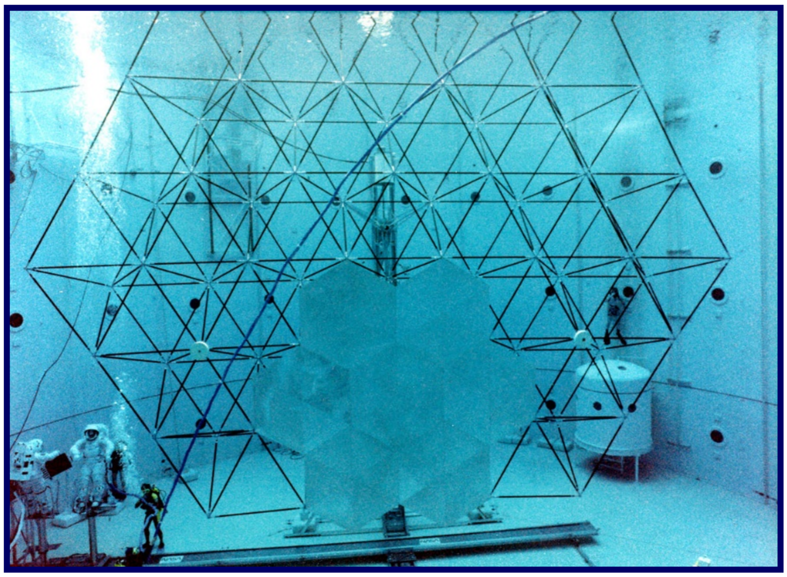

Figure 3. Astronaut Assembled 14m Precision Segmented Reflector Tetrahedral Truss.

Supervised Automated Assembly of an 8-meter Tetrahedral Truss

The LaRC Automated Structures Assembly Laboratory (ASAL) developed automated approaches to truss structure assembly, including: automated path planning, robotic techniques and tools for assembling observatory structures (aperture and metering trusses) and installing mirror (hexagonal) panels.[12] A planar tetrahedral truss structure, consisting of 102 approximately 2-meter long structural elements covered with 12 simulated telescope reflector panels was assembled using a supervised autonomy approach (Figure 4). The same supervisory system and hardware was used to build a beam, illustrating the versatility of the hardware and software system. Thus, with a small set of common elements, it is possible to build a variety of structural geometries ranging from planar structures and one-dimensional beams to complete three dimensional systems with multiple truss levels and appendages. While the main focus of the research was on automated assembly, the resulting structure (composed of 102 members) achieved an RMS surface accuracy of approximately 0.14 mm (0.00551 inches).[13]

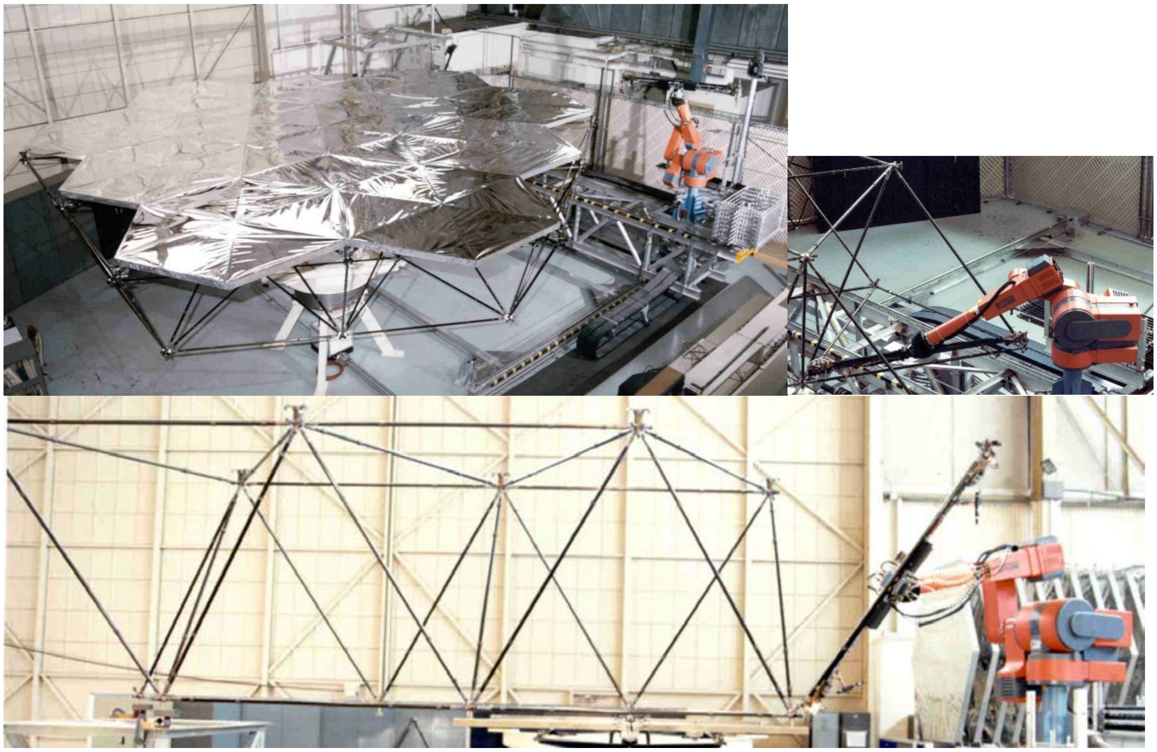

Figure 4. Automated Structures Assembly Laboratory.

Tri-Truss - Main aperture mirror raft/hexagonal panel support

For a large space telescope, one of the most challenging components to assemble is the large primary mirror, which must provide a stable wave front to the instruments with nanometer precision over 10's of hours of observation[14]. In order to enable efficient ISA of observatory aperture support and metering structures, LaRC recently developed the tri-truss structural module. Figure 5 depicts an individual tri-truss module as well as an assembly of tri-truss modules to form the mirror support structure on the left of center. On the right of center in the figure one of several packaging options for the tri-truss is depicted. Depicted on the left of Figure 5, a cluster of seven tri-truss modules, where each module supports a preattached mirror segment, are assembled to form the mirror surface. The modular tri-truss structural system achieves high structural efficiency and precision by mimicking the response of a honeycomb panel, with stiff top and bottom layers connected by core structural members that provide shear stiffness through the thickness. Because of its mass efficiency, modularity, capability for compact packaging for launch and compatibility with automated ISA capabilities, the tri-truss has been baselined as the observatory support structure in the iSAT Study. Currently, hardware has been designed, fabricated and is being used in automated module assembly tests at LaRC.

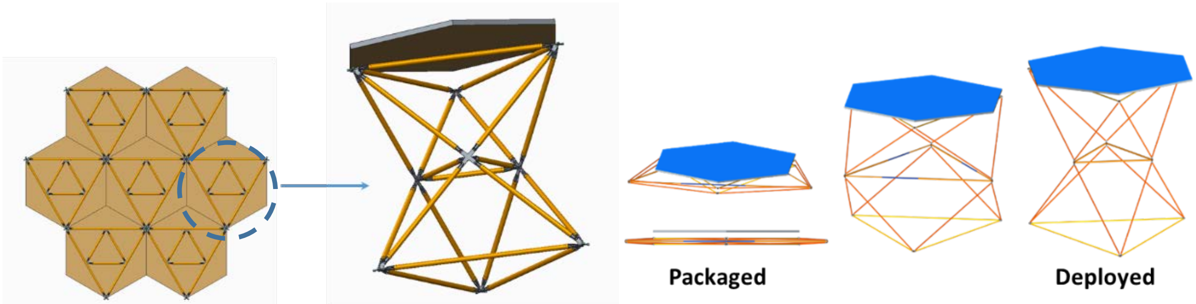

Figure 5. Assembly of Tri-Truss Collapsible Modules.

3. Supporting Agents and Infrastructure, Initial Elements in the ISA Toolbox

Astronauts and robots are the two agents typically used to perform ISA functions. Understanding and quantifying the capabilities and limitations of the agents is necessary to architect and design systems that leverage large-scale in-space assembly. LaRC capabilities and technologies for agents and infrastructure are summarized in this section forming a basic set of cross-cutting technologies and capabilities, referred to as the "ISA tool box".

Extra-Vehicular Activity (EVA, Astronaut Assembly)

The Assembly Concept for Construction of Erectable Space Structure (ACCESS) experiment was launched on the Orbiter Atlantis on Nov. 26, 1985[15]. ACCESS was designed to study manual assembly of a 13.7-meter long truss structure by two astronauts working in space suits in the Space Shuttle cargo bay. 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 EVA tasks were accomplished successfully (Figure 6) and simulated 0-g (i.e., wearing pressure suits) assembly times were shown to reliably estimate in-space assembly times for this class of structure.

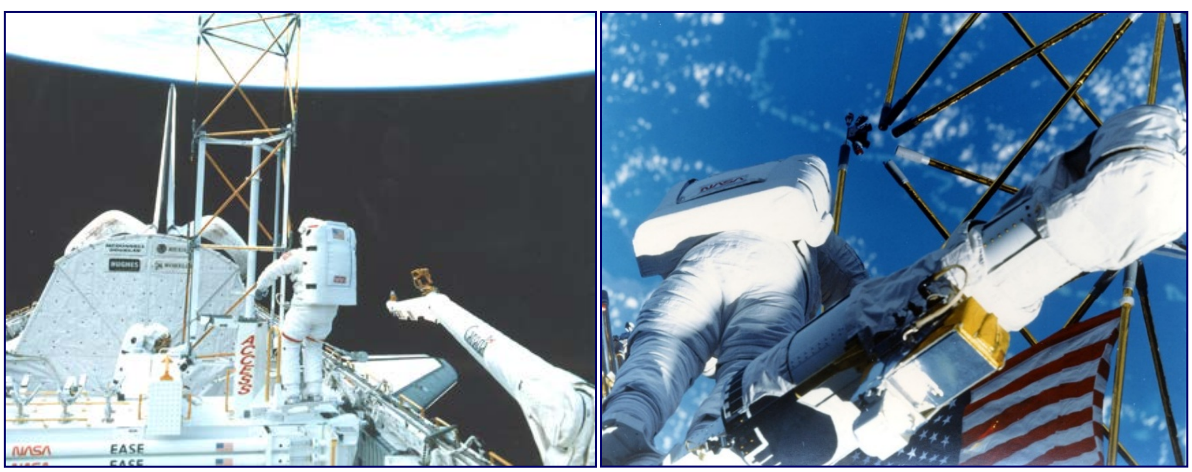

Figure 6. ACCESS Shuttle flight experiment (EVA Assembly).

Mobile Transporter

A Mobile Transporter (MT) concept, based on the Mobile Work Station construction fixture, was developed as an EVA aid for SSF assembly[16]. The SSF truss would be assembled out of the Space Shuttle cargo bay using the MT as a construction base, and two EVA astronauts would perform all construction tasks. 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-meter bay SSF truss structure in 1988. The MT was also designed (Figure 7) to transport agents across all 4 sides of the SSF using an efficient system that engaged guides on the SSF backbone truss.

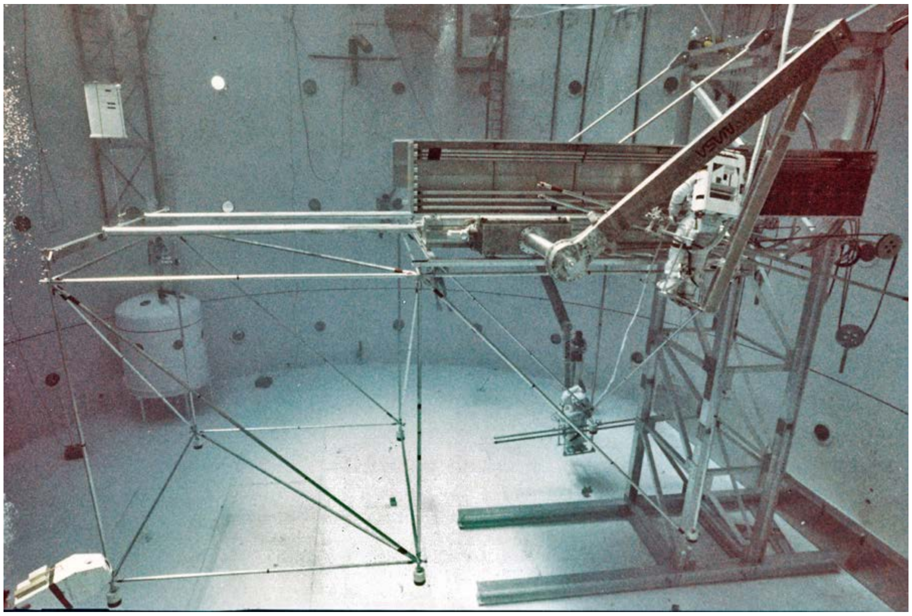

Figure 7. Mobile Transport used for Astronaut Positioning in Neutral Buoyancy Testing.

In-Space Construction Facility

During the 1980s and 1990s many large structures were being proposed for exploration. An in-space construction facility (ISCF) concept was introduced to provide infrastructure needed to build some of the large mission vehicles (Figure 8)[17]. The ISCF leveraged the versatility of the LaRC SSF truss hardware and ISA concepts by incorporating both into its architecture.

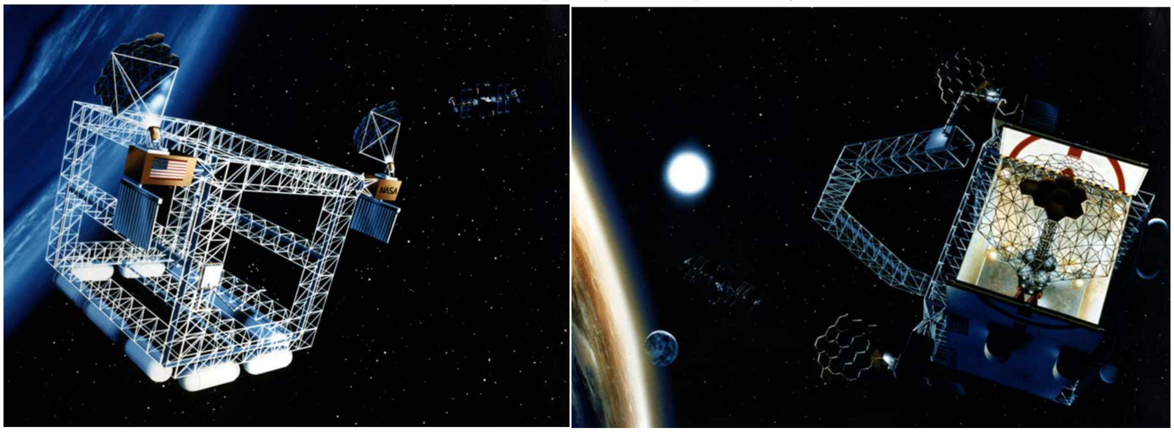

Figure 8. In-Space Construction Facility Concepts.

Space Crane

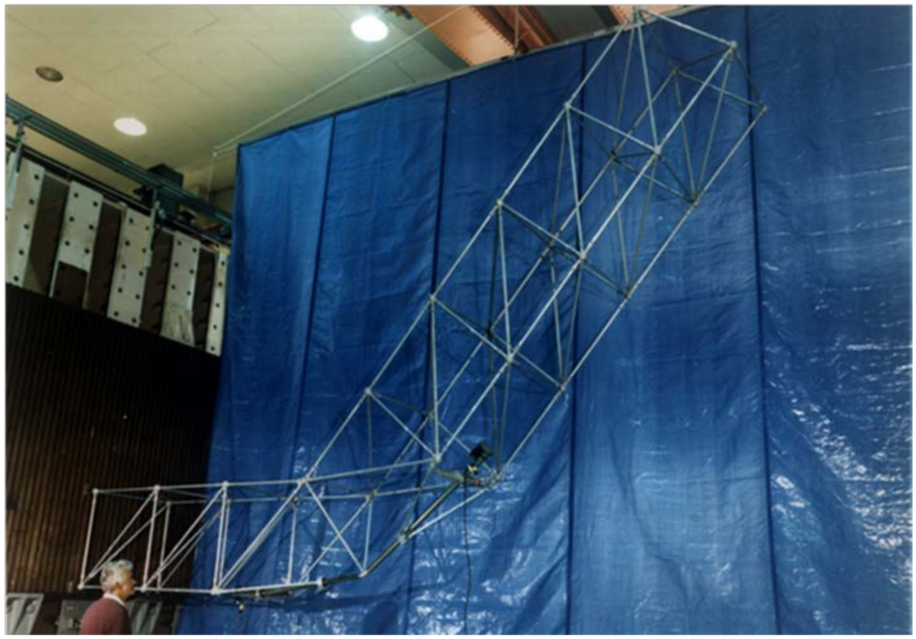

Figure 9. Space Crane Prototype Testing.

In the early 1990s, LaRC applied its knowledge from large space structure studies to conceive a long-reach manipulator concept called the space crane to operate at the ISCF[18]. This crane, conceived to support positioning and assembly tasks, also leveraged the previously developed SSF and PSR hardware and assembly methods. A prototype, shown in Figure 9, was built and tested at LaRC.

Tendon-Actuated Lightweight In-Space MANipulator

The Tendon-Actuated Lightweight In Space MANipulator (TALISMAN) created a new robotic agent for performing long-reach operations.[19] This long reach arm uses a series of tension members (often cables) for both structural stiffening as well as joint actuation. Figure 10 depicts the TALISMAN arm grappling a PA and maneuvering it within reach of more dexterous robotic arms. The unique arrangement of tension elements simultaneously provides improved structural performance and improved mechanical advantage for the motors. Compared to state-of-the-art in-space manipulators, such as the Shuttle Remote Manipulator System (SRMS) and the Space Station Remote Manipulator System (SSRMS), a TALISMAN-based manipulator 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. Two 20-meter long TALISMAN were designed, fabricated and tested in a simulated (flat floor) zero-g environment at LaRC. Testing demonstrated successful TALISMAN deployment from the (launch) packaged state as well as a variety of autonomous precision maneuvering, payload handling and positioning operations.

Figure 10. Tendon-Actuated Lightweight In-Space MANipulator.

NINJAR/SAMAURI

Most recently, LaRC has focused on developing robotic tools and automated techniques for large truss ISA.[20] A precision assembly system called the NASA Intelligent Jigging Assembly Robot (NINJAR) operated cooperatively with a TALISMAN tool called the Strut Attachment, Manipulation, and Utility Robotic Aide (SAMURAI) to autonomously construct a truss in the laboratory. In a ground demonstration performed in mid-2017 (see Figure 11), the NINJAR precisely positioned the joints during construction of a 32-inch square-bay truss, achieving an average error of under 2 millimeters in spatial positioning and 1 degree of joint rotation, demonstrating the NINJAR's precision performance.[21]

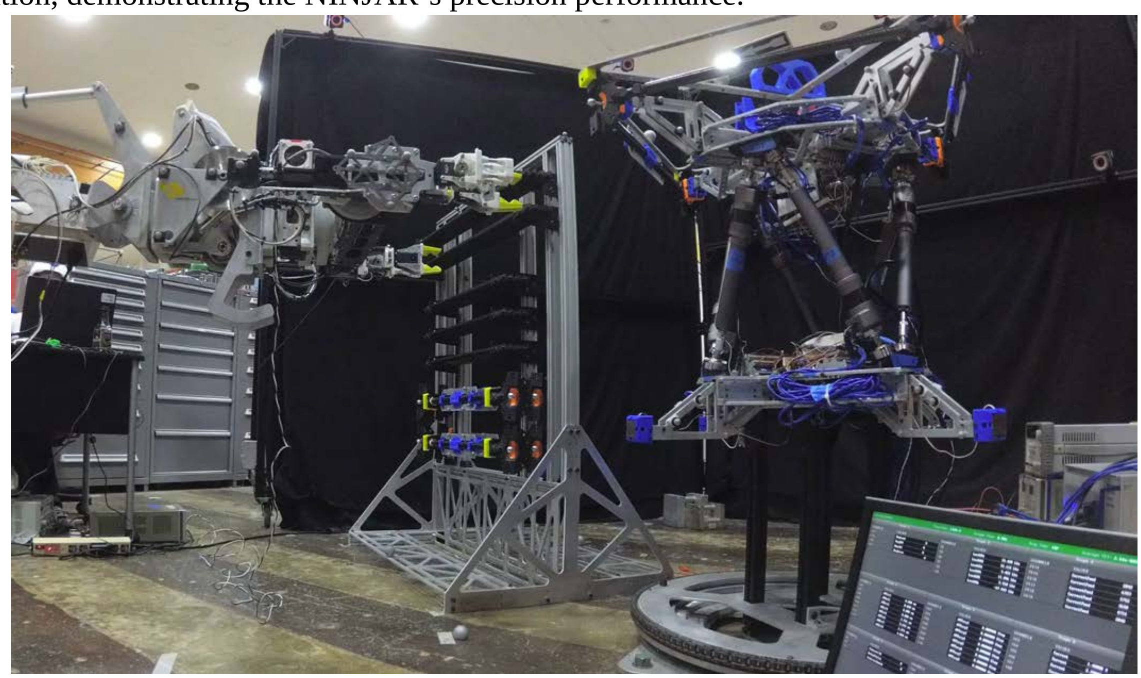

Figure 11. SAMAURI retrieving truss strut for NINJAR in construction demonstration.

Electron-Beam Welding, Welded Truss Joints

A great deal of experience was gained with welding in space by the Soviet Union up until the late 1980s/early 1990s. The Electron-Beam (EBeam) welding process was selected as the most viable for in-space applications leading to development of a Versatile (electron beam) Hand Tool by the Soviet Union. Currently, EBeam processes and hardware are being developed at NASA LaRC, Figure 12, with the emphasis being on ISA of trusses. LaRC developed weldable structural joints, and in the NINJAR/SAMAURI demonstration described previously, successfully demonstrated automated truss construction using the weldable truss joints.[22] The EBeam welding, cutting and rewelding process was successfully demonstrated on flight-like truss joints in a vacuum chamber. This current EBeam capability can be leveraged and used for welding (and cutting if required) in the new assembly paradigm.

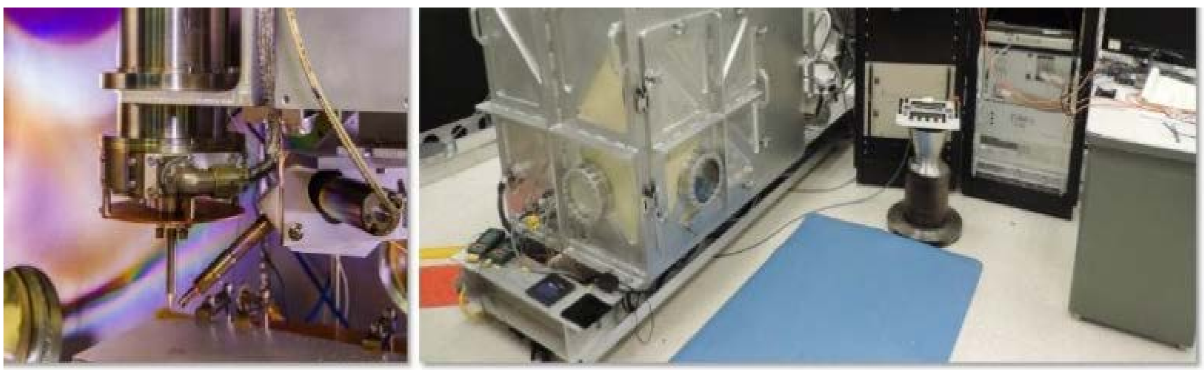

Figure 12. Electron Beam Welding, Welded Truss Joints.

4. Concluding Remarks

Numerous NASA exploration and science missions can benefit by employing a design architecture that takes advantage of the PA paradigm. A basic set of cross-cutting technologies and capabilities, referred to as the “ISA tool box”, have been developed at the NASA LaRC. The cross-cutting ISA capabilities most applicable to large space telescopes include: modular design with high stiffness and stable truss structures; automated/robotic assembly using long reach manipulators and specialized robotic tools; and, mechanical and electrical joining technology for components and modules. LaRC ISA and LSS technologies/capabilities have been presented to inform the community of existing robust capability supporting architect and assembly of the next astrophysics observatory, a type of PA. The maturity of the LaRC technologies and capabilities support the feasibility of applying ISA to future large-aperture space telescopes, sun shields, and star shade systems. Embracing the PA paradigm and an ISA approach for architecting, designing and fielding the next large astrophysics observatory will incur many programmatic benefits including: a pay-as-you-go approach and level funding profile; the ability to obtain a rapid science return (start science as soon as first mirrors and instruments have been assembled), and; capability for future growth by supporting expansion of (adding to) the aperture and number of instruments over the observatories lifetime.

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