An Efficient and Versatile Means for Assembling and Manufacturing Systems in Space

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Within NASA Space Science, Exploration and the Office of Chief Technologist, there are Grand Challenges and advanced future exploration, science and commercial mission applications that could benefit significantly from large-span and large-area structural systems. Of particular and persistent interest to the Space Science community is the desire for large (in the 10- 50 meter range for main aperture diameter) space telescopes that would revolutionize space astronomy. Achieving these systems will likely require on-orbit assembly, but previous approaches for assembling large-scale telescope truss structures and systems in space have been perceived as very costly because they require high precision and custom components. These components rely on a large number of mechanical connections and supporting infrastructure that are unique to each application. In this paper, a new assembly paradigm that mitigates these concerns is proposed and described. A new assembly approach, developed to implement the paradigm, is developed incorporating: Intelligent Precision Jigging Robots, Electron-Beam welding, robotic handling/manipulation, operations assembly sequence and path planning, and low precision weldable structural elements. Key advantages of the new assembly paradigm, as well as concept descriptions and ongoing research and technology development efforts for each of the major elements are summarized.

Nomenclature

ASAL	=	Automated Structure Assembly Laboratory
E-Beam	=	Electron Beam
EVA	=	Extra-Vehicular Activity
GMA	=	Gas Metal Arc
HLLV	=	Heavy Lift Launch Vehicle
IPJR	=	Intelligent Precision Jigging Robot
ISS	=	International Space Station
JWST	=	James Webb Space Telescope
LaRC	=	Langley Research Center
LRM	=	Long Reach Manipulator
LSMS	=	Lightweight Surface Manipulation System
NP	=	Non-deterministic Polynomial
OCT	=	Office of Chief Technologist
VHT	=	Versatile Hand Tool

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I. Introduction

WITHIN ithin NASA Space Science, Exploration and the Office of Chief Technologist (OCT), there are Grand Challenges and advanced future exploration, science and commercial mission applications that could benefit significantly from large-span and large-area structural systems. Examples for OCT include; "Efficient In-Space Transportation" (build large backbone truss for nuclear vehicles), "Affordable Abundant Power and Space Way Station" (enable platforms, fuel depots and pressure volumes), and "Space Colonization" (assemble large pressure vessels for habitats, shelters and hangers). Other examples include large platforms that can serve as infrastructure to support on-orbit servicing and assembly operations or communications transponder parks. Of particular and persistent interest to the Space Science Community is the desire for Large Space Telescopes in the 10-50 meter aperture range[1] that would revolutionize space astronomy. The technology needed to enable developing and fielding these large telescopes resides in the section of OCT's portfolio; "Near Earth Object Detection and New Tools of Discovery" (build very large telescopes and interferometers).

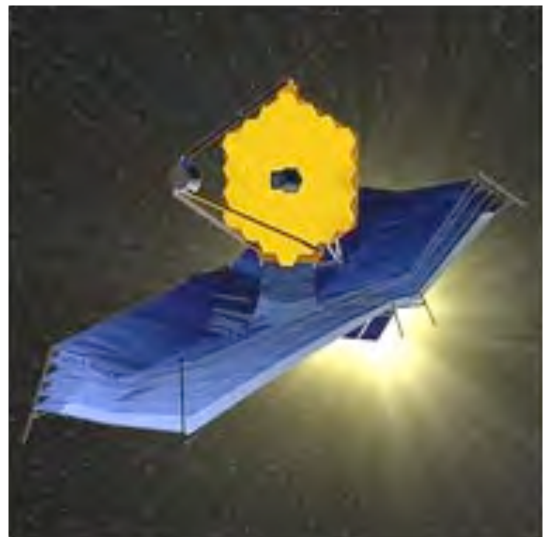


Figure 1. James Webb Space Telescope.

Except for the International Space Station (ISS), all current spacecraft are transported to orbit as an integrated unit using a single launch. This severely constrains the mass and size of the spacecraft system because it must be designed to the mass and volume constraints of the chosen launch vehicle and its payload shroud, as well as the loads imposed by the launch environment. Once on orbit, various systems, such as solar arrays, radiators and antennas are deployed to achieve an operational configuration. The James Webb Space Telescope (JWST), shown in Fig. 1, with a primary mirror diameter of 6.5 meters, likely represents an upper limit to the size of aperture that can be achieved for a single-launch telescope using deployable structures and mechanisms. This is because the spacecraft complexity rapidly increases with increasing number of deployable mechanisms and systems, as does the potential for deployment failure, resulting in a decrease in spacecraft and mission reliability. Although an on-orbit servicing and repair capability would help to mitigate spacecraft mission risk resulting from deployment and other early system failures, this capability does not currently exist. Furthermore, current spacecraft, including the JWST, are not designed to take advantage of such services (even if they did exist). An alternative, espoused by some, is to build a Heavy Lift Launch Vehicle (HLLV) that includes a larger payload shroud. The cost of designing and manufacturing such a special-purpose launch system would be very expensive, as would the cost for each launch (because of launch infrequency). Spacecraft designed to launch on a HLLV might be somewhat larger but there would still be a limit on the maximum size of spacecraft that could be launched. Also, lack of servicing and repair capability would still be inherent in the traditional design and operation approach.

One approach that can result in larger space systems and takes advantage of multiple launches, is to incorporate on-orbit assembly, as was used for the ISS. The ISS was assembled from a relatively small number of very large and massive modules or components, with each component requiring its own launch. The components were positioned and berthed robotically on orbit, and then permanent mechanical and utility line connections completed. However, many of the large telescope and exploration vehicle applications include large area or span trusses to provide lightweight, high stiffness and precise support and backbone structures, all of which require assembling a much larger number of small and lightweight truss elements. Previous approaches proposed for assembling truss and telescope structures and systems in space have been perceived as very costly because they require high precision and custom components that rely on mechanical connections, supporting infrastructure that is unique to each application and robust processes for other operations such as mirror-to-truss assembly. A new paradigm that results in a versatile and efficient means for assembling systems in space and that can also be extended to in-space manufacturing is proposed here. This new paradigm incorporates reusable and versatile on-orbit precision jigging in combination with inexpensive and low precision structural elements, which are joined using on-orbit welding, to build the foundations of precision space systems.

This paper will review concepts for large space telescopes designed for on-orbit assembly as well as past human and robotic methods proposed and developed for assembling their apertures. A new paradigm for on-orbit assembly, that can easily and naturally be extended to on-orbit repair, refurbishment and manufacturing, will be introduced.

The key elements that enable the paradigm will be described and a procedure that was developed to assemble a support truss will be used to illustrate their operation, integration and collaboration. Finally, the status of each element and ongoing work will be summarized.

II. Space Telescope, Trusses and On-Orbit Assembly

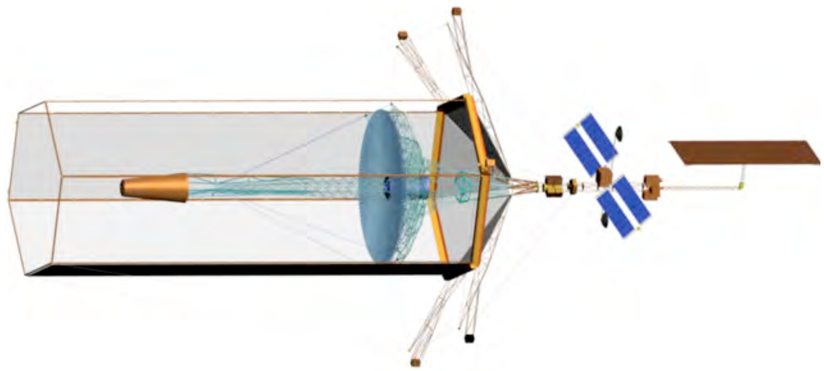


Figure 2. On-orbit assembled large space telescope example.

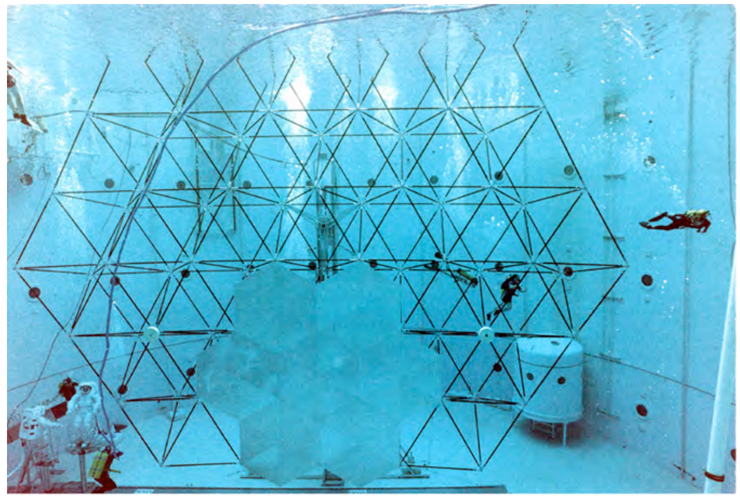
The desire to field large (i.e. greater than 10-meter diameter primary mirror) optical systems in space has been a dream of space scientists for many decades. Many concepts for such telescopes have been developed over the years, with one of the more recent examples being a 30-meter space observatory operating at the ultra violet-optical-near infrared (Hubble-like) wavelengths,[1] as shown in Fig. 2. This concept is scalable (the primary aperture diameter can be varied) and relies on multiple launches to place the telescope elements in space and in-space robotics to assemble the elements and complete the telescope. Another recent concept for a large space telescope, with a 10-meter diameter primary mirror and operating in the ultraviolet-optical wavelengths, is also conceived to be assembled robotically in space.[2] In the early 1990's NASA completed extensive technology development for a 20-meter diameter far-infrared space telescope that evolved into the precision segmented reflector,[3, 4] as depicted in Fig. 3.

Figure 3. Large precision segmented reflector.

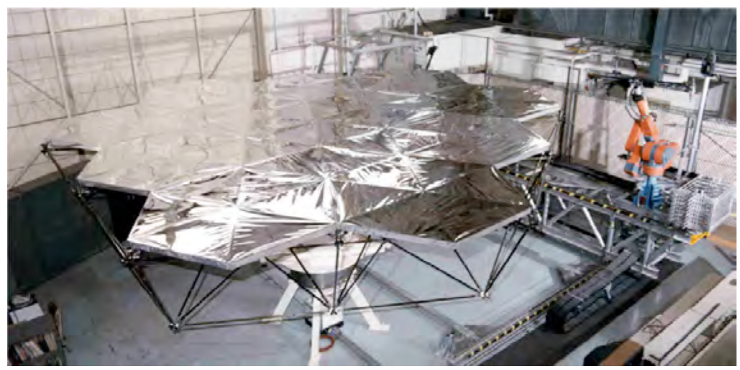
Since designing, building and fielding such large telescopes in space requires a large investment (in the billions of dollars for each), it makes little sense to treat these as disposable systems with short lifetimes. With the increasing capabilities being developed for in-space servicing, most concept developers propose that these new large space systems be designed for long life with the capability for in-space servicing, upgrading and repair, as has been done with the Hubble Space Telescope. This is identical to how large terrestrial telescopes are operated and would give the same benefits of amortizing the investment and reaping the science returns of such a large investment over the course of many decades. Many of the benefits and techniques for assembling and servicing large space observatories have been documented[5]. The reference describes how assembly and servicing techniques enhance mission versatility and can be applied to a variety of science mission and telescope concepts.

The structural architectures for the large space telescopes discussed previously have many similar features, such as: segmented primary mirrors, where the mirror size is determined by either manufacturing or launch-vehicle shroud size constraints; large-area stiff and lightweight trusses which support the primary mirror segments; truss beams/towers/masts to support secondary mirrors and/or instrument packages; and large lightweight sun shields. The rationale and benefits for using trusses as the primary structure for many space applications (including telescopes) has been documented[6] and their high degree of structural performance has been treated comprehensively.[7] Based on this rationale, a large amount of design and technology development efforts have focused on lightweight space trusses. Preliminary design approaches for large high precision segmented reflectors are well established,[8] forming the foundation for even more refined and detailed treatment of structural concepts and mechanics issues.[9] In what might be considered the culmination of the telescope mirror support truss development efforts, a precision truss structure was designed, fabricated, assembled and tested, ultimately validating the high surface precision, stiffness and strength that had been predicted.[10]

As mentioned previously, one of the key impediments to achieving large space telescopes is the assumption that the telescope must be launched as a complete system, subject to the inherent payload mass and volume limitations imposed by a single launch vehicle. Launch vehicle limitations and practical constraints that limit the likely size of a deployable telescope system (the JWST configuration for example) have been reported.[3] This reference also summarizes the rationale and benefits that accrue when a large space telescope is designed to be assembled on orbit, outlines a concept, estimates the performance and discusses assembling a 25-meter diameter space telescope. In addition to advances in telescope mirror support truss design, fabrication and structural performance, a great deal of progress has been made in assembling these structures both manually, by astronauts in Extra-Vehicular Activity (EVA), and robotically. EVA structural assembly development culminated in an experiment where a 14-meter diameter, doubly curved telescope truss, consisting of 315 individual struts, along with 7 (of the 37 total needed) mockup reflector panels was assembled in neutral buoyancy[11] as shown in Fig. 4a. Data from the tests indicated that a flight version of the design, which included all 37 reflector panels, could be assembled on orbit in less than 5 hours. In parallel research, methods were also developed to enable robotic telescope assembly. The robotic work culminated in the repeated autonomous assembly (and disassembly) of an 8-meter diameter truss structure, composed of 102 individual truss members along with 12 hexagonal panels[12] (Fig. 4b).



a) EVA assembly of a precision radiometer.



b) Robotically assembled tetrahedral truss structure.

Figure 4. EVA and robotic telescope assembly experiments.

III. New Assembly Paradigm and Concept Overview

Given the desired objective of fielding large telescopes in space, it is argued[3] that all of the limitations associated with deployable systems preclude that option from being considered viable. The options that use mechanical joining are feasible, but have limitations in terms of concept versatility, added mass and cost. The key change in the proposed space assembly paradigm is from one that uses high precision structural components and assembly infrastructure, that is designed for a specific application, to one that uses low precision components and versatile infrastructure that can be applied to many applications. The approach developed to implement this paradigm leverages a combination of historical and current capabilities and combines those with a proposed set of new developments to achieve viability.

The new space assembly approach incorporates and integrates the following key capabilities: Intelligent Precision Jigging Robots (IPJRs), Electron Beam Welding; robotic handling, manipulation and assembly; operations assembly sequence and path planning; weldable structural elements and components; and, integration and attachment of utilities and other systems. A brief description of each capability and its associated functional allocation (see Table 1) follows.

Intelligent Precision Jigging Robots (IPJRs): This is one of the new capabilities that is needed, with development and research efforts just beginning.[13] The desire is to develop versatile and reconfigurable IPJRs that can support and precisely locate structural elements as they are being welded. A set of identical Jigging Robots would be able to assemble a wide range of structural geometries over a range of scales.

Electron Beam (E-Beam) Welding: A great deal of experience was gained with welding in space by the Soviet Union up until the late 1980s/early 1990s.[14] Many welding processes as well as techniques for assembling structures were evaluated. Ultimately, the E-Beam welding process was selected as the most viable for in-space applications leading to development of a Versatile (electron beam) Hand Tool (VHT). The VHT was designed for operation by cosmonauts in EVA and many experiments were successfully performed outside of Soviet Space Stations. Currently, E-Beam processes and hardware are being developed at NASA Langley Research Center (LaRC)[15, 16] with the emphasis being on free-form fabrication. This current capability would be leveraged and used for welding (and cutting if required) in the new assembly paradigm.

Robotic Handling, Manipulation and Assembly: Technologies for EVA and Robotic assembly of large-span and large-area truss structures are well advanced and have been discussed previously.[11, 12] Capabilities for in-space robotics and robotic servicing are also advancing rapidly[17, 18, 19] especially those developed during the Hubble Robotic Repair mission investigation, and represent well established current capabilities that would be used in the new assembly paradigm.

Operations Assembly Sequence and Path Planning: Assembly sequences and associated path planning for one class of tetrahedral support truss was highly developed and validated by experiment.[20, 21] However, the details of these plans depend on many parameters, including the type and capabilities of the infrastructure available, integration of non-structural subsystems, etc. The algorithms that define feasible assembly sequences for the IPJRs,[13] coordinate their motions and plan their paths must be developed, taking into account jigging, robotic manipulator and welding system constraints.

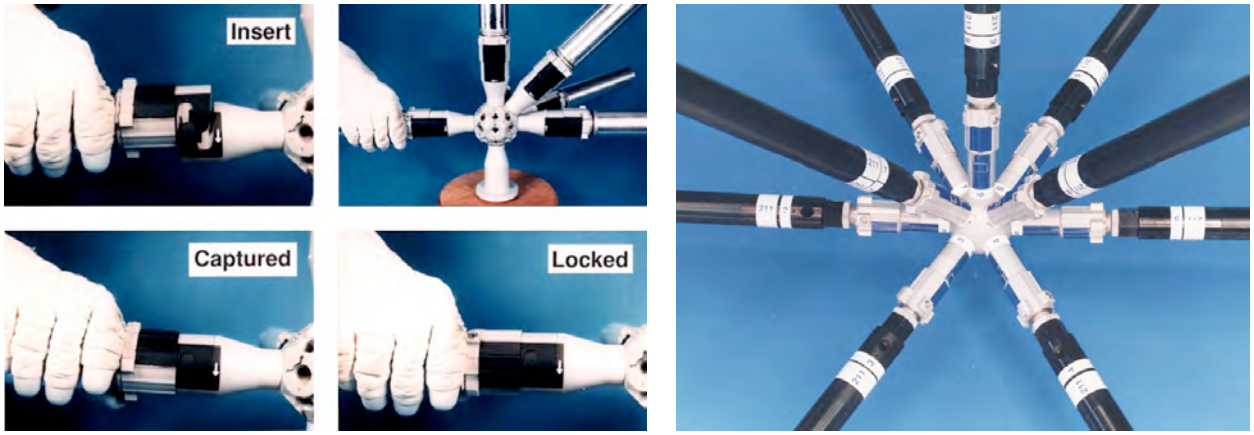
Weldable Structural Elements and Components: Another area where new capabilities are needed is in advanced materials and concepts for lightweight truss and other structural members that can be welded in space.

Integration and Attachment of Utilities and Other Systems: Although not addressed in depth in this paper, the proposed assembly method must be compatible with efficiently integrating the non-structural elements that are required to accomplish all of the spacecraft system functions.

Besides the IPJRs, a key feature of the proposed new assembly paradigm is using welding as the structural joining method. The more traditional method for space structural assembly uses mechanical joints that allow erec-

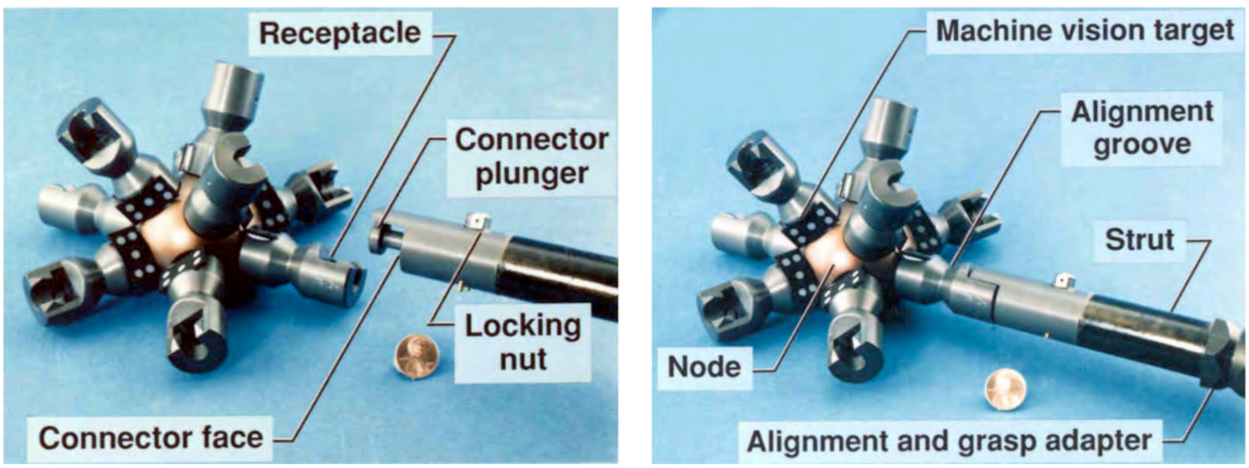
Table 1. Functional allocation to assembly concept elements.

Assembly System Elements	Functions
Intelligent Precision Jigging Robots	The jigs set the geometry and precision of the structure by engaging the truss nodes and setting their locations precisely using an on-board metrology system. The jigs also have means to accept nodes and struts from an auxiliary manipulator, locate the struts in their welding position and restrain the struts during welding. May verify welds by applying a proof load. May also have means to reposition to next assembly location.
E-Beam Welding System	Welds the structure: nodes to struts.
Auxiliary Robotic Manipulator(s) and Tools/End Effectors	Manipulator retrieves material (nodes and struts for example) from storage location. Performs gross positioning of material, tools and end effectors in work zone. Tools and End Effectors present nodes and struts to the IPJRs, position the welding end effector at its work site, supports welder during welding operations, presents inspection unit to welding site and supports it during inspection operations. May also reposition the IPJRs.
Assembly Sequencing and Path Planning system	Contains structural definition. Based on knowledge of other system components, develops an assembly sequence for the structure and defines paths for components to take during assembly. Commands IPJR movement and auxiliary manipulator gross positioning.
Weldable Structural Components (primary structure)	Provides the structural stiffness, thermal stability and strength necessary for the structure to meet its mission.
Assemblable secondary structure and systems	Systems that provide all non primary structural functions (mirrors, power generation/distribution, thermal management, attitude control, etc.) must be physically compatible (to be assembled to or integrated with) with the primary structure.



a) Two-inch diameter struts. **b) One-inch diameter struts.**

Figure 5. EVA compatible mechanically assembled truss joints.



a) Unlocked joint. **b) Locked joint.**

Figure 6. Robotically compatible mechanically assembled truss joints.

tion/assembly of structures with the joints designed to be compatible with either EVA astronauts (Fig. 5) or robots (Fig. 6) serving as the assembly agents.[11, 12] The attributes and implications of using mechanical versus welded connections for structures assembled in space are compared in Table 2.

A. Assembly Sequence Example: 3-D Triangular Truss

Detailed sequences have been developed for assembling tetrahedral telescope support trusses using both EVA astronauts[20] and robots.[21] The specific details of the assembly process were different for the two cases because of the particular attributes and constraints of the assembly agents (humans or robots) and the capabilities of the supporting infrastructure. However, many common assembly process themes and lessons were found to exist, and these were used to develop a tetrahedral truss assembly scenario that was then used to help define the capabilities and attributes needed for the elements in the proposed new system.

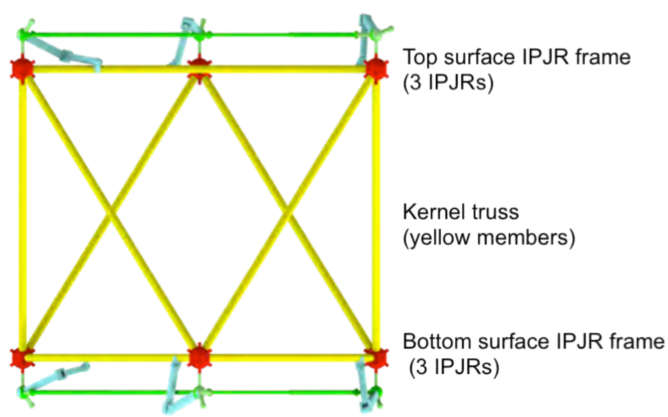
The system elements assumed in this scenario are: a pre-assembled octahedral truss core that serves as the kernel truss and that supports the IPJRs and auxiliary robotic manipulators during launch; and the weldable node and strut structural components. The IPJRs each have two arms attached to a central (rotational) hub, with one arm fixed length and the other arm capable of extension/retraction and a third strut-gripper arm. Two auxiliary Long Reach Manipulators (LRMs), one for each truss surface, retrieve material and position end effectors. The primary end effector will be one that can grasp and present structural components (struts with and without attached nodes) to the IPJRs, as well as perform welding operations.

Table 2. Features of assembly methods compared.

Feature/Attribute	Mechanical/Erectable Structure	Welded Structure
Joint (Nodes/connectors) Mass	High	Minimal
Connection Complexity (and cost)	High: many mechanical features with high tolerances	Simple: butt joint that is welded
Truss strut complexity (and cost)	High: must have mechanical joints on each end, precision lengths set for each individual strut	Simple: tubes with sliding plunger or strut sleeve allows length setting and welding on orbit
Manufacturing Cost	High: for precision node balls and connector components	Low: simple balls, tubes and end fittings
Application Versatility	Low: all components must be manufactured and geometries set for a particular application being built. Infrastructure to support assembly is application dependent.	High: simple balls and struts allow different geometries and scales to be built from a few common elements. Assembly infrastructure adaptable to different geometries and scales. IPJRs can be programmed to build different systems.
Location of assembly complexity	Each individual structural element (nodes, joints) are complex; assembly infrastructure requires astronaut positioners, manipulators, tools and end effectors.	IPJRs are complex, and require auxiliary manipulators, tools and end effectors. Requires welding process equipment, inspection equipment.
Location of jigging	Built into each individual strut (lengths preset at high precision)	Separate IPJRs, which are reusable and versatile

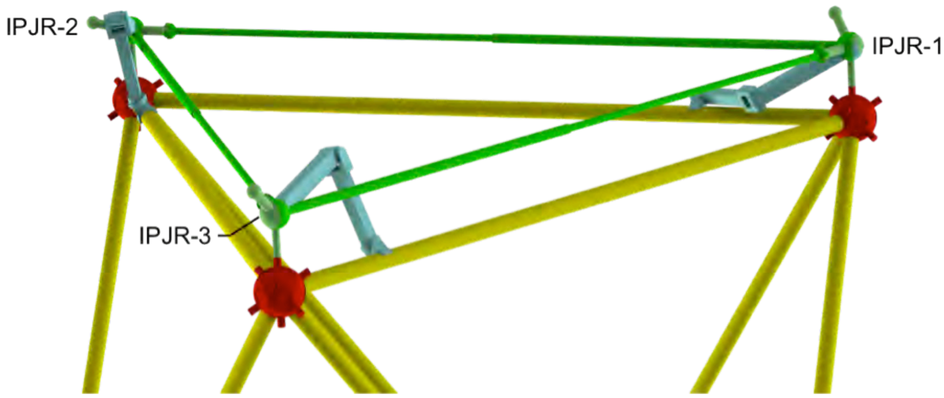
The scenario assumes that in the starting configuration, three IPJRs are connected to each other to form a reconfigurable triangular frame, with one frame each on the upper and lower surfaces of the kernel truss as shown in Fig. 7. The two sets of IPJRs are initially attached (by grasping the nodes) to one surface (either upper or lower) of the kernel truss and remain on that surface during the assembly sequence. Each IPJR frame can individually assemble truss struts in their respective surfaces, but they cooperate to assemble the core struts. In the scenario presented, when assembly results in a node at the end of a strut hanging in free space (i.e. unsupported) as shown in Fig. 8, the next step is always to stabilize the node by inserting a core strut. As the structure is being assembled, the sequence must also allow the auxiliary robot manipulators and end effectors access for welding operations and maneuvering struts into their assembly position.

A general description of the truss assembly sequence for the first truss ring is given in Table 3. The table describes what each of the IPJR robots and its associated auxiliary robotic manipulator is doing for each strut insertion (a blank entry means no activity for that particular strut assembly). The color coding in the first column (step & strut number) is used to illustrate that only three distinct operational procedures are required to complete the 16 steps for assembling the first truss ring. Including step 16 as a fourth procedure, it is anticipated that an entire support truss can be assembled with the repetition of only these four operational procedures. For the icons in column 2 showing the progressive truss assembly, yellow struts indicate the octahedral kernel truss (illustrated in step 0), red struts are on the upper surface, green struts are on the lower surface, and blue struts are in the truss core.

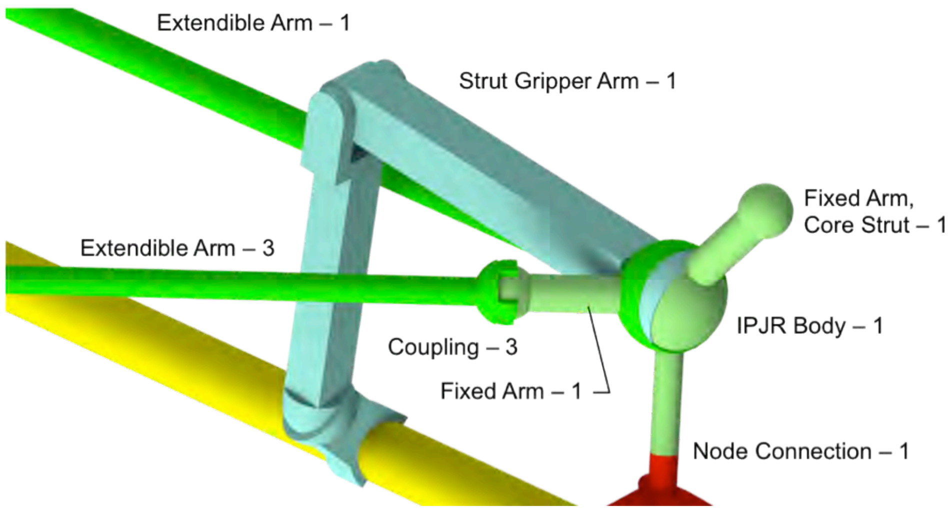


a) Kernel truss with IPJR frames – side view.

Figure 7. Truss assembly with 3 IPJRs forming triangular framework.



b) Close up view of upper IPJR frame.



c) Individual IPJR elements.

Figure 7. Truss assembly with 3 IPJRs forming triangular framework (concluded).

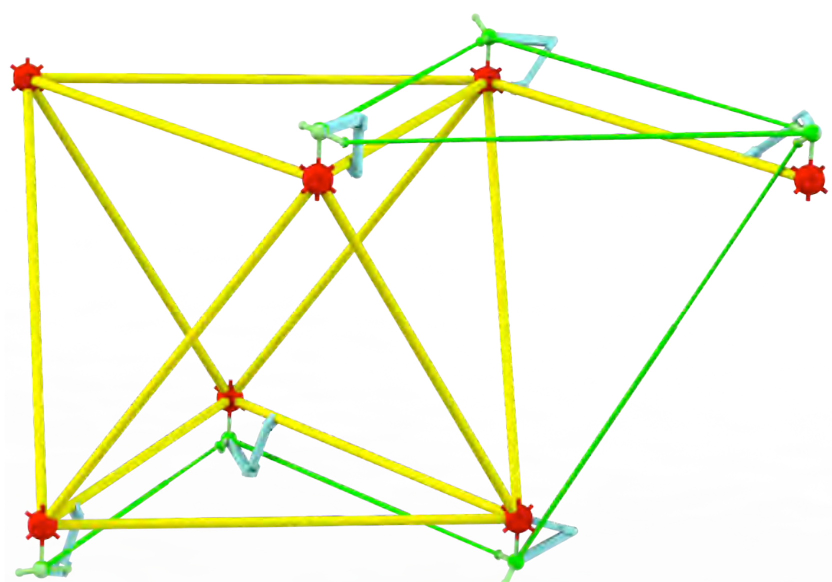


Figure 8. Strut with unsupported node on free end.

Table 3. Assembly sequence for the first ring of a 3-D tetrahedral truss.

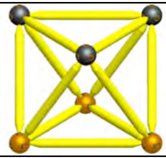
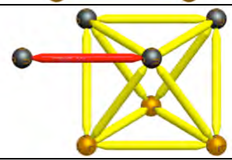
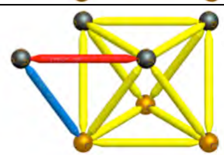
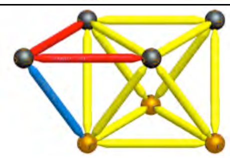
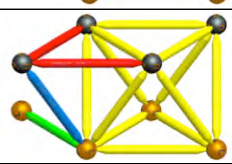
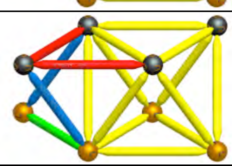
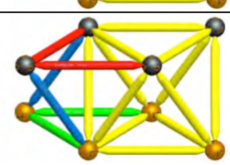
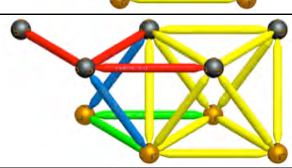
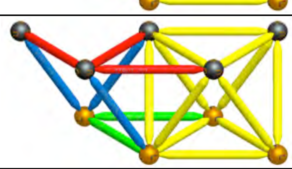
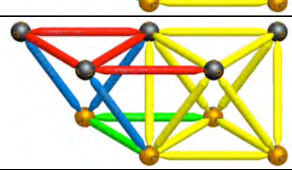
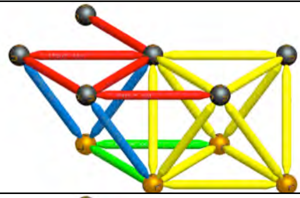
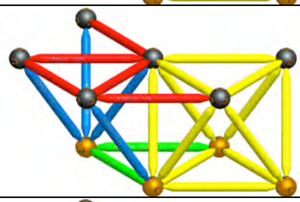
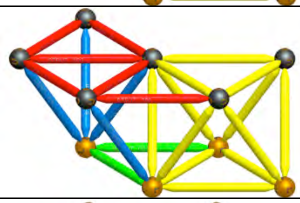
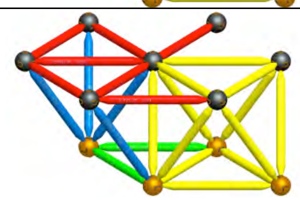
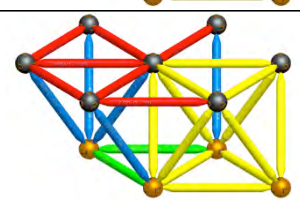
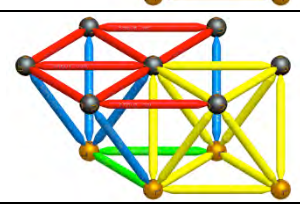
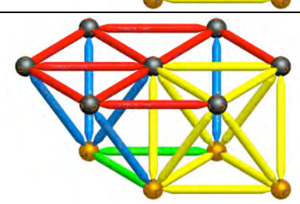
Step & Strut Number	Inserted Strut	Action Performed		
		Upper Surface IPJR Frame	**Lower Surface IPJR Frame**	**Auxiliary Robotic Manipulator**
0		Attached to kernel upper surface	Attached to kernel lower surface	Stowed within kernel truss
1		Positioned with body in free space, set spacing		Hand off strut/node 1 to IPJR, weld in place
2		Stingers set node spacing thru truss	Stingers set node spacing thru truss	Hand off strut 2 to IPJRs, weld in place
3		Sets node spacing		Hand off strut 3 to IPJR, weld in place
4			Positioned with body in free space, set spacing	Hand off strut/node 4 to IPJR, weld in place
5		Stingers set node spacing thru truss	Stingers set node spacing thru truss	Hand off strut 5 to IPJRs, weld in place
6			Sets node spacing	Hand off strut 6 to IPJR, weld in place
7		Positioned with body in free space, set spacing		Hand off strut/node 7 to IPJR, weld in place
8		Stingers set node spacing thru truss	Stingers set node spacing thru truss	Hand off strut 8 to IPJRs, weld in place
9		Sets node spacing		Hand off strut 9 to IPJR, weld in place

Table 3. Assembly sequence for the first ring of a 3-D tetrahedral truss (concluded).

Step & Strut Number	Inserted Strut	Action Performed		
		Upper Surface IPJR Frame	Lower Surface IPJR Frame	Auxiliary Robotic Manipulator
10		Positioned with body in free space, set spacing		Hand off strut/node 10 to IPJR, weld in place
11		Stingers set node spacing thru truss	Stingers set node spacing thru truss	Hand off strut 11 to IPJRs, weld in place
12		Sets node spacing		Hand off strut 12 to IPJR, weld in place
13		Positioned with body in free space, set spacing		Hand off strut/node 13 to IPJR, weld in place
14		Stingers set node spacing thru truss	Stingers set node spacing thru truss	Hand off strut 14 to IPJRs, weld in place
15		Sets node spacing		Hand off strut 15 to IPJR, weld in place
16		Positioned to engage 3 existing nodes, set spacing		Hand off strut 16 to IPJR, weld in place
* This Completes Assembly of the First Truss Ring				

B. Key Advantages of New Assembly Paradigm

Future space systems will accrue many advantages from the successful development and implementation of this new paradigm, the major ones being:

1. With welded joints, the structure will have highly predictable performance. Free-play, hysteresis and other non-linear behaviors are eliminated from the joints, allowing analytical methods to more accurately predict the

structural behavior. This is especially important since large space systems designed and optimized for zero-g will be difficult to test (in 1g) before flight.

2. The structural system becomes completely customizable in dimensions, truss bay size and shape. Spacecraft scale is eliminated as a limitation.

3. The structural system becomes extremely lightweight with weldable joints (compared to either mechanical joints for assembly or deployable joints and mechanisms).

4. Assembling and welding in space results in a simple structural system and eliminates mission risk and reliability issues associated with deployable systems.

5. The IPJRs and robotic assembly infrastructure are versatile and reusable and can be used for many different spacecraft and applications. The cost of the spacecraft assembled using this method will decrease (compared to traditional designs) as a result of amortization over many assembly missions.

IV. Status of Concept Elements

The features, operations and concepts for the major elements that make up the new assembly paradigm (as listed in Table 1) are described in more detail in this section. The section also summarizes the development and testing that are being planned.

A. Intelligent Precision Jigging Robots

In this new assembly paradigm, the allocation of responsibility for structural precision is transferred from the structural elements to the Intelligent Precision Jigging Robot (IPJR). This is achieved by allowing a set or framework of IPJRs to precisely form individual cells within a truss, and thereby guide the placement and welding of the permanent struts. The IPJRs, either individually or collectively, must be able to:

- Connect to a node at a location known precisely relative to the node center.
- Connect to another IPJR positioned on a neighboring node and receive a connection from other IPJRs.
- Set and hold a precise distance between two nodes.
- Set and hold a strut that is provided by an auxiliary manipulator.
- Communicate with the other IPJRs in its group to coordinate cell formation.
- Communicate with the auxiliary manipulator in order to commence welding, and to request reconfiguration.
- Communicate with a central metrology station to verify overall structure geometry.
- Apply proof load to a strut after welded (as a means of assembly verification).

The most likely IPJR system design candidate consists of a set of three IPJRs that combine to create triangular cells for assembling struts in a surface, and which include another means for assembling truss core struts. We are currently considering three options for assembling the core struts: 1) a fourth IPJR attached to one of the other IPJRs, 2) an additional active arm on each IPJR, or 3) operating one of the frame IPJRs as a "stinger" by allowing it to disconnect from its frame, reach through the truss core, and connect to a IPJR on the opposite truss face as shown in Fig. 9. Each IPJR will have a connection mechanism at its base to both localize itself and to connect to the node to which it is associated. Since tetrahedra have three edges meeting at each vertex, each IPJR should be able to accommodate connections to three other IPJRs. The only exception to this requirement is if the stinger is a component on a single IPJR as opposed to an entirely distinct IPJR. Two or three arms will extend from the base: one active arm and one or two passive arms (see Fig. 7c for example of two passive arms). The active arm will be able to attach to a passive arm on a

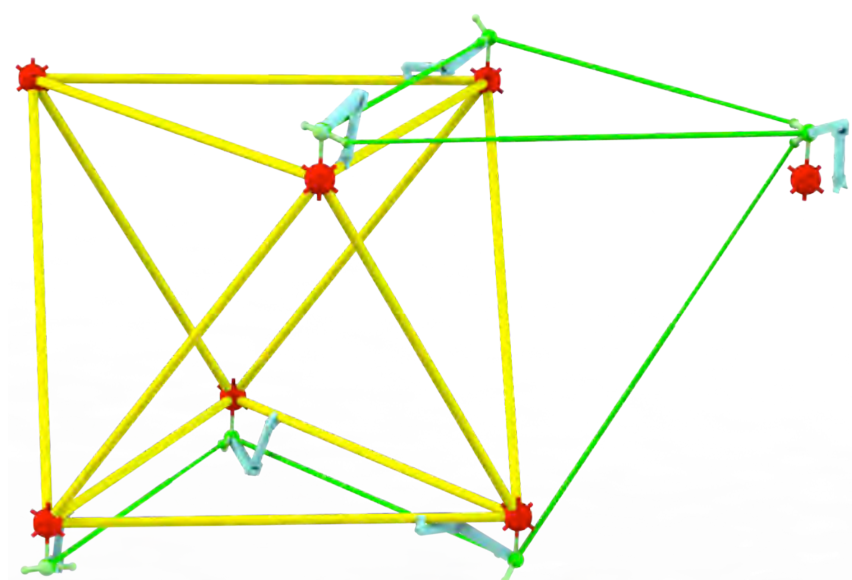


Figure 9. Bottom IPJR connecting to top IPJR frame to form stinger.

neighboring IPJR and the passive arm(s) will receive connections. The active arm will be able to change its length through linear actuation. A triangle can be thus envisioned: IPJR 1 actively connects to IPJR 2, which actively connects to IPJR 3, which finally actively connects to IPJR 1 (see Fig. 7b). A separate stinger may connect to one of the three IPJRs and extend orthogonally to the triangle.

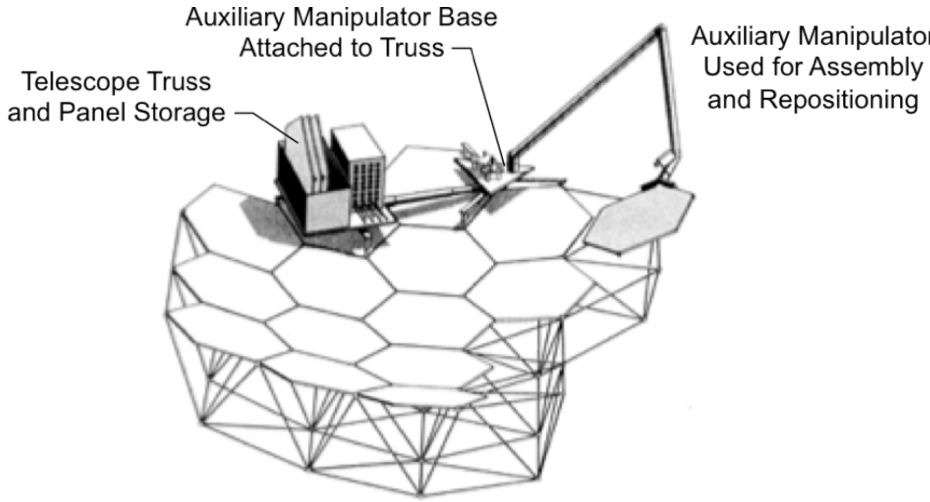


Figure 10. Concept showing example of relocating using an auxiliary manipulator.

For assembling a tetrahedral truss, which consists of two surfaces of triangular cells with core struts connecting the two surfaces, two sets of three IPJRs will be able to work simultaneously on either surface, forming triangular frameworks. To orient each triangle properly, the two IPJR frameworks will coordinate by attaching their stingers and manipulating their lengths. Once a framework has been formed by the IPJRs, the IPJRs will precisely set their lengths. Following this, an auxiliary manipulator will bring struts to the IPJR set for installation. Each IPJR will have at least one strut gripper that can accurately locate a strut between two nodes and ensure that it is parallel to the IPJR's active arm. The auxiliary manipulator will then weld the strut in place. When the welding is complete, the IPJR's active arm will apply a proof load and then the IPJR can reposition to a new location in preparation for the next strut. There are two options for repositioning the IPJR: using its own strut grippers to move around the truss, or being moved by the auxiliary manipulator. Currently, the second option is the preferred and could take place in a manner that is similar to the method and configuration shown in Figure 10 where truss assembly has been completed and panel installation is proceeding. The auxiliary manipulator is assumed to be self mobile: for example, as a zone of truss structure within its workspace is completed, it remains affixed to the last structure cell constructed or to the set of IPJRs and relocates it's base and associated construction materials to enable further construction. Other modes of IPJR locomotion can be executed by varying individual IPJR separation options from the framework: a framework of IPJRs may 1) remain connected, 2) may partially detach but connect in the same topology, or 3) may completely separate from each other. To minimize the number of active-arm-to-passive-arm connections required, the first option is preferred.

Design, construction, and test of the IPJR systems will proceed in two phases. The first phase will be a 2D experiment for assembling a planar truss, and the second phase will be a full 3D assembly experiment. The 2D experiment is expected to be simpler (for example, no coordination between faces required), but will still allow for a full vetting of the hardware that will be used to perform the 3D experiment. The 2D experiment will focus on testing and verifying the IPJR distance measurement, object gripping and manipulation, path planning, and assembly sequence algorithms. Disturbances due to external forces such as gravity and thermal expansion will not be modeled. In the 2D experiment, stinger operation is not required because all triangles will be confined to a single plane, allowing the IPJRs to form into groups of 3. Several prototypes will be developed during the first phase, ranging from very simple proof-of-concept devices to devices representing highly detailed versions of the struts, welding equipment, and auxiliary manipulators. The proof-of-concept prototypes will also be used to investigate various algorithmic issues, such as arbitrary trusses and parallelism.

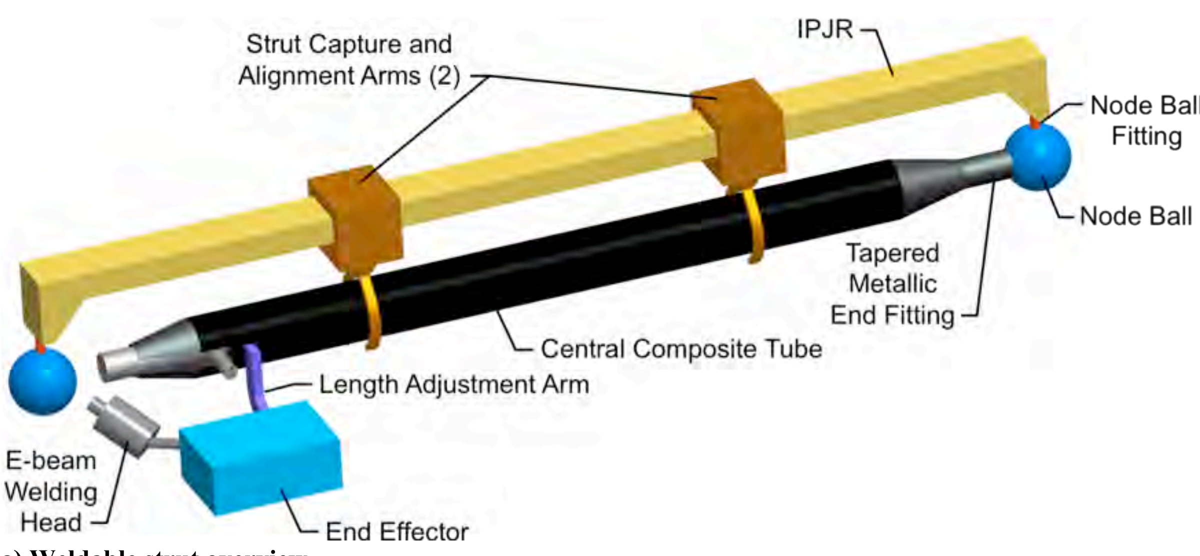
The second phase will address assembly of complete 3D trusses, including a telescope support truss. This will further validate the algorithms tested in the first phase, and will also introduce the additional challenge of structure deformation due to gravity loading that must be overcome by the auxiliary manipulator and the IPJRs. This phase will also allow stinger operations to be tested. The end result will be the assembly of a complete (first ring) telescope support truss.

B. Weldable Structural Elements and Components

In general, the truss structures that were previously assembled using either EVA[20] or robotics[21] consisted of two basic elements; the strut members (with connecting mechanisms on each end) and node balls (which also had an arrangement of connecting mechanisms). Examples of this erectable truss technology are shown for both EVA and robotic assembly in Figures 5 and 6 respectively. Many features were incorporated into these mechanical joints, which resulted in extremely good structural behavior and efficient structural assembly.[10, 20, 21] The connecting mechanisms were complex because they were required to perform a large number of functions, such as; aligning the struts for insertion, correcting for slight perturbations in length between nodes, precisely setting the distance between truss nodes, capturing and holding struts at insertion, locking struts (which preloaded them and provided linear load-deflection behavior), and enabling unlocking and disassembly of struts. Since two connection mechanisms were required for each end of a strut (one attached to the strut and one attached to the node ball), manufacturing the structure was expensive, and the mass associated with the node balls and the connection hardware was usually at least as much as that of the struts themselves.

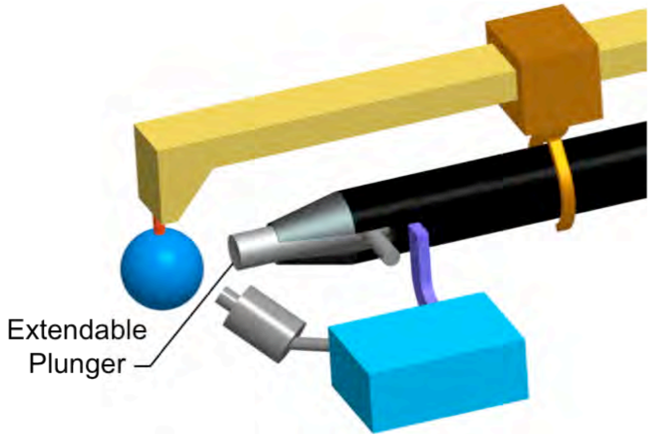
As an alternative to requiring a pair of connecting mechanisms for each strut in the truss, the assembly paradigm here proposes that the struts be very simple structure. The jigging and length setting functions are now accomplished by the IPJRs. The cost of these functions should be drastically reduced since only six copies of a single jigging robot are required, compared to the hundreds or thousands (depending on the truss details) of strut connections. In addition, the jigging robots are reusable, so that their costs (and mass to put into service) can be amortized over a large number of spacecraft assemblies. The joining function is accomplished by welding, which reduces the mass of the connections and results in a strong, linear (in load-deflection response) and stiff connection. Since the E-Beam welding process advocated here can also cut, these joints can also be disassembled if required.

The current concept for the weldable struts would have a lightweight, high-stiffness central tube section made from graphite epoxy,[10] with simple metallic fittings bonded into each end of the tubes, as illustrated in Fig. 11a. The end fittings would be tapered to minimize the size of the node ball, with the fitting on one end being fixed length and the fitting on the other end having a capability to adjust length; using for example, a simple extendable plunger (Fig. 11b) or collar. The strut would be presented to the IPJRs with the plunger retracted. When the IPJR framework set the proper spacing between nodes, the IPJR would place the fixed end of the node (for struts where both ends must be welded) against the node ball and hold in place during welding. The welding end effector would then move to the other end of the strut, push the plunger against the node ball, and perform two welds (Fig. 11c); first welding the strut end to the node ball, and second, welding the movable plunger to the fixed portion of the end fitting to complete that strut's assembly (Fig. 11d). The node balls would be small diameter simple spheres with a protruding feature perpendicular to the sphere surface. The feature performs several functions: it serves as the reference point for the node center, which the IPJRs use to set precise lengths; it is the feature that the IPJRs grasp when they connect to a node; it will be the support structure for other spacecraft components which might be attached to the node (telescope reflector panels for example); and could also provide a means for the IPJRs and other robots to move around on the structure after it has been assembled. Titanium is currently the preferred material for both the strut end fittings and the node balls because it is; lightweight, compatible with E-Beam Welding, has a low coefficient of thermal expansion and compatible with polymeric composite materials.

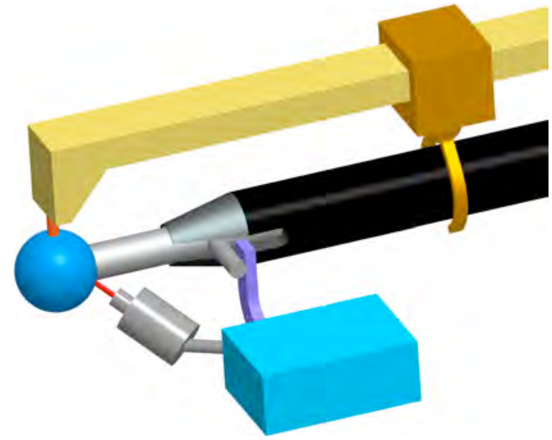


a) Weldable strut overview.

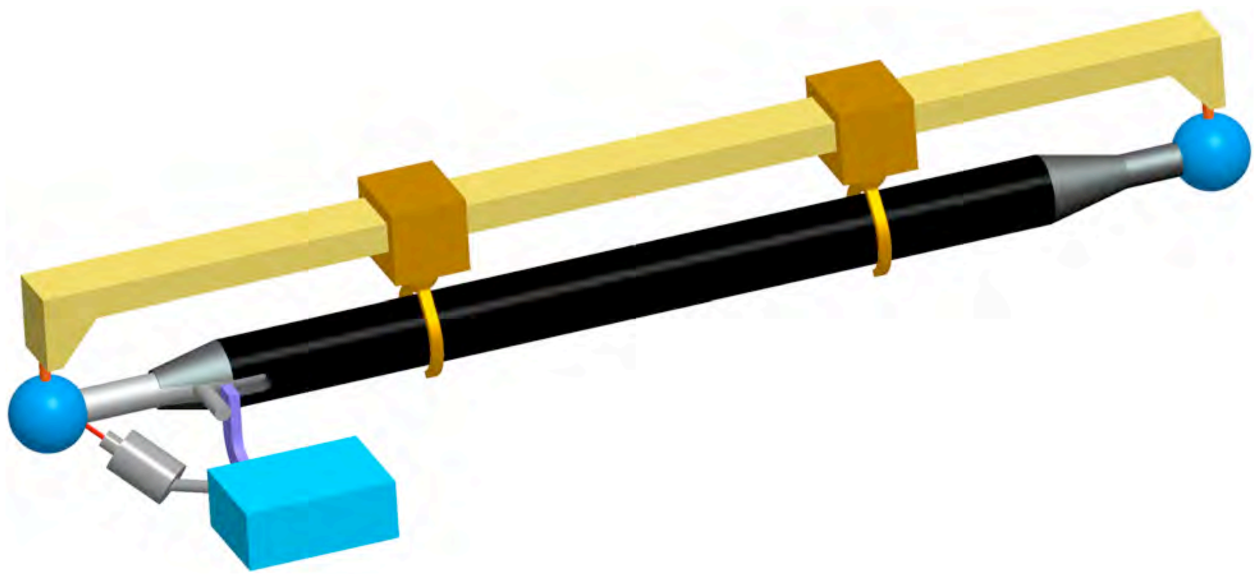
Figure 11. Weldable truss strut and assembly.



b) Strut inserted and aligned.



c) Strut extension and welding.



d. Assembly completed.

Figure 11. Weldable truss strut and assembly (concluded).

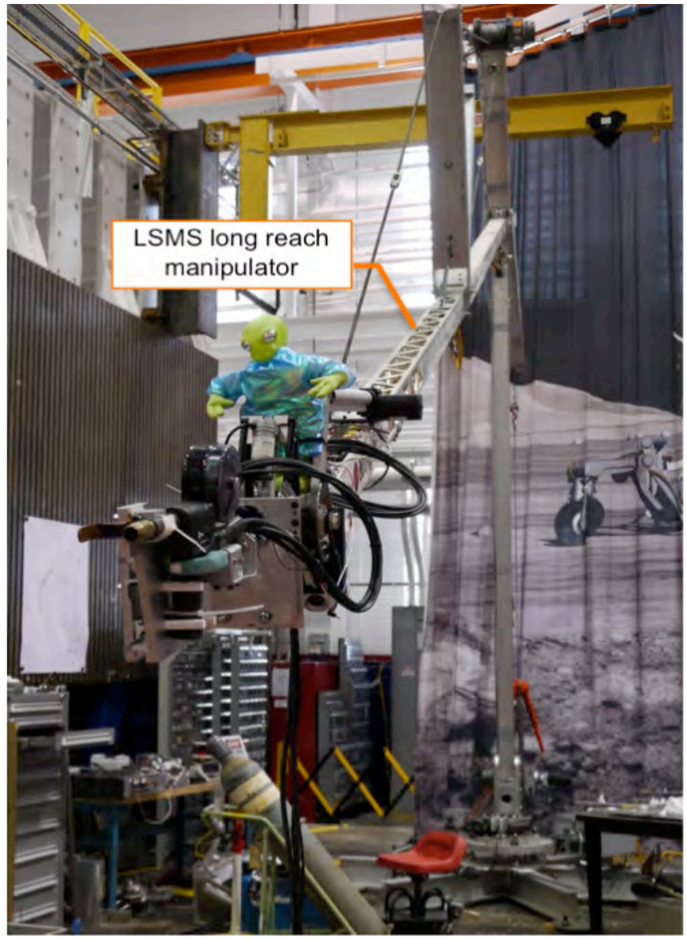
C. Electron Beam Welding

Welding experiments have been performed on-orbit since the 1970s by both the US, in Space Lab, and the Russians, on Mir. Both arc welding and electron beam welding trials were successfully conducted. The Russians demonstrated electron beam welding, heating and cutting with the Universal Hand Tool, a hand-held low accelerating voltage (<8 kV) electron beam gun.[14] The low accelerating voltage minimized the production of x-rays that occur with the interaction of the electron beam with the work piece.

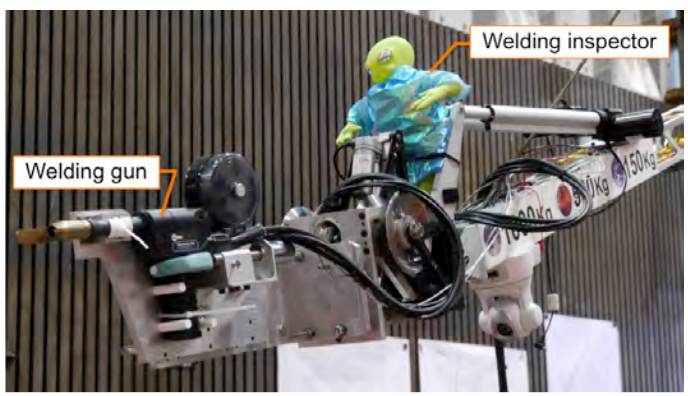
An electron beam has several advantages over arc or laser processes for use in on-orbit welding. Production of the electron beam and coupling with the work piece is very energy efficient, with over 90% of the power used being input to the work piece. In contrast, the best lasers are only about 50% efficient in generating a beam and less than 10% of that beam energy is input to the work piece. The only consumable in the electron beam process is the cathode, which can have a lifetime of hundreds of hours. In contrast, a gas is required in arc welding processes, not to shield the weld, but in order to carry the arc.

The new concept currently being developed for on-orbit assembly of a truss structure would use welded joints at the nodes. The welds would be made using an electron beam (E-Beam) gun that is the main component of an end effector on the auxiliary robotic manipulator. An advantage of using the E-Beam gun is that it may accommodate a large standoff distance from the work piece, eliminating potential interference when accessing joints. An optical system on the end-effector would be used to measure the standoff distance and the gross position of the joint. Then, the seam-tracking mode of the E-beam gun would be used to determine the precise location of the joint. In seam-tracking mode, the joint is scanned with a very low power beam and an antenna on the gun records the position. The electron beam is magnetically focused and can also be steered by using magnetic deflection coils. This permits joints to be welded without physically moving the electron gun. Since the electron beam can be magnetically steered with very fine position control, the auxiliary manipulator does not necessarily need to have high precision for welding operations. Depending on the details of the structural configuration, the entire joint can be welded while repositioning the end effector only two or three times. The electron beam is a multi-purpose tool; in addition to welding most aerospace alloys it can also be used for cutting, drilling, or, with the addition of a wire feeder, additive manufacturing.

The capability of robotic welding using a long-reach manipulator is currently being demonstrated using the Lightweight Surface Manipulation System[22] (LSMS). The LSMS (see Fig. 12a), a 3-degree-of-freedom manipulator, has a very large work envelope as would be required by the auxiliary manipulators. Similar to the space assembly approach, experiments have been performed using the LSMS that demonstrate the ability to precisely position a welding end effector at any location within the work envelope and hold the end effector steady during welding operations. Electron beam gun welding is complicated because it generally requires a vacuum to operate. Because of the preliminary nature of the current investigation and the desire to develop operational concepts, a low cost gas metal arc (GMA) welder is currently being used. In these experiments the welding gun was integrated into an end effector that was attached to the LSMS wrist (Fig. 12b), and the LSMS elbow joint was rotated to achieve vertical welds on the structural components. Simulated truss nodes and flat plates have been joined successfully using this equipment, as shown in Figs. 12c and 12d respectively. It is planned to demonstrate the beam deflection technique in LaRC's electron beam welding system in the near future.



a) LSMS long reach manipulator with welding end effector.



b. Close up view of welding end effector.

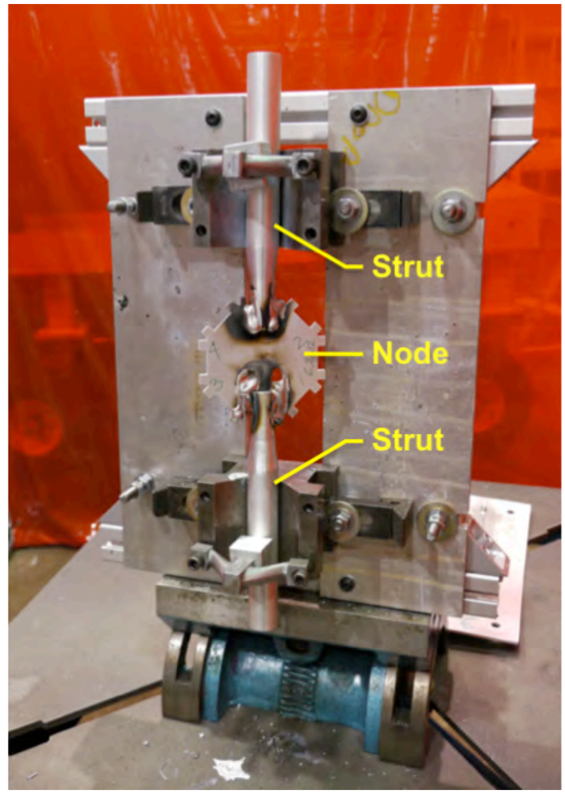
Figure 12. Welding experiments using the LSMS.

D. Robotic Handling, Manipulation and Assembly

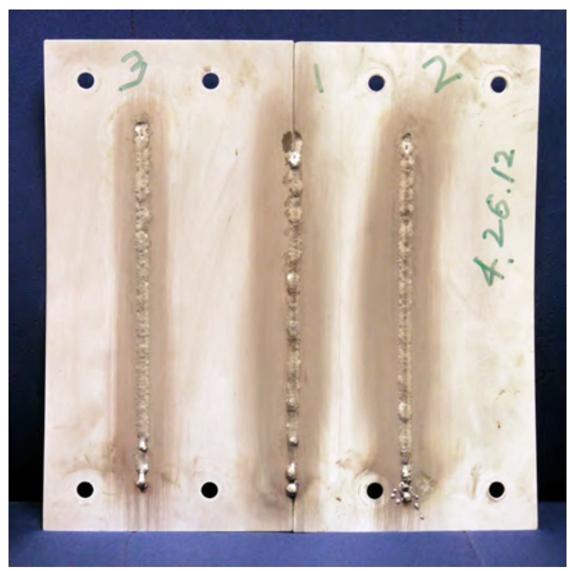
One or more auxiliary robotic manipulators will be an integral part of the complete assembly system. Because of the large scale of the envisioned spacecraft and telescopes being assembled, manipulators with long reach, on the order of several strut lengths, will be desirable. This will allow the manipulator to fix its base at one location yet have sufficient reach; to retrieve material from a storage site and present it to the IPJRs at the assembly site, and also to reposition itself and the IPJRs (if that option of IPJR relocation is chosen) during the assembly process. The auxiliary manipulator will also acquire and position various end-effectors used during spacecraft assembly. The over arching operational philosophy is to use versatile general-purpose manipulators along with specialized end effectors to perform required assembly functions, a philosophy successfully applied during earlier automated truss assembly efforts.[12, 21] A welding end-effector is key to the scheme proposed here. Its main functions will be to locate the E-Beam welding head at the proper stand-off distance and angle from the area being welded and hold it there during node-to-strut welding. It then relocates the welding head and positions it to weld the interface between fixed and extendible portions of the strut. Then it repositions the welding head ~180 degrees to the opposite side of the strut and performs the same set of welds. Since some struts must be welded on both ends, the end effector also must have the capability to point the welding head at both strut ends. The welding power supply and control system would also be integrated into the end effector.

Many of the detailed operational techniques and hardware concepts previously developed at the Automated Structure Assembly Laboratory (ASAL) for robotic truss assembly[12, 21] can be applied to the current assembly concept. The ASAL, depicted in Fig. 13, included three motion bases, an industrial robot, two special-purpose end-effectors and several surveillance cameras, which were used to assemble the hardware shown in Fig. 4b. The experiments verified the ability to automatically assemble telescope structures.

Lessons directly applicable from the ASAL assembly experience include; the approach for planning assembly sequences that maintain rigid structures and minimize manipulator motion, and the approach of supervised autonomy which requires automated (usually redundant) verification of each step in the assembly process. Only unexpected situations require human intervention. Cameras were used to record the last 4 hours of video continuously so that when a problem occurred requiring human intervention, the video could be reviewed prior to selecting an approach to continue. Key to the assembly robustness is the use of sensor systems to guide the robot while it is in close proximity to the structure. The ranges of the sensor systems overlapped allowing for hand-off zones where smooth transitions were made from one sensor system to another. For example, visible in Figure 6 are domino-like machine vision targets (often referred to as vision fiducials) that were used to guide the manipulator to a position where the structure could be captured by grippers, at which point a force torque system was used for final alignment. Robotic control transitioned from vision to force-torque only after the structure was captured, which was visually verified using video from the vision system. These overlapping sensor zones inherently enable the ability to reverse the assembly sequence should that be required for repair or to resolve an assembly problem. Within ASAL, manipulator and motion base motions were preplanned using off-line path planning algorithms. Similar path planners will likely be used to plan the motions of the IPJR's and the auxiliary manipulators that are providing materials and positioning special purpose end-effectors during welded assembly.



c) Simulated truss node/strut welding.



d) Simulated plate/pressure vessel welding.

Figure 12. Welding experiments using the LSMS (concluded).

Several new technologies are critical to and need to be developed to support assembly using IPJRs. These technologies include; an efficient mechanism to attach to and align the nodes, reliable methods to adjust the geometry of the set of IPJRs forming a triangular framework, reliable methods to move the IPJRs and structural components during assembly, reliable power distribution to the IPJRs and auxiliary manipulators as they maneuver around the structure, updated assembly sequence and path planning tools for generic structures, lightweight long-reach auxiliary manipulators to support the assembly process, and innovative ways to ground test the assembly sequence using proven IPJR sets and subsets.

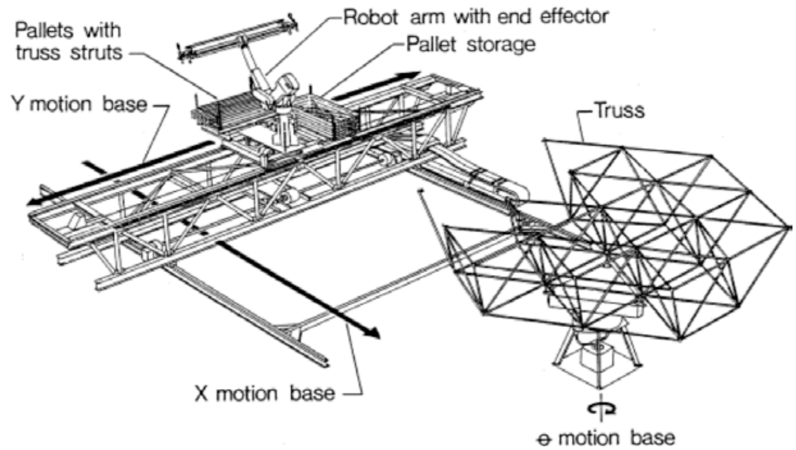


Figure 13. Automated structure assembly test bed.

A robotic manipulator is currently being developed that has many of the features that would be desirable for the general-purpose long-reach auxiliary manipulator described here. This manipulator is being designed to have ¼ the mass and ¼ the packaging volume of the current state-of-the-art long reach manipulator, the Space Shuttle Remote Manipulation System, while having similar tip force capability. The new manipulator architecture is scalable to accommodate any large truss geometry and is designed to stow compactly and deploy using the same motors that are used to actuate the manipulator. A patent disclosure has been filed for this new manipulator concept and in order to protect the intellectual property no further details can be provided at this time.

E. Operations Assembly Sequence and Path Planning

The assembly sequence can be decomposed into a sequence of IPJR placements, attachments, length adjustments, strut manipulations, and welding. An abstract version of this model was previously considered[13] in which arbitrary structures made of cubes are decomposed into a feasible assembly sequence, which is then used by "Intelligent Scaffolding" to assemble a structure. Although general truss assembly will share several similarities, it will also pose unique challenges. An optimum assembly sequence will be obtained by including the following:

- Reducing backtracking, or minimizing IPJR and auxiliary manipulator movements.
- Reducing obstacles to IPJR and auxiliary manipulator movement.
- Reducing sequence steps (strongly correlated to backtracking).
- Reducing surface error.
- Maintaining robustness to IPJR failure, welding mistakes, and auxiliary manipulator failure.
- Efficiently assembling secondary structures such as mirrors, sunshades, utilities, etc.

For regular telescope trusses, an assembly sequence can be carefully designed to encounter the fewest problems. However, the general case of automatically devising a build sequence for an arbitrary truss, is a challenging algorithmic problem[13] that will continue to be a focus for development.

A telescope support truss consists of rings and has a trivial build sequence: start in the center and build each successively larger ring in order. However, finding the build sequence that minimizes or eliminates backtracking is computationally difficult. To prove this assertion, consider a graph in which each cell is mapped to a node (called a "graph node" to distinguish from truss nodes), and cell adjacency is represented by edges between the graph nodes. An assembly sequence that has no backtracking assembles cells in adjacent order, and can be thought of as a path through the graph that visits each graph node only once. Backtracking occurs when an IPJR set must move from one graph node to a distant node by taking a path through already-assembled cells. Finding a path through a graph that visits every graph node exactly once is known as the Hamiltonian Path problem, and is Non-deterministic Polynomial (NP)-Complete. Although this is a difficult problem to solve in the general case as previously mentioned, some trusses, such as those for the telescope aperture support, provide easy and intuitive solutions.

When factoring in other requirements listed above, finding a shortest path that minimizes backtracking is not the only consideration: it is possible that there is some path that has extra backtracking but leads to a better overall solution. Finding this optimum path requires two things: 1) a scalar fitness function that can assign a fitness value (where a higher value is better) to each proposed assembly sequence, and 2) an algorithm for quickly locating an assembly sequence that is better than some required fitness parameter. As previously mentioned, this NP-Complete problem is difficult to solve, but heuristic methods are likely to be successfully applied. One such approach, a greedy method used previously,[13] states: when choosing which cell to add next, add a cell that is adjacent to the cell on which the IPJR is currently resting. This will only require backtracking when the current cell does not have any neighbors that have yet to be added. The ability to backtrack may also be hindered by obstacles, such as large physical objects that prevent attachment (such as mirror panels). The algorithm must also consider that some assembly sequences may result in trusses that have a higher average positional error than others. Designing a fitness function and an algorithm for determining very good assembly sequences is not trivial. However, this research may help advance the field of automated assembly, opening the door for robots to build increasingly larger space structures.

An additional challenge for arbitrary trusses is assembly by multiple sets of IPJRs working in parallel. Parallel assembly has the following benefits: 1) it can speed up the assembly process, 2) it is robust to failure because IPJRs are able to substitute for one another, 3) each individual robotic component is less likely to fail because it is only performing a subset of the required steps, and 4) the entire structure could eventually be completed even if only a single set of IPJRs remains functional. Research into parallel assembly will not likely be used for assembling a single telescope truss, however large-scale concepts such as orbital stations will benefit from robots working in parallel.

The IPJRs and the auxiliary manipulator robots will require on-board path planning software to execute the assembly sequence reliably. All such robots are subject to numerous sources of error, including hardware failure, imprecise construction, inaccurate actuation, and imperfect sensors. As these problems have been a major focus of robotics for years, the IPJRs and manipulator robots must implement state-of-the-art algorithms for handling these inaccuracies. This can then be combined with an inverse kinematic solver to plan the overall sequence of moves that constitutes a single step in the assembly sequence.

High-accuracy sensors must be used by each IPJR to determine the distance between two nodes. Since two IPJRs are used on each edge, the distance measurement can be made more robust by requiring that each IPJR measure the distance and come to a consensus. The distance actuation will be controlled using this as feedback.

The auxiliary manipulators and IPJRs must also be able to detect structural deformation and warping. One approach would be to use a metrology station (much like a survey station) in the center of the telescope to verify and guide the assembly process and counteract systematic error buildup. Uneven structural heating induced by incident sunlight, as well as thermal expansion or contraction during the welding of individual struts can both lead to surface errors during the assembly process. Care must be taken to model or mitigate these effects, by using sun shades, welding in patterns that avoid distortion, scheduling hold times (to allow for thermal equilibrium) into the processes, etc.

V. Conclusion

Many NASA missions could benefit significantly if large space systems (such as telescopes) and methods for their in-space assembly were available. Several space science missions that defined large telescope concepts and that rely on assembly are reviewed. A great deal of research and technology development has been performed for the on-orbit assembled truss structures that serve as the foundation for large space telescopes and is summarized. Also summarized are astronaut and robotic procedures and techniques that result in very (time) efficient assembly of large telescope trusses having mechanical connectors.

However, these previous approaches for assembling large scale telescope truss structures and systems in space have been perceived as very costly because they require high precision and custom components. These components rely on a large number of mechanical connections and supporting infrastructure that is unique to each application. In this paper, a new assembly paradigm that incorporates reusable and versatile precision jigging in combination with inexpensive and low precision structural elements, is proposed to mitigate these concerns. Key advantages of the new assembly paradigm are: welded joints will result in highly predicable and linear structural performance; welding as a joining/assembly method provides very simple lightweight joints; the jigging robots and infrastructure are versatile, eliminating spacecraft scale and geometry as a limitation; and, the jigging robots are reusable for many different spacecraft assemblies which will reduce their cost to any one assembly.

A new assembly approach has been developed to implement the paradigm and the major elements in this new approach are described in the paper. These elements represent converging capabilities that can be integrated to provide a game-changing ability to assemble (with manufacturing as a natural extension) spacecraft structural systems on orbit. The result will be Custom-Built Welded Space Structural Systems that are assembled in space and have no limit on size. The approach is able to leverage a combination of historical and current capabilities and combine those with a proposed set of new developments to achieve viability. In a broad sense, the historical capabilities leveraged are those that have been developed for both EVA and Robotic assembly of large-span and large-area truss structures. The current capabilities leveraged are the development of the E-Beam process and hardware that will be used for welding (and cutting if required) and current capabilities in space robotics and robotic servicing. New capabilities must be developed in versatile and reconfigurable jigging that supports the structure as it is being welded, in robotic assembly sequence and path planning, and in advanced structural concepts for lightweight truss members that can be welded on orbit. The current status of each major capability and ongoing research and development efforts are also summarized.

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