Persistent Assets in Zero-G and on Planetary Surfaces: Enabled by Modular Technology and Robotic Operations

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Space operations are on the cusp of a revolutionary new operational paradigm that leverages modular systems and recurring robotic visits to "Persistent Assets" enabling asset maintenance, repair, and enhancement. A "Persistent Asset" is defined here as any zero-g or planetary surface system that benefits from in-space assembly (ISA) or multiple visits for servicing, repairs, and upgrades. This term is an extension of the term "Persistent Platform" used by Ms. Pam Melroy at the Defense Advanced Research Projects Agency to describe the vision of the Agency for a geosynchronous Earth orbiting platform. In this paper, the term "Persistent Asset" is introduced to encompass not only zero-g systems; such as telecommunication platforms, Earth observing science platform, Department of Defense platforms, and scientific telescope systems, but also planetary surface systems that support missions such as human outposts, science stations, and in-situ resource utilization systems. In contrast to the current state of the art, where space systems are typically launched as a single unit and operated without any further physical intervention after launch; future systems will be maintained, enhanced and reconfigured in-situ as new technology becomes available or mission needs change. Visits to the persistent asset can be regularly scheduled or dictated by funding constraints enabling a pay-as-you-go approach, which is largely independent of time-constraints and able to exploit launches of opportunity.

In this paper, historical in-space assembly activities which relied heavily on astronaut extra-vehicular activity will be reviewed as well as early robotic assembly activities. These approaches will be contrasted with emerging modular approaches supporting realization of a new Persistent Asset operational paradigm. The paper will define attributes of the Persistent Asset paradigm and illustrate advantages by applying the paradigm to two relevant applications: 1) a large space telescope backing structure and 2) the backbone structure for a solar electric transport vehicle. Finally, recently developed unique Persistent Asset elements (modules, and interface approaches) will be described.

Nomenclature and Acronyms

CFRP	=	Carbon Fiber Reinforced Plastics
CIRAS	=	Commercial Infrastructure for Robotic Assembly
ConOps	=	Concept of Operations
COTS	=	Commercial Off The Shelf
CTA	=	Compact Telescoping Array
CTSA	=	Compact Telescoping Surface Array
DARPA	=	Defense Advanced Research Projects Agency
DEOS	=	Deutsche Orbitale Servicing
DLR	=	Deutsche Zentrum fur Luft und Raumfahren (German Aerospace Center)
DOD	=	Department of Defense

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EBW	=	Electron Beam Welding
EVA	=	Extra-vehicular activity
eXCITe	=	eXperiment for Cellular Integration Technology
g	=	gravity
GEO	=	GEosynchronous Orbit
HISat	=	Hyper-Integrated Satellite
HPA	=	Hosted Payload Assembly
HST	=	Hubble Space Telescope
Hz	=	Hertz
iBLOCK	=	prequalified off-the-shelf building blocks in DLR iBOSS approach
iBOSS	=	intelligent Building Blocks for On-orbit Satellite Servicing
iSAT	=	iBoss based SATellite
IRMA	=	In-space Robotic Manufacturing and Assembly
ISA	=	In-Space Assembly
ISRU	=	In-Situ Resource Utilization
ISS	=	International Space Station
iSSI	=	intelligent Space Systems Interface
KABER	=	NanoRacks Microsat Deployer System
Kg	=	kilogram
kW	=	kilo Watt
LaRC	=	Langley Research Center
LEO	=	Low Earth Orbit
m	=	meter
MALSP	=	Modular Assembly of Large Space Platforms
MEV	=	Mission Extension Vehicle
MRV	=	Mission Robotic Vehicle
NASA	=	National Aeronautics and Space Administration
NINJAR	=	NASA Intelligent Jigging and Assembly Robot
PA	=	Persistent Asset
PAC	=	Package of Aggregated Cells
PASIST	=	Persistent Asset Staging, Improvement, Servicing and Trade-out
PATI	=	Persistent Asset Technologies and Infrastructure
PEM	=	POD Ejection Mechanism
POD	=	Payload Orbital Delivery
PODSat	=	Payload Orbital Delivery system Satellite
PPU	=	Power-Propulsion Unit
RAMSES	=	Robotic Modular Assembly of Space Exploration Systems
RMS	=	Root Mean Square
ROS	=	Robot Operating System
RSGS	=	Robotic Servicing of Geosynchronous Satellites
satlet	=	Satellite architecture component
SAMAURI	=	Strut Attachment, Manipulation And Utility Robotic aId
SBIR	=	Small Business Innovative Research
SEP	=	Solar Electric Propulsion
SETV	=	Solar Electric Transport Vehicle
SIMPL	=	Satlet Initial Missions Proofs and Lessons
SSF	=	Space Station Freedom
SSL	=	Space Systems Loral
STMD	=	Space Technology Mission Directorate
TALISMAN	=	Tendon-Actuated Lightweight In-Space MANipulator
UDS	=	Universal Docking System
W	=	Watt
zero-g	=	near zero gravity, i.e. not on a planetary surface or on the surface of the earth
3D	=	Three Dimensional

I. Introduction and Background

Space operations are on the cusp of a revolutionary new operational paradigm that leverages modular systems and repeated robotic visits to "Persistent Assets" enabling asset maintenance, repair, and enhancement. A "Persistent Asset" (PA) is defined here as any zero-gravity (zero-g) or planetary surface system that benefits from multiple visits. These visits can be used for assembly, servicing, repairs, reconfiguration, and upgrades.[1-5] Several companies are developing vehicles and robotic assets to support these operations.[5-8] The term "Persistent Asset" encompasses not only zero-g systems; such as telecommunication platforms.[9] Earth observing science platform, Department of Defense persistent platforms, and scientific telescope systems[4], but also planetary surface systems.[10-12] "Persistent" is used to emphasize that the asset has a long lifetime. In-Space Assembly (ISA) to efficiently deploy PA's has been predicted for decades (Hedgepath, Mikulas).[13] Only recently has the commercial need for methods to reliability modify on-orbit spacecraft capabilities become critical due to the rapid advancement of electronic system technology and the increased competition from alternate approaches such as shorter life low earth orbit constellations. This need makes it imperative to upgrade systems more frequently than the 15+ year lifetime of existing systems. In addition, to remain competitive satellite operators need approaches to rapidly respond to changes in customer requirements. These needs, coupled with the advent of low cost launch providers[14] and proven reliable operation of space manipulation systems with high degrees of autonomy[15-19] has created a unique environment for the adoption of a PA operational paradigm.

The Persistent Asset paradigm is defined to include the following attributes: 1) provides rapid emplacement of capabilities followed by planned upgrades and enhancement, 2) benefits from multiple visits; 3) can be anywhere in space (zero gravity or planetary surface); 4) incorporates modular systems and connectors; 5) enables modules to be integrated and tested before launch; 6) modules can be assembled, serviced, repaired, exchanged, etc.; 7) emphasis on robotic (as opposed to crew) interactions; 8) modular components are launch-vehicle agnostic; 9) space operations make use of a standard toolbox of technologies, capabilities, and infrastructure tools; and 10) modules reused for multiple missions. These terms will be defined in detail in section III.

Incorporating ISA fundamentally alters the design of a space system since the first time the complete system will be realized is in the operational space environment. Because the system cannot be tested prior to launch, a greater reliance on analytical modeling is necessary to accurately predict final operational system performance. An ISA PA can largely be designed for in-space operational loads, as opposed to launch loads. In addition, components may be arranged to optimize packaging over multiple launches with few operational constraints limiting their final location on the spacecraft. The impact of expanding the design space and associated design freedom results in significant mass and volume reductions while simultaneously improving overall mission robustness and reliability.[20] PA design is fundamentally a co-design problem involving the PA, as well as the infrastructure, agents and tools necessary to realize the PA. Here, an agent is either a semi-autonomous robot, tele-operated robot or Extra-Vehicular Activity (EVA) astronaut, with final selection of a particular agent decided by considering capability, availability, costs, and risk.

A large number of terms are used to describe features and capabilities that enable effective operation of long duration PAs. Terms such as in-space assembly, in-space servicing, in-space repair and refurbishment, modularity, in-space upgrade, in-space expansion among others. In an attempt to provide an over-arching system architecture and framework for space systems, the term "Persistent Asset" is being introduced in this paper. In contrast to the current state of the art, where space systems are typically launched as a single unit and operated without any further physical intervention. Future systems will be maintained, enhanced/upgraded, and reconfigured in-situ as new technology becomes available or mission needs change by visiting the asset multiple times.[14] A key benefit is that the schedule of visits to a PA can be responsive to funding constraints which enables a pay-as-you-go approach that can be largely independent of time constraints and is also able to exploit launches of opportunity. The new paradigm described in this paper is made possible by the recent emergence of: 1) new commercial launch capabilities providing low cost and frequent launch opportunities; 2) the emergence of in-space robotic capabilities[14-19] integrated with commercial spacecraft enabling frequent and economical visits to Persistent Assets;[3,5,6,8] and 3) advances in electronics, computational architectures and software systems enabling these robotic systems to perform reliably for extended periods of time autonomously.

This paper will begin in the next section (section II), by providing a brief summary of current and past activities that have addressed in-space assembly and servicing capabilities and technologies. Then, a PA, its features and benefits will be defined in section III and that definition applied to relevant missions in section IV to illustrate how the PA paradigm is a new and more comprehensive paradigm for architecting future space systems. A key point is that the systems must follow a "Design For Persistence" philosophy from their inception, effective PA's cannot created by retrofitting a heritage design. Next, recent efforts being conducted by the Langley Research Center (LaRC) to develop technologies that enable the PA paradigm will be summarized in section V. Finally, the paper will be summarized in section VI.

II. Recent and Historical Activities for In-Space Assembly and Servicing

A. Recent Activities

The ability to manage persistent assets through multiple visits has experienced renewed attention. Both the agents and infrastructure elements needed to maintain, repair, upgrade and assemble systems are being developed. Also under development are the fundamental modules and interfaces that form the basic building blocks of these systems. Several commercial companies and government organizations are pursuing agents and zero-g transportation systems to support servicing and repair.[21] These include:

Space Systems Loral **-** who is developing the:

a) Robotic Servicing of Geosynchronous Satellites (RSGS) platform for the Defense Advanced Research Projects Agency (DARPA),

b) Restore L platform for NASA

c) Dragonfly system through a government industry partnership including Tethers Unlimited and NASA.

Northrup Grumman *(formally Orbital ATK)* - who is developing the:

a) Mission Extension Vehicle (MEV)

b) Mission Robotic Vehicle (MRV)

c) Commercial Infrastructure for Robotic Assembly and Servicing (CIRAS) system

Airbus – who is developing a space tug named the

DLR DEOS system - i.e. the Deutsche Orbitale Servicing (DEOS) mission

In addition, several other significant activities, which contribute capabilities to realize PAs are ongoing. They are included here because they provide additional module interface solutions. These activities include:

a) **NovaWurks HISat:** NovaWurks has developed a "satlet" for the DARPA Phoenix program called the Hyper-Integrated Satlet (HISat).[22] "A satlet is a satellite architecture component into which the functional capabilities of a conventional spacecraft are decomposed and can then be aggregated back together to provide desired subsystem capabilities".[22]

Currently, there are 3 missions in which the HISats are being used. 1) Satlet Initial Mission Proofs and Lessons (SIMPL), has launched six satlets along with two deployable arrays to the International Space Station (ISS). The SIMPL was assembled by the crew and then deployed via the KABER Microsatellite deployer.[23] 2) The eXperiment for Cellular Integration Technology, (eXCITe), is a mission developed for functional and environmental testing of the HISats and Package of Aggregated Cells (PAC) configuration, specifically studying payload adaption and use. Fourteen HISats were launched in a PAC configuration with payloads attached. Once in orbit, the PAC is planned to undergo a reconfiguration to test the capabilities of the HISats.[24] 3) The Payload Orbital Delivery system Satellite (PODSat) is another DARPA funded project using the POD system as a backbone for a four HISat PAC which will be deployed once in orbit.[24]

b) **DLR iBOSS**: The German Aerospace Center (DLR) is funding an approach for performing in-space assembly called iBOSS (intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly) (Figure 1).[25] iBOSS focuses on using cubesats to assemble a novel spacecraft that can create configurations for a myriad of missions. Since the spacecraft is comprised of cube-sat building blocks, it can be reconfigured and expanded. Each individual cube, referred to as an iBLOCK, has an intelligent Space System Interface (iSSI) on each face.[25] As described in Ref. 24, each iSSI consists of mechanical and thermal coupling features, data and power transfer connections. Each iBLOCK can connect with payloads, separate spacecraft, solar panels, and a variety of additional subsystems or components.

Figure 1. iBOSS-based satellite (iSAT).

Figure 2. iBLOCK with iSSIs on each face.

Each iBLOCK (Figure 2) is 40x40x40 cm^3, but can be expanded to multiples of the baseline shape for special payloads and tasks.[§§] Each iBLOCK can hold whole or parts of a subsystem within an inner volume of 25x25x25 cm^3.[§§] The mass of each iBLOCK without any subsystems is about 17 kg.[§§] The iBLOCK structure is made of Carbon Fiber Reinforced Plastics (CFRP) with aluminum nodes on the corners to carry load into the central load-carrying structure.[§§] Each iBLOCK provides a Robot Operating System (ROS) node which allows for balancing of thermal conditions, power consumption, and processing loads.[§§] The iBOSS based satellite (iSAT) can distribute tasks across all of the iBLOCKs to keep computation time low and increase efficiency.[26] The iSAT can be configured in many different shapes and sizes thanks to the iSSIs on each face of the iBLOCK.

c) **DARPA PODs**: In order to reduce cost and provide an "express delivery to Geosynchronous Orbit (GEO)", the Payload Orbital Delivery (POD) System was developed under the DARPA Phoenix program (Figure 3).[27] The POD is the payload delivery system on the Hosted Payload Assembly (HPA). Also included in the HPA is the POD Ejection Mechanism (PEM), which holds the POD using launch locks and a Universal Docking System, UDS.[27] The UDS allows for power and data transmission between the host spacecraft and the POD and its payload while also releasing the POD safely. The standard POD chassis can support a payload manifest of up to 60 kilograms, allowing multiple Cubesats or satlets to be used on a POD.[27] Additionally, a payload can be developed to directly interact with the UDS and bypass using the POD as a support structure. For spacecraft hosting the HPA, after deployment of the POD, only the PEM remains connected, therefore lowering the excess mass carried on the host spacecraft throughout its lifetime.

B. Historical Activities at the Langley Research Center

Current efforts can also leverage significant past developments in ISA technologies. Historical efforts in ISA began within NASA at the Langley Research Center (LaRC) in the 1980's-1990's. investigating assembly of a specific PA, the Space Station Freedom (SSF) [28], by astronaut EVA's. The LaRC efforts focused almost exclusively on the structural assembly, and did not sufficiently address the complexities of producing an operational system. While plans and tests were performed to address routing the electrical harnesses along the structure,[29] standardization of the interfaces with the; habitation system, instruments, docking equipment and robotic assets were never matured. However, the efforts demonstrated many of the advantages of the ISA paradigm including efficient packaging, repairability, and upgradeability.[30] Two of the most important outcomes of the work were; the ability to predict the final (as-built) resulting structural performance a priori, and 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. The SSF effort resulted in detailed design 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;[31] 2) a mobile transporter (Figure 4), capable of transporting agents around all 4 sides of the SSF using an efficient system that engaged guides on the SSF backbone truss[32]; 3) efficient rotary joints (called the alpha joint) capable of orienting large solar arrays[20]; and 4) a unique approach to installing cable harnesses during assembly.[32]

In addition to SSF, a series of other significant EVA assembly activities were undertaken using a similar erectable joint system that was approximately one inch in diameter, which was derived from the two-inch diameter SSF

[§§] URL: http://www.iboss-satellites.com/fileadmin/Templates/iBOSS_Satellites/Media/iBLOCK.pdf [5/29/2018].

hardware. Three of these activities are highlighted here. The first involved the design and assembly of a 14m diameter radiometer (Figure 5) reflector based on a telescope concept developed during the Large Deployable Reflector program.[33] Ultimately, the critical performance requirements for diameter and stiffness, drove the study group to

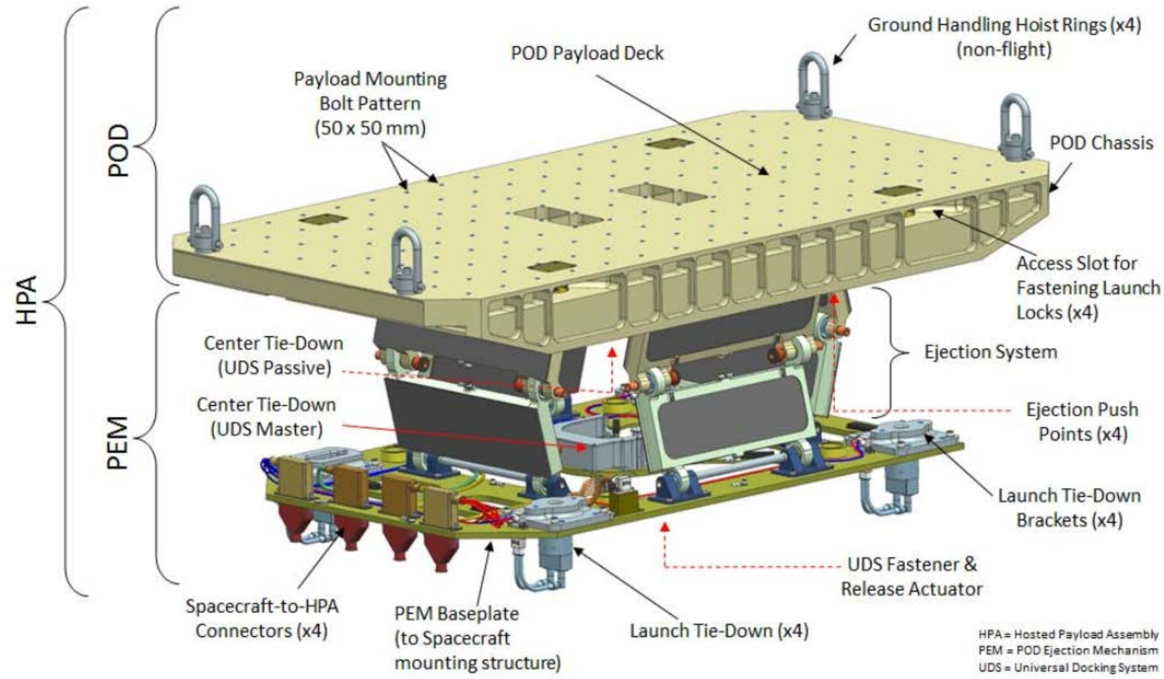


Figure 3. DARPA HPA.[27]

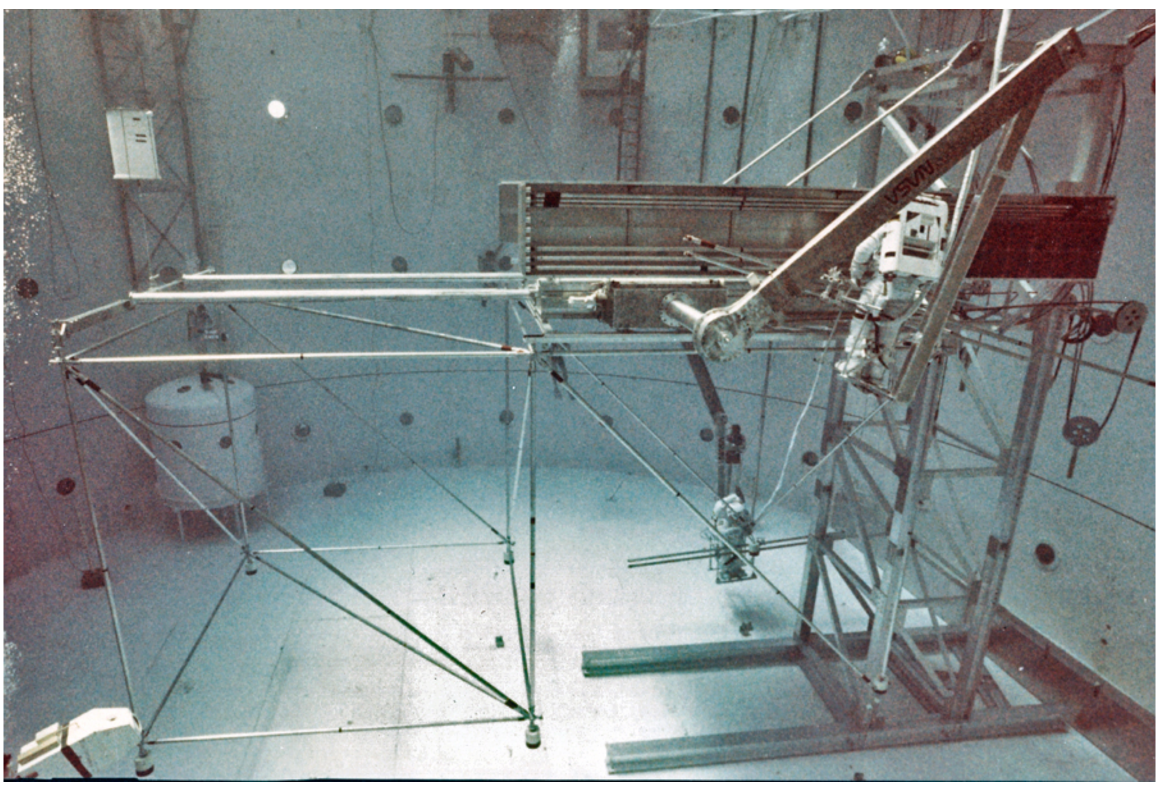


Figure 4. Mobile Transport used for Astronaut Positioning in Neutral Buoyancy Testing.

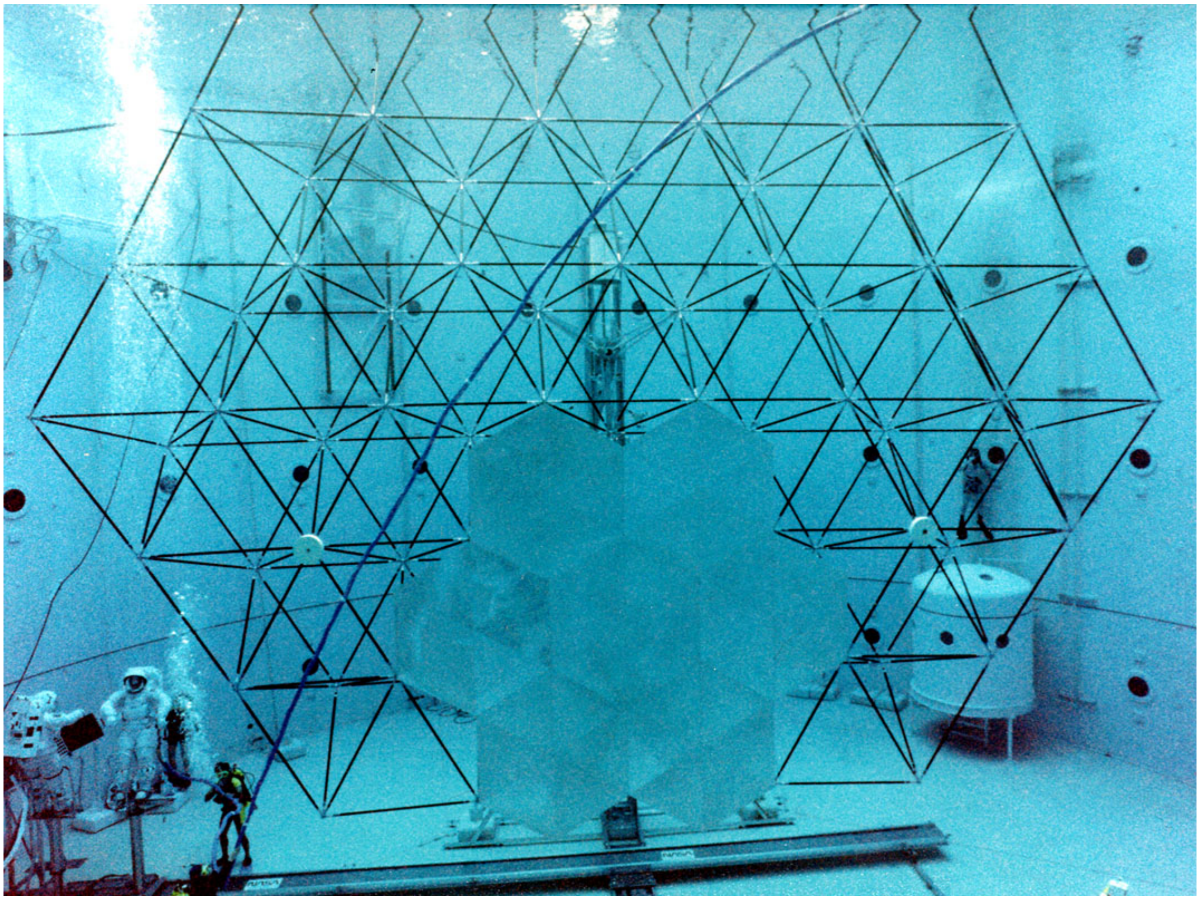


Figure 5. Astronaut Assembled 14m Radiometer.

recommend an erectable approach, i.e. an ISA approach. Second, the precision segment reflector, a 2 ring curved tetrahedral structure, 4m in diameter was assembled and tested. The assembled structure achieved a measured surface precision of ~0.00283 inches root-mean-square (RMS).[34, 35] This assembly precision is nearly independent of diameter if the same number of truss rings are used. Thus, using 3m structural elements instead of 1 m elements results in a 12m diameter structure with similar accuracy. Third, the same fundamental hardware was used to create long reach articulating structures such as a space crane (Figure 6) and variable geometry truss.[36, 37] Both of these articulating structures resulted in manipulator concepts having long reach while exhibiting high stiffness and the ability to exert significant forces.

In parallel with the astronaut EVA assembly activities described previously, a planar tetrahedral truss structure, consisting of 102 ~2m structural elements covered with 12 simulated telescope reflector panels was assembled using a supervised autonomy approach (Figure 7).[38, 39] The same supervisory system and hardware was used to build a beam (Figure 8) illustrating the versatility of the hardware and software system.[40] 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. The assemblies shown in Figure 7 and 8 were constructed using an automated path planning system. Plans were visually verified using a high fidelity simulation that automatically checked for collisions, this system planned paths using an ideal geometric model. The path constraints included adjustment ranges to accommodate robotic maneuvering required for a successful assembly. The assembly process relied on overlapping sensor feedback beginning with machine vision and ultimately culminating in a precision alignment of the structural members based on force feedback.[39, 41] While the main focus of the research was on automated assembly, the resulting structure (composed of 102 members) achieved an RMS surface accuracy of ~0.14 mm.[42] More recently, precision assembly of a planar structure assembled with primitive elements was studied.[43] An important feature of this work was to mathematically model node position error growth during assembly and use that capability to predict surface accuracy based on a known set of measurements, adjusting during assembly to achieve a high degree of surface accuracy ~4mm with low precision structural elements.[44]

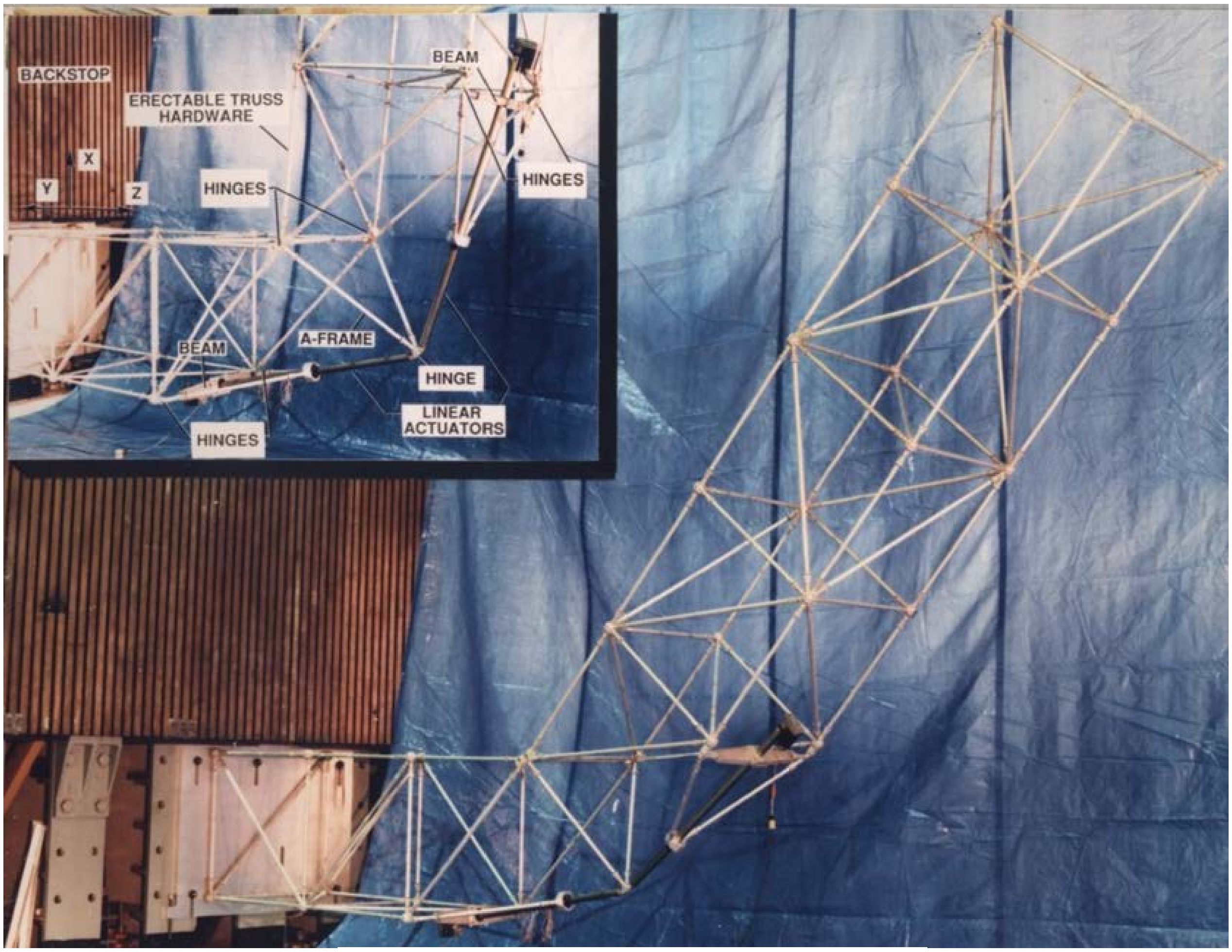


Figure 6. Erectable Space Crane.

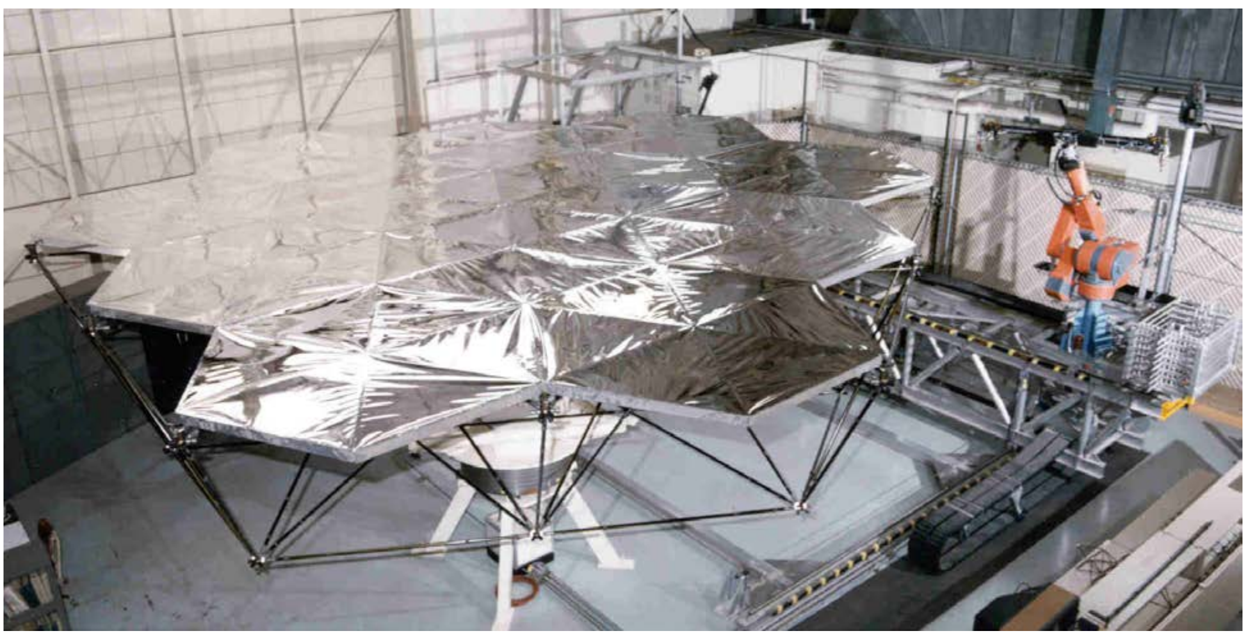


Figure 7. Automated Structures Assembly Laboratory.

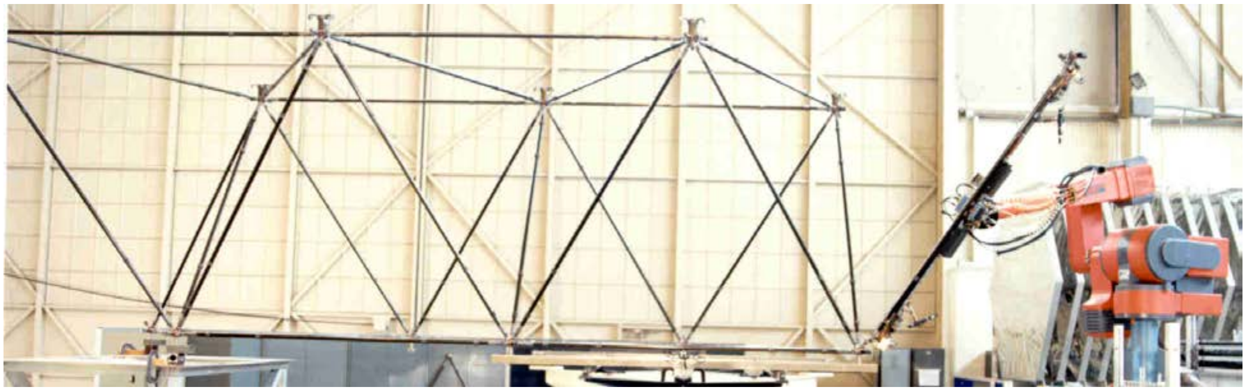


Figure 8. Automated Beam Building.

III. Persistent Asset Definition

A key feature of Persistent Assets is that they incorporate modularity in their design. In fact, a fundamental attribute of a system that is designed for persistence is its modularity. The goal of modularity is to simplify space-platform design by developing versatile units that have a range of common features and interfaces. For maximum benefit and when possible, the modular units should not be mission specific, allowing for commonality between spacecraft having different mission architectures. Modularity reduces mission risk and allows replacements to be available during system creation or assembly, both during terrestrial check out as well as in-space and on planetary surfaces. Module replicates can be used for initial construction and later if servicing or repair become necessary. A suite of available modules can provide the building blocks for a variety of spacecraft, allowing rapid development and deployment of new missions at substantially reduced time and cost. Properly executed, modularity enables reconfiguration and upgrading through the exchange of existing modules with new modules having different or improved functionality. Modularity, together with a robust capability to perform in-space assembly and servicing have the potential to greatly expand the design space for new space mission system architectures and implementations.[6]

The Persistent Asset paradigm applies not only to the space systems/missions described previously, but also to the servicing spacecraft, robotics arms, tools, and the infrastructure used to perform the assembly, servicing, repair and upgrade functions.

A. Persistent Asset Attributes

The Persistent Asset Paradigm definition has a number of key attributes that are described next:

1) Provides rapid emplacement of capabilities followed by planned upgrades and enhancements: A mission system can be designed such that it achieves initial operational capability quickly, after the first launch for example. Subsequent visits to the asset can expand the asset to enhance mission performance, as well as upgrade capabilities based on new or advancing technology.
2) Benefits from multiple visits: The initial system design assumes there will be multiple visits that will occur; on a defined schedule (for servicing or upgrading operations), or on an unscheduled basis (when critical repair is needed for example). Multiple visits may also be used to assemble the system to achieve its initial operating capability. The multiple visit approach can ensure that one launch failure does not result in mission failure.
3) The approach is broadly applicable allowing assets to be located anywhere in space; orbiting or on planetary surfaces: Scientific, exploration, commercial, other government agency missions will have applications not only in various orbiting locations, but also on the surface of other planets, moons and asteroids. It will be extremely beneficial to apply the Persistent Asset paradigm to planetary surface systems where permanent occupancy is desired.
4) Incorporates modular subsystems and connections: Modules can be developed for structures (backbone trusses for example), power, propulsion, etc. In general, any spacecraft system that will be assembled, serviced, repaired, upgraded or expanded in capability should be modularized. As modules become standardized, the costs associated with design, development and manufacturing will reduce drastically. A hierarchy of modules classes will eventually be developed and standardized, having different sizes, masses and capabilities; 1-kilowatt-class, 5-kilowatt-class and 25-kilowatt-class solar arrays for example. The

connectors for these modules will be designed for assembly/disassembly so that the modules can be easily connected and removed, most likely using robotic assets.

5) Modules are fully integrated and tested on the ground before launch: A risk is that for some persistent assets, the full system cannot be tested as an integrated system before launch. The system could be: 1) too large, 2) planned for periodic updates, or 3) be designed solely for its operational (zero-g) environment, and unable to be tested in 1-g. To mitigate this risk, individual modules designed to be assembled in space using modular interfaces can be tested and integrated on the ground before launch and the entire PA validated through analysis. However, confidence in such an approach must be matured through correlation with flight data.
6) Modules have the ability to be assembled, serviced, repaired, and exchanged: These abilities are inherent in the system design. The term "in-space assembly" has been used extensively as a paradigm for increasing the performance and lifetime of space systems. The term Persistent Asset recognizes that there can be missions that require no in-space assembly, but will still be modular and benefit from the PA paradigm. Assets can be put in service using a single launch, but be designed to be serviced, and upgraded to achieve their persistence.
7) Emphasis is placed on cost effective supervised robotics, as opposed to crew, interactions: Space robotic capabilities are advancing under a variety of programs for both Low Earth Orbit (LEO)[45], and GEO[46], whereas crewed operations remain limited to LEO and the International Space Station (ISS).
8) Modular components are launch-vehicle agnostic allowing multiple launch vehicle options: Within a certain class of launch vehicle capabilities, a modular payload will have no preference for a particular launcher delivery system. For example, there are a large number of launch vehicles that have 5-meter diameter fairings and a payload mass in the 10 metric ton class, such as the Falcon 9, Atlas 5, Antares, and New Glenn. Modular components should be agnostic to a particular launch vehicle in this class, so that they are able to take advantage of lowest launch cost or ride sharing opportunities. This capability has the potential to drastically reduce the costs associated with any mission designed under the Persistent Asset paradigm. Multiple options in a class of launch vehicle ensures that a mission system or capability can continue if a particular launch vehicle is retired or ceases operations (the Space Shuttle and Hubble Space Telescope being a prime example of a detrimental linkage).
9) Space operations make use of a standard toolbox of technologies, capabilities and infrastructure: As more systems are designed for and implement the Persistent Asset paradigm, there will naturally evolve standards for modules and connectors, standards for operations, and a standard set of robotic capabilities, etc. Ultimately permanent infrastructure will evolve (space dock, space tug, servicing vehicles, etc.) to support mission operations. This will become the standard toolbox that mission planners are able to draw on to reduce the cost, risk and schedule for missions.
10) Modules reused for multiple missions: Initially standards will evolve for modular connectors, but it is anticipated that a set of standard modules will evolve subsequently. Likely modules types include: power (solar array), communications, propulsion, and attitude control. Reuse of these standard modules during system design has the potential for achieving significant reductions in mission schedule and costs.

New space system architectures and designs that embrace the PA paradigm will benefit from major changes to traditional requirements:

1) With frequent and inexpensive launches, minimum mass will no longer be the primary driver and increases to system mass can be traded to reduce mission cost (design, development and fabrication), risk (increased structural margins, carry spares) and test time.
2) By modularizing the spacecraft for a specific launch vehicle class, the launch volume and payload shroud dimensions will no longer be a primary driver because multiple launches can be economically procured.
3) By modularizing the spacecraft, 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 total spacecraft 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.

To illustrate the fact that Persistent Asset is a new paradigm, the attributes just described are applied to three missions in Table 1 to show that no current system meets the Persistent Asset definition.

Table 1. Example of Persistent Assets attributes applied to current missions.

Persistent Asset Attribute	Example Mission		
	International Space Station	Hubble Space Telescope	James Webb Space Telescope
1) Provides rapid emplacement of capabilities followed by planned upgrades and enhancements	√	√	
2) Benefits from multiple visits	√	√	
3) May be located anywhere in space			
4) Incorporates modular systems and connectors	√	√	
5) Modules are full integrated and tested on the ground before launch	√	√	
6) Modules can be assembled, serviced, repaired, exchanged, etc	√	√	
7) Emphasis is placed on robotics, as opposed to crew, interactions			
8) Modular components are launch-vehicle agnostic allowing multiple launch vehicle options	Initial assembly required Space Shuttle.		
9) Space operations make use of a standard toolbox of technologies, capabilities and infrastructure	√		
10) Modules reused in multiple missions			

The ISS and Hubble Space Telescope (HST) both have many of the Persistent Asset attributes noted above in Table 1. However, both required the retired Space Shuttle Transportation System for launch and the HST required a shuttle like systems for servicing, and upgrades. Both systems also heavily relied on astronaut assistance for assembly, and servicing. It is notable that the James Webb Space Telescope (JWST) embraces none of the Persistent Asset attributes. For the Webb, a launch failure will equate to mission failure, and “Out of the 180 or so deployments, there are probably, maybe, a half dozen or so that if they didn’t work, we could probably adjust to and live with. For the most part, it all has to work.”[47]

B. Requirements/Design Considerations

The Persistent Asset paradigm will require a new approach for implementing mission systems and spacecraft that we call “Develop For Persistence”. The word “Develop” has been used to not only include system design but also include other important factors, such as what servicing infrastructure and capabilities will be assumed or used (for the visiting servicing vehicles for example). Some of the high-level requirements and design considerations which must be addressed for a Persistent Asset include:

1) Operational/Mission location: options are many, including LEO, GEO, Sun-Earth libration points, lunar surface, Mars surface, etc. The assets/spacecraft available to provide transportation and servicing options will be different for each location.
2) Mission lifetime: the space spacecraft system might have a 5-year, 10-year, or essentially unlimited expected life. However, even short lifetime vehicles/platforms may benefit from having capability for repair or upgrade.
3) In-service concept of operations: Four possible approaches with increasingly complex operations are: 1) pre-launch integration (where integrated systems are defined to be those that are not designed for any on-orbit assembly or dis-assembly but the system supports servicing, for example refueling); 2) pre-launch assembly (systems that feature interfaces designed for on-orbit assembly and dis-assembly, but the interfaces are assembled prior to launch); 3) on-orbit assembly to attain the spacecraft initial operating configuration; and, 4) sustained in-space operations (including servicing, component replacement, expansion, etc.).
4) Number of launches required to achieve initial operating capability: ranging from 1 to multiple, with multiple launches enabling the pay-as-you-go approach to be executed.

5) Planned expansion over lifetime and growth configuration. It will be important to establish and understand a growth approach. For example, will a solar electric propulsion (SEP) vehicle double its power? The initial system will have to be designed to support future growth.
6) System performance: the stiffness of the structure may be important for a platform that is hosting instruments/payload, the stability and precision of the support structure and its connections may be important for large-area telescopes.
7) Assembly/infrastructure approach: many scenarios are possible, the spacecraft system might carry its own robotics on board and need no support, visiting spacecraft might arrive with modules/payloads and have the onboard robotics capability to disconnect modules from the host (and store for disposal) and attach replacements/upgrades. Eventually, permanent infrastructure (a space dock or in-space construction facility[48]) is likely to exist that provides all of the required capabilities to construct a PA.
8) Module types/classes on spacecraft/system (dimensions, volume, mass, etc.): a standard set of module types are expected to include structural, power, propulsion, etc. Within each type of module there might exist a finite hierarchy of capabilities; 1-kw, 5-kw and 20-kw solar array modules for example.
9) Classes of connectors: connectors are expected to have one or more combinations of functional classes including; mechanical, electrical, data, fluid, thermal, optical, etc.
10) Utilities provided by host spacecraft/platform via standard interfaces: range from operational footprint, to power, communications, fluids, etc.
11) Verification and Validation: onboard metrology is expected to monitor and measure spacecraft performance parameters, which are verified using pre-flight predictions. Verification can occur in phases during assembly, or for the final system configuration. Onboard systems might also monitor both spacecraft system and hosted payload systems health and give warning of system degradation.

In order to facilitate the application of the PA paradigm to a set of applications in the next section, the paradigm of assembly, repair, and upgrade of PA's will be referred to in this document as Persistent Asset Staging, Improvement, Servicing and Trade-out (PASIST). In addition, the overall approach and use of an interconnected set of technologies and capabilities that support the PASIST paradigm will be referred to as the Persistent Asset Technologies and Infrastructure (PATI) ecosystem, which includes the launch vehicles, PAs, robots, tools and support equipment.

IV. Persistent Asset Paradigm Applications

The Persistent Assets (PA) paradigm benefits a variety of missions, including both those in zero-g and on planetary surfaces. This section discusses several PA applications covering a range of sizes and system architectures for both commercial and government missions. These applications range from single launch modular satellites to the multi-launch modular construction of a surface outpost on the moon or Mars. Next, two examples providing a cross-section of the most probable near-term applications of PA's will be discussed, but many novel and innovative uses are expected as this approach becomes the standard practice in future space systems.

A. Modular Bus Satellites for Telecommunication, Science and Defense

The PASIST paradigm applies to single launch, single asset applications as well as to the assembly of larger space systems. Two primary applications are described in this section. The first uses a satellite bus with modular receptacles for nanosat-scale payloads that provides an alternative to CubeSats for cheap access to space with increased capabilities. The second application is to add serviceable primary components to typical commercial and government owned satellites, which could significantly decrease costs and increase mission capabilities or productivity over time.[9]

Nanosatellite-scale applications

Nano-satellites (Nanosats) have created new opportunities for academia, industry and the government to launch low-cost, lightweight (1 - 10kg) payloads to orbit. However, Nanosats must carry their own communications, power, propulsion (including enough to deorbit) and control electronics in addition to their payload, thus constraining their mission capability. An alternative approach, using PASIST, is to customize a standard commercial satellite bus with modular bays that can accept CubeSat sized payloads that are transported via ride-share on a variety of launch vehicles. The satellite bus provides communications, power and station-keeping for all connected modular payloads. This approach provides a number of advantages:

- The launched module(s) can be essentially 100% payload, only requiring a standardized connector for power and data. This greatly simplifies mission design.

- The payload is able to leverage the capability and services of the larger satellite it is attached to.
- Mission life can be extended. A bay on the PA could be bought or rented, with additional mission time negotiated if desired.
- The payload could be retrieved if this capability is deemed important or common enough: a servicing spacecraft could bring up new instrument modules and retrieve old ones for science missions for example.
- It reduces the proliferation of Nanosats in orbit and the increasing danger of orbital debris from defunct satellites.
- It enhances the ride share model by allowing cost sharing of a single location for multiple modular payloads that benefit from frequent servicing and upgrades.

Standard satellite bus applications

The nearest-term application where PASIST is being considered is in commercial off the shelf (COTS) satellite buses designed from their inception to be serviceable by incorporating modular components for many primary systems. Satellite buses used today are already modular in design, in that a suite of communications, power, and payload options are available within a core model family. This principle can be extended to allow for in-space maintenance, refueling and upgrade of these components by integrating robotic compatible modular interfaces and designing the spacecraft to allow external access to these components. A great benefit of this approach is in the reduced time to design, test and fly new capabilities on a satellite. Components could be designed for shorter lifetimes, with simplified requirements and redundancy due to the ability to repair and upgrade them on orbit.

The Hubble Space Telescope (HST) is the best example of a large, singular asset, extending its mission life and capabilities through multiple servicing visits. Five repair and upgrade missions have corrected fabrication errors, increased the capabilities of the sensors, maintained and repaired the structure, added new instruments and replaced other components over the HST's current 28 years of operation. HST was designed for EVA servicing, which added complexity and time to the servicing missions due to the logistics of human missions. Future satellites, designed for robotic servicing can simplify maintenance and upgrade procedures to nominally a plug-and-play approach for the majority of servicing operations using a standardized suite of tools.

Modularity and in-space serviceability of current satellite classes could significantly impact the economics of commercial and government space assets, reducing the number and risk of large, single-use assets, while taking advantage of smaller more frequent servicing missions. Modularity of the primary components as described in this sub-section could also be combined with the modular bays described in the previous section to provide the entire asset and its payloads with the advantages of PASIST.

B. Large-scale Zero-G Applications

As single satellites become larger in size, several applications call for using and assembling multiple modules in space to construct much larger and more capable assets. These assets may be assembled from single or multiple launches, and can expand their core structure and primary components over time to add greater capability. This allows for flexibility in mission and financial planning, which is often challenging when launching large assets under programmatic and budget constraints. Commonality and modularity, including; standard sizes of connectors and modules, standard plug-and-play components, and infrastructure elements, will be especially important for large-scale asset applications.

NASA LaRC has performed extensive research over the last decade on a small suite of robots and end-effectors that could be used to perform assembly, servicing and repair operations in-space and on planetary surfaces. These include: a long-reach, lightweight manipulator for coarse maneuvering and positioning of components or assets; a dexterous serial or parallel manipulator to perform fine positioning (which could be attached to the end of the long-reach manipulator); and a suite of tools providing a range of functions including: grappling, manipulating, cutting, welding, inspection and evaluation. The entire PATI ecosystem can be thought of as modular, including the robots themselves. This is achieved by using standard interfaces not only for the PA, but also for the tools and grapple locations of the robotic systems. In addition, it is possible to modularize the agents and infrastructure elements. For example, the robots have sufficient manipulation capability to replace motors, gearboxes, electronic boxes and structural members of the robotic systems enabling the robots to function reliably over the same period as the assets they service, adding additional robustness to the system.

The PASIST approach greatly reduces operational and lifetime risk for these large-scale assets for several important reasons. The component modules can be tested and handled in 1-g and that data can be used to analyze the larger system. The modules would be structurally simple so analytical models can be readily validated. Further, on-orbit performance data of the structure could be used to enhance the design of the next generation of modules. The development and test cycles for new components would be shorter enabling quick adoption of state-of-the-art technology. This reduces initial as well as replacement component costs. No single component or launch failure would result in a loss of mission, since any lost or failed component would be replaceable and the components would likely be distributed over multiple launches. Finally, the Concept of Operations (ConOps) would include multiple visits for maintenance and upgrades, thus design or fabrication errors can also be corrected over time, and their impact mitigated.

This next section details two examples of large zero-g persistent assets constructed from multiple module elements: a solar-electric tug and a large precision reflector.

Solar Electric Transport Vehicles

A solar electric transport vehicle (SETV) is a proposed persistent asset used to ferry payloads between destinations in cislunar or interplanetary space. It is modular in design, to gain the benefits of PASIST, but it also acts as a component of the PATI ecosystem, providing the capability to relocate assets as well as ferry agents and material between PAs. Spacecraft with megawatt class performance are desired,[49] and because, using electric ion or plasma thrusters for propulsion and maneuvering requires large, to ultra-large solar arrays for power (Figure 9). Figure 9 depicts the relative sizes of the solar array systems for different SETV power levels. Studies conducted in reference Ref. 50 showed that the support structure size and mass increases dramatically with increases in solar array module size in order to meet a system-level structural frequency requirement for spacecraft attitude control. A practical single-module power limitation of approximately 200 to 300 kilowatts (kW) was identified, with greater power levels likely requiring modular ISA.

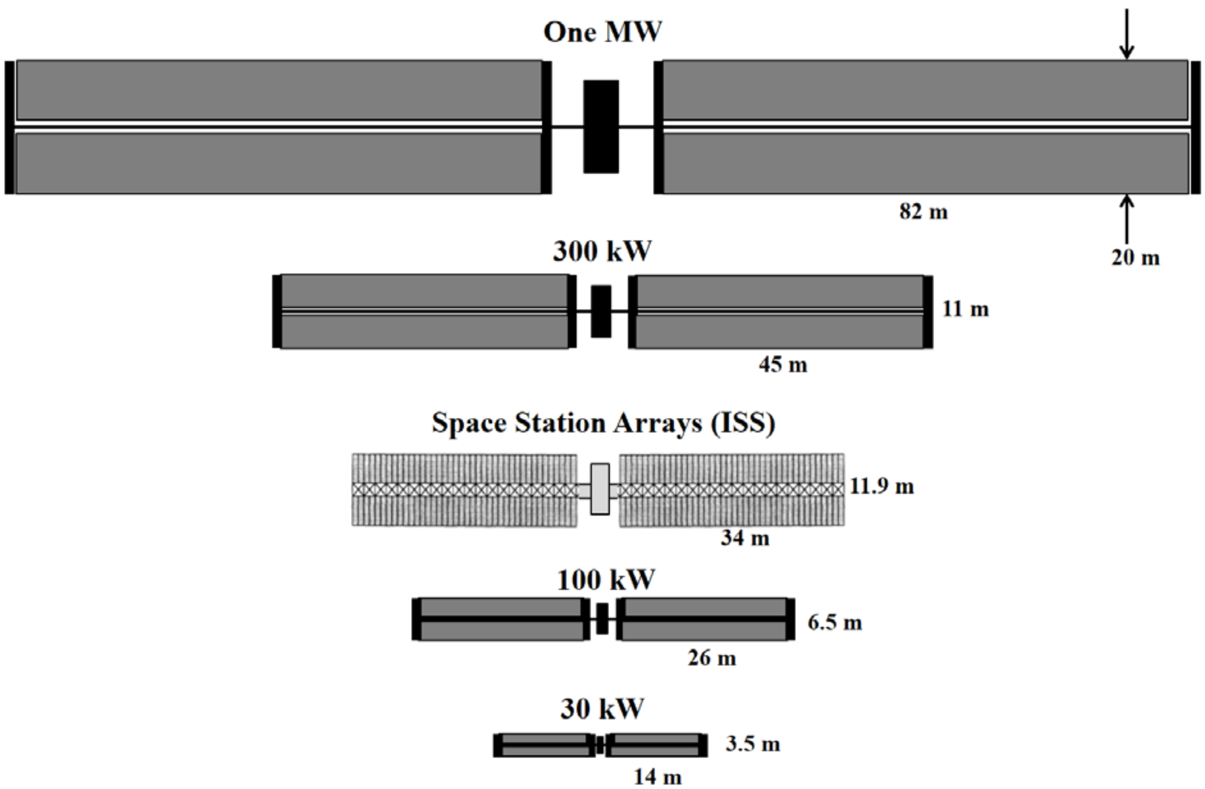


Figure 9. Relative sizes of various compact telescoping array modules compared to International Space Station solar arrays with assumed 300 W/m^2.

As an example, one near-term approach for architecting an SETV is to use 100-300 kW Compact Telescoping Arrays (CTAs) with a predicted packaging energy density of 60 kW/m^3 as modules that are connected to a larger modular backbone or keel truss.[50] Several studies have developed modular concepts for SETVs[51-54] based on the PASIST paradigm. Figure 10 illustrates a modular SETV concept, where the solar arrays and support trusses could be CTA modules attached to a central truss. The concept in Figure 10 was developed under the Modular Assembly of Large Space Platforms (MALSP) program at NASA, that considered several applications of modular system design including power beaming platforms, artificial gravity structures, surface construction facilities and large reflectors. However, the effort mainly focused on an SETV, which was evaluated on the basis of performance, life cycle cost and life cycle risk. Although modular structures may incur some performance penalty for incorporating features for servicing and upgrade, life cycle costs and risk can be substantially reduced over time. Several assembly scenarios were studied, with the most promising decomposing the SETV into a series of primary modules (deployable array and truss, propulsion, backbone truss segments), which could be easily assembled or replaced using an assisting agent (either robotic or human).

In Refs. 50 and 55, a study was conducted to determine the general packaging efficiency trends for solar arrays as a function of size, and the results are shown in Figure 11. In Figure 11, the achievable power per stowed unit volume is shown as a function of module wing power. The gray shaded area at the left of the chart is for relatively small solar arrays deployed on a sandwich panel support substrate. The power per unit volume for such array concepts decreases rapidly with increasing power because the sandwich thickness required to maintain a desired structural frequency increases with increasing area. In order to circumvent the packaging penalty imposed by these sandwich solar arrays, tensioned solar array blankets were developed. The green area on the left of the figure indicates the packaging trend for current tensioned solar arrays, where the primary support structure is a coilable-longeron beam. The packaging performance of an ISS solar array is indicated by the open red circle. As shown by the green area, although the tensioned arrays provide a significant improvement in performance when compared to the sandwich arrays, the packaging efficiency of these arrays also drops with increased power levels. To improve performance, the CTA, was developed in Ref. 50. The projected packaging trend for the CTA is indicated by the gray area on the right of the figure, showing an optimistic upper packaging efficiency of 60 kW/m^3. The theoretical upper packaging limit for solar array blankets with a thickness of 0.76 mm and a power efficiency of 30 W/m^2 is 390 kW/m^3 as shown at the top of Figure 11. Independent of what support structural concept is used, it is estimated that the canister required to house and support the solar cells during launch will reduce this theoretical packaging efficiency to ~160 kW/m^3 as shown at the top of Figure 11. Due to the relatively preliminary nature of the current studies, the range of all three shaded areas are limited in extent until more detailed analyses are available.

An alternate concept that could achieve very high launch packaging efficiency would be to launch compactly packaged individual structural members and assemble the module support structure on-orbit. Various scenarios for performing such operations have been considered in Ref. 56 and 57. The blue area shown to the right of the chart of Figure 11 is an estimate of the packaging efficiency that can be achieved using erectable truss technology. Designing the erectable support structure to provide an orbital frequency of 0.05 Hz results in the packaging efficiency of about 120 kW/m^3. Note, the erecting agent mass is not included in the erectable solar array performance. It is assumed that the erecting agent would be utilized in a variety of operations.

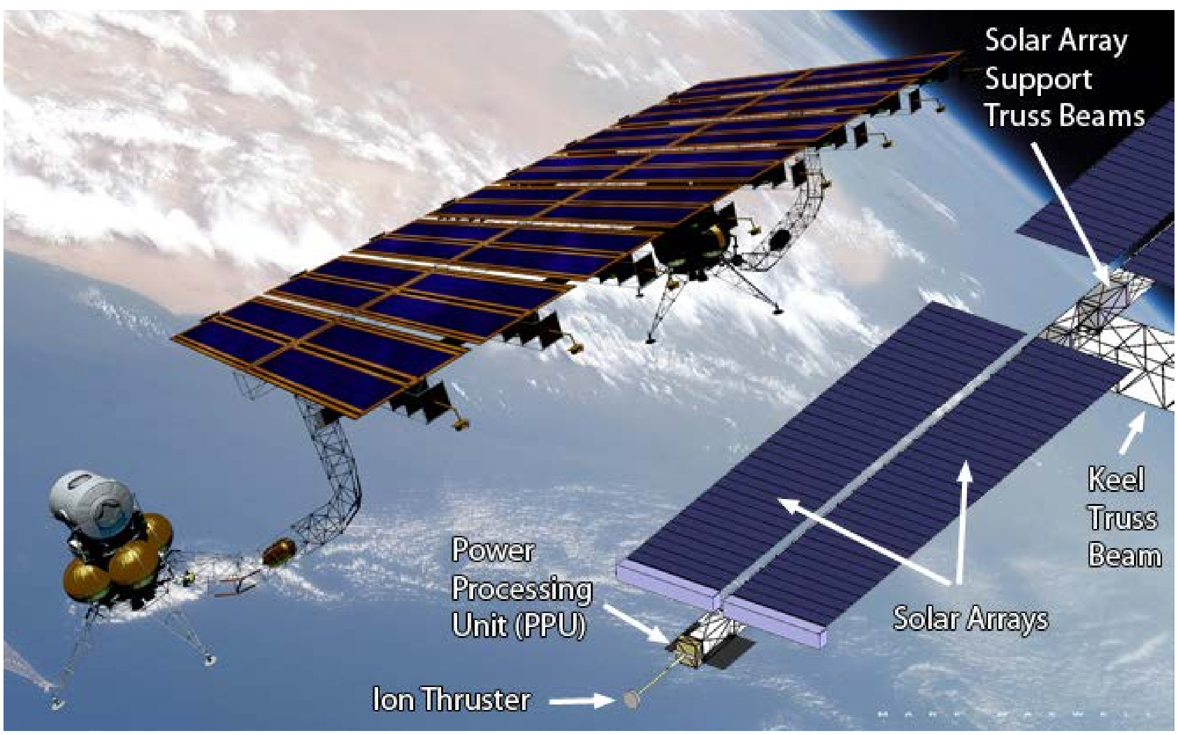


Figure 10. Solar Electric Transport Vehicle (SETV) with Component Details.

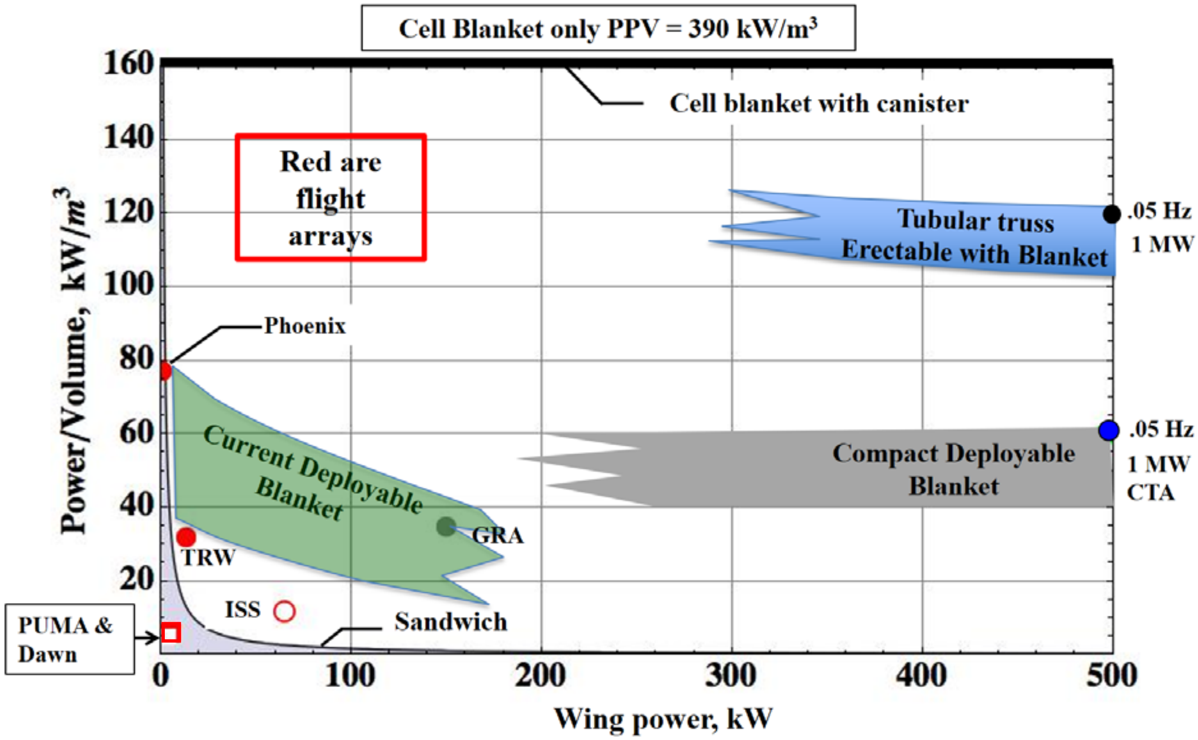


Figure 11. General trends for power per unit volume performance for various solar array types.

Array deployment were also envisioned to rely on the same agents, allowing deployment motors, cables and mechanisms, that typically add parasitic mass, to be eliminated. The SETV could be assembled from modules brought to orbit using a variety of launch vehicles over multiple visits, with each launch carrying, at a minimum, a stowed keel beam section, two deployable solar array wings and two ion thruster/power-propulsion unit (PPU) assemblies. The first and possibly second flight would bring up any required robots and tools needed for assembling subsequent components or modules. As described in Ref. 53 a modular SETV illustrates the ability of a PA to rapidly enter service, then increase capability and integrate new technology throughout its life cycle. This can be accomplished without the need for any initial in-space infrastructure beyond the resident robotic agents.

Large Precision Reflectors

Since the early 1980s, NASA has had an interest in developing 20 meter-class, precision reflectors. The wavelengths of interest to scientists for these reflectors range from optical to submillimeter. The major requirements for a representative 20-meter diameter precision reflector, as shown in Figure 12, are discussed in Ref. 58. A major technology barrier for achieving such a large reflector is reliable and affordable on-orbit deployment or assembly, regardless of the telescope precision requirements. In Ref. 58, it was assumed that a parabolic support truss would first be deployed onto which the precision reflector panels would subsequently be assembled. Numerous other approaches for constructing such large reflectors in space have been considered in the past and several of these are discussed in Refs. 13 and 56.

In Ref. 56 an assembly scenario is presented where the reflector support truss is erected one member at a time after which the hexagonal panels are then attached. The advantage of such an approach is that it minimizes the launch volume required for a large reflector. The novelty introduced in Ref. 56 is that the reflector is mounted to a rotary base, or “Lazy Susan” which minimizes the amount of motion required by the agents. This assembly process was demonstrated in full-scale tests using EVA astronauts as the agents.[56] A similar rotating mount was used to assist robotic agents in Ref. 38 during construction of the planar tetrahedral structure shown in Figure 7. A major unresolved concern with this erectable approach was how to efficiently perform on-orbit integration and verification for all of the required utilities and subsystems.

In order to reduce this on-orbit integration concern, a modular construction approach was conceived.[13] The module consists of a hexagonal reflector panel along with its integrated and compactly packaged support truss. Somewhat similar approaches were presented in Ref. 59 for radio frequency, mesh type reflectors. In both cases, the concept involved deploying unit modules, then assembling them on-orbit to form the desired size of precision reflector, as depicted in Figure 13. In the approach presented in Ref. 13, the support structure for each of the modules consists

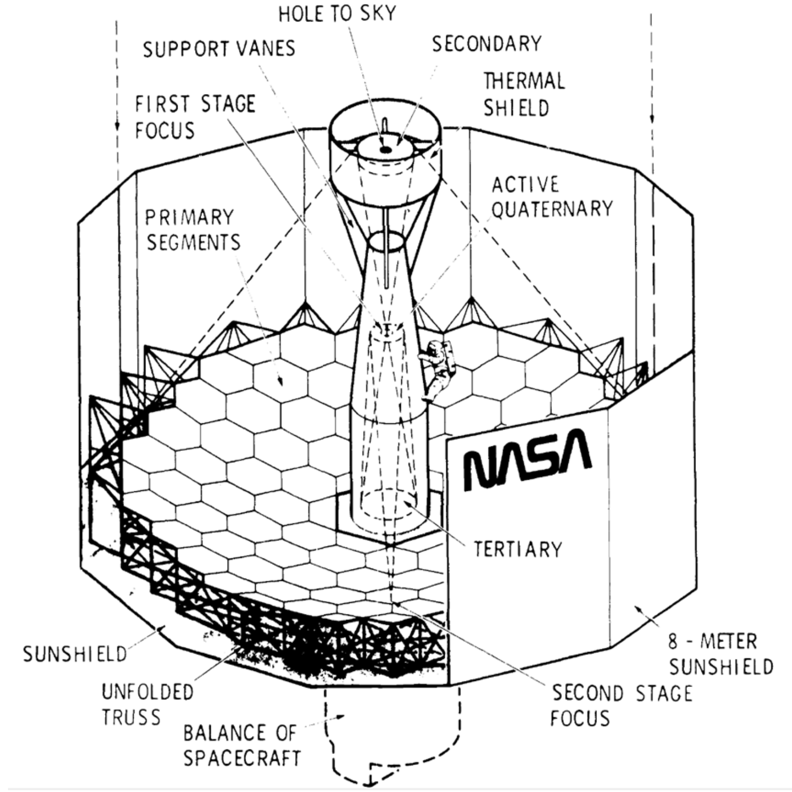


Figure 12. 20-meter diameter Large Deployable Reflector (LDR) from Ref. 58.

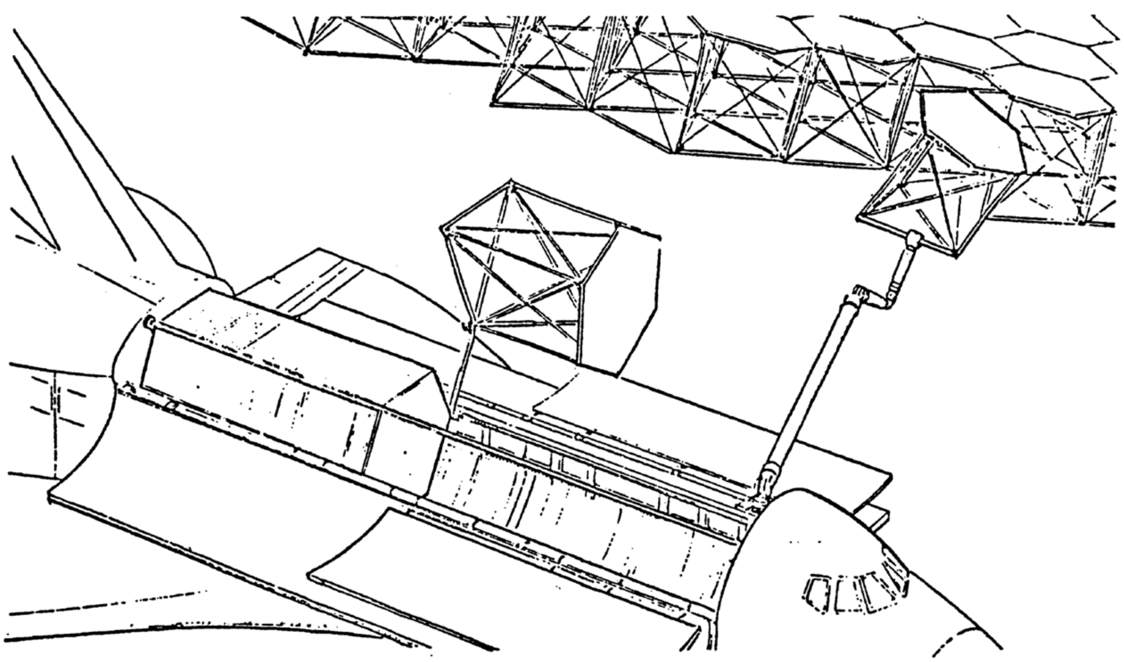


Figure 13. Reflector modules being assembled to form larger precision reflector from Ref. 13.

of a top and bottom triangular planar truss separated by six pre-tensioned diagonal members forming the truss core. Three buckled members at each corner tensioned the core diagonals. The resulting module is similar in function to the well-known coilable-longeron deployable beam.[60] More recently, a scheme which first deploys structural modules, then assembles the structural modules followed by the assembly of reflector panels onto the completed structure has been studied.[61]

In section V, an alternate version of the module presented in Ref. 13 will be presented that is specifically designed to meet the stringent accuracy requirements for very high precision reflectors. The resulting module has been developed to the level of prototype hardware.

C. Planetary Surface Applications

Many applications for PASIST exist within current plans for missions to the surface of the moon and Mars, particularly in building a human outpost and assembling the various elements that support it. A recent study by Jefferies *et al*[62] evaluated the impact of using in-space assembly for exploration and science missions. A surface outpost was identified as a primary application where assembly and servicing would yield significant benefits. As with large zero-g PAs, surface applications greatly benefit from a similar suite of robotic agents, including a long-reach manipulator, a precision manipulator and a toolbox of end effectors for a variety of tasks. It was noted that incorporating autonomous capabilities into robotic agents will enable assembly and maintenance operations to be performed with little increase in overall system mass or volume. In addition, the interfaces could be designed to be agent agnostic, so that either a robot or an astronaut with tools can perform the operations.

Once the core elements of a mission were emplaced and checked out, many other persistent assets that support the mission would need to be installed. Communication towers and a power system would need to be positioned, and likely require deployment or assembly of their support structures. Using a robot to deploy or assemble the structure, as with the SETV example, can eliminate the parasitic mass and failure risk associated with the motor drives and deployment mechanisms. A solar power installation directly exploits the PASIST approach, using robotic agents for emplacement, maintenance and expansion. If a nuclear reactor is used, it will need to be positioned remote from the outpost and shielded. This requires a smaller subset of the PASIST capabilities, to position the reactor and place a regolith shield. Science payloads or assets, such as telescopes, interferometers or other instruments, may also need to be deployed on the surface and possibly at some distance from the outpost. These distributed assets might require cabling to be laid down between them, for communications and power. Cabling could be emplaced, cut to length and prepared robotically using standardized connectors. For assets at greater distances, the surface mobility platform can act like the SETV, ferrying payloads and robots between assets to provide maintenance and upgrade as needed. Future missions are envisioned to adopt in-situ resource utilization (ISRU) which benefits from the PASIST approach for system setup, maintenance and expansion as well as the transportation of the raw goods.

Planetary surfaces, as opposed to zero-g applications, present a specific set of challenges for emplacing and maintaining assets. Assembling structures in gravity requires careful consideration of how to support and manipulate large or massive components as they are assembled. Dust is a significant issue on the moon and Mars, both while connecting elements and once assets are emplaced. Dust control and mitigation will be a primary consideration for future surface missions and robot agents can perform tasks to minimize transport into the human shirt sleeve areas. The wind on Mars can also drive dust particles at high velocity into components and can create large forces on surface solar arrays resulting in the need for frequent maintenance.

Planetary surface missions, particularly to Mars, require a substantial investment of resources. The modular PASIST approach provides significant opportunity for commercial and international collaboration and partnership by using standard connectors, modules and protocols. Components and modules from many different participants can be used together to drive healthy competition and find optimal solutions for future missions.

Erectable Support Structures for Solar Array Modules

A new concept for Mars surface power, based on the CTA concept depicted in Figure 9, is called the Compact Telescoping Surface Array (CTSA). CTSA achieves a 30 kW/m^3 packaging efficiency at 1 MW of power on the Mars surface.[63] A major emphasis of both the CTA and CTSA efforts was to develop structural concepts which reduce mass and improve packaging efficiency for high power solar arrays. The CTSA has a decrease in packaging efficiency compared to the CTA because Mars surface arrays must withstand wind and 0.38 g loading requirements. For both solar electric propulsion and Mars surface power, there is likely to be a practical module size limitation in the range of 200 to 300 kW. Thus, achievement of greater power levels will require modular construction, as was done for the International Space Station.

V. Current LaRC Technology Development Efforts

NASA Langley Research center is actively involved in several ISA actives. Currently, these activities are focused on zero-g applications, as opposed to surface applications. These zero-g applications include satellite servicing, geosynchronous communication satellite construction, solar tug assembly and telescope assembly. This section will describe those activities starting with the more mature activities.

A. In-space Robotic Manufacturing and Assembly projects

The first two efforts are funded by NASA's Space Technology Mission Directorate (STMD) In-space Robotic Manufacturing and Assembly (IRMA) portfolio, managed by NASA's Technology Demonstration Missions Program. This program is using commercial public-private partnerships to advance in-space manufacturing and assembly. Descriptions of two of the phase one IRMA projects; Commercial Infrastructure for Robotic Assembly and Services (CIRAS), and Space Systems Loral Dragonfly, along with highlights of their recent ground demonstrations are discussed next.[64]

The IRMA CIRAS project, led by Northrup Grumman of Dulles Virginia, is advancing key technologies needed to perform space-based robotic assembly of flight hardware and space systems. The CIRAS team includes:

- Prime contractor Northup Grumman (formally Orbital ATK), supported by its wholly-owned subsidiary, Space Logistics, LLC;
- NASA LaRC in Hampton, Virginia; developing long-reach and dexterous robotic systems and Electron Beam Welding (EBW) for mission applications;
- NASA Glenn Research Center in Cleveland, Ohio; conducting concept feasibility studies;
- NASA Goddard Space Flight Center in Greenbelt, Maryland; providing robotic tool changer hardware;
- U.S. Naval Research Laboratory in Washington, D.C.; developing robotic command and control software;
- COSM Advanced Manufacturing Systems of Ipswich, Massachusetts; a Small Business company developing the requirements and a design for fabricating a miniaturized EBW gun.[65,66]

During phase one, the CIRAS project team has matured some of the technologies that are necessary to enable robotic assembly of large space systems, such as next-generation telescopes or solar-powered systems for transport vehicles or communications platforms.[65] Technologies developed by LaRC include: methods to connect or disconnect structural joints while meeting precision and alignment requirements; 20-meter-long Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) robotic arms, a precision assembly system called the NASA Intelligent Jigging Assembly Robot (NINJAR); a TALISMAN tool called the Strut Attachment, Manipulation, and Utility Robotic Aide (SAMURAI); and design of an EBW gun system for autonomous in-space welding.

In a ground demonstration performed in mid-2017, the NINJAR positioned the joints of a 32-inch square-bay truss achieving an average error of under 2 millimeter and 1 degree demonstrating its precision performance. In the first of a series of ground testing demonstrations in early 2018, the CIRAS team manipulated one of the TALISMAN 20-meter long arms between two different poses, as shown in Figure 14, to demonstrate that it is fully operational and ready for more comprehensive testing. The ground demonstrations are being conducted in the flat floor facility of the Structures and Materials Test Laboratory at NASA's LaRC in Hampton, Virginia.[65]

The second major activity is the IRMA Dragonfly project, led by Space Systems Loral (SSL) of Palo Alto, California, which is demonstrating technologies that are key to enabling robotic self-assembly of satellites on orbit.[67] The Dragonfly project also leverages a previous SSL study called Dragonfly funded by the DARPA Tactical Technology Office. The Dragonfly team includes:

- Primary contractor SSL;
- NASA LaRC in Hampton, Virginia; developing high precision structural interfaces that are robotically assembled;
- NASA Ames Research Center in Moffett Field, California; developing situational awareness software;
- Tethers Unlimited of Bothell, Washington; a Small Business Innovative Research (SBIR) company developing in-space truss manufacturing methods and hardware;
- SSL affiliate MDA US Systems LLC of Pasadena, California; developing the dexterous robotic arm and advanced robotic control software.[67]

Figure 14. An artist's rendition of TAISMAN servicing the Hubble Space Telescope (left). The first test series of the CIRAS TALISMAN 20 meter (four link arm) demonstrations in the flat floor facility of the LaRC Structures and Materials Lab (right).[65]

During Phase 1, the Dragonfly project team is maturing capabilities for high precision reversible robotic joint assembly, and antenna support structures fabricated with additive manufacturing techniques. This enables the Dragonfly team to exploit alternative packaging methods to optimize reflector stowage for launch. Maturing these capabilities will lead to more powerful satellites that can be packaged in the payload shrouds of standard launch vehicles, thereby decreasing costs to its satellite customers.[67]

In September 2017, the IRMA Dragonfly project team conducted its first major ground demonstration at the MDA US Systems LLC robotics laboratory, in Pasadena California. The demonstration used a highly dexterous robotic arm, high precision reversible robotic joint interfaces, and control software to perform installation and reconfiguration of an antenna reflector (Figure 15).[68]

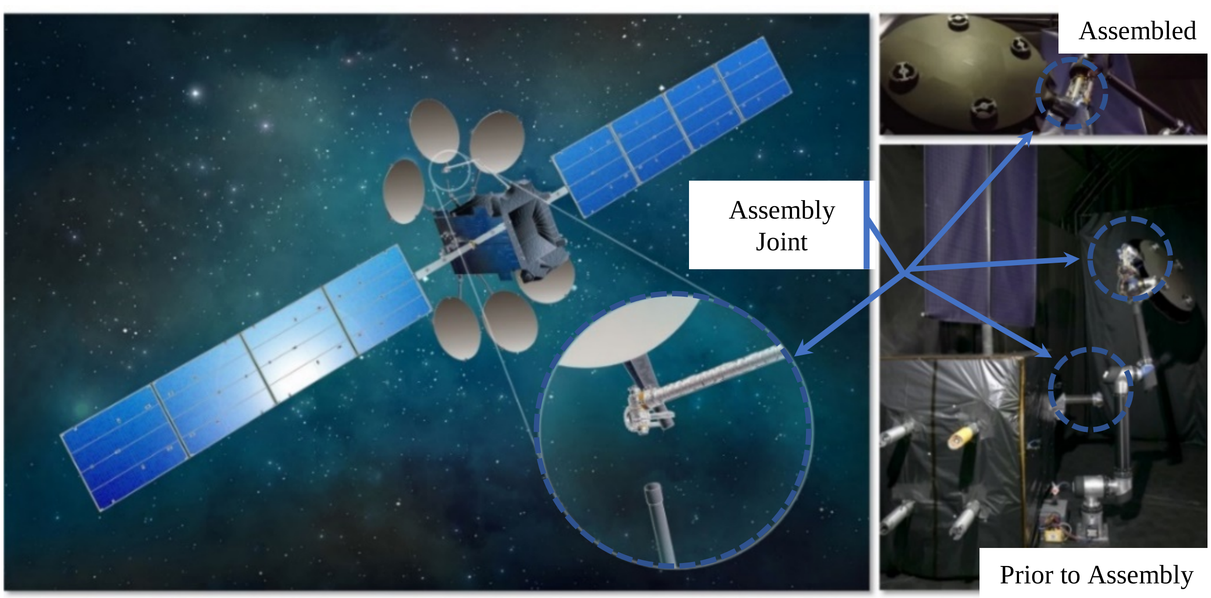


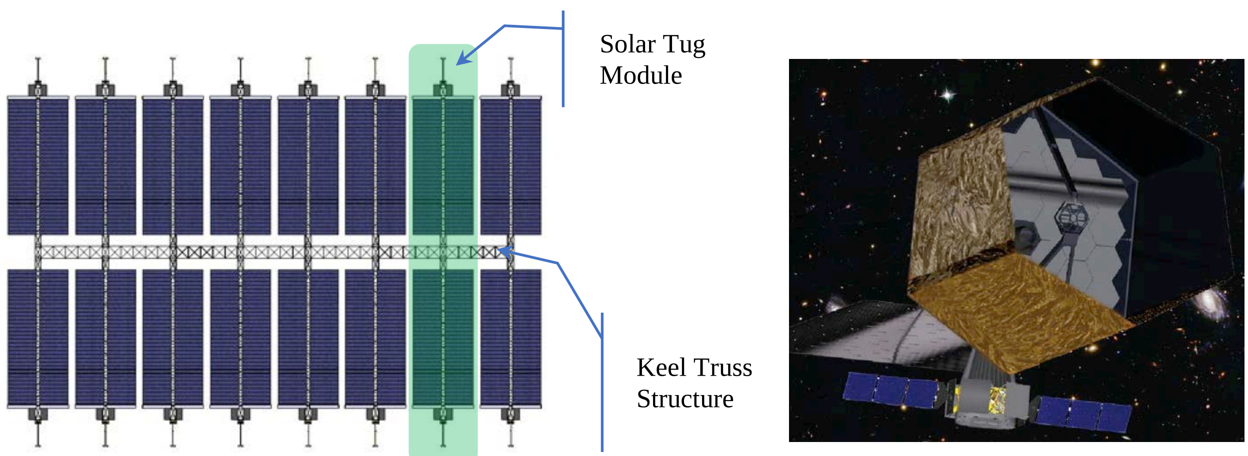
Figure 15. An artist's rendering depicts Dragonfly assembling and deploying large antenna reflectors on a satellite in Earth orbit (left). Dragonfly's first robotic ground demonstration test using reversible precision robotic joint developed by NASA LaRC and connected to a reflector dish boom (right).[68] Credit: NASA/SSL.

B. Robotic Modular Assembly of Space Exploration Systems (RAMSES)

In parallel to these activities, NASA LaRC is developing modular assembly architectures and associated reversible joining technology through an internally funded project called RAMSES. As discussed in section II on pg. 4, historical ISA activities focused on an assembly strategy relying on a small number of versatile structural members. While this approach directly supports construction of a wide range of structural forms, it necessitates that the utility systems such as wiring harnesses and heat transfer systems be routed and secured throughout the structure on-orbit. This severely reduces the ability to validate subsystems prior to launch and extends the duration and complexity of the on-orbit operations.

In contrast to the historical approach, recent work has concentrated on new architectures. These new architectures result in modular structural forms and interfaces enabling stand-alone subsystems to be assembled, verified, and characterized prior to launch. It is important to note that a complete system can be created with these modules without requiring any on-orbit assembly; by adopting the modular units described here, these systems still benefit from multiple visits for upgrades, repair and maintenance. In the case where the system is expanded on-orbit or is too large to be launched economically as a single unit, then a small number of reversible connections are made on-orbit. The modular approach described here has the advantage of enabling a high degree of integration and test prior to launch, but still relies on accurate modeling of the modules to validate the on-orbit performance following ISA activities. Fundamental to a succesful modular approach, is minimizing parasitic mass, volume, and power demands on the completed system. Parasitic mass, volume, and power demands result from including features required to support on-orbit operations that are not required to fullfil the spacecraft mission, such as grapple points, active vision targets, etc. Minimizing these parasitic features requires a careful co-design between the spacecraft and the tools and agents that are used to make changes to the spacecraft. In addition, the new modular designs endeavored to:

- Eliminate repeated members at the interfaces.
- Create predictable structural systems with:
  - no hysterisis, and
  - repeatible well defined response.
- Exhibit short preload paths.
- Assembled through a reliable assembly concepts of operaton.



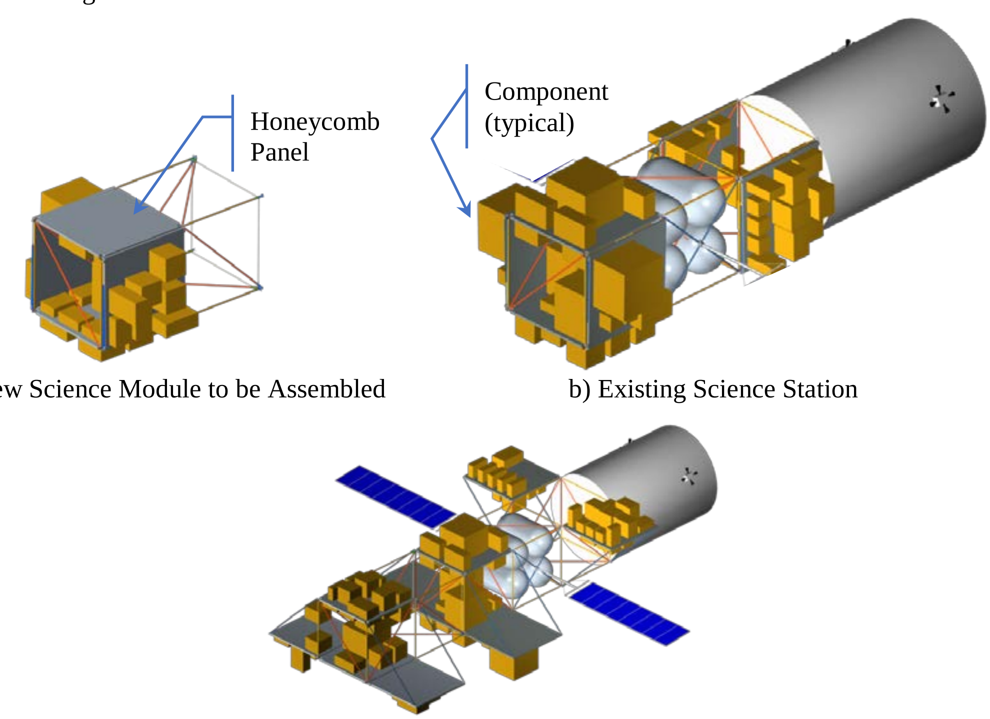
a) Generic Persistent Platform b) Large Space Telescope

Figure 16. Target Missions for Modular Assembly.

Modular approaches for two target systems have been studied in detail; a generic persistent platform (Figure 16a) and a large precision space telescope (Figure 16b). A persistent platform is a cross-cutting foundational example of a PA which fulfills the needs of many customers, both commercial and government. These include GEO-communication systems used by the commercial sector to provide telecommunication signals, GEO-stations described by DARPA (who coined the term persistent platform), and SETVs relied upon by Lunar and Mars architectures for exploration. The precision and stability requirements needed for a persistent platform are satisfied by assembly precision on the order of a few millimeters (specific modules or instruments can achieve higher levels of precision within the module as needed). The capability to assemble to this level of precision has been proven in the past[34,35,42] and is readily achievable with current state of the art robotic systems if properly combined with new joining technologies that support modularity. Developing this capability is a logical first step on the path to systems that can provide pico-meter stability for instruments required by future large space telescopes, such as a chronograph space telescopes to image distant planets.

Most persistent platforms benefit from a backbone structure, similar to the central keel truss structure identified in Figure 16a and this is the first modular interface that will be discussed. Joining modules using a reversible connection of the backbone truss structure can support addition of a solar tug module (Figure 16a) or expansion of a science station (Figure 17). Figure 17 depicts assembly of a new science instrument module (Figure 17a) to a parent science station (Figure 17b) on-orbit to form an expanded science station (Figure 17c). This assembly relies on at least one assembly agent which is not shown. This assembly agent may reside on the existing spacecraft, or in the preferred approach, resides on an assembly vehicle which accompanies the new module to the existing science station. An assembly vehicle provides significant versatility and reliability not available from a resident assembly agent. The assembly vehicle can bring new tools and enhanced agents to perform the assembly, potentially decades after the original spacecraft was launched.

A reversible modular assembly approach for the backbone truss currently being developed is depicted in Figure 18. A structurally significant advantage of this approach is that both the existing spacecraft and new module are in stable configurations at all times. Starting in the upper left of Figure 18, a long reach manipulator with a precision positioner are the assembly agents. The long reach manipulator provides coarse positioning to approximately 12 cm (~5 in) from the final installation position. From this approach point, the new module is guided toward the existing spacecraft system using the precision positioner. This operation relies on machine vision feedback from cameras located on the new module that provide alignment data to preattached fiducials on the existing spacecraft. Alignment guides (Figure 18) at each corner ease requirements on the assembly accuracy. Capture spring pins activate to secure the connection after the new module is inserted into the mating features on the existing spacecraft. Once the new module is captured, the precision positioner can release the structure. At this stage the connection is secure but not locked, i.e. the connection has not been rigidized to achieve required structural precision and stiffness. To lock the new modules, a second tool is envisioned to be used by the assembly agent to visit each structural connection and lock the connection. Following or during this process, the non-structural supports used to hold the non-structural elements (Figure 18) in the correct locations as well as the cameras and other parasitic element associated with the assembly can be removed. Though not described here in detail, it is also feasible to join the modules at a few corners, and then install the remaining structural elements.



a) New Science Module to be Assembled

b) Existing Science Station

c) Completed Science Station Assembled and Deployed

Figure 17. Modular Assembly of Persistent Platform.

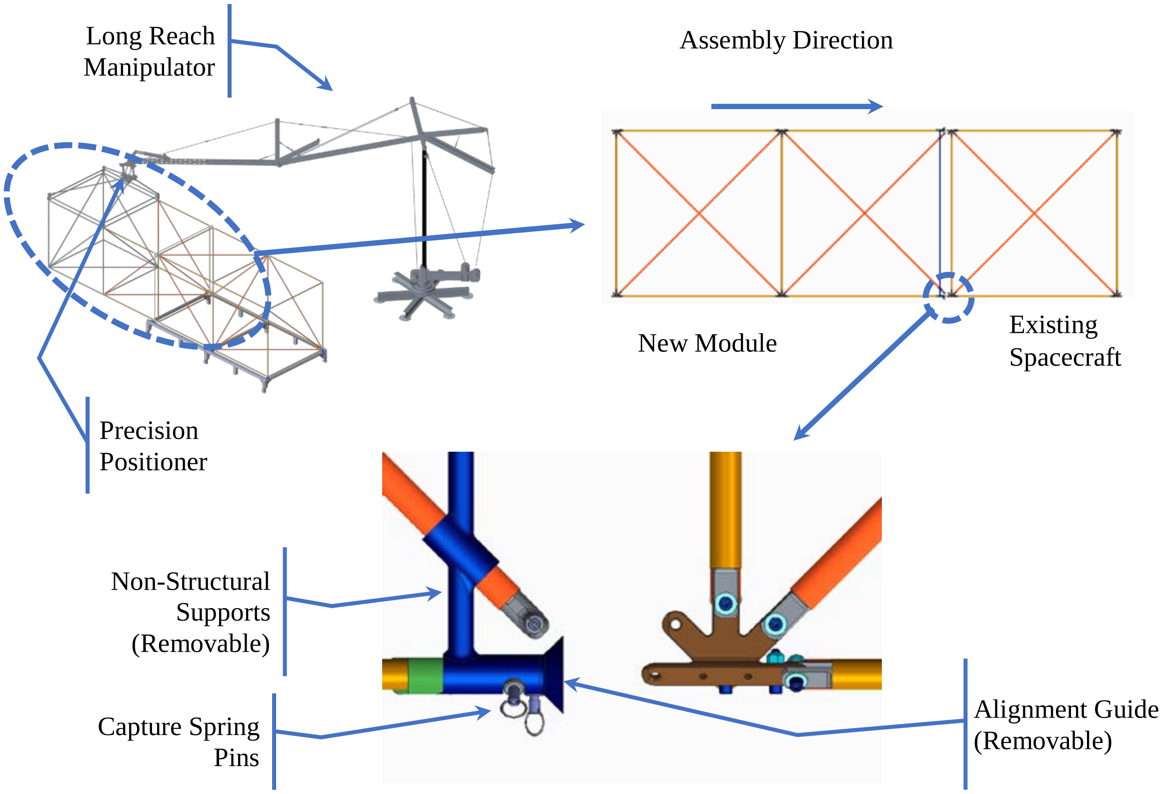


Figure 18. Back Bone Truss Module Assembly.

The second target system that the modular approach has been applied to is a large space telescope as depicted in Figure 16b. References 69 and 70 discuss options for an evolvable space telescope which benefits directly from the modular designs discussed here. The ability to repair and maintain the entire telescope system is the objective. However, one of the most challenging components to assemble will be the large primary mirror, which must provide a stable wavefront to the instruments with nanometer precision over 10's of hours of observation.[71] Hexagons provide an efficient geometry for segmenting the mirrors and are often considered in large telescope systems.[72, 73]

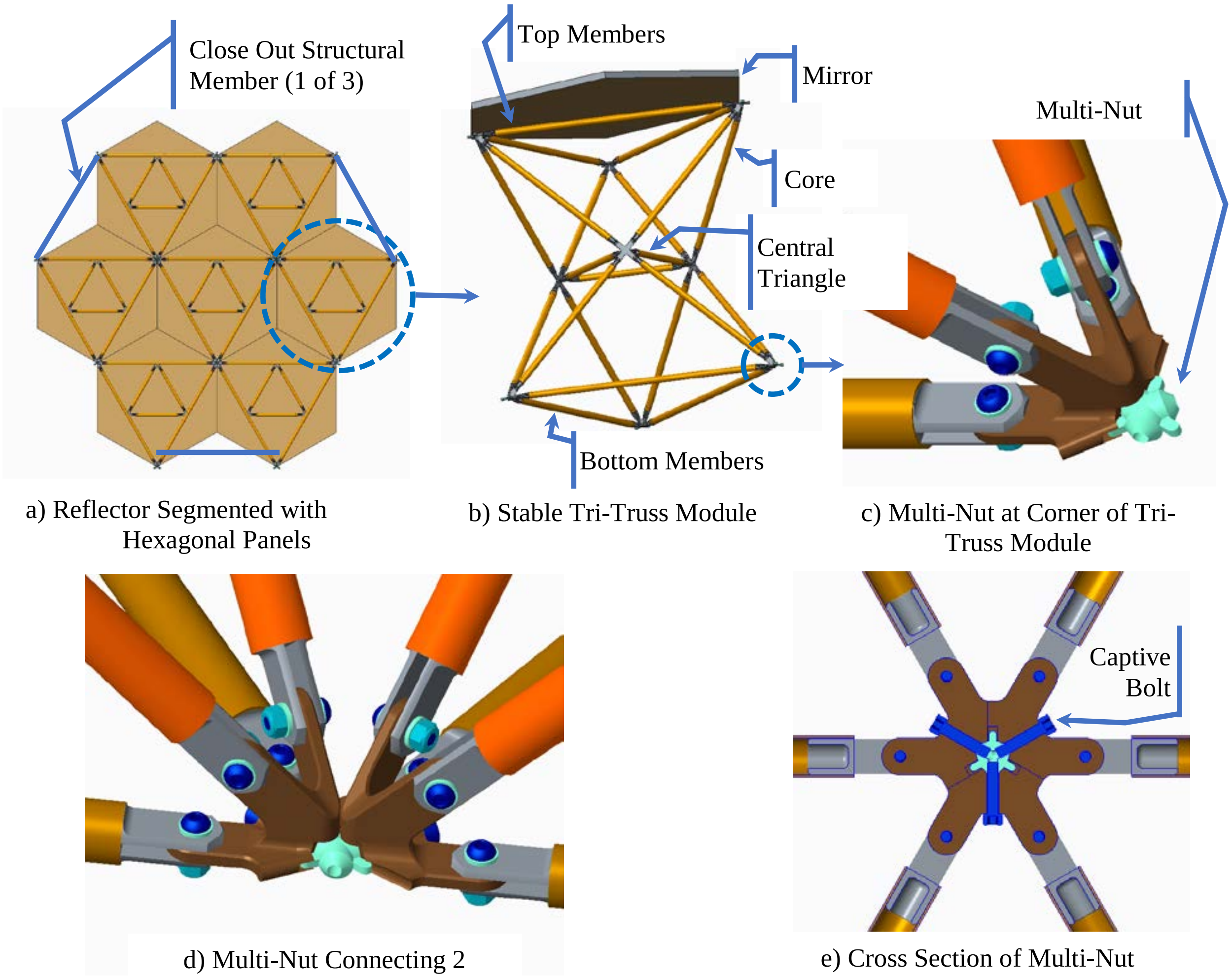
Figure 19 will be used to describe the basic tri-truss module and the connection of tri-truss modules. Figure 19a depicts a cluster of seven tri-truss modules and Figure 19b depicts a single tri-truss module. In this case, each module supports a preattached mirror segment. The tri-truss module has the following important features:

1) the module is statically determinate,
2) when connected to other modules, there are no repeated structural members at the interface,
3) primary load paths along the top and bottom faces of the connected tri-truss modules pass though the center of the struts and nodes,
4) the tri-truss can be collapsed and packaged through the thickness, and
5) mirrors and their support systems can be pre-integrated.

The modular structural system is designed to behave similar to a honeycomb panel, with axially stiff top and bottom layers connected by core structural members that provide shear stiffness through the thickness (Figure 19b). The overall structural performance is improved by adding a small number of close-out structural members around the perimeter, installed in the top and bottom surfaces as shown in Figure 19a. With these close out members in place, the top and bottom layers become isogrid structures, a very efficient structural form, with the primary load paths aligned with the center of these layers. Feature 5 listed previously, is significant because it enables the panel and mirror assembly to be tested on the ground as an integrated unit, with the mirror position system fully integrated. This is one advantage of the modular approach; subsystems can be integrated and tested on the ground prior to launch, significantly reducing the programmatic cost and risk. Modules are connected at the corners as depicted in Figure 19c - 19e using a multi-nut. In this design, the multi-nut has three pre-integrated threaded holes to connect three modules at a node location. Multi-nuts are preattached to a module using a captive bolt (Figure 19e), which is used to preload the interface between modules. This connection strategy is reversible, compact and lightweight. The connection strategy does not place any constraints on the order in which modules are removed, with each module maintaining a multi-nut in the top and bottom layers. Although it is most convenient to maintain multi-nuts at the same relative location in the top and bottom layers, this is not required.

The Tri-Truss module enables several options for packaging. The module may be launched in the configuration depicted in Figure 19b, or may be packaged as depicted in Figure 20a. Deployment from the packaged configuration depicted in Figure 20a to the operational configuration depicted in Figure 20b is accomplished by telescopically retracting the central triangle. In addition, it is straightforward to package half of the Tri-Truss depth, either the portion below the central triangle (Figure 20c) or the portion above the central triangle (Figure 20d) by telescoping the appropriate struts.

Both the backbone truss of Figure 17 and the Tri-Truss of Figure 19 have numerous internal volume locations available for installing modular components. “Components” are sub-systems within a module that support module operations. For example, components making up a bi-propellant propulsion module may include: tanks, thrusters and gimbals. In Figure 17 for example, the modular components are depicted as yellow boxes, and these components can be any size or shape as long as they fit in the geometric constraints of the persistent platform. In Figure 17, honeycomb panels are an option for replacing the structural members along a face of the truss, to provide a surface for attaching individual components. Around the perimeter of the panel, utilities are provided and it is the component designer’s responsibility, in consultation with the platform operator, to provide the interconnects for required power, data, and thermal connections between these utilities and the components operational locations. Similarly, components can be integrated into the Tri-Truss of Figure 19. Figure 21 shows examples of volumes available for integrating components,



a) Reflector Segmented with Hexagonal Panels

b) Stable Tri-Truss Module

c) Multi-Nut at Corner of Tri-Truss Module

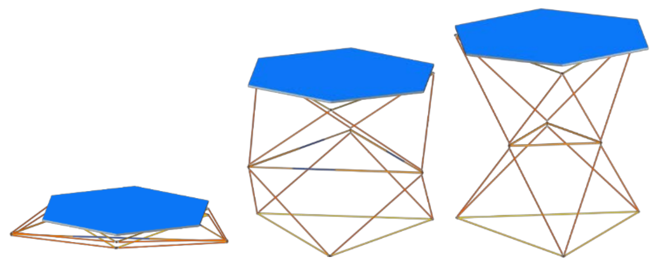
d) Multi-Nut Connecting 2 Modules

e) Cross Section of Multi-Nut Connecting 3 Modules

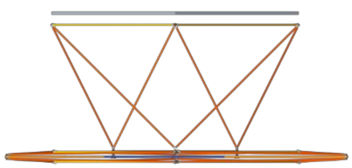
Figure 19. Tri-Truss Modules Connected by Mult-Nut.

either as inscribed cylinders above or below the central triangle (Figure 21a), or around the upper perimeter (Figure 21b). When the Tri-Truss modules are aggregated, the resulting system has numerous options for integrating components (Figure 21 c). Figure 21c shows that entire equilateral triangle volumes are available between the tri-truss modules for additional component installation, either pre-integrated to the tri-truss modules or after the Tri-Truss modules have been assembled.

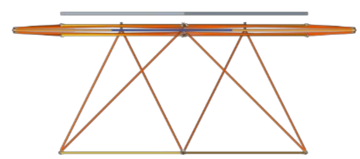
a) Packaged Tri-Truss



b) Deployment Sequence from a)

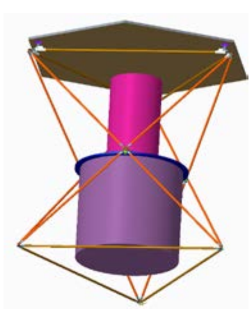


c) Partially Packaged Tri-Truss below Central Triangle

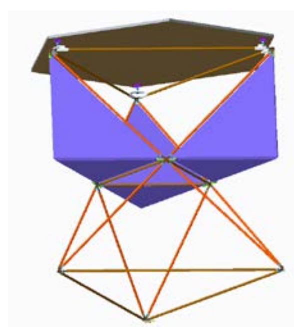


d) Partially Packaged Tri-Truss above Central Triangle

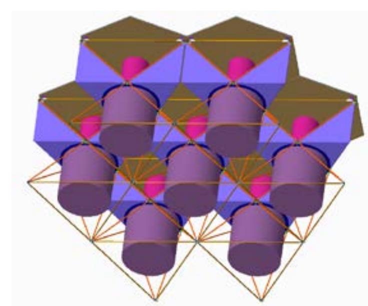
Figure 20. Tri-Truss Packaging.



a) Inscribed Cylinders



b) Exterior Attachment Locations



c) Platform

Figure 21. Representative Volumes Available for Components.

VI. Summary

Historically, spacecraft are; constructed on Earth, launched as an integrated, fully functioning system on a single launch vehicle, and are not updated. However, this historic approach is inflexible to changing customer desires and limits the lifetime, performance, size, volume, and mass of those systems. Space operations are on the cusp of a revolutionary new operational paradigm enabled by new space robotic capabilities and frequent low cost launch opportunities. The new paradigm leverages these capabilities and a new modular approach to enable long term operation of Persistent Assets (PAs). PA is a new term introduced here to identify any in-space or planetary asset that benefits from multiple visits. For example, multiple visits of robotic spacecraft are used for servicing, repair, upgrade, and modular assembly of PAs ultimately leading to significant cost savings and robustness improvements for systems operating in space. Savings are provided by the ability to upgrade individual instruments, add instruments, add fuel, and modify services provided to customers. PAs can have many forms, ranging from commercial GEO-communication satellites to large astrophysics telescopes. Key attributes of PAs were enumerated as well as benefits enabled by new operational paradigms involving PAs. This new operational paradigm introduces new design considerations that, properly managed, will have broad benefits across many missions. The PA paradigm was applied to two application domains, near zero-g applications and surface applications, to illustrate the benefits achievable by adopting this paradigm. It is important to note that the greatest benefits arise from early adoption of the paradigm.

Current development efforts were described in detail, starting with two projects funded by NASA's In-Space Robotic Manufacturing and Assembly (IRMA) portfolio. The first, led by Northrup Grumman and called the Commercial Infrastructure for Robotic Assembly and Services (CIRAS), is developing new agent and infrastructure technologies. Under the CIRAS project, a long reach agent called the Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) is being developed as well as a new infrastructure tool enabling e-beam welding. The second IRMA project, led by Space System Loral, is called Dragonfly and is developing robotic self-assembly technologies. In September 2017, the IRMA Dragonfly project team used a highly dexterous robotic arm, high precision reversible robotic joint interfaces, and control software to perform installation and reconfiguration of an antenna reflector

In parallel to IRMA projects, an activity named Robotic Modular Assembly of Space Exploration Systems (RAMSES) has been focusing on new architectures exploiting opportunities for modular design of PAs. The resulting new modular designs support high degrees of pre-integration followed by ground testing, in contrast to historical efforts in space assembly that used a small number of unique components to achieve a versatile assembly approach. The historical approach required utility integration following structural assembly, increasing the number and complexity of on-orbit operations.

The RAMSES activity has concentrated on two target systems; a persistent platform and a large space telescope. The resulting modules are structurally efficient and designed to minimize parasitic mass and volume associated with the on-orbit operations. For the telescope application, a unique structurally stable module has been developed called the "tri-truss". The novel architecture of the tri-truss module enables a variety of options for packaging and integration of auxiliary components.

The recent availability of frequent low cost commercial launch opportunities coupled with the significant improvements in on-orbit robotic capabilities provides the catalyst for adoption of the new PA paradigm. For the first time, it is cost effective to consider multiple visits to an asset and multiple commercial firms are providing vehicles aimed at supporting this emerging market.

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Appendix A

3d Tri-Truss and 3D Quadra-Truss Modules

In this appendix, a topological discussion is presented for two truss modules that are capable of being assembled into a beam, a platform, or a three-dimensional truss without duplicative members at the module interfaces. This topology is advantageous because it enables design of predictable load paths with minimal structural mass and volume. These two modules represent a generalized three-dimensional (3D) extension of the planar tri-truss module presented in section V. Although the tri-truss module of section V was capable of being formed into a planar truss with no duplicate members at the module interfaces, it could not be used directly to form a linear beam or 3D truss without auxiliary or duplicate members respectively. For purposes of this discussion, the geometric proportions shown in this appendix were selected to illustrate the module topology and a wide range of proportions are easily achievable for specific applications. The modules discussed in this appendix are treated as simple wire frame models, but an example of the type of joints that would be required for actual physical hardware is shown in section V for the planar tri-truss module.

3D Tri-Truss Module. The 3D tri-truss module is shown in Figure A1. In all figures of this appendix, a yellow tracer is assigned to a node to assist in keeping track of the geometry in the different orientations. The fundamental requirement for developing this module geometry was to establish a minimal truss network that could be continuously repeated in one, two, or three dimensions to form a larger truss system without duplicating any members at the interfaces. For the module in Figure A1, the core truss consists of 9 members which form the red geometric shape that is back to back tetrahedrons. This shape with six facets is called a triangular dipyramid. Onto each facet, 3 truss members are added to form the completed module. The resulting complete module consists of 11 nodes and 27 members. This part count exactly satisfies Euler's equation for a statically determinate truss as follows:

Number of members = 3(Number of nodes) - 6 A1

Thus, the module is statically determinate. As modules are assembled into a larger truss system, redundant members result (but not duplicative at the interfaces), and the system is no longer statically determinate.

3D Tri-Truss Module Platforms. The 3D tri-truss modules can be formed into a sparse array platform or a dense array platform as shown in Figure A2. The yellow tracers indicate the module orientation used. The module orientation is not unique and may be altered as desired. Although not shown, the modules could also be stacked in the third dimension to form a 3D truss.

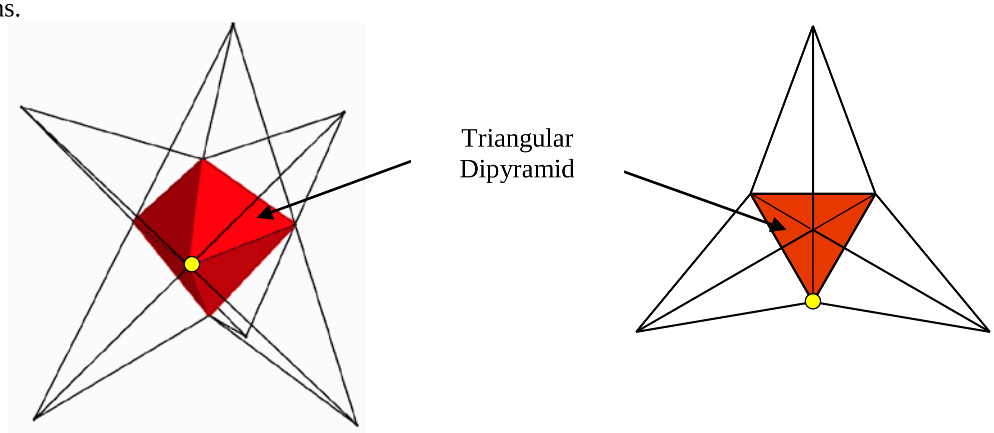
Hexagonal panels could be added to each module of the sparse array truss of Figure A2 to achieve a continuous-surface platform as shown in Figure A3. This platform could be configured as a curved surface to form the telescope reflector surface as discussed in section V.

3D Tri-Truss Module Beams. By stacking several of the 3D tri-truss modules shown in Figure A1, a linear beam can be obtained, as shown in Figure A4. Since these are topologically the same modules as used in Figure A3, out-of-plane modular beams could be added to the planar platforms.

Planar Tri-Truss Module. If extensibility to nonplanar solutions is not required, a somewhat simpler tri-truss module can be achieved as was discussed in section V. This alternate tri-truss module is shown in Figure A5a for comparison to the more general 3D tri-truss module repeated in Figure A5b for comparison. The planar tri-truss module has 2 fewer nodes and 6 fewer members than the 3D tri-truss module. However, its part count also satisfies equation A1, so it is a statically determinate truss. The planar tri-truss can only be used to form a sparse planar truss as shown in Figure A2a.

Quadra-Truss Module. A 4-sided truss, referred to as the quadra-truss module, is shown in Figure A6. As with the tri-truss module, the fundamental requirement for developing this 4-sided module was to establish a minimal truss network that could be continuously repeated in three dimensions to form a larger truss system without duplicating any members at the module interface. For the module in Figure A6, the core truss consists of 12 members to form the red octahedron geometric shape. Onto each of the 8 triangular facets of the octahedron, 3 truss members are added to form the completed module. The complete resulting module consists of 14 nodes and 36 members. This part count again, exactly satisfies Euler's equation for a statically determinate truss.

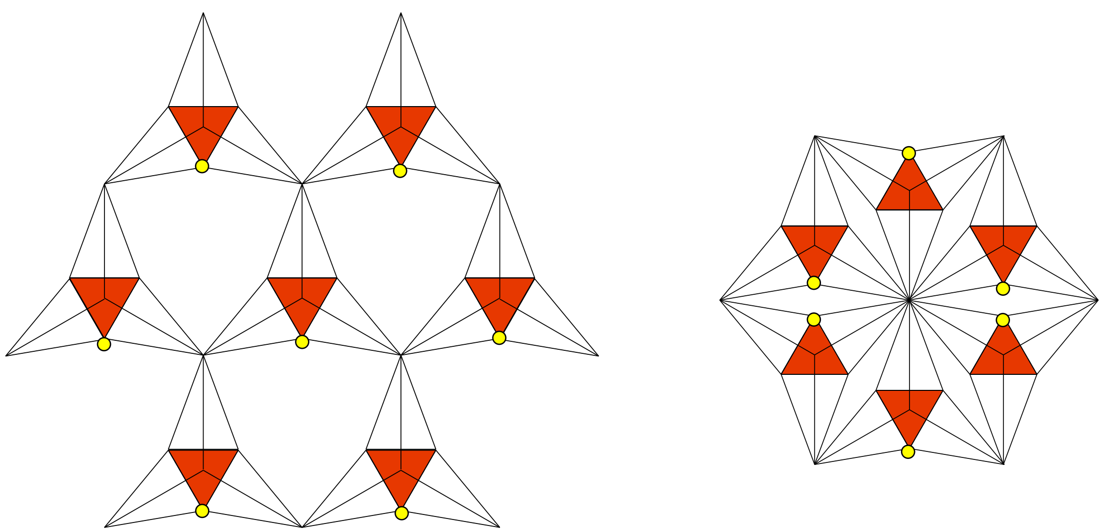
A top view of a planar truss formed from the quadra-truss modules is shown in Figure A7. Unlike the tri-truss module that could form either a sparse or a dense array planar platform, the quadra-truss module can only form a dense array truss. This is because a sparse array truss would result in non-triangulated truss arrays that would be mechanisms.



a) 3D Tri-Truss Module (11 nodes 27 members)

b) 3D Tri-Truss Module (top view)

Figure A1. Statically determinate tri-truss module capable of being assembled into an area platform or a 3D truss with no doubled members.



a) Sparse array of 7 tri-truss modules

b) Dense array of 6 tri-truss modules

Figure A2. Two stable platform arrays using 3D tri-truss modules.

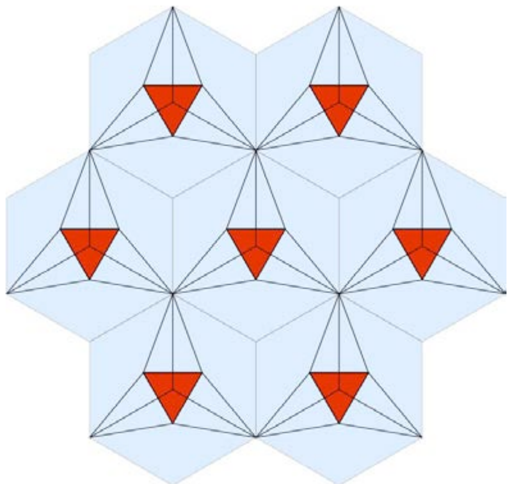


Figure A3. Sparse array of 3D tri-truss modules with attached hexagonal panels.

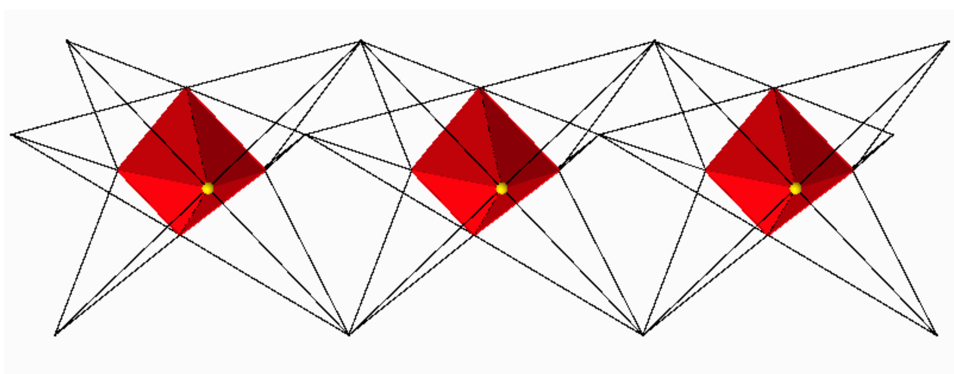
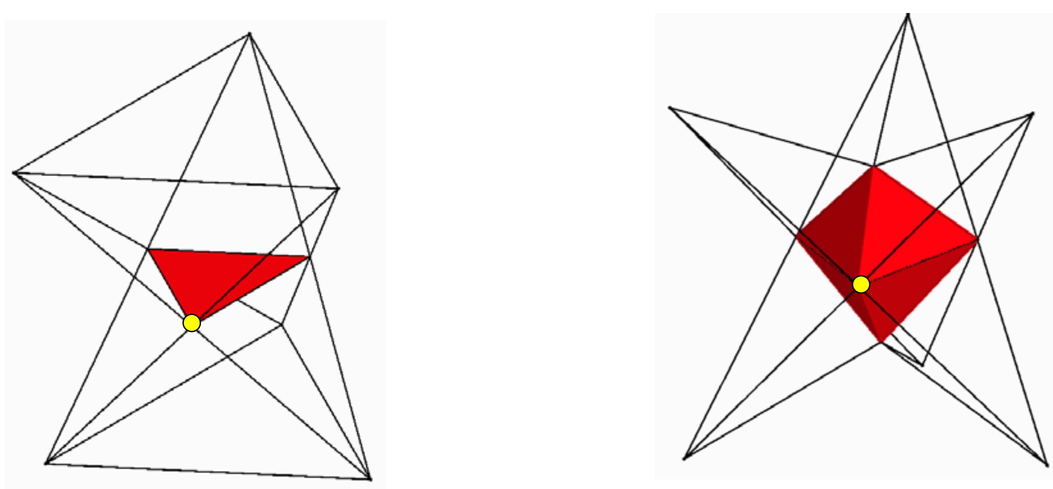


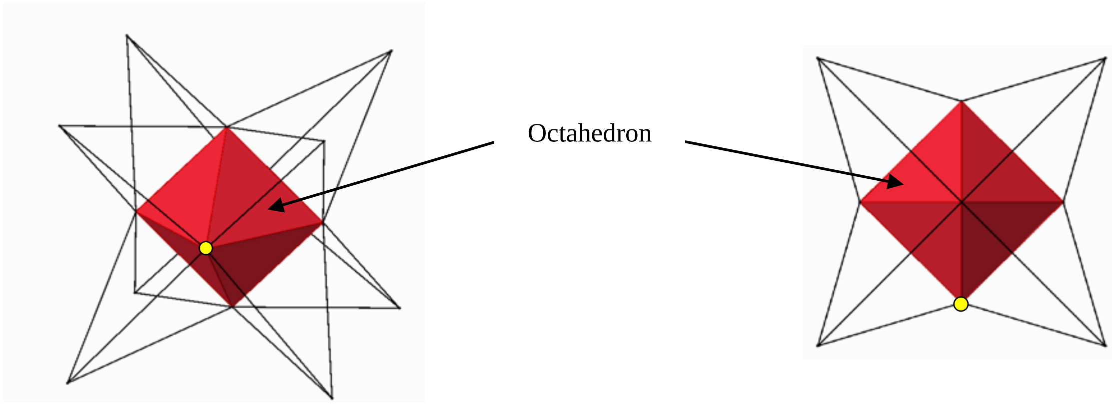
Figure A4. Linear array of 3 3D tri-truss modules.



a) Planar tri-truss module
(9 nodes, 21 members)

b) 3D tri-truss module
(11 nodes, 27 members)

Figure A5. Two statically determinate versions of a tri-truss module.



c) Quadra-Truss Module
(14 nodes 36 members)

d) Quadra-Truss Module
(top view)

Figure A6. Statically determinate quadra-truss module capable of being assembled into an area platform or a 3D truss with no doubled members.

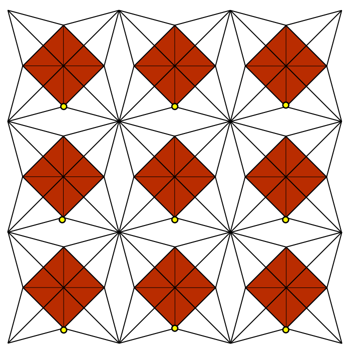


Figure A7. 3x3 array of quadra-truss modules.