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Assembly of a Large Modular Optical Telescope (ALMOST)

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ABSTRACT

Future space telescope programs need to assess in-space robotic assembly of large apertures at GEO and ESL2 to support ever increasing aperture sizes. Since such large apertures will not fit within a fairing, they must rely on robotic assembly/deployment. Proper assessment requires hardware-in-the-loop testing in a representative environment. Developing, testing, and flight qualifying the myriad of technologies needed to perform such a test is complex and expensive using conventional means. Therefore, the objective of the ALMOST program is to develop a methodology for hardware-in-the-loop assessment of in-space robotic assembly of a telescope under micro-gravity conditions in a more cost-effective and risk-tolerant manner. The approach uses SPHERES, currently operating inside ISS, to demonstrate in-space robotic assembly of a telescope that will phase its primary mirror to optical tolerances to compensate for assembly misalignment. Such a demonstration, exploiting the low cost and risk of SPHERES, will dramatically improve the maturity of the guidance, navigation and control algorithms, as well as the mechanisms and concept of operations, needed to properly assess such a capability.

Keywords: On-orbit Assembly, Space Telescopes, SPHERES, SWARM, SPOT

1. INTRODUCTION

1.1 Motivation

NASA is rapidly approaching the need for in-space robotic assembly of large systems that cannot be fit, or folded to fit, within a launch vehicle fairing. A perfect example is a large primary telescope mirror (Figure 1). While JWST will unfold its 6-meter primary, larger systems must face the need to completely decouple the stowed from the deployed geometry. For filled-aperture systems, this will probably require some form of human and/or robotic assembly. However, as one might expect, developing, testing, and flight qualifying the myriad of technologies needed to achieve such a capability is complex and expensive. Furthermore, the inherently three-dimensional aspect of assembly is difficult to impossible to test in a 1-G environment.

Therefore, the goal of the Assembly of a Large Modular Optical Space Telescope (ALMOST) program is to demonstrate in-space robotic assembly of precision, potentially flexible structures under micro-gravity conditions. Such a demonstration, if conducted at low cost and risk, will dramatically improve the maturity of the guidance, navigation and control (GN&C) algorithms, as well as the mechanisms and concept of operations, needed to support a capability to deploy large, strong, lightweight, precise, dynamically stable structures.

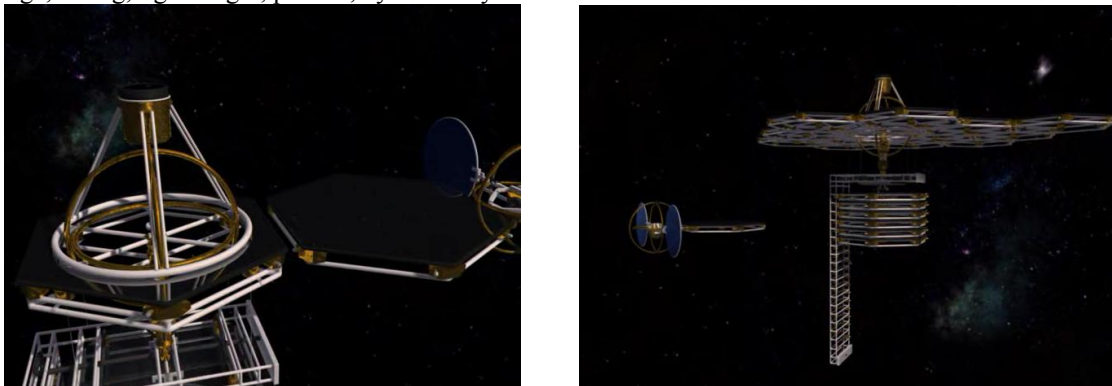


Figure 1: Concept for Robotic Assembly of a Segmented Space Telescope

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edited by Jacobus M. Oschmann, Jr., Mattheus W. M. de Graauw, Howard A. MacEwen,
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1.2 Literature Review

Related work on robotic assembly for space telescopes can be grouped into two categories: testbed development/experimental validation and assembly concepts for telescopes.

Many groups have sought to build a ground testbed to develop and demonstrate technology associated with on-orbit autonomous robotic assembly. Three such programs are Beam Assembly Teleoperator (BAT), Autonomous Multi-agent Physically Interacting Spacecraft System (AMPHIS), and Modular Reconfigurable High Energy (MRHE). These programs demonstrate the path for advancement of technologies related to robotic assembly. BAT was designed to assemble the six element tetrahedral truss structure of STS-61-B EASE (Experimental Assembly of Structures in EVA). [1] AMPHIS is a project developed at the US Naval Postgraduate School Spacecraft Robotics Laboratory. The program seeks to validate spacecraft systems technology, navigation techniques and control approaches using the ground testbed. Autonomous docking has been successfully performed experimentally on this testbed. Currently in development, this testbed will allow for hardware-in-the-loop simulation of autonomous proximity operations and assembly of a cluster of small spacecraft. [2] The MRHE program, a joint venture between Marshall Space Flight Center and Lockheed Martin Advanced Technology Center, seeks to develop technologies for automated assembly and large scale space structures. This program includes a ground testbed for the validation and demonstration of technologies, utilizing hardware such as a motorized docking latch (an adaptation of a Lockheed Martin kinematic latch design) and a deployable boom mounted on robotic vehicles. The testbed is used to conduct navigation, motion planning, and control algorithm development and demonstration. [3]

On-orbit assembly of space telescopes is a much researched area due to the great benefits in capability that will arise if telescope designs are no longer limited by launch restrictions of mass and size. Two concepts for the on-orbit assembly of a telescope are presented here. Basu et. al present a concept for an autonomously assembled space telescope (AAST). The telescope was a 10m aperture Cassegrain optical telescope with hyperboloids for both primary and secondary mirrors, based on the design of the Keck telescope in Hawaii. The telescope will consist of hexagonal rings of segment mirrors, of up to 2.5m. AAST considers the use of dexterous manipulators to accomplish the servicing, with space vehicles during the assembly and alignment process. [4] Izzo et. al. present a concept for the self assembly of a large reflector in geosynchronous earth orbit (GEO) based on the use of solar-sail technology and collective robotic path planning. The general scheme is that several single array elements are launched into medium earth orbit (MEO); then, the segments spiral up from MEO to GEO, using solar flux as the propulsion system. Trajectories and simulation have been developed to validate the concept of this type of trajectory transfer. Also, a technique named Equilibrium Shaping is used to perform the assembly sequence in GEO, based on a behavior based navigation technique. This allows the agents to autonomously plan the design path for multiple possible final configurations without inter-agent communication, but rather with inter-agent sensing. [5]

2. Concept and Approach

The MIT Space Systems Laboratory, Aurora Flight Sciences and the NASA Goddard Spaceflight Center have developed a concept that uses the SPHERES satellite formation flight and docking research laboratory that is currently operating inside the ISS (Figure 2) to demonstrate in-space robotic assembly. SPHERES has been performing precision formation flight and docking experiments in ISS since May 2006. Each SPHERE has a built-in expansion port that allows payloads to be developed, launched to ISS, and attached to the SPHERE by the astronauts for subsequent testing. This demonstration would use the three SPHERES currently on ISS to assemble a flexible, three-dimensional, free-floating structure inside the US Laboratory (Figure 3, left). Additional payloads that would need to be launched to ISS could include docking ports, camera systems, structural panels, optics, etc. The assembled optical structure would closely resemble NASA GSFC's SPOT testbed [6]. SPOT uses a hexagonally-segmented spherical primary with piston, tip, and tilt actuators to phase itself using center-of-curvature illumination and measurement (Figure 3, below).

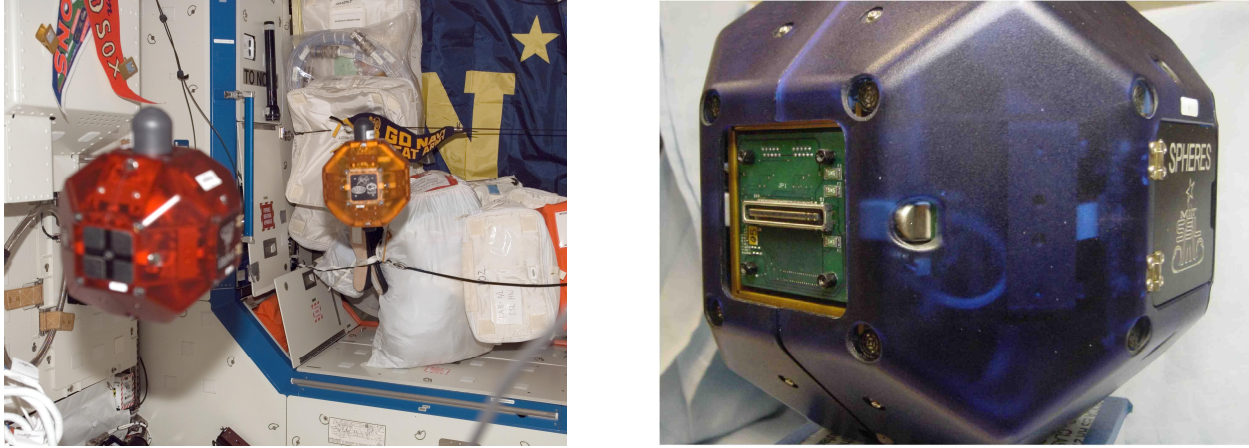


Figure 2: Three SPHERES inside ISS (left) and SPHERES Expansion Port (right)

The concept of operations could be to have a stack of structural components mounted to the wall with a SPHERE station-keeping in the center of the US Laboratory (Figure 4) to which the panels will be attached. A second SPHERE with a docking port docks with a panel, maneuvers it to the first SPHERE, attaches it to that SPHERE, and then releases. The third SPHERE, with a camera, provides an “eye-in-the-sky” view of the assembly process to assist with situational awareness. The second SPHERE then retrieves the second panel and the assembly sequence proceeds, as the first SPHERE controls attitude and position of the assembled structure. Once assembled, the separate segments are “phased” into a single optical surface to a fraction of a wavelength using an internal center-of-curvature sensor. This end-to-end robotic assembly and phasing sequence will demonstrate the ability to precisely phase a diffraction limited, segmented optical system that has sufficiently loose mechanical tolerances to be assembled.

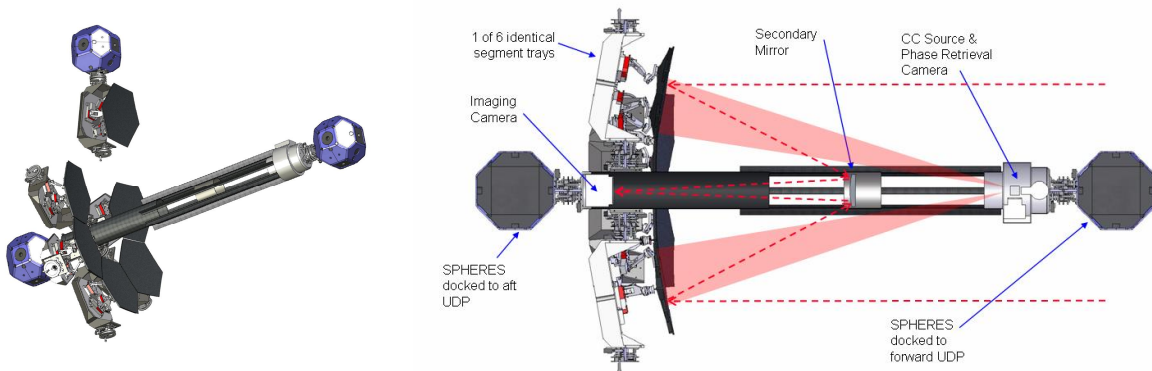


Figure 3: NASA GSFC's SPOT telescope architecture modified for ALMOST Robotic Assembly

The reason for using SPHERES is that it is a comparatively low cost, in-space facility for testing space robotics that is also risk-tolerant. If a collision occurs or panel fails to dock properly, no components are lost or damaged. Furthermore, the astronaut can assist, terminate, or reset the test. Software is not a safety control allowing telemetry data to be retrieved and algorithms to be refined for subsequent testing within a few weeks. The reason for assembling SPOT is that it is an active mirror that uses internal metrology for wavefront sensing and control (WFS&C). The active position control allows correction for assembly misalignments and the internal metrology allows phasing to be performed independent of external illumination sources which are difficult to impossible to create and stabilize inside the ISS.

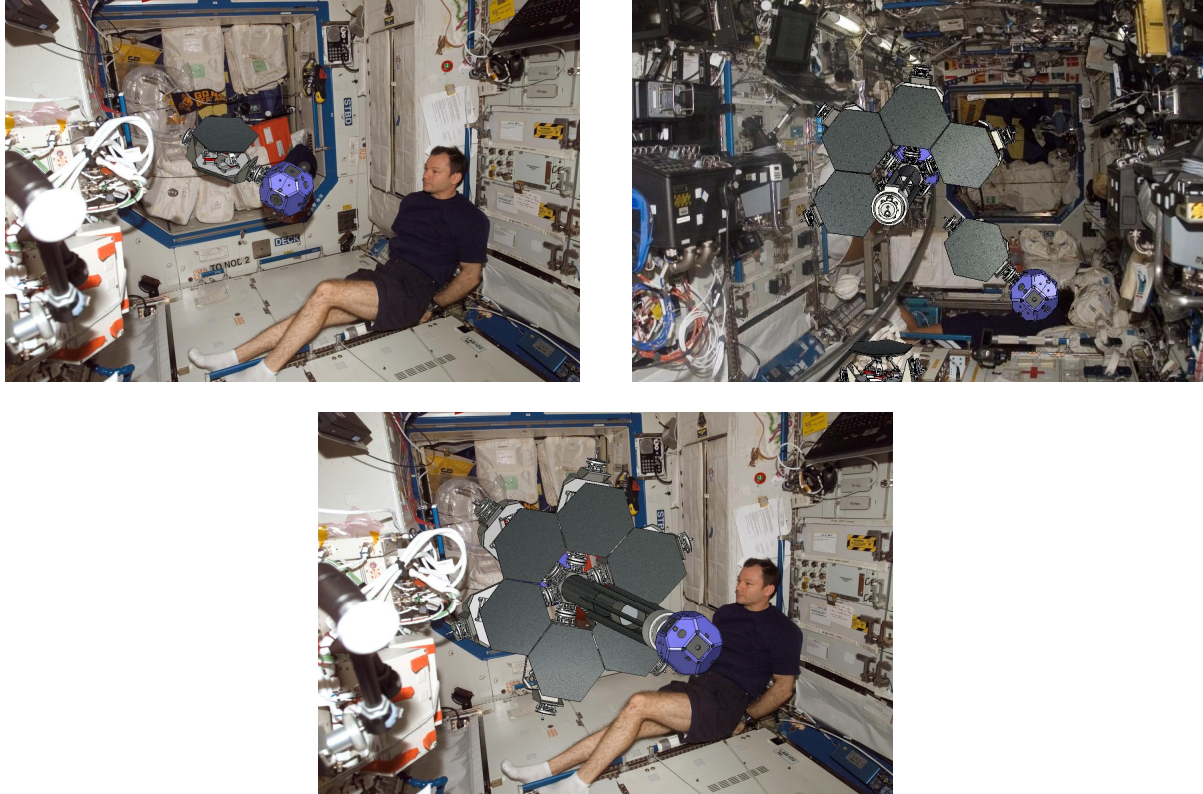


Figure 4. Assembly Sequence inside ISS

A strawman concept for the testbed is to use the SPHERES, with perhaps the assistance of a robotic arm, to dock three to six 30cm hexagonal mirror segments to a free flying SPHERE. This would form a .76m diameter segmented primary mirror with a radius of curvature of approximately 1.5m. The SPHERES then maneuver and dock the secondary support tower to this primary along with the center-of-curvature optics that illuminate and measure the wavefront. The segments are mounted on piston, tip and tilt actuators that allow phasing at >1 Hz bandwidth. This will permit phasing in a moderately harsh dynamic environment such as being mounted to a SPHERE with thrusters or mounted to the ISS wall. The assembly and phasing sequence is estimated to take no more than sixty minutes. The SPHERES batteries last two hours and a propellant tank typically lasts longer.

For integration and launch, SPHERES benefited from being composed of many small components that allowed it to be launched on five different launches (two Progress and three Shuttles). The same is true for the additional components needed for ALMOST. All safety guidelines will be followed. For example, the intensity of the illumination of the optical surface will be kept low for eye safety. Metal or composites will be used for mirrors instead of glass for fracture control.

3. Relevance, Significance, and Innovation

The development and maturation of the myriad of technologies that are required for in-space robotic assembly of telescopes is primarily focused on the integration of low TRL technologies (H/W, S/W, and ConOps) in order to raise their TRL through on-orbit testing. This doesn't mean that the particular hardware and software components tested are those that would be used in an eventual operational system. Instead, ALMOST is pioneering a technology maturation process for transitioning laboratory research to mission application. This is a perfect role for the ISS since it allows scale model testing in a representative yet risk-tolerant environment, analogous to a wind tunnel. In the process, there will be many lessons learned about how to make the process robust from a software perspective, how to trade tolerances between mechanisms and control, and what works and what doesn't work in terms of operational concepts.

The reason why ALMOST addresses the end-to-end process from robotic assembly of a structure to optical phasing is to highlight the issues associated with assembly of optical subsystems and wavefront sensing and control because the requirements for each are often at odds with each other. This is clearly important because:

1. This program provides a truly three-dimensional, micro-gravity, hardware-in-the-loop demonstration of robotic assembly of an optical system that can subsequently phase itself to a diffraction-limited surface.
2. Robotic assembly of structures is an inherently three-dimensional operation. Gravity offload devices, necessary for testing in a 1-G environment, substantially constrain the motions and dynamics of the assembly sequence and add substantial mass.
3. Conducting a fully autonomous assembly sequence of a functional optical system is essential. It forces the development of all hardware, software and operational components that are required for such a system to function. Nothing is abstracted.
4. It permits the technology to be exercised from start to finish, where start corresponds to the delivery of the stowed system to orbit and finish corresponds to the creation of a diffraction-limited optical surface.
5. Assembling an active optical system with self-contained measurement capability forces the demonstration to address the imprecision needed to permit assembly while subsequently being able to align the system to optical tolerances.

ALMOST will achieve several technological firsts while taking the first steps towards large space apertures after JWST:

- First in-space assembled telescope mirror,
- First space structure assembled by free-flying agents,
- First segmented space system using image-based WFS&C to maintain a diffraction-limited primary mirror surface (assuming operation before JWST),
- First segmented space system phased at high rate (JWST phases roughly once per month) allowing segmented systems in hostile (non-L2) thermal environments (LEO, MEO, GEO).

3.1 Why should this experiment be conducted in space, and more precisely, why should it be conducted inside ISS?

Conducting an experiment in space is complicated, time-consuming, and when compared to ground experiments, expensive. Therefore, the case must be made that the experiment cannot be done on the ground in a sufficiently high fidelity mockup, or in a computer simulation. The ALMOST program has the following characteristics which make it appropriate and desirable to test inside ISS using SPHERES:

- **Full 6-DOF dynamics.** Ground-based testbeds cannot provide an operational environment in which all the degrees-of-freedom (DOFs) of a close-proximity, multi-satellite operation are in play. The robotic assembly maneuvers being tested require this full set of DOFs in order to properly account for any interactions and couplings.
- **Realistic sensor suite.** SPHERES provides direct analogs of the sensors that will be used in an operational system, both for absolute position as well as relative distance between satellites. Our pseudo-GPS system provides 2mm ranging and one degree bearing angle measurement relative to the ISS body frame as well as equivalent accuracy for inter-satellite range and bearing. Although we use ultrasonics, the time-of-flight measurement accuracy and five hertz bandwidth are comparable to differential GPS. We are also currently developing a vision-based capability. Therefore, algorithms developed and tested using SPHERES do not "cheat", i.e., they do not achieve their performance by using measurement types that will not be available in the real system.
- **Realistic actuator suite.** Similarly, SPHERES uses compressed gas thrusters, which are directly analogous to thrusters that would be used in an operational system. Each 4 kg SPHERE has 15 m/s of delta-V from each propellant tank. Again, no "cheating." Obviously, we'd need more capability onboard the SPHERES: camera (under development), docking port (exists in ground testbed), manipulator arms (do not currently exist). Just like a computer, each SPHERE has an expansion slot that allows payloads to be attached by the astronauts.

- **Operational environment.** Granted, the operational environment inside ISS is different from what would be present in a free flying cluster of spacecraft. However, the constraints imposed by ISS requirements, the procedures development, the various operational protocols, etc., do bring you closer to what you would see in a "real" mission, and provide an invaluable tool for developing experience in the team that can be directly brought to bear when the full-scale mission is flown in the future.
- **Moving up the TRL ladder at a low cost.** We do not claim that one can fly a SPHERES-based technology development experiment and then directly proceed with the full-scale mission without conducting a larger scale demonstration experiment outside the ISS. What we do claim is that for very low cost, you can increase the TRL of various critical technologies such that, when you do fly a pre-cursor demonstration experiment, you can do so with more confidence. Even the simplest pre-cursor demonstration will cost hundreds of millions of dollars and take years to fund, develop, and carry out. SPHERES, for about 1% of that cost, can provide a near-term demonstration of key robotic technologies that can then be further demonstrated and developed on a larger scale system.
- **Risk free environment.** Again, given the cost of any large scale demonstration experiment, the price of failure is too high. Project managers understandably become very conservative. So instead of providing a means for developing necessary technology, these flights serve to demonstrate systems and technology that is reasonably well-understood, with few surprises. On SPHERES, this is exactly the opposite situation: we encourage developers to push the envelope of their algorithms, maneuvers, etc. If a controller goes unstable, if one satellite bumps into another, all that happens is that we reset the experiment, and go on to the next test. The whole purpose of SPHERES is to provide a platform for project managers to do this without risking their multi-billion dollar operational satellites or their multi-million dollar precursor demonstration missions.

3.2 Innovation

The key innovative feature is that ALMOST will demonstrate and mature in-space robotic assembly using an existing reconfigurable robotic facility in a risk-tolerant environment under long-duration micro-gravity conditions for a fraction of the cost of alternatives. The reconfigurable robotic facility (SPHERES) permits reconfiguration of software and hardware without the need to bring the vehicles back to Earth. Risk-tolerance is provided by the fact that software is not a safety control; the hardware cannot hurt itself, the crew or the ISS; and that the astronauts can easily intervene in the event that a test fails. The long-duration micro-gravity conditions inside the US Laboratory, while not permitting the assembled structure to be large, does permit the assembled structure to be flexible, which is a key attribute of a large, lightweight structure. Also, assembly tests can take advantage of three-dimensional motion and sensor vantage points. In essence, using ISS allows the technology of in-space robotic assembly to be matured without the risk and cost of large in-space demonstrations. By buying down the risk using this intermediate step, subsequent demonstrations can be less risky and perhaps more representative of an actual operational system.

The state-of-the-art in space technology maturation is through three paths: computational simulation; ground-based hardware-in-the-loop testbeds; and flight demonstrations. ALMOST is distinct from computational simulations in that it incorporates hardware-in-the-loop testing, in concert with computational simulation, in a relevant environment (micro-gravity). In fact, this is a requirement levied by NASA Technology Readiness Levels 6 and 7.

TRL 6: System/subsystem model or prototype demonstration in a relevant environment (ground or space).

TRL 7: System prototype demonstration in a space environment

Hardware-in-the-loop testing is required starting at TRL 3.

TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept

Computational simulation alone does not address the myriad of non-idealities that exist in the physical world and therefore does not properly mature the hardware, software and operational techniques needed to overcome them.

ALMOST is distinct from ground-based hardware-in-the-loop testbeds because it operates in the long-duration micro-gravity environment inside ISS. The dynamics of ground-based robotic testbeds are dominated by gravity effects. Often, air carriages are used to float vehicles on a level, two-dimensional surface. The inertia of these carriages, as well as imperfections in the surface (friction and slope), dominate the dynamics of these vehicles and often dictate the amount of available test time. Furthermore, true three-dimensional motion is unachievable. Vehicles are unable to circumnavigate each other in all three dimensions in order to visually access all sides of the vehicles, assemble three-dimensional structures, and demonstrate three-axis attitude control of the assembled structure. Robotic manipulators have been used in ground-based facilities to maneuver two vehicles in close proximity. These systems need to be sufficiently strong to precisely maneuver these vehicles through large motions, making them heavy and impacting the coupled dynamics. Contact dynamics that occur when two vehicles touch are difficult to emulate properly causing chatter to occur when two high back-drive impedance systems come into contact. When a third vehicle is added, motion constraints become considerably more complex and the assembled structure needs the ability to support its weight in gravity.

ALMOST is distinct from on-orbit flight demonstrations because it is considerably less expensive and risky. For example, PSI-MIT's SPHERES program on ISS has cost \$3.5M to date including the flight hardware and software design, fabrication, and qualification as well as the crew training, on-orbit operations, and IG&N algorithm development and test. This is about 1% of the cost of a typical flight demonstration. Furthermore, the technology can be pushed more aggressively with the knowledge that if something does go wrong, the astronauts inside ISS can assist. Given the complexity of the operations that ALMOST will demonstrate, a free-flying on-orbit demonstration would cost substantially more than \$350M. Therefore, ALMOST permits full hardware-in-the-loop system testing in the long-duration micro-gravity environment of space for approximately 1% of the cost of in-space flight demonstrations. And, it can be incrementally upgraded at modest cost as promising technologies emerge.

4. TECHNICAL PROGRESS TO DATE

4.1 Hardware Testing

Preliminary ground testing has demonstrated the concept for assembling a telescope through the SWARM program. The SWARM program (Self-assembling Wireless Autonomous Reconfigurable Modules) is a ground testbed for the developing and maturing control algorithms for autonomous assembly. The objective of Phase 1 of SWARM was to assemble two telescope sub-apertures using a single SPHERES satellite as a tug (Figure 5).



Figure 5. SWARM Phase 1 set-up. SPHERES satellite in center with two telescope sub-apertures (left) and Relative position of SPHERES satellite center (with respect to docking port of sub-aperture) during a successful docking sequence.

The system employs an Extended Kalman Filter to do relative navigation using ultrasound beacons and transmitters on the docking ports. The docking is performed in three phases: alignment, approach, and capture. Figure 5 shows results from ground testing of the SPHERES satellite docking to a telescope sub-aperture. Autonomous docking was performed successfully in repeated tests.

In order to demonstrate a full assembly sequence, reconfiguration is necessary to update the mass properties in the tug's control design such that the tug can maneuver the aperture around

Reconfiguration was successfully demonstrated on the SPHERES ISS testbed by updating the mass, inertia, center of mass, and thruster properties. The control allocation algorithm converts control inputs to thruster firing commands. The reconfigurable control allocation takes as inputs the location of the thrusters with respect to the geometric center, the center of mass, and the force vectors of the thruster. The mapping from control input to thruster commands is calculated on-line, versus in the original algorithm where it was a hardcoded conversion.

Figure 7 demonstrates the performance of the reconfiguration. Figure 7a shows the performance of a single SPHERES satellite going through a set of three position targets ($t=5s$, $t=100s$, and $t=200s$). The target changes are reflected as spikes in the position error (plotted) that is driven to zero by a simple proportional-integral-derivative controller. Figure 7a reflects the ideal or baseline performance.

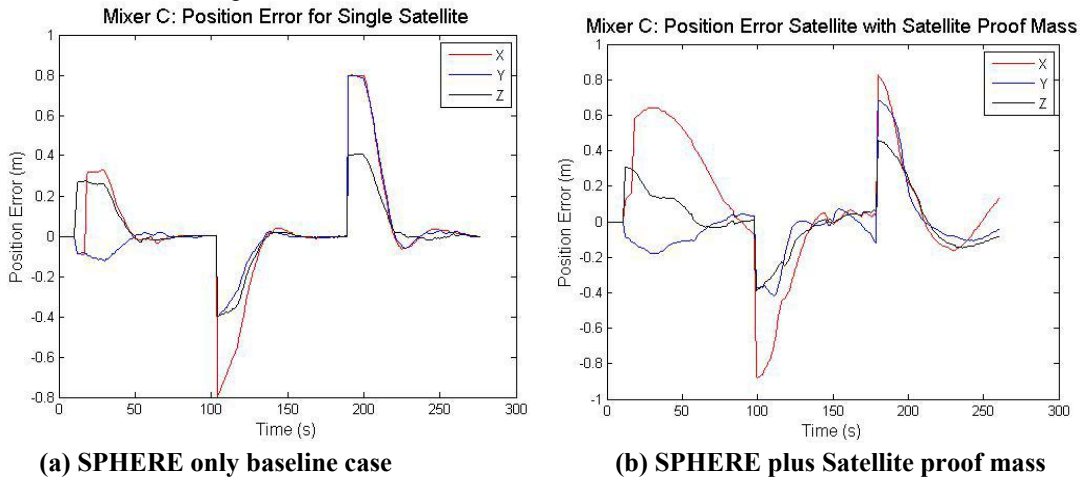


Figure 7. Position Error for three position targets using PID control

Figure 7b demonstrates the achieved performance for the same set of targets when a second SPHERES satellite is attached to the figure satellite via Velcro. The second satellite acts as a proof mass and does not actuate. This set-up mimics the scenario with the SPHERES satellite as a tug attached to a mirror segment. The model includes the updated gains, mass, inertia, and thruster configuration. Though the performance does not match the baseline case, it has been demonstrated to be controllable. Further methods of improving performance (ex. overshoot, settling time) that are currently being implemented are accounting for plume impingement in the maneuvering and accounting for thruster saturation.

The objective of SWARM Phase 2 is to demonstrate the full assembly sequence, including reconfiguration, on flexible structures. The motivation to move to flexible structures stems from lightweight mirror segments having flexible dynamics and the desire to develop the control algorithms to account for that flexibility. End-to-end ground testing is planned using a flexible beam as the payload instead of the telescope sub-apertures. Figure 8 shows a picture of a SPHERES satellite attached to the flexible beam payload. The objective is to dock the docking port at the end of the flexible beam into the base structure. This test sequence is designed to test control of a flexible structure, control and estimation reconfiguration, and assembly sequencing.

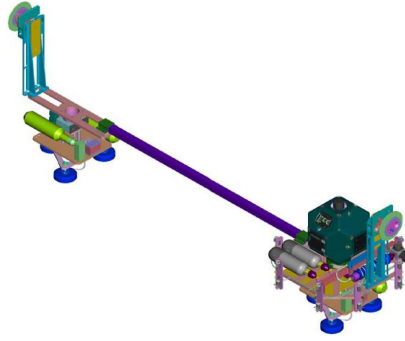


Figure 8. SPHERES satellite with flexible beam payload.

4.2 Reconfiguration Challenges

Several key control and reconfiguration challenges have been identified through this preliminary testing. First, several parameters must be updated in the control system to enable adequate performance after docking. Examples of these parameters are mass, inertia, and center of mass. However, there are additional factors that limit performance, such as thruster saturation and plume impingement that have yet to be addressed. Also, similar to control reconfiguration, the estimation algorithms also need to be reconfigurable, particularly for the addition of states to model the flexible modes of the mirror segment. Overall, the SWARM program testing is facilitating the development of the control and reconfiguration algorithms for autonomous assembly. Autonomous docking algorithms have been developed and tested; reconfiguration algorithms to incorporate mass properties and thruster configuration have been implemented and tested. Future work includes reconfigurable estimation algorithms and control algorithms for flexible structures. An integrated end-to-end ground test is planned for Fall 2008.

4.3 SPOT Optical Testbed

The optical component of ALMOST has been a GSFC internally-funded activity since 2004. The WFS&C algorithms utilizing image-based phase-retrieval have been successfully demonstrated both in the lab at GSFC and on the JWST Testbed Telescope (TBT) [7]. The SPOT optical testbed utilizes .86m glass mirror segments (as opposed to the 30 cm ALMOST segments) as shown in figure 9. The SPOT architecture can be readily scaled down for application to ALMOST. 3MV/SPOTLite, a SPOT precursor which was coarse-phased in early 2006, used a segment size equivalent to ALMOST.

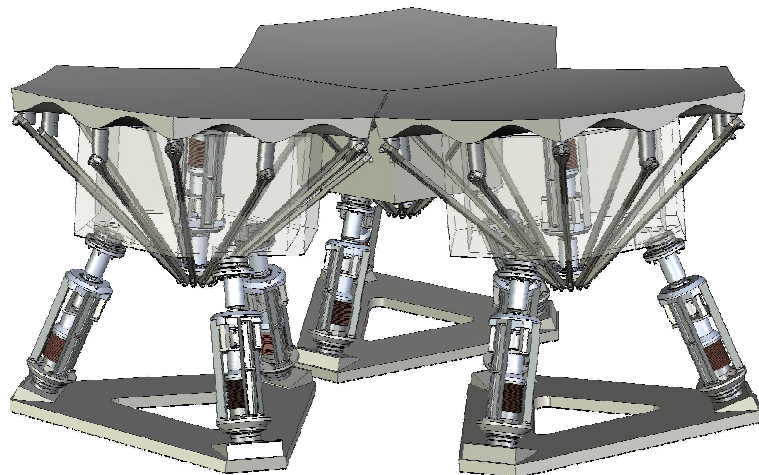
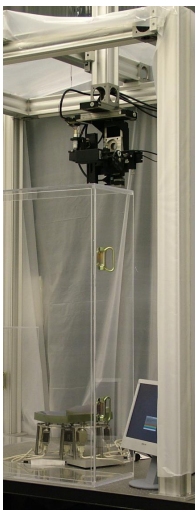


Figure 9. (left) 3MV/SPOTLite lab setup showing the phase retrieval camera at the top and the active mirror segments on the bench top adjacent to the monitor. (right) The SPOT 1.5m demonstrator using .86m segments currently in fabrication at GSFC

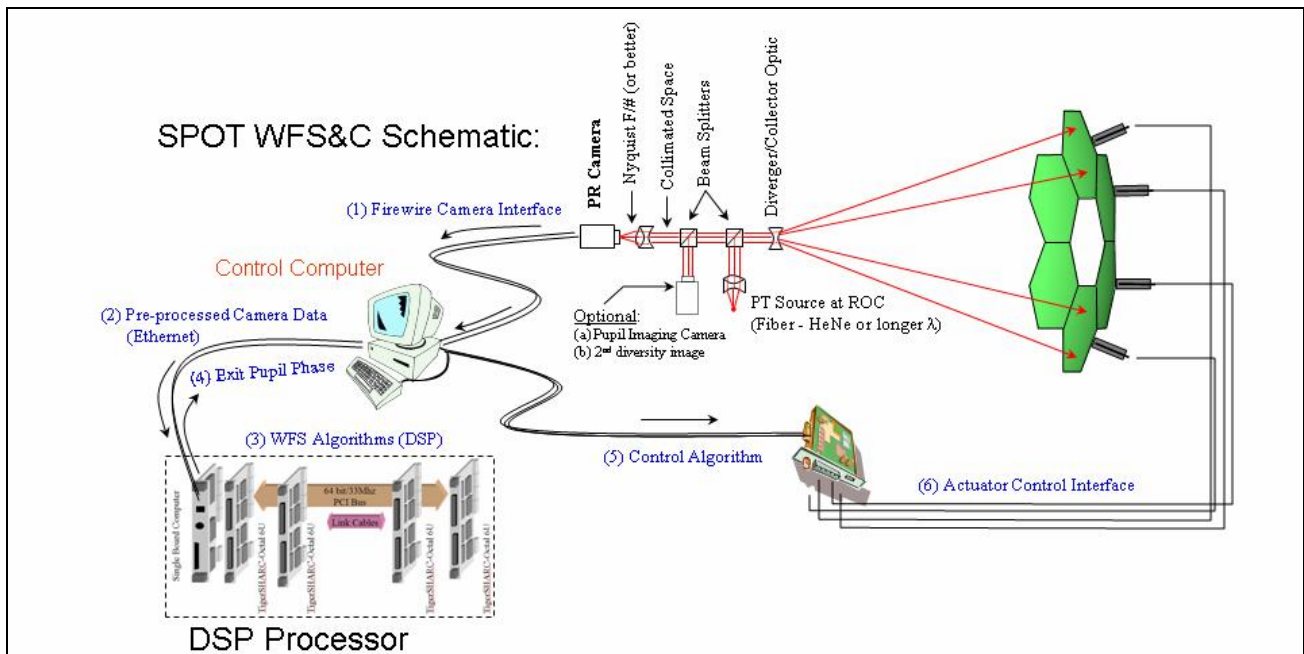


Figure 10. Schematic of the SPOT wavefront sensing and control architecture

The SPOT mirror segments are currently in fabrication and the testbed should be functional by Spring 2009. The development path from SPOT to ALMOST has been determined to include:

- Opto-mechanical analysis and design of smaller mirror segments that meet ISS safety requirements. New active radius-of-curvature (ROC) matching small segments will be designed based on the larger SPOT active ROC segments.
- Implementation of wireless command & telemetry. It is likely that signals will be transmitted from the cameras and commands relayed to the mirror segments via a wireless interface to ease harness requirements, and physically separate the experiment DSP processor array from the ALMOST instrument.
- Design of control electronics that meet ISS experiment interface requirements. The current laboratory electronics are non-flight and require redesign to meet all ISS experiment requirements.
- Implementation of battery power. The ALMOST optics cameras and mirror actuators must be run on batteries. A power system using approved batteries will be designed.

The above items may all be accomplished with little risk. The ALMOST optical system, based on GSFC SPOT architectures, can be realized in a short time, and at comparatively low cost and risk.

5. CONCLUSIONS

Future space observatories of the 2020 timeframe will compete with 30-50m ground facilities and must produce compelling science. In-space assembly is the only way to achieve comparable apertures for reasonable cost. Heritage space servicing/autonomy missions such as ETS-7, HST, Orbital Express, and ATV have made some progress towards this goal. However, mission failures, such as the Progress/Mir collision and DART navigation failure, show that technology is not mature and requires further development to realize the benefits of large space structures/instruments. The objective of the ALMOST program is to develop a methodology for hardware-in-the-loop assessment of in-space robotic assembly of a telescope under micro-gravity conditions in a more cost-effective and risk-tolerant manner. The approach uses the SPHERES testbed aboard the ISS, which has a demonstrated record of successful technology development.

Significant progress has already been made towards developing the tools needed for the ALMOST demonstration. The guidance, navigation, and control algorithms are being developed using the SPHERES and SWARM testbed. Initial algorithms for docking and reconfiguration have been demonstrated on the SPHERES ISS testbed and on the SWARM ground testbed (Phase 1). These techniques will be used to demonstrate a full assembly sequence of a flexible payload using the SWARM testbed (Phase 2). The development of the SPOT testbed enables ground testing of the optical components, as well as a larger scale version of the ALMOST telescope that is to be assembled on the ISS. The ALMOST project will dramatically improve the maturity of the guidance, navigation and control (GN&C) algorithms, as well as the mechanisms and concept of operations, needed to support a capability to deploy large, strong, lightweight, precise, dynamically stable structures. Successful completion of ALMOST is a pathfinder for a larger “outside” demonstration and substantially buys down mission risk; it is a critical step in developing autonomous in-space assembly capability.

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