THE SPHERES ISS LABORATORY FOR RENDEZVOUS AND FORMATION FLIGHT

Authors: Alvar Saenz-Otero*, David Miller†
MIT Space Systems Laboratory, † Director , *Graduate Research Assistant

MIT Room 37-354
70 Vassar St
Cambridge MA 02139
alvarso@mit.edu

Abstract

The International Space Station (ISS) provides the ability for the creation of true laboratories in a micro-gravity environment. The availability of humans in the ISS presents a further advantage: the ability to put humans in the design loop. The MIT Space Systems Laboratory developed a new laboratory design philosophy to take advantage of these new resources. The new philosophy is implemented in the SPHERES testbed, which creates a laboratory environment in the ISS that allows multiple scientists to develop and validate high-risk control, autonomy, and metrology algorithms for separated spacecraft that enable formation flight, rendezvous, and docking of satellites. By incorporating humans into the design loop of a micro-gravity system, as well as providing the ability to replenish consumables, the testbed provides a low-risk yet high-payoff environment where algorithms can be tested to their limits prior to deployment in full space missions. Subsequent deployment can be performed with a higher degree of confidence.

Introduction

The International Space Station (ISS) is opening the doors for humans to perform true laboratory tasks in a micro-gravity environment. To take advantage of these new resources, scientists and engineers must broaden the exiting views on the use of space facilities and the astronauts that inhabit them. Astronauts must become scientists in space and carry out full engineering and research cycles. But to enable the astronauts to carry out these tasks, substantial research and design must go into each laboratory environment created to operate in the ISS. The MIT Space Systems Laboratory (SSL) developed a laboratory design philosophy based on its previous experience with the MODE (Middeck 0-gravity Dynamics Experiments) and MACE (Middeck Active Control Experiment) family of dynamics and control laboratories (STS-40, 42, 48, 62, 67, MIR, ISS). This philosophy presents the main characteristics that must exist in a laboratory for the research of dynamics, controls, and metrology algorithms – all topics of research at the SSL. Utilizing this philosophy to develop a new cost-effective and successful research laboratory, the SSL has built the SPHERES (Synchronized Position Hold Engage Re-orient Experimental Satellites) Laboratory for Rendezvous and Formation Flight.

The SPHERES testbed provides a cost-effective, long duration, replenishable, and easily reconfigurable environment with representative dynamics in which multiple scientists can develop and validate metrology, formation flight, and autonomy algorithms. Formation flight and docking algorithms are high risk, yet high payoff control algorithms that enable coordinated motion of multiple satellites that perform missions such as sparse aperture telescopes, interferometer, re-supply, and upgrade missions which achieve the capabilities of single large spacecraft with multiple small separated spacecraft. These technologies are critical to the operation of future missions such as TechSat21, Starlight, Terrestrial Planet Finder, and Orbital Express. While the testbed itself will not provide the science hardware to fulfill any one individual mission; it will allow scientists to develop the theory to control the satellites that will perform said missions. To meet this goal, the SPHERES testbed design must allow for the *demonstration and validation* of experiments, demonstration of *repeatability and reliability* of algorithms, *determination of simulation accuracy*, *identification of performance limitations*, identification of *operational drivers*, and *identification of new physical phenomena* of the experiments being run. Therefore, rather than meeting the usual quantitative requirements for a specific mission, the testbed was designed to allow multiple scientists to clearly determine the validity of new theories.

The many characteristics of the SPHERES laboratory enable it to perform a multitude of tests among the formation flight, rendezvous, and autonomy research areas. Due to the broad range of experiments that can be carried out using the SPHERES laboratory, its integration into the ISS presented several unique experiences. While the majority of previous space experiments utilized the astronaut mostly as a means of deployment, the SPHERES laboratory pulls the astronaut directly in the design loop, asking them not only to follow procedures, but also make decisions on the experiment itself; these situations only used to present themselves outside standard procedures. The SPHERES laboratory will utilize the astronauts' full capabilities. But the SPHERES integration still had to account for the physical limitations of the ISS, as well as safety and procedural concerns. A careful balance has to exists between the scientific requirements to fulfill the design philosophy and the need to adhere with established guidelines for the use of the ISS. The experiences during the development of the interfaces, procedures, and training, provide useful feedback to broaden the concepts on the use of the ISS.

The SPHERES laboratory has been manifested in flight 12A.1 scheduled for launch on July 1st, 2003 (subject to NASA launch schedule); it will remain in orbit for a minimum of six months of operations aboard the ISS. Figure 1 shows a schematic of the flight units.

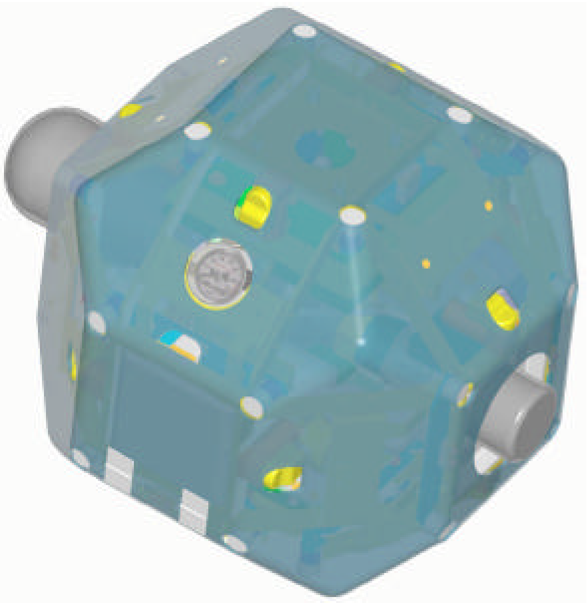

Figure 1. SPHERES flight unit

Laboratory Design Process

Previously space mission design has concentrated on the creation of experiments with one main science goal; the vast majority of past experiment sent to space always provide final results, rather than providing a laboratory environment for research. In the past this has been essential since the cost of each experiment prohibits designing hardware that must meet different requirements and/or perform multiple tasks allowing for the possibility of the science to fail since there will be no opportunity to make changes and try again. These restrictions arise from the fact that the hardware can only be used once and for a limited amount of time while in space or the Space Shuttle. With the availability of a laboratory environment in the ISS, the design of new experiments must change. Rather than utilizing the space station to run single-use experiments, the space station can host laboratories that cover larger areas of research such that different groups of scientists can benefit from the results. The design of these new facilities must account for a new design process. The standard process consists of defining the science requirements and the functional requirements (conception), creating a design, implementation of the design, and operation. Each step of the design process suffers modifications, each change is explained below individually, as well as how they apply to the SPHERES testbed.

Design Requirements

The conception of the project and definition of its requirements constitutes the most important part of virtually any project. While most of the time is spent in designing the system, it is errors during the requirements development phase that usually determine the success or failure of the project. Therefore, the SSL laboratory design philosophy concentrates mainly on the qualitative requirements of a testbed. Unfortunately, though, the new design philosophy makes the requirements more difficult to fulfill, since these tend to be qualitative and encompass a range of tests, rather than quantitative values for a specific experiment; since the exact tests that will be performed within the laboratory are not known, no exact values are known a-priori. In a few cases, it is possible to define a set of *minimum* quantitative requirements for the laboratory given a set of specific tests expected to be performed – if the laboratory cannot fulfill these requirements, it will not be able to successfully run these useful tests. But in those cases, the requirement is limited to a specific set of pre-planned tests, rather than to allow for a multitude of tests. Therefore, in general, the testbed needs to fulfill each qualitative characteristic as best as possible, such that it can be used for a host of applications. The quantitative properties of the testbed become limitations, rather than a requirement set forth during development.

The SSL design philosophy calls for the following characteristics to be present in space laboratories:

Demonstration and Validation – Demonstration of a research result on a physical system in its operational environment often provides the only acceptable information to a person who needs to make a go/no-go decision, but who may not be fluent in the details of the technology.

Repeatability and Reliability – The results of an experiment must be repeatable, that is, they must happen more than once under similar operating conditions. Further, positive results must be obtained in the presence of the different disturbances and commands that may be present during a mission to demonstrate the reliability of the algorithms.

Determination of Simulation Accuracy – It is desirable to demonstrate the validity of simulations and to measure their accuracy. The results of control experiments in a space research laboratory can be compared with simulations to provide confidence in simulation techniques and to gauge the simulation accuracy. The resulting increased trust in simulations allows ground researchers to achieve a higher order of completeness prior to low-risk tests in the space-based research environment.

Identification of Performance Limitations – In order to determine the success of new technologies or algorithms one must push these to their limits. Tests in a representative environment provide insight into most of the physical constraints of a system that may not be observable in a simulation or ground test. Further, knowing quantitative values of the limitations speeds up the creation of cost matrices during the development of optimal controllers.

Operational Drivers – Systems issues such as sensor-actuator resolution, saturation, non-linearity, power consumption, roll-off dynamics, degradation, drift, and mounting techniques are most often constraints rather than design variables. It is important to learn the quantitative values of these constraints during the creation of system models used in the design of control and autonomy algorithms. Experiments provide the information necessary to determine the values of these constraints as well as the coupling between them.

Identification of New Physical Phenomena – New physical phenomena are usually discovered through observation of physical systems. A research facility should provide for the ability to identify these phenomena, create models for them, and exploit this new knowledge in future investigations.

The specific major area of study for which the design philosophy applies to the SPHERES project is the development of control, metrology, and autonomy algorithms for separated spacecraft. Therefore, the principal science requirement for the design is simply to develop such a testbed. Secondary requirements arise from limitations inherent to every space project: money and space. The project must stay within budget. The whole testbed, to keep up with its physical limitations, must fit in 1.5 MLE – Space Shuttle Mid-deck Locker Equivalent. The rest of the requirements derived from implementing the design philosophy into these requirements.

Demonstration and Validation – is needed in order to provide both researchers and those that need to make go/no-go decisions with results that are truly representative of the system that will ultimately be developed. In the case of SPHERES, this meant developing a system with separated independent spacecraft which operate in a 6 DOF environment. Further, the operations of the testbed must be similar to those of the intended system. The validation of the tests by the scientist requires precise data acquisition; while the demonstration to those who make go/no-go decisions requires the ability to clearly interpret and present the results.

Repeatability and Reliabitly – the SPHERES testbed is required to perform similarly during different runs of the same test. This introduces two characteristics needed from the testbed: the ability to run the same tests multiple times, and to be able to start each test under similar conditions, requiring the ability to re-supply any consumables.

Determination of Simulation Accuracy – during each test run a scientist obtains data that can be compared to simulations of lower accuracy than the SPHERES testbed. The SPHERES laboratory program gives the participating scientists multiple levels of simulations. A scientist may have their own simulation of their system; the results from their simulation can be compared directly with results from the SPHERES testbed. The SPHERES program also provides the scientists with its own simulation of the testbed, allowing the scientists to perform experiments at different levels of accuracy and demonstrate the robustness of their theory.

Identification of Performance Limitations – in order for the SPHERES testbed to demonstrate the limitations of an algorithm, it must require that algorithm to run under circumstances that are truly representative of its intended operations. In the case of separated spacecraft, the testbed must operate in full 6 DOF to push the theory to its true limits; operation in a 3 DOF (under earth gravity in a frictionless environment) is not representative of the dynamics and other physical characteristics of the systems being modeled.

Operational Drivers – the results obtained from the testbed must be such that they present the limitations of the theory being tested, and not the testbed itself. Therefore, the requirement to provide with the performance limitations of the theory means that the SPHERES testbed must provide with both actuators and sensors that outperform the precision and bandwidth of the theory being tested.

Identification of Physical Phenomena – new physical phenomena is hard to identify unless the testbed truly represents the intended system. Therefore, the SPHERES testbed dynamics must match as closely as possibly the dynamics of intended systems; further, this once again highlights the need for high performance sensors and actuators that will not limit the system operation.

SPHERES Testbed Design

From fulfilling the characteristics outlined in the SSL laboratory design philosophy the following functional requirements were obtained:

? data feedback precision
? repeatability and reliability
? physical end-to-end simulation
? generic versus specific equipment
? hardware reconfiguration
? supporting extended investigations
? risk tolerant environment
? software reconfiguration
? human observability and manipulation
? facilitating iterative research process
? supporting multiple investigators

In order to better understand how the SPHERES laboratory environment fulfills these requirements, an overview of the testbed follows.

Testbed Overview

The SPHERES testbed needs to fulfill all the characteristics specified in the laboratory design philosophy. The resulting testbed must be a physical *end-to-end simulation* to ensure valid *demonstration and validation* of algorithms. Such a testbed enables developed algorithms to be easily transferred to space programs in the future. To fulfill this simulation requirement, the SPHERES testbed consists of three autonomous free-flyers that represent the spacecraft, a laptop computer that operates as a ground station, and five small metrology transmitters that create a pseudo-GPS environment. Each of the SPHERES sub-system is designed to further ensure this traceability. The testbed is designed specifically for operation in the shirtsleeve environments of the SSL laboratory (3 DOF), KC-135 reduced gravity airplane (6 DOF), and International Space Station (ISS – 6 DOF).

The SPHERES testbed is designed to produce results traceable to proposed formation flying missions. The individual self-contained satellites have the ability to maneuver in six degrees of freedom, to communicate with each other (satellite to satellite: STS) and with the laptop control station (satellite to laptop: STL), and to identify their position with respect to each other and to the experiment reference frame. The laptop control station is used to collect and store data as well as to upload control algorithms to the satellites. Currently, from one to three satellites may be used, depending on the algorithm being tested. The software architecture allows additional SPHERES to be added to the array, if desired. Figure 2 shows an operational concept for the SPHERES testbed, with inter-satellite and satellite-to-laptop interactions illustrated.

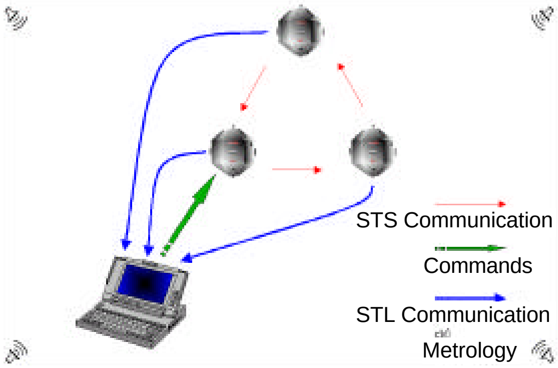

Figure 2. Testbed Operational Concept

The simplicity and hands-on nature of the testbed allow for easy reconfiguration and replenishment of consumables, resulting in a *risk tolerant environment.* The ability to re-supply all consumables further enhances the *repeatability and reliability* of the laboratory, by ensuring that even failures in the theory will not prevent the testbed from operating again. The KC-135 and ISS environments provide 3-D environments to test algorithms that may be directly applied to real satellites. The additional laboratory environment at the MIT SSL enables 2-D experiments to be performed before testing on the KC-135 or ISS, reducing even further the cost and risk to develop and verify algorithms. By operating in these controlled environments, the testbed provides *human observability and manipulation.* Also, operation of the testbed should never result in catastrophic failure of the testbed or its environment, ensuring a *risk-tolerant environment.* By allowing tests at all these levels, and fast feedback of data to the scientists, the testbed *facilitates the iterative research process.* To ensure the laboratory can *support multiple investigators*, regardless of their location, the SPHERES testbed provides a program that fully integrates remote investigators into the design loop.

As mentioned above, the SPHERES testbed was designed to test new control, metrology, and autonomy algorithms for separated spacecraft. Most of these are still in the conception or early implementation stages. Therefore, during the design phases of the SPHERES testbed the team had to determine a set of requirements that ensure future algorithms will run in the testbed and provide significant results. These requirements include the precision, accuracy, and operational ranges of sensors and actuators, processing power, untethered operational lifetime, and communications bandwidth. Table 1 summarizes the quantitative requirements derived from trade analysis. This set of requirements ensures the *data feedback precision* necessary to conduct useful experiments. These requirements account for the *operational drivers*, *identification of performance limitations*, and *identification of physical phenomena.*

The SPHERES testbed equipment was designed to fit in a Space Shuttle mid-deck locker, with room for expendables such as propellant tanks and batteries. In this way, the laboratory can integrate seamlessly into existing space available in the ISS environment. Subsequent hardware upgrades would either fit in the same locker, or take only a fraction of another locker space. Therefore, at all times, the SPHERES testbed will occupy only minimal space in the ISS, while providing a multitude of research options. The locker space constraints limit the satellite diameter to 0.25 m, about that of a volleyball, and the total volume of the system, including consumables, to 0.057m2.

Table 1. SPHERES derived requirements

Item	**Requirement**
Translation (1m start to stop)	5s
Rotation (360? start to stop)	5s
Translation accuracy	0.5cm
Rotation accuracy	2.5?
Propulsion lifetime	20s
Power lifetime	90min
Mass (all units + consumables)	24.5 kg
Processing Power	23 MFLOPS
Communications Data Rate	40kbps

The SPHERES units are identical since they constitute the *general equipment* of the laboratory. Yet, each unit can easily be outfitted with external components that change their dynamics and/or add operational elements. Therefore, the SPHERES testbed can simulate the operation of both homogeneous (all identical units) and heterogeneous (units with different physical or operational components) systems.

A short description of the major sub-systems, and their links to the design philosophy are presented next.

Sub-system design

Propulsion – The satellites are propelled by a cold-gas thruster system which uses carbon dioxide as fuel. The CO2 propellant is stored in liquid form at 860 psig, without the need for a cryogenic system. A regulator reduces the pressure to between 20-70 psig; the operating pressure may be adjusted manually prior to each test. A Teflon tubing system distributes the gas to twelve thruster assemblies, grouped in six opposing pairs. The thrusters are positioned so as to provide controllability in six degrees of freedom, enabling both attitude and station keeping control. Each thruster assembly consists of a solenoid-actuated micro-valve with machined nozzles optimized for the desired thrust of 0.25 N. The propulsion system may be easily replenished by replacing a spent propellant tank with a fresh, unused tank.

The system is replenishable, ensuring that *extended investigations* can take place. A single tank provides approximately 10 minutes of active operation, using non-optimal trajectories and with environmental disturbances (such as air currents inside the ISS). Ten minutes allows for most control experiments to return substantial information. After a test, a tank can be left in the system partially full, for use at a later time, or can be replaced with a new tank. In both cases, a subsequent test can be done either immediately or the units can be stored for use at a subsequent date.

The use of an easily replenishable propellant, finite thrust, and benign gas creates a *risk-tolerant environment.* In the case of unexpected behavior (such as an unstable controller), the units cannot cause catastrophic damage to themselves, the crew, or the ISS. The operator can simply grab the unit(s), reset it (them), and replace any tanks that may be empty.

The propulsion system is directly traceable to the propulsion systems of most existing spacecraft. The dynamics created by the SPHERES propulsion system directly simulate those of other thruster systems: non-linear dynamics, on/off operation, pulse width modulation or frequency modulation, and full controllability in 6-DOF. The system’s bit pulse of 5ms ensures the precision necessary to operate the system at frequencies of up to 100Hz.

Position and Attitude Determination – The Position and Attitude Determination System (PADS) has local and global elements that work together to provide metrology information to the satellites in real-time. While the global and local elements are capable of independent operation, the readings of both systems are combined during nominal operations to produce continuously updated state information at 50 Hz via a Kalman filter, such as those commonly used in spacecraft systems. The local PADS elements consists of three accelerometers and three gyroscopes, which provide inertial measurements at no less than 500Hz and 50Hz respectively. The global element is a pseudo-GPS ranging system that uses ultrasonic time-of-flight measurements from transmitters placed at known locations in the testbed’s reference frame to ultrasonic microphones distributed on the surface of each satellite. These time-of-flight measurements are converted to ranges and then used to derive position and attitude with respect to the reference frame.

The software sub-system provides further characteristics that fulfill the need for an end-to-end simulation. In order to ensure software reconfiguration and support multiple investigators, software filters can be easily added. These filters can process the PADS data in real-time to simulate different types of metrology systems. For example, a software filter could add a drift factor to the attitude data of the state vector, in order to simulate a system with only a local (IMU) attitude determination sub-system, while maintaining the position data outside of the Kalman filter to simulate a one antenna GPS system.

Power and Avionics – A Texas Instruments C6701 Digital Signal Processor (DSP) provides the computational power. DSP processors provide multiple features that ensure real-time operation. Further, the DSP processors include all support functions of a standard processor, allowing it to control the whole unit. The ability of the C6701 to provide between 167MFLOPS up to 1.0GFLOPS, provides significant processing power to prevent being the limiting factor in the performance of the system. The processor is supported with 16MB of RAM and 512KB of FLASH memory. The FLASH memory allows software re-configuration at all levels, ensuring that multiple investigators are supported while the system is in the ISS.

The power system utilized in the Space Station consists of packs of AA alkaline batteries. The packs provide each unit with approximately two hours of operation; once a pack is consumed, it can be easily replaced. The power system supports *repeatability*, *extended investigations*, and a *low-risk environment.*

Communications – Each SPHERES unit uses two separate frequency communications channels with an effective data rate of approximately 45kbps. One channel is used for satellite-to-satellite (STS) communications; the other channel enables satellite-to-laptop (STL) communications. Both channels are bi-directional; however, the communication hardware is half-duplex, meaning that only one unit can transmit at a time. The choice of two communications channels closely models the expected operations of future formation flying missions, creating a physical *end-to-end simulation* of a real mission. A high-bandwidth, low-power (short distance) communications link sends data between the units while in space. This link is used to send information in real-time, which is needed by the controllers in order to maintain formation. Due to the autonomy of the units, this channel does not require the power to establish communications with the ground, since only high-level commands/tasks will be sent from ground.

Ground communications links with formation flying missions are expected to be high-power and high-bandwidth, but have limited visibility and high latency. To correctly simulate this operation, the SPHERES testbed has a dedicated ground channel, the STL channel. For example, a separated spacecraft telescope may only be in communications with ground during the perigee of its trajectory, at which point it must send a burst of high-quality images to ground. While farther from earth, the ground link will not be utilized. The STL channel of SPHERES, though, is not limited in any way. The channel also serves to download the necessary telemetry information to the “ground” laptop computer to ensure that the researchers have the necessary information feedback. In a method similar to that proposed for the metrology system, software filters can be added to simulate a specific test of the program. For example, a software filter could ensure that commands are only sent every 5 minutes, rather than continuously, simulating an orbital period.

Since communication channels are expected to be a main operational driver of separated spacecraft system, it is important that the communications channels provide enough bandwidth so that the testbed can provide useful data. The generic communications equipment must provide the bandwidth necessary to allow meaningful formation flight algorithms to be tested, which means the communications bandwidth must be higher than that of the expected system dynamics. For the desired precision of 0.5cm position and 2.5deg attitude, the expected system dynamics range between 5Hz to 10Hz. The selected communications channels use a carrier frequency of 900MHz, a frequency compatible with the ISS frequency spectrum. The system provides a maximum effective data rate of approximately 40kbps, the maximum available during the development of the SPHERES testbed. This data rate allows full state information exchange between the three units and to ground at rates up to 50Hz; communications between two units can be up to 100Hz. Therefore, the communications channels ensure that the necessary information can be shared between the different units.

The SPHERES interface program contains all the necessary software to upload programs to a SPHERES unit, save telemetry information, present the user with the status of the units, start or abort a program, and reset the units remotely. Two different user interfaces are under development. A “research” interface, used by investigators on the ground or KC-135 testbeds, puts emphasis on the availability of telemetry information in real-time. In this way, the investigators can immediately see the telemetry data to determine correct operation of the testbed with better precision than simple observation. This facilitates the iterative research process by providing information to make changes as fast as necessary. An “operations” GUI is used in the ISS and KC-135 tests. This GUI presents only the interface to operate the testbed; the telemetry data is still recorded, but not shown. In order to ensure good human observability and manipulation, this interface accounts for the fact that the operator is not the investigator. Therefore, this interface emphasizes the operation and status controls of the testbed.

Guest Scientist Program – A main feature of a laboratory is the ability to conduct *multiple research* *investigations*. By allowing multiple programs to use the facilities, the cost of the laboratory is greatly reduced, since it shared among the programs. The SPHERES project has a Guest Scientist Program (GSP) to allow multiple investigators. Figure 3 presents the program overview. The GSP program consists of:

- GSP Simulation – The GSP simulation is intended as a tool for the development and coding of SPHERES control algorithms. The GSP simulation provides enough fidelity to verify compilation of guest investigator code.

- GFLOPS Simulation – This simulation runs on the Generalized FLight Operations Processing Simulator (GFLOPS) at MIT. The GFLOPS simulation is intended as a high fidelity, easily reconfigurable verification tool.

- SSL Laboratory – The SPHERES ground laboratory testbed, at the MIT SSL, can be operated at a very low operational cost. The hardware used in the laboratory will be identical to the ISS flight hardware, and realistic imperfections, uncertainties, and unmodelled effects will be present.

- ISS Laboratory – The ISS test process is expected to have a turn-around time of approximately one to two weeks, once SPHERES is operational in the ISS. Tests are run by the astronauts in the ISS, who save the data and then download it to ground. Data analysis occurs a few days after the test, with the ability to restart the iteration also within a few days.

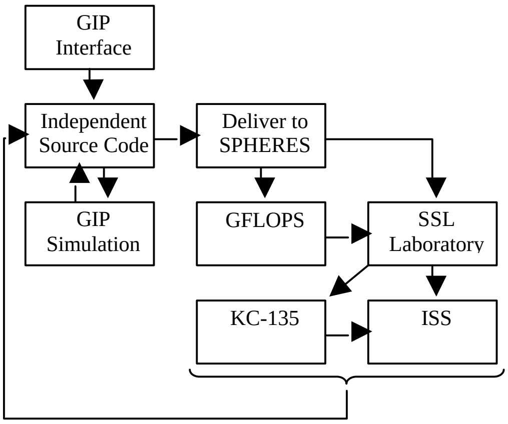

Figure 1. GSP Flow Diagram

Implementation

Implementation of the SPHERES testbed, such that it met all the requirements from the SSL design philosophy as well as the limitations presented due to operations in the ISS environment, presented multiple challenges. It is usually during the implementation phase that programs run into budget and time restrictions. Given that the requirements for the SPHERES testbed were never clear, when those restrictions become substantial, it is harder to determine what can and what cannot be cut from the system. At the same time, given the upgradeability of the testbed, it was easier to determine which functions could be left for future operations via expansion attachments. From the experiences learned in the development of the SPHERES testbed, it is clear that the design requirements played an important role in both the challenges and successes.

Implementation of an ISS program includes the need to interface and train the astronauts on the operations of the testbed. First, NASA presented the team with several guidelines for interfacing with the testbed, which accounted for the need for two different GUI’s, one for investigators and one for operators. Astronaut training, which is ongoing, presents a new challenge, since the operator of the experiment is no longer the scientist, but rather someone who is not necessarily as proficient in the topic. Therefore, new procedures are being developed by which the astronaut can understand the desired results, and evaluate the success of the experiment without direct interaction with the scientist. Results of these investigations will be presented in a future paper, after the SPHERES procedures and training have been completed, and an evaluation of the operations can occur after operations in the ISS.

Operations

As mentioned above, the SPHERES testbed is scheduled for launch and operations in the second half of 2003. Operations of the testbed have already taken place in NASA’s KC-135 Reduced Gravity Airplane during 2000, 2001, and 2002. The airplane provides 20 seconds of micro-gravity at a time, with a 1.8g 40 second pull-up between each micro-gravity period; it repeats this process 40 times each flight. These initial tests demonstrated the operational capabilities of the SPHERES Testbed in a micro-gravity environment, in preparations for deployment in the ISS. Yet, operations in the KC-135 are limited in time, while ISS operations will be over more than one hour at a time. Figure 4 presents a picture of the prototype (front) and flight (back) SPHERES units operating in the KC-135.

The expected operation loop for the SPHERES laboratory is as follows (assuming a scientist has already contacted the SPHERES program for a GSC package):

1. Scientist develops theory in GSP Simulation; after successful tests in the simulation, delivers the code to the SPHERES team.
2. The SPHERES team tests the code in the GFLOPS environment, the 2-D Laboratory setup, or both, to ensure the code is valid. If preliminary results are available will return them to the scientist.

Figure 4. SPHERES KC-135 Operations

3. Approximately every two weeks the SPHERES team will be able to upload new code and download data to the ISS. The new code is uploaded at this time.
4. In the next SPHERES test session, the astronaut loads the code into each unit, and runs the necessary experiments. The upload includes a description and preview of the code results, such that the astronaut can determine if the test ran successfully.
5. The astronaut will download the data approximately two weeks later.
6. The SPHERE team receives the data, and delivers it to the scientist.
7. Process repeats if necessary.

Once the process is complete, the scientists will have algorithms with high probability of success in a full 6DOF space environment.

Applications

While the SPHERES testbed has been designed mainly for the maturation and validation of control, autonomy, and metrology algorithms for separated spacecraft, the applications of the testbed – due to the broad requirements set forth in the design philosophy – extend beyond the intended design.

The identified high level applications of the testbed are:

Formation Flight – Formation Flight satellites are controlled to maintain relative attitude and position at large separation distances (100m-1km). Interferometry missions require high precision relative position and attitude control. Radar missions require less precise control, but by changing their baselines the mission can provide either large coverage or precision detection. Cluster communications missions can use artificial intelligence and the reconfigurability of the system to provide coverage in variable areas and ensure robustness.

Docking and Rendezvous – To reduce the costs of docking, these maneuvers must occur with minimal human intervention. Smaller satellites that perform all the tasks autonomously will lower the costs. Docking can then become standard for servicing, refueling, upgrading, and assembling.

Sample Capture – Several future missions call for spacecraft to land on Mars or other bodies and obtain samples. An orbiting craft will capture the sample and proceed with the return to Earth. The task must be performed autonomously by the orbiting craft, with co-operation from the sample unit.

Human Support – Support from robotic spacecraft can enhance the work performed by humans. Satellites can be sent into locations where the human cannot go or where it would be dangerous. Adaptability in the satellite would allow addition of tools to perform different tasks.

Human Training – The SPHERES testbed can also be used for training purposes. The SPHERES testbed allows a human operator to be trained to maneuver a unit, perform docking tasks, and train on limited feedback.

Conclusion

By realizing that the International Space Station provides a new setting which allows scientists to bring the laboratory environment into space, in lie of not being able to bring the space environment into a standard laboratory, the MIT Space Systems Laboratory has developed the SPHERES testbed. This testbed follows a new design philosophy that guides the design into a testbed that provides multiple scientists with the ability to develop and validate a multitude of algorithms with full dynamic representation, yet at a fraction of the cost of normal space programs. The openness of the design not only fulfills the needs for its intended science concentrations; even prior to deployment, uses for the testbed that go beyond the initial design goals have been identified. As new testbeds follow the SSL design philosophy, the ISS will become a true laboratory environment, where the astronauts will not only support, but also be part of the design process.