

Chapter 7

CONCLUSIONS

7.1 Thesis Summary

The objective of this thesis is to *create a design methodology for the development of microgravity laboratories for the research and maturation of space technologies*. This goal is motivated by the desire to combine the experiences learned by staff of the MIT Space Systems Laboratory through more than two decades of microgravity research aboard the Space Shuttle, MIR, and the International Space Station. This research includes experiments with the Middeck 0-g Dynamics Experiment (MODE), the Dynamic Load Sensors (DLS), and the Middeck Active Control Experiment (MACE). Further motivation arises from the call by the National Research Council to create a non-governmental organization to *manage all aspects of research on the ISS* in such a way that *the research community [has] early, substantive, and continuing involvement in all phases of planning, designing, implementing, and evaluating the research use of the ISS* such that *basic and applied scientific and engineering uses [of the ISS are] selected on the basis of their scientific and technical merit, as determined by peer review*. Further, the NRC report states that *the organization must be flexible and capable of adapting over time in response to changing needs and lessons learned* [NRC, 1999].

The development of the design methodology follows the steps of the scientific method: objective definition, hypothesis formulation, experimentation, results analysis, and conclusions determination. Based on the objective defined above, the hypothesis states that

the use of the International Space Station as a host and following the MIT SSL Laboratory Design Philosophy as design guidelines enable the development of a low-cost environment for the development and operation of facilities to conduct space technology research. The experimentation consists in the design, implementation, and operation of the SPHERES Laboratory for Distributed Satellite Systems. The laboratory consists of several facilities, including a simulation, ground-based operations for 2D tests, and operations aboard the ISS for 3D tests. Analysis of the design of SPHERES, the MIT SSL Laboratory Design Philosophy, and the resources and operations of the ISS results in the creation of the Microgravity Laboratory Design Principles, a design framework for scientists to develop new laboratories, and an evaluation framework for ISS staff to determine if a project utilizes the station correctly. The thesis concludes with the application of both frameworks to the SPHERES laboratory.

In order to better understand the existing resources available to mature space technologies and how research is performed at remote locations, Chapter 1 presents an overview of the NASA Technology Readiness Levels used to determine technology maturation; it reviews existing facilities that allow research in actual or simulated microgravity conditions; and reviews existing remote laboratories. The NASA TRLs provide an example of an existing methodology to evaluate a technology after its testing environment has been designed and the tests conducted. They also provide specific information on the requirements of a laboratory designed to demonstrate space technology maturation.

Chapter 1 reviews the microgravity facilities and remote research facilities summarized in Table 7.1. The review of existing facilities includes facilities located at the home location of researchers, such as simulations, robots, and air tables. Remote ground-based facilities, including flat floors, drop towers, neutral buoyancy tanks, and reduced gravity airplanes, are researched to determine their capabilities and operations. The Space Shuttle and International Space Station are the only space-based environments currently available for research in a microgravity environment. Their capabilities and operations are reviewed. The operations, capabilities, and research conducted aboard previous space based research

TABLE 7.1 Research facilities studied in the thesis

In-house	3rd Party/Full μ-g	Space	Remote
Robot Helicopters	RGO (KC-135)	Free Flyer	Ocean Exploration
6 DOF Robot Arms	Neutral Buoyancy	ISS	Antarctic Research
Helium Balloons	Drop Towers	Shuttle Payload	
Robot Cars		Shuttle Middeck	
Flat Floor			
Air table			
Simulation			

stations (Salyut, US Skylab, SpaceLab, and MIR) are also researched. A comparison of the capabilities and operations of the available facilities, with an understanding on how research was conducted aboard previous space stations, indicates that the ISS provides many unique opportunities for research which allow technology maturation through TRL 5 and up to TRL 7. Ground based facilities are not able to simulate the required environment; the use of the Space Shuttle is now highly restricted. Therefore, further research on the ISS is presented in Chapter 2.

Because operations aboard the ISS require that scientists not be present in the operational environment, Chapter 1 also presents research on two existing remote facilities: antarctic research and ocean based research. These facilities create a laboratory environment in remote locations, with strict operational plans and limited resources. The research on these facilities showed that the main goal of the designers is to enable the presence of the scientist at the research locations. Both facilities continuously increase the resources available for humans, specifically the scientists, to be present at the research locations. Therefore, even though these locations are remote, they do not require an operator external to the mission to conduct tests and report results. Rather, they provide operators to assist the scientists in conducting the research in an efficient manner. Given that the presence of the scientist aboard the ISS is practically impossible at this point, this review indicates that research conducted aboard the ISS must stress the need to extend the capabilities of the operator such that they can become an extension of the scientist. The operator should not

only conduct repetitive tasks which could be automated; the ability of the human operator to process information and make educated decisions must be used as an extension of the scientist.

Chapter 2 identifies the challenges of microgravity research observed in the review of present and past research facilities in Chapter 1. These challenges are:

- *Risk* - Every space mission has inherent risks, the possibility of failure at some step of the mission. The risk considered in this thesis involves the possibility of a facility failing in such a way that research can no longer be conducted and technology maturation is not achieved. The goal in the development of the design methodology for microgravity research is to allow a laboratory to reduce the risk of research for technology maturation and of the operational mission.
- *Complexity* - The complexity of space missions grows increasingly as a mission approaches operations. The need to account for system integration without the ability to test all the components usually leads to increased complexity to reduce the possibility of failure; but the increased complexity adds cost to the mission, as well as more failure modes. Therefore, it is desirable to reduce the complexity by allowing tests of integrated systems at every step.
- *Cost* - As a mission approached operational state, its costs increase substantially due to the increase of risk and cost involved, as well as the need to account for the space environment. The use of a microgravity laboratory should allow the cost to be controlled by providing model environments that better represent the operational environment.
- *Remote Operations* - Operations aboard the ISS are necessarily remote; the scientist remain in the Earth, while the operator conducts tests aboard the ISS. To efficiently conduct research, the operator must be provided with the necessary tools to assess experiments and make decisions that help to advance the science, even if it is not possible for the scientist to be in real-time communications with the operator.
- *Visibility* - Space missions usually stand at the extremes of visibility by the public (and funding sources). A mission that is very visible cannot take any risks that could result in failure, many times leading to conservative science goals and/or an increase in the cost of development to minimize the risk in the use of new technologies. On the other hand, missions with low visibility usually don't receive the necessary resources. Therefore, it is desirable that missions receive resources due to their scientific merits, rather than their visibility.

Next, the chapter presents an in-depth review of the environment and resources of the International Space Station that can help in overcoming these challenges. The chapter introduces the modules that form the ISS, concentrating on those that have been specifically designed to support research: US Destiny Laboratory, US Centrifuge Accommodations Module, US Integrated Truss Attachments, Japanese Experiment Module, ESA Columbus Module, and two Russian Research Modules. Further, the ISS provides scientists with several shared resources: controlled environment, power, communications, thermal management, cryofreeze systems, and payload stowage. The station will also provide up to 22 (most under development) shared research facilities for specific areas such as biotechnology, materials processing, human physiology, and more. But no space technology facilities are planned. The research identifies five special resources of the International Space Station which directly help to overcome the challenges of microgravity research:

- *Crew* - The presence of humans aboard the ISS helps reduce the risk, complexity, and cost of missions to research space technology maturation. Humans can determine incorrect operation of an experiment, preventing critical failures in facilities aboard the ISS, therefore reducing the risk. The use of the crew allows scientists to reduce the complexity and cost of facilities, since they do not require expensive automation tools to operate and collect data. Further, humans can perform direct observations and provide feedback to the scientists.
- *Communications* - Existing communications equipment at the ISS reduces the cost of missions. More importantly, the availability of real-time communications and a substantial bandwidth for data transfer allows scientists to communicate with the operator as needed. The scientist can upload data for the operator to review, and download their data in an efficient manner. The operator can ask questions to the scientist with little delay.
- *Long-term experimentation* - The ability to conduct research over extended periods of time lowers the effects of visibility on a mission. A project which is researched aboard the space station for a long time will not have the public visibility and impact of other missions, but the presence of the project aboard the ISS adds visibility among the scientific community.
- *Power* - The ISS provides substantial amounts of electrical power, as well as several gases. This helps missions reduce their cost, since power sources and storage are no longer required of each project. Further, this reduces the complexity and risk of a mission, due to the simplified power sub-system and guaranteed availability of power over extended periods of time.

- *Benign Environment / Atmosphere* - The benign environment of the ISS creates a risk-tolerant environment for research projects. The availability of humans to oversee operations, combined with the ability to repair faults, reduces the risk of a mission. The availability of an atmosphere allows projects which operate in the pressurized modules to develop their hardware in standard ground-based facilities, without the need to account for the effects of an actual space environment. This results in reduced cost and complexity of the mission.

The benefits of utilizing the ISS are summarized in Table 7.2.

TABLE 7.2 Benefits of the ISS for microgravity research

Resource	Risk	Complexity	Cost	Remote Operations	Visibility
Crew	↓	↓	↓		
Communications			↓	↓	
Long-term experimentation					↓
Power Sources	↓	↓	↓		
Atmosphere	↓	↓	↓		

↓ = reduces challenge

Research aboard the ISS covers multiple fields through several operational modes. Three types of operations were identified: observation, exposure, and iterative experiments. Observation experiments involve equipment and/or astronauts making observations of the Earth or space and providing that information to scientists on Earth. Exposure experiments require the presence of the test artifact in the microgravity environment of the ISS, either in the pressurized areas (e.g., effects of microgravity on humans) or exposed areas (e.g., materials exposure to space radiation). These experiments do not process any data while the artifacts are aboard the ISS; all data is analyzed in ground-based facilities after the exposed artifacts return to Earth. Iterative experiments collect data while aboard the ISS;

this data is used by either the astronauts or the scientists to review the experiment and conduct new tests until the desired results are obtained.

Three main areas of research have been identified: educational, pure science, and space technology. Educational experiments provide methods for students at all levels to become involved with space experiments. Pure science missions provide insight into how systems behave differently in microgravity and full gravity conditions; they address the better understanding of physical laws and biology. Space technology experiments allow research to develop products for use in space missions and facilitate access to space. The thesis specifically addresses the design of iterative space technology missions aboard the ISS.

Chapter 3 introduces three past MIT SSL microgravity programs. The Middeck 0-gravity Dynamics Experiment flew on STS-48 and STS-62 to measure the non-linear dynamics of fluid slush and jointed structures. The Dynamics Load Sensor experiment operated aboard the MIR space station for approximately three years to measure loads of humans as part of the ISS risk mitigation program. The Middeck Active Control Experiment flew on STS-67 and was operated by Expedition One aboard the ISS. The first mission developed dynamics and controls tools for predicting and refining robust, multi-variable control algorithms. The ISS mission of MACE studied dynamics and controls technologies ranging from neural networks to nonlinear dynamic characterization to adaptive reaction wheel isolation.

The MIT SSL Laboratory Design Philosophy was developed from the lessons learned in the development and operation of these experiments. The philosophy calls for new laboratories to exhibit a specific set of features that facilitates research of dynamics and controls experiments. The philosophy is based on the need of a mature control algorithm to be demonstrated in a valid environment; produce repeatable and reliable results; allow the determination of simulation accuracy; and identify performance limitations, operational drivers, and new physical phenomena. For a laboratory to enable demonstration that show characteristics are met, the MIT SSL Laboratory Design Philosophy calls for a laboratory to exhibit the following features:

- **Facilitating Iterative Research** - A laboratory must allow scientists to conduct research following the scientific method: formulate a hypothesis, design an experiment, run tests, collect and analyze data, and compare the results with the hypothesis to demonstrate the problem has been solved or modify the hypothesis to run new tests. This is an iterative process; the research iterates on multiple hypothesis until the desired performance is achieved. Specifically for the dynamics and control experiments conducted at the MIT SSL, a laboratory must allow formulation of new models (dynamics) and algorithms (control) based on the analysis of collected data and its comparison with predicted results.
- **Support of Experiments** - The features that support experiments ultimately facilitate the iterative research process by reducing the time to conduct experiments and providing relevant data. Several features encompass the support of experiments:
 - *Data Collection and Validation* - A laboratory must provide the facilities necessary to collect substantial data which can support or refute the hypothesis. The facility must provide methods to validate the accuracy and precision of the data independently of the original sensors used to collect the data.
 - *Repeatability and Reliability* - The facilities must allow easy repetition of experiments with minimal time invested in setting up and starting new tests. Further, the facility must be reliable such that each test is conducted with reasonable expectations that the environment is controlled and any changes external to the experiment are observed.
 - *Human Observability and Manipulation* - A dynamics and controls laboratory allows humans to directly or indirectly observe every step of the experiment without the need for expensive data analysis when an observation can be used to determine results. Further, the ability of humans to manipulate the facilities allows humans to modify the experiment conditions.
 - *Supporting Extended Investigations* - To allow iterative research, a laboratory must provide scientists with substantial time to analyze data and determine the need of new hypothesis and/or design of new experiments.
 - *Risk Tolerant Environment* - A laboratory for research must provide an environment where a scientist can take risks in the design of their experiments. Specifically in the case of dynamics and control algorithms, the scientists should be able to push the limits of their algorithms to determine the performance limitations without the possibility of a critical failure to the facilities.

- **Support Multiple Investigators** - Aerospace research involves the study of a wide range of areas. Even within the dynamics and control fields, many scientists come up with different hypothesis, all of which could achieve the desired performance. Therefore, a laboratory must support multiple scientists to test their different hypothesis. This enables the use of a laboratory to determine the best solution among the field, rather than provide a single data point within the field.

For collaborative science to be effective it must allow each scientist to achieve goals they would otherwise not be able to do on their own. The experiments developed for collaborative research must support multiple investigators by design. These experiments must identify the common elements shared between scientists, and allow individuals to add their own components for their specific research. This requires a systematic approach which must clearly define the goals and structures of the collaboration while creating trust between the parties. Effective inter-personal and data communications channels must be established

- **Reconfiguration and Modularity** - The ability to reconfigure an experiment provides benefits to facilitate the iterative research process (redefine the experiments and/or hypothesis) and to support multiple investigators (allow individuals to utilize science-specific components). The use of modular systems allows for simpler methods to allow reconfiguration. Several features are considered for reconfiguration and modularity:
 - *Generic versus Specific Equipment* - The facilities that support collaborative research must identify the generic equipment which supports all scientists involved in the research. Provisions must be made for scientists to provide science-specific equipment. This can be in the form of either hardware or software.
 - *Hardware Reconfiguration* - Hardware reconfiguration refers to the ability to change the hardware not only to support multiple scientists, but also to change the configuration of the facility for individual tests. In the area of dynamics and control the hardware configuration of a test apparatus directly affects the results by changing the dynamics of the system. Hardware reconfiguration also allows the addition of new sensors and actuators to better represent the intended system.
 - *Software Reconfiguration* - The need to support iterations and multiple scientists requires that facilities provide software reconfiguration. The correct use of software reconfiguration can lead to the development of a good platform where multiple scientists can implement their own modules for their specific research area. This development must utilize simple APIs that enhance the collaborative efforts.

- *Physical End-to-End Simulation* - An experiment designed to mature a space technology must exhibit all the relevant physical characteristics of the operational system to reach a TRL 5 or greater. Requiring an experiment to fulfill end-to-end simulation means that the experiment includes the necessary sub-systems and operates in the correct environment to provide realistic operations. No critical elements of a program can be missing in the tests, otherwise the experiment does not satisfy being an end-to-end simulation and the technology cannot advance.

The SPHERES Laboratory for Distributed Satellite Systems was designed specifically for operations aboard the ISS (Chapter 2), following the guidelines of the MIT SSL Laboratory Design Philosophy presented in Chapter 3. Chapter 4 presents detailed information about the features exhibited by the SPHERES testbed to satisfy the philosophy and enable efficient remote operations aboard the ISS.

SPHERES consists of five nano-satellites, metrology and communications hardware, a researcher interface, an astronaut interface, and a guest scientist program to allow multiple researchers to use the facility. In its final configuration, three of the satellites will be aboard the ISS, where the astronauts will conduct tests in 6DOF. Two units will remain in the ground facilities of the SSL where MIT researchers will test algorithms prior to up-link to the ISS. The guest scientist program provides a simulation which allows researchers outside of the MIT SSL to develop their initial algorithms in house. Operation of the SPHERES satellites (prototypes, left; flight right) aboard the KC-135 RGA is illustrated in Figure 7.1.



Figure 7.1 SPHERES operations aboard the KC-135 RGA

The SPHERES features to fulfill the MIT SSL Laboratory Design Philosophy are:

- **Facilitate the Iterative Research Process**

- *Multi-layered operations plan* - The SPHERES operations plan directly accounts for the need to conduct iterative research. It provides scientists with multiple steps to incrementally increase the fidelity of their tests, while always ensuring that complete iterations are possible. The need for efficient data collection and ability to update the experiments and/or hypothesis are accounted for at every step.
- *Continuous visual feedback* - Visual observation of the experiments is available at all steps. In most cases where experiments are conducted in ground-based facility the scientist can directly observe the tests. All ISS missions will be recorded; the video will be made available to scientists within a few days of the test.
- *Families of tests* - The SPHERES software allows scientist to program a large number of tests into each of their programs to be used in a test session. In this manner, scientists can have ready several experiments which incrementally demonstrate more features of their algorithms, even before the first test. As successful experiments are conducted, the operators can conduct more complex tests, allowing a single session to substantially advance knowledge of a technology.
- *Easy repetition of tests* - The hardware and software have been designed to allow quick repetitions of tests. Ground-based experiments can be re-started by simply positioning the satellites and using a one-key command. ISS experiments require that the satellite be positioned and then enabled, followed by two step process to ensure the astronaut is ready for the test to start.
- *Direct link to ISS data transfer system* - By using a direct link to the ISS data transfer system, the SPHERES operational plan minimizes the lag for scientists to obtain the collected data. It also simplifies the operations needed to upload new programs to the ISS facilities.
- *De-coupling of software from NASA safety controls* - Software that is controlled by NASA requires lengthy reviews before being deployed to the ISS. By not requiring safety reviews, SPHERES allows scientists to make any modifications necessary and upload them to the ISS efficiently.

- **Support of Experiments**

- *Data Collection and Validation Features*
 - *Layered metrology system* - The SPHERES metrology system provides both high-frequency inertial measurements and low-frequency

absolute measurements to provide scientists with the necessary data to determine the full state of a 6DOF satellite.

- *Flexible communications: real-time & post-test download* - The communications mechanism allows scientists to define the amount of data they need. If the real-time bandwidth is not sufficient, scientists can download large amounts of data after a test has finished.
- *Full data storage* - To minimize the effects of errors during wireless transmission, all the data received by the control laptop is stored intact. While the interfaces process some of that data to show information to the operators and scientists, all of the data is available for post-processing.
- *32 bit floating point DSP* - The use of a 32-bit floating point DSP provides scientists with high precision data and quick calculations to meet the precision needs of their research.
- *Redundant communications channels* - While the use of two communications channels is directly related to creating an end-to-end simulation, it also increases the reliability of the system since the two channels are interchangeable.
- *Test management & synchronization* - Tests with SPHERES can be repeated easily by using the test management software, part of the implementation to support families of tests. The software also synchronizes all the satellites in a multi-unit test.
- *Location specific GUI's* - SPHERES provides two separate interfaces: one for use in ground-based facilities, where the researchers are likely to be the operators, and one for ISS research, where astronauts are the operators. The use specific interfaces allows scientist maximum observability by providing real-time state and debug information in ground-based operations. The ISS interface provides astronauts with the information necessary to understand the objectives of a test and to determine the state of the satellites at all times.
- *Re-supply of consumables* - The ability to re-supply consumables allows tests to be repeated multiple times to collect sufficient data. It creates a risk-tolerant environment because the scientist can design their experiments to push the limits of their algorithms knowing that an error in the tests will not result in the end of the mission due to depletion of all consumables. Further, it enables supporting extended investigations.
- *Operations with three satellites* - The use of three satellites creates redundancy for a large number of DSS experiments which require only one or two satellites to demonstrate the technology (e.g., docking, tethers).

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- *Software cannot cause a critical failure* - The design of the satellites guarantees that the software cannot cause a critical failure of the facilities, such that scientists can program any algorithms, regardless of how aggressive it is, enhancing the risk-tolerant environment of SPHERES.
 - **Support Multiple Investigators**
 - *Guest Scientist Program* - The SPHERES Guest Scientist Program provides scientists with several tools to support their research both at their home locations and remotely. Specifically, the GSP provides:
 - *Information Exchange* - A clearly defined data path for scientists to collect the data. Further, members of the SPHERES team can provide substantial feedback when operations are conducted at the MIT SSL without the scientists.
 - *SPHERES Core Software* - The core software of SPHERES has been designed with modularity and simple interfaces in mind. It provides all the basic functions to control the satellites, while allowing scientists to program only those parts they are most interested in (e.g., metrology, control, or autonomy).
 - *GSP Simulation* - The GSP simulation allows scientists to predict results of their experiments at their home location.
 - *Standard Science Libraries* - These libraries provide scientists with several routines to simplify the development of their algorithms. Scientists can utilize math, metrology, and control functions developed by the SPHERES team.
 - *Expansion port* - The SPHERES Expansion Port fulfills the need for scientists to utilize custom hardware for their specific science goals.
 - *Portability* - The facilities required to operate SPHERES are highly portable, allowing their operation in a multitude of facilities, including at the home locations of several scientists and special environments such as NASA's RGA and MSFC's Flat Floor. This allows multiple scientists to conduct ground-based tests in the environment that best meets their needs.
 - *Schedule flexibility* - The schedule to conduct research aboard the ISS has been set at periodic intervals of two weeks. While that time cannot be reduced, the SPHERES team is able to manage that time so that scientists can take more time to analyze their data.
 - **Reconfiguration and Modularity**
 - *Generic satellite bus* - The SPHERES team identified the generic equipment required for research on DSS algorithms and developed the satellites to represent a generic satellite bus. In this manner, the satellites can

be used to model the operations of a 6DOF satellite representative of standard space missions.

- *Science specific equipment: on-board beacon and docking face* - As an example of specific equipment, and to fulfill the original requirements of the SPHERES project, the satellites provide an on-board beacon and a docking face to demonstrate docking technologies.
- *Generic Operating System* - The core software not only provides with modular interfaces and simple API's, it also creates a generic real-time operating system for dynamics and controls experiments similar to commercially available RTOS's (based on a COTS RTOS).
- *Physical Simulation of Space Environment*
 - *Operation with three units* - The operation with three units aboard the ISS allows SPHERES to model the exact operations of mission that utilize one, two, or three satellites which constitutes a substantial portion of DSS research. Further, operations with three satellites models the essential complexity of missions that utilize more units.
 - *Operation in 6DOF* - SPHERES is able to simulate the space environment with 6DOF operations aboard the ISS.
 - *Two communications channels* - The use of two communications channels in SPHERES directly models distributed satellite systems which are expected to utilize at least one channel for inter-satellites communications and one channel for satellite-to-ground communications.
- *Software interface to sensors and actuators* - While sensors and actuators can be added via the expansion port, SPHERES allows scientists to define their own software interfaces to sensors and actuators. In this manner, a scientist can model a sensor or actuator representative of the operational mission they are researching (of lower bandwidth than the sensors and actuators available in SPHERES).
- *Hardware expansion capabilities* - Hardware elements can be added to the SPHERES satellites via two different locations: the docking port supports passive elements, while the expansion port supports active elements. This allows scientists to develop hardware which better represents the operational mission.
- *FLASH memory and bootloader* - To enable software reconfiguration a custom bootloader was developed. The bootloader allows the full software of a SPHERES satellite to be reprogrammed and stored in FLASH. This enables software changes to range from simple corrections to algorithms to completely new hypothesis.

After development of the SPHERES Laboratory (Chapter 4), it was possible to review the different ways to fulfill the MIT SSL Laboratory Design Philosophy (Chapter 3) for a project specifically intended to operate aboard the International Space Station (Chapter 2). The lessons learned resulted in the development of seven design principles for microgravity laboratories for space technology maturation. These principles, based on the fundamentals of the scientific method, collaborative research, and existing resources of the ISS, apply to laboratories beyond the areas covered in the MIT SSL Laboratory Design Philosophy by identifying those traits that are almost always true of all laboratories, as required by the definition of a principle. The seven principles are:

- *Principle of Iterative Research* - A laboratory must enable scientists to conduct iterative research through repetition of experiments to obtain sufficient data; provide the capability for scientists to analyze that data and compare it with predicted results while on a flexible schedule; and allow reconfiguration of the facilities to allow for changes in experiments and hypothesis.
- *Principle of Enabling a Field of Study* - To enable research in a field of study, it is almost always true that a laboratory needs to support multiple scientists. This includes the need to provide: the ability for scientists to create models and analyze data in their home location; simple operational interfaces; and efficient data transfer mechanisms.
- *Principle of Optimized Utilization* - This principle calls for the correct utilization of the special resources available aboard the ISS in such a way that they add value to the mission. The use of these facilities should not be considered a cost to the mission. The principle identifies five special resources: crew, power, long-term experimentation, and a benign environment/atmosphere.
- *Principle of Focused Modularity* - The facilities of a laboratory almost always include common parts that can be used by a wide range of applications within the field of study of the laboratory. Those parts, the generic equipment, should be identified and designed in a modular fashion so that they can be utilized by as yet unforeseen research.
- *Principle of Remote Operation & Usability* - Because operations aboard the ISS occur in a remote environment where it is practically impossible for the research scientist to be present in the operational environment, a laboratory for research aboard the ISS must provide tools and information to conduct effective runs of experiments, while the scientists need efficient access to data obtained from the experiments for analysis. Ultimately, the operator should become a virtual extension of the scientists aboard the ISS.

- *Principle of Incremental Technology Maturation* - Utilizing the ISS should allow technology maturation to TRL 5 or TRL 6 with the risk and cost increasing incrementally rather than in steep jumps. Successful use of the ISS should allow operational missions with a lower total cost and risk than deployment of the mission directly from ground-based tests.
- *Principle of Requirements Balance* - For a laboratory to succeed, the requirements which arise from the previous principles must be balanced, without one single requirement driving the majority of the cost and effort in development of the mission. The hard requirements, which directly affect the ability to succeed in the mission, must drive the mission efforts. Soft requirements, desired features not directly affecting the success of the mission, should only be implemented when they do not cause the mission to break its constraints and do not contradict any hard requirements.

To enable scientists to use the design principles when developing a new laboratory, a design framework is presented. The framework involves a four-step iterative process. First, the scientist must identify the field of study covered by the laboratory. Next the scientist can determine the functional requirements by designing the laboratory such that it facilitates the iterative research process, enables incremental technology maturation, and utilizes the resources of the ISS correctly. This design can then be refined by identifying the modularity of the system which enhances its capabilities, but does not hinder the ability to satisfy all the mission objectives. The design must also consider the need to support remote operations. The fourth step is to identify the hard and soft requirements, ensure that the hard requirements drive the mission, and then iterate on the design to ensure that the requirements use a balanced amount of cost and effort.

An evaluation framework for members of the proposed NGO that will manage research activities aboard the ISS is also presented. This framework presents guidelines for an NGO evaluator to determine the effective use of the ISS while taking into account the success of the mission and the achievement of technology maturation.

Chapter 6 presents the results from operations of the SPHERES laboratory up to date and assesses the laboratory through the design and evaluation frameworks. SPHERES currently supports multiple research programs, including: mass property identification,

autonomous rendezvous and docking, TPF formation flight maneuvers, TPF multi-stage control, tethered formation flight, and the Mars orbit sample retrieval (MOSR) program. The first three programs are scheduled to be studied during the first phase of ISS research, while the later three programs will require delivery of new hardware to the ISS. The results to date include tests at the MIT SSL, NASA's RGA, and MSFC's Flat Floor. Tests at the MIT SSL have included formation flight algorithms and communications, docking control, mass ID, fault detection identification and recovery, tethered formation flight, and tests for MOSR. Five week-long campaigns aboard NASA's RGA (KC-135) consisted of tests on metrology (inertial and global), single satellite 6DOF controls, formation flight, docking, mass system ID, thruster ID, tracking, TPF maneuvers, and distributed control algorithms. The two week-long campaigns at the MSFC Flat Floor consisted of TPF formation flight, docking, and tethered tests.

The review of these operations and results provide the necessary information to evaluate the design of SPHERES utilizing the design framework; the existing design can be considered a first iteration of the design process, while this evaluation provides guidelines for further iterations. The review of the SPHERES design based on the design framework provides the following conclusions:

- **Step 1 - Identify a Field of Study**

For SPHERES to obtain a benefit from supporting multiple investigators, it must allow research in at least five of the research areas identified within DSS. These include specific missions (docking and rendezvous, formation flight, separated spacecraft telescopes, tethered spacecraft and sample capture) and several areas of study (metrology, control, autonomy, artificial intelligence, communications, and human machine/interfaces). The first ISS mission of SPHERES is scheduled to conduct research on metrology, control, and autonomy algorithms. These will be specifically applied to docking missions and TPF formation flight. Future missions will support tethered spacecraft and sample return, as well as artificial intelligence programs. It is unclear if SPHERES will be able to support separated spacecraft telescope and human machine/interfaces research aboard the ISS. Therefore, SPHERES does allow study in a sufficient number of research areas.

- **Step 2 - Determine Functional Requirements**

The SPHERES laboratory closely follows the guidelines of the Principle of Iterative Research. The metrology and communications systems provide sufficient data collection and transfer features to facilitate iterative research. SPHERES clearly allows not only repetition of experiments, but also modification of both the experiments and the hypothesis. The SPHERES operations plan has demonstrated great flexibility. Not only has iterative research been conducted at the MIT SSL, but also at two remote facilities. At all locations, the SPHERES operations plans work to minimize the overhead time to collect data and update modifications. Each of the facilities has been used to successfully accomplish iterations.

SPHERES obtains substantial value from the correct use of most of the resources available at the ISS. SPHERES slightly under utilizes crew time, but the benefits obtained from its use greatly enhance the risk-tolerant environment, its ability to facilitate the iterative research process, and provide substantial feedback to scientists. The total power of SPHERES is minimal, at only approximately 50W for the complete system; but because it does not use ISS power sources, it obtains no value from that resource of the station. The correct use of telemetry, with flexible download data rates and limited data sizes, allow it to minimize data transfer times and maximize the capabilities obtained from communications. The duration is considered slightly short, although well within the expected lifetime of an ISS mission. Lastly, SPHERES utilizes the ISS environment to a large extent; reducing its development and operational costs substantially, while ensuring a risk-tolerant environment.

SPHERES enables the maturation of metrology, controls, and autonomy algorithms implemented through software to reach TRL 6. The satellites provide the necessary understanding of the interactions between the sub-systems of a satellite through empirical tests under stressful operating conditions. But the facilities do not allow maturation of hardware technologies to TRL 6 unless these hardware elements can be operated through the SPHERES Expansion Port and the resources exist to deliver them to the ISS. Only a limited number of missions (those of the same scale and properties as SPHERES) can utilize the laboratory to advance to TRL 7.

- **Step 3 - Refine Design**

The SPHERES satellites as a whole provide modularity and reconfiguration by being identical satellites, interchangeable with each other, and by using the docking port and expansion port to allow reconfiguration. The satellite sub-systems, on the other hand, do not provide modularity since, in most cases, that would violated the 1 MLE mass/volume constraint for the system with little added value. The software sub-system is highly reconfigurable and modular as a direct result of the mission goals. The metrology beacons are modular in their ability to be interchanged and reconfigured with ease to

provide accommodate different operational environments of the global metrology system. The laptop transceiver enables the use of the SPHERES facilities through any standard PC serial port at many locations.

To satisfy the Principle of Remote Operations and Usability, SPHERES provides two separate interfaces to operate the facilities: a ground-based interface and an ISS interface. Further, the SPHERES simulation was developed to account for the remote location of scientists who are not members of the SPHERES team. The ground-based interface was designed for operations at the MIT SSL, NASA RGA, MSFC Flat Floor, and other facilities where the operators are either the researchers and/or members of the SPHERES team. This interface provide simple, single-key-stroke, operations for all common tasks and incorporating program upload directly into the interface. The availability of optional windows with real-time state and debug data allows the interface to provide relevant data when the operators are the research scientist. The interface does require the operator to initiate data storage, therefore creating the potential situation where data is not stored due to operator error, but to minimize that the interface clearly indicates when data is being saved. Further, the SPHERES team developed several Matlab functions to analyze the data. The SPHERES simulation and the information provided with the Guest Scientist Program allows the scientist to create models of their experiments and compare the information.

The ISS interface utilizes several steps to ensure the operator selects the correct program and test and is aware of the expected results of each experiment. The ISS interface stores data immediately upon starting. Regardless of the operator's actions, the program will save all outgoing and incoming raw data, ensuring the data is safe regardless of the operator's actions. The flight GUI presents information to the operator to always be aware of the state of the satellites through a status bar. Descriptions of the tests are presented to allow the operators to know expected results and make decisions on the test performance. By providing sufficient details on the test, the interface reduces the dependency of real-time communications with the researcher. Further, the interface presents a questionnaire to the astronaut at the end of each test, requiring the astronaut to provide feedback The astronaut is also allowed to enter notes freely after the questionnaire effectively creating an electronic laboratory notebook.

- **Step 4 - Review Requirements and Design**

A total of 31 system-level functional requirements were identified for this iteration of the SPHERES laboratory design. Of those 21 are hard requirements and 10 soft requirements. Further review into the efforts needed to implement the requirements resulted in the following conclusions.

- The requirements relevant to 6DOF operations did not require substantial trade-off's in the implementation of the sub-systems.

- The hard requirements to *operate aboard the ISS* and to *facilitate iterations* by allowing the *collection of substantial data* and *enabling reconfiguration* forced trade-offs in the following implementation decisions:
 - *One-time Use Batteries* - The need to operate aboard the ISS and meet safety requirements prevented the use of rechargeable batteries which would have provided benefits to iterative research, long-term experimentation, and modularity.
 - *Custom Metrology System* - The decision to develop a custom metrology system resulted in the investment of too many resources and effort to this sub-system, while the resources allocated to other sub-systems (such as propulsion and the expansion port) were not balanced.
 - *Propellant Selection (CO₂)* - The selection of the propellant correctly balanced the need to support iterative research and create a representative environment for technology maturation even though it required increased resources to operate aboard the ISS.
 - *Expansion Port* - The development of the expansion port towards the end of the program implementation prevented sufficient resources to be used in developing a simpler interface. Still, the port has allowed the development of several expansion items to increase the research possibilities of the facility.
 - *Communications Channel Frequency* - The need to operate aboard the ISS without creating any bureaucratic issues due to safety concerns by NASA required the selection of wireless communications in the 900MHz range, which is limited to 56.6kbps, rather than the use of 802.11b hardware which allows over 1Mbps. This trade-off was necessary to ensure the iterative research process is efficient when using SPHERES.
- The soft requirements did not account for substantial effort or use of resources, since the most important design decisions were not driven by requirements not essential to the mission.

The current iteration of the SPHERES laboratory design meets the principles to a large extent. The facility enables research on multiple areas within Distributed Satellite Systems. The facilities enable iterative research with few limitations, minimal overhead, and flexible schedules. The iterative nature of the research in a microgravity environment allows technologies to mature incrementally to TRL 5 or TRL 6. SPHERES achieves this by utilizing many of the resources available aboard the ISS. Both the software and hardware allow reconfiguration, although hardware changes do require delivery of the new

items to the ISS. The software is highly modular, allowing scientists to work only on their specific area of study. Overall, the resources and effort put into the implementation of the features are correctly balanced.

A new iteration of SPHERES would consider utilizing rechargeable batteries to benefit the iterative research process by allowing more repetitions, ensure long-term experimentation, and lower its need for launch mass and storage volume aboard the ISS. If the metrology system were still in the design stages, the selection to use a custom system would be revised; since it is already implemented, the program should ensure that substantial metrology research occurs to warrant the amount of resources used to implement the subsystem. Lastly, the expansion port should be reviewed to provide better interfaces that allow easier development of expansion items.

Finally, the evaluation framework was applied to SPHERES. An ISS evaluator concentrates on the correct utilization of ISS resources, the ability to demonstrate technology maturation, and the scope of the program. The review of SPHERES concludes that:

- SPHERES enables iterative research by allowing repetitions, experiment modification, and hypothesis modifications. Reservations exist due to the consumables required for operations.
- SPHERES has been correctly designed to support multiple investigators conducting research aboard the ISS. The resources necessary from the ISS are acceptable, and the necessary programs exist for efficient data transfer to scientists.
- The utilization of crew, communications, long-term experimentation, and benign environment resources is acceptable. The crew time is small but provides important benefits to the mission. The use of ISS telemetry systems has been well incorporated into the program. Long-term experimentation, while limited by consumables, is of the correct length (six months to a year). The benign environment is fully accounted for. SPHERES does not use the power resources of the ISS correctly, and its design should be reviewed to analyze the possibility to make better use of this resource.
- SPHERES offers little modularity from the perspective of the ISS. The global metrology system is the only component which can be easily used by other programs beyond SPHERES. The communications system could provide modularity, but utilizes too much custom hardware. The satellites

enable research by multiple scientists, but cannot be considered modules for use by other programs independently from SPHERES.

- From the ISS NGO perspective, the SPHERES team has accounted for all the necessary tools to allow successful remote operations of the SPHERES facilities, even without real-time communications between the scientists and the operator.
- SPHERES can allow technology demonstrations to TRL 5 for a large number of programs. TRL 6 can also be achieved, for a limited number of programs, especially if new hardware can be delivered. SPHERES cannot be considered a laboratory to demonstrate a technology to TRL 7.

As a result, an ISS NGO evaluator following the evaluation framework would conclude that SPHERES can operate aboard the ISS, but several reservations exist which should be addressed. The long-term experimentation is greatly challenged by the consumables required in SPHERES, and steps should be taken to minimize the dependence on consumables. Specifically, the use of rechargeable batteries should be considered. Further, the SPHERES team should develop contingency plans which detail operations and science benefits from the use of SPHERES without propellant. While SPHERES provides little modularity for the ISS, any changes to the modularity would be too large and costly for the program; therefore, the evaluator should not propose the changes, but should consider the limited modularity when evaluating other projects. None of the reservations are substantial enough to preclude the use of SPHERES aboard the ISS; to the contrary, SPHERES fulfills a substantial part of the design principles. It utilizes the crew of the ISS wisely, allowing astronauts to become scientists in space. Further, it opens the use of the ISS to multiple scientists who would otherwise not be able to conduct research in a microgravity environment. Therefore, the SPHERES laboratory enhances the science capabilities of the ISS allowing it to better achieve its primary objective: *to provide and “Earth orbiting facility that houses experiment payloads, distributes resource utilities, and supports permanent human habitation for conducting research and science experiments in a microgravity environment.”* [NASA, 1998]

7.2 Contributions

The research presented in this thesis extracts the fundamental characteristics that a laboratory must exhibit and condenses them into a set of design principles for the development of space technology maturation laboratories. The principles also derive from the lessons learned in the design, implementation, and operation of the SPHERES laboratory, which provides a special research environment for the maturation of technologies related to distributed satellite systems. The following are the specific contributions identified from the research:

- Identified the fundamental characteristics of a laboratory for space technology maturation and formalized the features required in the design of a laboratory to exhibit said characteristics.
 - Identified the need for a laboratory to support iterative research utilizing the definition of the scientific method. While laboratories are continuously created at research institutions, no previous literature specifically addresses the need for a laboratory to enable every step of the scientific method. This thesis formally calls for a laboratory to support iterative research, including development of a hypothesis, design and operation of experiments, data collection and analysis, and the ability to modify the hypothesis until the desired performance is met.
 - While literature on the Design of Experiments (DOE) emphasizes the need to collect data at operationally interesting points, this thesis goes a step beyond DOE towards the development of a laboratory that allows repetitions of experiments at all data points. A laboratory reduces the dependency on DOE techniques to minimize the number of experiment runs.
 - The review of existing research facilities, definition of a laboratory, and collaborative science identifies the need for a laboratory to enable research of a field of study by supporting multiple scientists. Given the restricted access to a space environment, projects which support space technology maturation must enable research of a field of study.
 - Determined the use of the International Space Station as a location which helps reduce the major challenges of space technology research: risk, complexity, cost, remote operations, and visibility.
- Established a set of principles to guide the design of research laboratories for space technology maturation aboard the International Space Station.

- The principles address the need to facilitate the iterative research process, enable a field of study, and enable incremental technology maturation, coupled with the need to account for remote operations aboard the International Space Station.
 - Enables the use of the ISS to incrementally mature technologies in such a manner the total risk and cost of a mission can be reduced.
 - The principles are based on a comprehensive review of ISS research, existing resources, and programmed upgrades to ensure they account for the correct utilization of the station.
- Developed a design framework for application of the principles by research scientists.
- Developed an evaluation framework which can be used to respond in part to the call by the National Research Council to define the functions of a non-governmental organization which manages the science aboard the International Space Station.
 - The application of these principles in the design of new laboratories for research aboard the ISS can result in an expanded base of scientists who can conduct research under the microgravity environment of the ISS.
 - Calls for a change in attitude towards the use of resources aboard the International Space Station: rather than treat the use of those resources as a cost which must be minimized, the resources should be treated as added value, which must be maximized.
- Designed, implemented, and operated the SPHERES Laboratory for Distributed Satellite Systems.
 - Provides a facility for multiple researchers to advance metrology, control, and autonomy algorithms in a microgravity environment able to meet the requirements for TRL 5 or TRL 6 maturation.
 - Demonstrates the implementation of miniature embedded systems to support research by multiple scientists through the creation of a *flexible* embedded system which allows implementations of multiple types of algorithms.
 - Developed a real-time operating system with modular and simple interfaces for use by multiple scientists.
 - Demonstrates the ability to create generic equipment while enabling future expansion through both hardware and software.
 - Approaches virtual presence of the scientists in a remote location by providing the necessary interfaces to present the operator with the necessary

knowledge to be an integral part of the research process. Further, it creates a laboratory environment by allowing astronauts to provide feedback to the scientists.

7.3 Future Work

The recommendations for future work concentrate on two main areas: further development of the design principles and operations of the SPHERES laboratory. While the concepts behind the laboratory design principles have been reviewed with more than twenty experiments conducted during Expedition 6 aboard the ISS, the actual application of the principles lacks data points. Validation of the design principles by their application and evaluation in several new programs would provide the necessary validation. The design framework provides a few initial quantitative measures to utilize in the application of the principles. These measures are extracted from available information about product platforms and the review of the International Space Station existing capabilities. These quantitative models should be validated with new data as experiments are designed following the guidelines of the design principles.

These principles concentrate on the creation of the engineering and technical aspects of the program. This thesis does not introduce the need to also provide financial support for the laboratories, as it assumes that a well designed laboratory will have high demand within the scientific community. A parallel study, which considers both the development and maintenance costs of these type of laboratories should be created.

The ability of scaled experiments aboard the ISS to demonstrate the maturity of space technologies depends directly on the ability of scientists to prove that these models are representative of actual mission. To this end, research should be conducted to develop a set of *scaling laws*, equivalent to those used in aeronautical engineering when testing with wind-tunnels, which enable scientists to scale the results of models used aboard the ISS to for application in full-scale space missions.

Due to circumstances outside the control of the SPHERES program, its operations aboard the ISS have not taken place yet. Therefore, future work must evaluate ISS operations to corroborate the expected results presented in the evaluation of SPHERES in Chapter 6. While the usefulness of the Guest Scientist Program has been demonstrated through multiple ground-based programs, the ability of SPHERES to facilitate the iterative research process through complete ISS iterations are yet to be demonstrated. Future work must support or refute the ability of SPHERES to minimize the overhead time and maximize the science time available during each research cycle. The lack of demonstrations in a space environment has also prevented any algorithms developed with the use of SPHERES to mature to TRL 5 or TRL 6. Therefore, continued research is necessary to confirm that SPHERES can help mature technologies to those levels.

Work should also be performed to enhance the capabilities of the SPHERES facilities:

- The SPHERES metrology system requires continued research to ensure it can provide the necessary accuracy and precision in a 3D environment. While the system has been tested and its capabilities demonstrated in 2D environments, 3D tests have been limited to operations aboard the reduced gravity airplane (KC-135) and limited tests at the MIT SSL.
- Future work to upgrade the software capabilities of SPHERES is also recommended. The current software concentrates on the ability to test metrology, control, and autonomy algorithms. Future work should allow scientists to test different communications protocols and test the real-time requirements of operating systems for distributed satellite systems.
- As clearly indicated by the frameworks, the SPHERES satellites should be upgraded to use rechargeable batteries.

Future research to be conducted with the SPHERES laboratory already includes tethered formation flight, multi-stage optical formation flight telescopes, and the Mars orbital sample return. The development of active docking ports is also planned. An area missing to research with SPHERES is human/machine interfaces. SPHERES provides the unique capability for humans aboard the ISS to control a 6DOF satellite with minimal risks in a full microgravity environment. This enables the creation of training environments where humans can use advanced interfaces (e.g. special joysticks) to control 6DOF satellites.

SPHERES allows research on the human factors engineering aspects (e.g. design of the joysticks) as well as actual training of astronauts for general or specific missions once an interface has been selected. The possibility for the SPHERES satellites to support astronaut activity aboard the ISS via the use of wireless video should also be considered.

7.4 Concluding Remarks

This thesis concentrates on the development of seven design principles for the design of space technology maturation laboratories to operate aboard the International Space Station. The research required substantial background information on previous space programs, other microgravity facilities, other remote facilities, the scientific method, collaborative research, and NASA Technology Readiness Levels. The resulting principles address the most basic mission of the International Space Station: to conduct research in a microgravity environment.

But all this research would not have been complete without the lessons learned from the design, implementation, and operation of the SPHERES testbed. The words *design, implementation, and operation* appear multiple times in this thesis. They are the force behind the development of the SPHERES prototype system: teaching undergraduate students the complete design process in the form of CDIO - conceive, design, implement, operate. The road traversed through the development of SPHERES was so rich with information on the requirements of a laboratory because the teaching staff was learning together with the students. While staff could provide simple implementation answers, the staff continuously evaluated the *why's* of the design; this knowledge represents the lessons learned from SPHERES which resulted in the development of the design principles. Therefore, the work in this thesis represent the knowledge acquired not only by the author, but also by thirteen undergraduate students at MIT, over a dozen staff members, and the several guest scientists who participate in the SPHERES Guest Scientist Program.

The laboratory environment created by SPHERES will provide many scientists with the ability to demonstrate their algorithms in space, something they would not be able to do

otherwise. Expansion items will reach the ISS so that the SPHERES facilities can better represent new missions. This will allow the study of the origins of our galaxy through missions such as TPF, make autonomous re-supply of spacecraft a reality, and even enable the development of technologies, such as tethers, to permit extended human travel into space.