Chapter 1

INTRODUCTION

This thesis utilizes the lessons learned from the development of the SPHERES experiment and other MIT Space Systems Laboratory (SSL) projects to define a set of design principles for developing facilities to conduct space technology research in the International Space Station (ISS). The thesis follows the standard scientific process to define the principles. The objective of the thesis is to create a design methodology for the development of microgravity laboratories which allows the maturation of space technologies. The objective is motivated from the lessons learned by the MIT SSL during the design and operation of multiple space-based experiments and by a call by the National Aeronautics and Space Administration (NASA) and the National Research Council (NRC) to define how to institutionalize research aboard the International Space Station (ISS). The thesis objectives address the use of the ISS in two ways: the need of multiple researchers to access microgravity conditions to cost-effectively mature technologies and to make the best possible use of ISS resources. The hypothesis rests on the use of the MIT SSL Laboratory Design Philosophy, which consists of a set of features desired from a laboratory identified through the review of past experiences at the MIT SSL, and the correct utilization of existing resources to mature space technology. The hypothesis states that by using this laboratory design philosophy to develop projects to operate aboard the ISS, the resulting laboratory environment facilitates the maturation of space technology in an ideal environment. The SPHERES facility constitutes the experimentation. Based on the lessons learned from building SPHERES, the laboratory design philosophy and the knowledge of the ISS environment were condensed into a set of design principles that characterize successful laboratory environments. Frameworks to apply the principles both at the design and evaluation phases complete the results. The conclusions identify the ability of the principles to meet the objective by analyzing the success of SPHERES as well as other experiments already aboard the ISS. Figure 1.1 summarizes these steps of the scientific process (objective, hypothesis, experimentation, results, and conclusion) as they are addressed in the thesis.

Objective:
Create a design methodology for the development of microgravity laboratories for the research and maturation of space technologies.

Hypothesis:
The conjunction of the International Space Station as a host and the MIT SSL Laboratory Design Philosophy as the design guidelines enable the development of a low-cost environment for the development and operation of facilities to conduct space technology research.

Experimentation:
The SPHERES laboratory for distributed satellite systems has been developed following the MIT SSL Design Philosophy for microgravity operations specifically aboard the ISS.

Results:
The MIT SSL Design Philosophy and research on the characteristics and operations of the ISS are condensed into a set of Design Principles that define the proper design of a research laboratory for the ISS.

Conclusion:
While the availability of the ISS has not proved as efficient as originally desired, the Design Principles and corresponding frameworks do create a valid methodology for the development of microgravity research facilities which reduce both the cost and risk of maturating space technologies. Further, by following of these principles can allow facilities to benefit the research community even if not all operational environments are available.

Figure 1.1 Thesis research process

1.1 Motivation

Precision space systems are becoming increasingly difficult to fully test prior to launch. New mission architectures continuously increase the complexity of the system design, to the point where simulations or tests in the presence of gravity no longer provide the necessary results. Of particular concern are those that depend heavily upon accurate dynamic characterization as well as high bandwidth, multi-channel control to meet their requisite precision. Ground based testbed results and on-orbit behavior are different and therefore provide a reduced level of confidence that the system will perform to the required precision.

Similar issues have been faced in other fields. For example, wind tunnels fulfill an important role between aerodynamic modeling and aircraft manufacturing. By guiding the development of modeling capabilities, calibrating those models, providing high fidelity scale model tests, etc., they play an important role in evolving new technologies from theory to application. The question arises: is there an equivalent facility to wind-tunnels for microgravity research?

There is an opportunity to take advantage of a new development environment to aid in the technology maturation process that entails the use of dynamics and controls research laboratories which enable long duration, microgravity testing while facilitating the iterative research process and being tolerant of risk during the development of the technology. Throughout two decades, the MIT Space Systems Laboratory has deployed a series of microgravity experiments for the development of new technologies to help in the areas of dynamics and controls which have filled this step in different manners. These experiments were conducted in multiple microgravity facilities (space shuttle, MIR Space Station, and ISS) and under different operational scenarios (long-term, short-term, highly interactive, etc.). Important questions arise from the experience obtained in designing and operating these different experiments:

- What are the common design elements between these experiments?

- Which design elements helped these experiments fulfill the need for this new step in the technology maturation process?
- Can the lessons learned from these experiments apply to future experiments?

The answers to these three questions motivates the development of the design philosophy presented in this thesis.

Further motivation arises from the first question presented above: *is there an equivalent facility to wind-tunnels for microgravity research?*

The answer lies within the ability to make the best use of the ISS. In 1998 NASA asked the National Research Council (NRC) to study how to manage and conduct research in the International Space Station (ISS) over the long term. The NRC team, which included scientists, engineers, and educators, studied the options of maintaining all operations within NASA, outsourcing science management to industry or educators, or creating a new entity. The NRC concluded "that NASA should establish a Non-Governmental Organization (NGO) to manage all aspects of research on the ISS and the NGO should have sufficient authority to carry out its assignments and responsibilities." [NRC, 1999]. The NGO would carry out management of all research activities, while NASA and its international partners would continue to carry out maintenance and upgrades of the ISS. However, the NRC report did not specify the structure or operations of the NGO, rather NASA is accepting proposals from multiple groups, composed of industry and education leaders, on how to shape the NGO; NASA will then seek congressional approval once a proposal is selected.

The NRC report concludes that the principal use of the ISS must be for research. While other activities may take place (e.g., education, staging for human space exploration missions, commercial services, and possibly tourism), the only activity which is immediately ready to begin and which justifies the existence of the ISS is research. Therefore, the NRC recommends that the following principles should guide the operations of the ISS:

- High-quality basic and applied research should be paramount.

- Responsibility for managing and supporting research would not require that the organization manage other ISS activities.
- The research community should have early, substantive, and continuing involvement in all phases of planning, designing, implementing, and evaluating the research use of the ISS.
- The organization must be flexible and capable of adapting over time in response to a changing needs and lessons learned.
- Basic and applied scientific and engineering uses should be selected on the basis of their scientific and technical merit, as determined by peer review.

The report further states that the proposed non-governmental organization must fill four key roles:

- Provide the highest caliber scientific and technical support to enhance research activities
- Provide the research community with a single point of contact through which it can utilize the capabilities of the ISS
- Promote the infusion of new technology for ISS research
- Stimulate new directions in research, for both established and new user communities

This thesis presents methods to respond to the NRC guiding principles and help partially fulfill the key roles of the NGO. The thesis identifies the special resources of the ISS which enhance the ability to conduct science, presents a methodology for designing research experiments that best use these resources, and creates evaluation guidelines for research proposals for the ISS which are best performed by peer scientists. The goal of the design principles is to encourage the researcher to look at the ISS in new ways. Not only should the scientist see the ISS as a general tool in their research; they must realize the unique capabilities of the ISS and utilize them to their greatest extent in support of their research, making the best use possible of what the ISS offers.

Research on the ISS will cover a broad range of areas that range from human physiology to space technologies to education. NASA identified the following research directions for the ISS in 2000 [NASA, 2000]:

- Biological Research and Countermeasures / Advanced Human Support Technology
- Biotechnology
- Combustion Science
- Fluid Physics
- Fundamental Physics
- Gravitational Biology and Ecology
- Materials Science
- Space Science
- Engineering Research and Technology Development
- Space Product Development
- Earth Science

This thesis will concentrate on the aspect of engineering research and technology development. The advancement of space technologies has been closely tied to a set of levels called the "Technology Readiness Levels" (TRL). Therefore, when considering the use of the International Space Station for space technology, a goal is to permit an experiment to advance in TRLs. This thesis studies how to ensure that a technology destined to be tested in the ISS can move closer to space worthiness.

1.1.1 NASA Technology Readiness Levels

> "Technology advances do not occur and mature in an orderly or even predictable manner, and they certainly do not occur in regular, well-organized steps. Still, the progress of a technology advance from that first glimmer of inspiration to its implementation on an operational spacecraft can be conceptualized as progress on a road toward ever increasing understanding, modeling fidelity, and confidence. The technology readiness levels described below represent milestones that demark progress along that road." [NMP, 2003]

Space technology maturation is a challenging process. Substantial amounts of money, time, and human resources go into the development of new spacecraft. At every point in the design life of a new spacecraft there are substantial risks involved, especially as the complexity of new design increases. Over a decade ago NASA developed the Technology

Readiness levels to determine where in the design process a specific technology stands. Is the technology in its infancy? Is it ready for use in spacecraft? These levels are a guide to engineers and scientists in the development of new technologies, with the goal to reduce the ultimate risk of deploying a space technology. The levels attempt to divide the design process into nine steps, each one building upon the previous steps, driving a technology to mature in increments.

> "Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on-and-off in NASA space technology planning for many years and was recently incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA." [Mankins, 1995]

Appendix A presents the definition of the nine TRLs as presented in the TPF Technology Plan, which presents a concise general description of the levels.

While the use of TRLs is not universal, they have been widely accepted as one important method to determine the state of development of a technology. TRLs are widely used within NASA in major programs such as the New Millennium Program (NMP) and the Origins Program. The use of TRLs, which began at NASA, has expanded to other major research institutes, including part of the DoD. In this case an independent study concluded that "it is feasible for TRLs (or an equivalent) to support or add value to the decision-making process. However, it is only one of several critical factors in the decision-making process..." [Graettinger, 2002] In most cases when TRLs are used, these are refined for the specific application. In the case of the DoD, for example, the TRLs have been modified to more directly follow specific technologies: "TRLs are described in the DoD 5000.2-R document from a systems perspective, and thus are intended to be appropriate for both hardware and software... The Army, for example, has developed a mapping of the TRLs to software... and the Army Medical Research and Materiel Command is working on defining corollaries for biomedical TRLs" [Graettinger, 2002]. The NASA NMP has made similar modifications: "Added to their description are criteria used by NASA's New

Millennium Program to determine when a particular TRL has been reached." The wide use of the TRLs and the maintenance of their overall guidelines show that the concept behind them is valid across a wide range of disciplines.

But TRLs are not necessarily simple to follow. While initially defined as "systematic", the TRLs are not necessarily linear, and every step is not always followed: "The linear metaphor of a road is not a perfect one. On a road every milestone must be passed to go from one end to another. Sometimes one or more Technology Readiness Levels are skipped because they are not appropriate to the technology advance at hand." [NMP, 2003]. The amount of cost, complexity, and risk from one TRL level to the next are not always the same nor small; by the definitions of TRL 7 itself: "Because of cost, it is a step that is not always implemented." Achieving TRLs 1-4 usually present small risks, complexity, and cost. Developing the representative hardware called for in TRL 5 adds a substantial amount to the cost. Creating the operational environment of TRL 7 adds substantially to the cost, risk, and complexity. Once TRL 8 is achieved, the only substantial increase is on cost to develop the flight system. Figure 1.2 shows a pictorial representation of how complexity, risk, and cost may increase for a program if it were to follow each TRL one at a time. As mentioned, TRLs are not necessarily followed one at a time; but skipping one TRL which may not be appropriate for the technology does not cancel the fact that these factors increase substantially from the previous TRL.

The amount that cost and risk increase from one TRL to the next often depends on the ability to demonstrate the technology in a *relevant environment*. In some cases this means demonstrating the technology in space. These demonstrations were limited to free-flyer spacecraft or space-shuttle experiments after the MIR Space Station was retired. The ISS can fill the void in the availability of representative environments for technology maturation. A part of the motivation is to answer the question *how can the ISS help mature technologies through the TRL scale?*

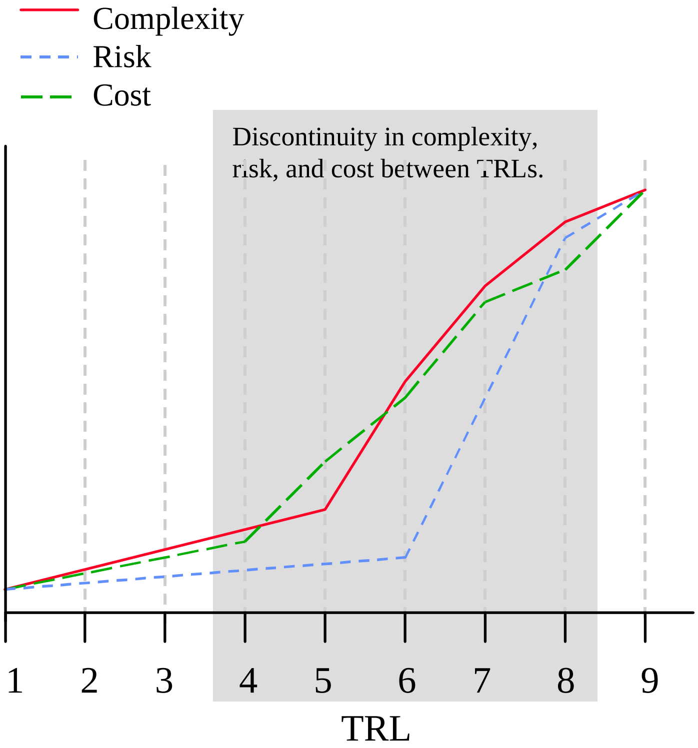


Figure 1.2 Discontinuity in complexity, risk, and cost at each TRL

1.2 Microgravity Research Facilities

Microgravity experimental research can occur in a wide range of facilities, depending on the fidelity, cost, and operational limitations necessary and/or available for the project. While not necessarily exhaustive, the list presented in Table 1.1 shows a wide range of possible facilities which can provide an environment to reproduce or simulate microgravity conditions for research purposes. The table lists 14 different environments to conduct microgravity research in different operational conditions. The first column shows facilities which can be housed by the individual researchers, but which don't necessarily simulate full 6DOF microgravity. The second column lists facilities which have full 6DOF capabilities, but which are usually managed by a third party. The third column lists the existing facilities which provide full microgravity conditions, but which present the largest development challenges.

TABLE 1.1 Sample of available facilities for μ-g research

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

Microgravity research has also taken place aboard several space stations that are no longer in operation. These past space stations provided NASA and its international partners with important concepts for the design of the ISS.

Appendix B presents an in depth review of the most distinguishable characteristics of the different microgravity environments and their general operational procedures, as well as an overview of the research conducted aboard prior space stations. Each of the facilities have shortcomings. Some shortcomings do not affect the scientific nature of the experiment (e.g., high costs), but they can affect the success of the mission. Other shortcomings affect the scientific results (e.g. limited dynamics or DOF). Each of these factors is important in selecting the most appropriate path for technology maturation.

Table 1.2 summarizes how the different facilities reviewed in Appendix B compare with each other. The table concentrates on the ability of the facilities to provide an environment representative of microgravity in terms of degrees of freedom and dynamics; they also described the operational nature of each facility, since a trade-off exists between achieving a realistic microgravity environment and the complexity and costs of the operations. The DOF column shows how many degrees of freedom are possible in the facilities; the number outside parenthesis shows the commonly achievable number of DOFs, the number in parenthesis shows the maximum achievable via special hardware. The last column indicates the relative cost of the projects; more expensive projects have a larger number of

TABLE 1.2 Sample of available μ-g research facilities

	Representative Environment				**Experiment Operations**				
Facility	**DOF**	**Dynamics**	**Exposure**	**micro-g Duration***	**Campaign Duration***	**Operations**	**Data Xfer**	**Accessibility**	**Cost**
Free Flyer	6	5	5	5 (mo-y)	5 (mo-y)	1	2	1	$$$$$
ISS	6	4	4	5 (h-y)	5 (mo-y)	2	5	3	$$$$
Shuttle Payload	6	4	4	4 (h-w)	4 (h-w)	2	3	2	$$$$
Shuttle Middeck	6	4	3	4 (h-w)	4 (h-w)	2	3	2	$$$$
RGO (KC-135)	6	3	1	2 (20s)	3 (1w)	3	5	4	$$$
Neutral Buoyancy Tank	6	1	1	3 (h)	3 (1w)	3	5	4	$$$
Drop Towers	6	4	1	1 (10s)	3 (1w)	3	4	4	$$$
Robot Helicopters	4(6)	2	1	2 (m-h)	5 (mo-y)	4	3	5	$$
6 DOF Robot Arms	6	2	1	3 (h)	5 (mo-y)	5	5	5	$$$
Helium Balloons	4(6)	1	1	3 (h)	5 (mo-y)	4	4	5	$$
Robot Cars	3(5)	1	1	3 (h)	5 (mo-y)	5	4	5	$
Flat Floor	3(5)	3	1	3 (h)	3 (1w)	4	4	5	$$
Air table	3(5)	3	1	3 (m-h)	5 (mo-y)	5	4	5	$
Simulation	6	2	1	5 (s-y)	5 (mo-y)	5	5	5	$

* Key to times: y = year, mo = month, w = week, h = hour, m = minute, s = second

dollar signs. The other columns use a scale of 1 (worst) to 5 (best) to illustrate the ability of each facility to better serve the project. The dynamics column indicates the ability of the facility to allow experiments to demonstrate their full dynamic effects, including orbital dynamics. The exposure column indicates if a facility can provide an environment which exposes the project to the space environment. The operations column indicates how easy it is to operate the experiment; a lower number means more complex operations (it is not easy). The data transfer column shows the ability of a facility to support data transfer in real-time and at minimum cost to the scientist. The accessibility column indicates how easy it is for the researcher to access their experiment for upgrades, changes, and repairs. The microgravity duration column indicates how long the experiment is exposed to microgravity continuously; while the experiment duration column indicates how long a campaign of tests can last.

This summary shows the ability of the ISS to create a representative microgravity environment. The review of past space stations indicates that the ISS has a clear set of qualities that set it apart from the other experiments. Chapter 2 identifies the special qualities of the space station, especially as they differ from other facilities that can provide good microgravity conditions and with respect to free flyer experiments

1.3 Other Shared Remote Facilities

The development of both Antarctic and Ocean research facilities provides several insights into the design of microgravity research laboratories. Appendix C presents an in depth review of these two remote environments. As the reviews indicated, the Antarctic program stresses the need to ensure that science guides the design of the facilities. Both types of research address the need for life support and operations in stressful environments. Ocean research provides further insight into where to conduct analysis and the need for large areas to conduct the actual experiments. Both Antarctic and Ocean research facilities ensure that multiple projects are supported; neither of the programs would be viable if they did not continuously welcome scientists to conduct new research.

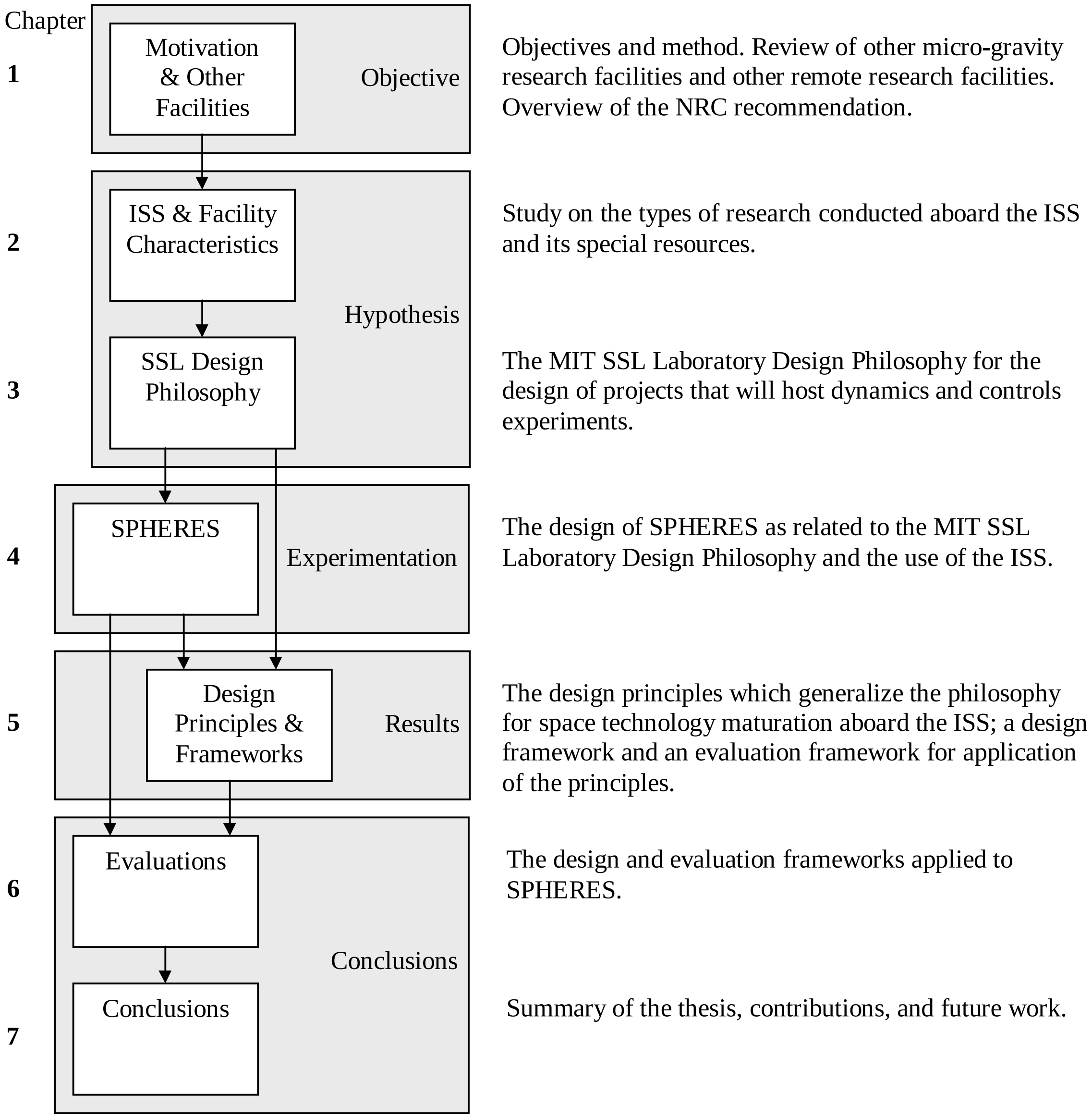
But these facilities account not only for humans to be present, but for the researcher themselves to conduct the research. This is not an option available, at least yet, for space research. Antarctic researchers reported that human presence was essential to maintain the programs operational; emphasis was placed on the need to have staff to support researchers on location. Ocean research vessels are designed to host scientists on board; the capability of on-board laboratory equipment continuously grows, allowing scientists to analyze data during the mission. Space research is constrained by the need for experiments to be conducted by a limited set of humans, rather than the researchers themselves. The need for this type of remote operations where the scientist is not in direct contact with the experiment will be further addressed in this thesis in subsequent chapters.

1.4 Thesis Roadmap

Figure 1.3 presents the thesis overview graphically. It summarizes the content of all the chapters and relates them with the steps of the scientific method presented at the start of this chapter. This first chapter presents the objectives of the thesis and the motivation behind it, as well as background research on microgravity and remote research facilities.

Chapters 2 and 3, together, present the two parts of the hypothesis presented at the start of this chapter. Chapter 2 defines the major challenges of space research for successful technology maturation. The chapter also presents an in-depth review of the facilities available in the ISS and the challenges faced in conducting successful scientific research. Through this review the chapter identifies the special resources of the ISS which clearly distinguish it from the other microgravity facilities presented in Chapter 1. These special resources will be taken into account later on in the development of experiments.

The MIT SSL Laboratory Design Philosophy is presented in Chapter 3. The chapter first identifies the qualities that demonstrate successful research in the specific area of dynamics and control, an area of expertise for the MIT SSL. Next the chapter defines the 11 features identified as essential for a successful research facility; these are grouped into four main areas. The basic scientific guidelines that stand behind these groups are then presented. The chapter concludes by a review of the past MIT SSL microgravity experiments which inspired this philosophy.



Objectives and method. Review of other micro-gravity research facilities and other remote research facilities. Overview of the NRC recommendation.

Study on the types of research conducted aboard the ISS and its special resources.

The MIT SSL Laboratory Design Philosophy for the design of projects that will host dynamics and controls experiments.

The design of SPHERES as related to the MIT SSL Laboratory Design Philosophy and the use of the ISS.

The design principles which generalize the philosophy for space technology maturation aboard the ISS; a design framework and an evaluation framework for application of the principles.

The design and evaluation frameworks applied to SPHERES.

Summary of the thesis, contributions, and future work.

Figure 1.3 Thesis roadmap

Chapter 4 describes the design of the SPHERES laboratory for distributed satellite systems (DSS), which constitutes the experimental portion of the thesis. After introducing the overall design of the hardware and operational programs, the chapter describes in further detail how SPHERES implemented the features of the MIT SSL Laboratory Design Philosophy presented in Chapter 3. Each of the four groups is presented separately.

Chapter 5 presents the seven design principles that resulted from implementing SPHERES to a) follow the MIT SSL Laboratory Design Philosophy and b) to operate in the ISS. This chapter presents each of the principles in a separate section, explaining the derivation of the principles from the experimentation with SPHERES, and then describing the principle itself. Two application frameworks are presented in Chapter 5: a design framework to aide investigators in the creation of experiments that best utilize the resources of the ISS and an evaluation framework to determine if a project uses the ISS appropriately. These frameworks can be utilized as part of an "institutional arrangement" for conducting science on the ISS. Chapter 6 thoroughly analyses the SPHERES facility using both frameworks.

Chapter 7 concludes the thesis by summarizing how the design principles and frameworks fulfill the objectives of the thesis.