Chapter 3

THE MIT SSL LABORATORY DESIGN PHILOSOPHY

This section presents the second part of the hypothesis presented in Figure 1.1: the MIT SSL Laboratory Design Philosophy can serve as a set of guidelines for the successful development of microgravity research experiments. These guidelines were created from the experience of designing, building, and operating multiple μ-g testbeds, and were the guidelines that drove the design of the SPHERES testbed.

This chapter contains three main parts. The first part discusses the characteristics of a space technology which must be demonstrated to prove technology maturation, as related to the fields of dynamics and controls. Next, the chapter presents the experiments conducted by the MIT SSL which allowed the demonstration of those characteristics. The development of these experiments led to the identification of features required of a testing environment to allow the demonstration of the technologies. That is, the demonstration must show the technology posses the characteristics to prove its maturation without being limited by the testing environment. These features are grouped into four common areas; each of these four areas is explained based on scientific research practices. These features form the MIT SSL Laboratory Design Philosophy.

3.1 Definitions

Before presenting the MIT SSL micro gravity projects and the Laboratory Design Philosophy which resulted from them, it is important to understand two concepts that will appear continuously throughout the remainder of this thesis. The Laboratory Design Philosophy contains one key word: laboratory. The term laboratory is used not only to represent the physical research where research is conducted. From the dictionary (Merriam-Webster) definition of a laboratory we can obtain further insight:

> Main Entry: lab·o·ra·to·ry
>
> 1 a : a place equipped for experimental study in a science or for testing and analysis; broadly : a place providing opportunity for experimentation, observation, or practice in a field of study b : a place like a laboratory for testing, experimentation, or practice <the laboratory of the mind>

The meaning of the word laboratory in the design philosophy, and for the remainder of the thesis, specifically addresses the need to support experimentation in a field of study. The support is provided not only by physical equipment, but also by the correct organizational structure to ensure that a field of study can be researched.

The physical equipment which forms part of a laboratory is the facility. A facility is defined (Merriam-Webster) as:

> Main Entry: fa·cil·i·ty
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> 1 : the quality of being easily performed
>
> 2 : ease in performance : APTITUDE
>
> 3 : readiness of compliance
>
> 4 a : something that makes an action, operation, or course of conduct easier -- usually used in plural <facilities for study> b : something (as a hospital) that is built, installed, or established to serve a particular purpose

This thesis follows the definition that a facility makes […] a course of conduct easier and is established to serve a particular purpose. In the case of this thesis, a facility serves to facilitate research in the field of study for which a laboratory is established.

Therefore, a reference to a facility indicates the presence of hardware equipment to make conducting research easier. The use of the word laboratory means that a full research program has been created to enable research on a field of study.

3.2 Characteristics of a Mature Technology Demonstration

The MIT SSL concentrates its research on dynamics and controls technologies. Therefore, the experiments developed at the MIT SSL test a wide range of metrology and control algorithms, as well as sensor and actuator technologies which enable the algorithms to succeed. This section presents the characteristics which must be exhibited by a dynamics and control technology to demonstrate it has matured. These characteristics form the basis behind the objectives of the different dynamics and controls experiments; while the goals of each specific mission are unique, the goal is that the mission-specific algorithms all exhibit the characteristics presented in this section. While these are related directly to the topics of dynamics and control studied at the MIT SSL, their application can be expanded to more general demonstrations in most cases.

These characteristics can also be related to the Technology Readiness Levels. The NASA TRLs provide high-level guidelines of when a technology matures for operation at different steps in its reach for space operation. These characteristics go one level down, they are those properties of a dynamics and control test that must be met every time to demonstrate that a specific TRL level has been met. To demonstrate fulfillment at a specific level, the technology must exhibit the following characteristics:

Demonstration and Validation. For a technology to mature, it must be demonstrated in the correct environment, with results clearly showing the accomplishments of the technology. Results observed in a physical system must be validated with data obtained during the successful completion of the demonstration.

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

Determination of Simulation Accuracy. A successful technology demonstration must help validate simulations and other tests of lower fidelity. The results of control experiments in a space research laboratory can be compared with simulations to provide confidence in simulation techniques and to gauge the simulation accuracy.

Identification of Performance Limitations. In order to determine the success of new technologies or algorithms one must push these to their limits. Mature technologies must provide insight into most of the physical constraints of a system that may not be observable in a simulation or ground test.

Operational Drivers. Systems issues such as sensor-actuator resolution, saturation, non-linearity, power consumption, roll-off dynamics, degradation, drift, and mounting techniques are most often constraints rather than design variables; that is, these quantities cannot be easily changed by the scientist, but rather scientists must design their experiment around them. Hardware experiments allow scientists to learn the quantitative values of these constraints, which are important during the creation of system models used in the design of control and autonomy algorithms. A mature technology operates successfully in the presence of these drivers.

Identification of New Physical Phenomena. New physical phenomena are usually discovered through observation of physical systems. A mature technology demonstration allows for the identification of these phenomena, creation of models for them, and the exploitation of this new knowledge in future investigations.

The MIT SSL has conducted microgravity experiments over the past two decades to demonstrate and validate dynamics and control technologies. While these experiments covered different areas of research (non-linear dynamics, fluid slosh, load sensors, robust control), each of them attempted to demonstrate each of these characteristics in the technology they tested. The following section summarizes the experiments.

3.3 MIT SSL Previous Space Experiments

The MIT SSL has designed, built, and operated a multitude of flight experiments in the past. The lessons learned from these experiments led to the development of the sets of demonstration characteristics and test environment features. The experiments include:

- Mid-deck 0-g Dynamics Experiment (MODE), which flew on STS-48 in September 1991 and its re-flight on STS-62 in March 1994.
- Dynamic Load Sensors (DLS), which flew on MIR for about three years.
- Middeck Active Control Experiment (MACE), which flew on STS-67 in March 1995.
- MACE Re-flight, which was the first crew-interactive space technology experiment conducted aboard the ISS by Expedition 1 in December 2000.

Appendix E reviews the research conducted through the three programs (MODE, DLS, and MACE) and further discusses the identification of the common features that enabled these experiments to advance dynamics and control algorithms for space technologies. Table 3.1 presents a summary of past MIT SSL microgravity experiments. The table summarizes the mission and its areas of study.The table also shows the total cost of the mission and the time to flight. Re-flight opportunities clearly lowered both metrics. The MODE experiment characterized itself by the creation of the generic equipment (the ESM), which allowed future missions, including DLS, to be developed with low cost and in a small time-frame. DLS further enhanced the success of MODE by operating over an extended period of time. The MACE program developed its own set of generic equipment, which was used over two flights. The MACE re-flight made substantial use of the original MACE hardware to lower its cost and time to flight. Further, MACE allowed algorithms to be selected and modified during the mission, allowing a larger number of areas of study to be investigated.

MODE, DLS, and MACE tested a number of different space technologies to aid in the development of new algorithms and sensors for dynamics and control. Each of these experiments exhibited special features which helped to mature the technologies in a cost effective manner by utilizing the available environments to their full extent. The identifi-

TABLE 3.1 Summary of MIT SSL microgravity experiments

Experiment	**Host**	**Date** (year)	**Areas of Study**	**Cost**	**Time-to-flight*** (years)	**On-orbit time** (weeks)
MODE	STS-48	91	Microgravity fluid and structural dynamics	$2M	3	1
MODE Reflight	STS-62	94	Non-linear structural dynamics on truss structures	$1M	2	1.7
DLS	MIR	96-97	Crew induced dynamic disturbances	$0.75M	1	40
MACE	STS-67	95	Advanced control design on non-linear structures	$4M	3	2
MACE Reflight	ISS (Exp 1)	00-01	Neural networks, non-linear characterization, reaction wheel isolation	$1M	1.5	36

* Time to flight = contract start to actual flight

cation of these features led to the development of the MIT SSL Laboratory Design Philosophy which helps guide the design of new experiments. These features are presented below.

3.4 Features of a Laboratory for Space Technology Maturation

In the area of dynamics and control different technology validation tools play different roles in the maturation process. Simulations, while versatile, low cost, and low risk, only address issues that the control engineer remembers to consider. Implementation on hardware forces the engineer to pay attention to not only the technology but also the details of its implementation. It is these details which a hardware testing facility must allow to be identified correctly.

A testing facility designed to mature technologies must ensure that the tests meet the characteristics presented above in such a way that the technology, rather than the facility itself, limits the ability to demonstrate the maturation of the technology. The facility must create the necessary environment for successful demonstration, so that the results are relevant to the operational environment of the technology. The performance limitations of the facility must not limit the technology; it is the only way to ensure that the results of the tests are bound by the technology being tested. Further, to create a laboratory environment, the facility must allow the demonstration of all the areas of study which comprise a technology, allowing multiple scientists to conduct experiments over long periods of time. Overall, the laboratory must facilitate reaching technology maturation. Therefore, a laboratory must meet a minimum set of requirements that will surpass the capabilities of the technology.

Each of the MIT SSL microgravity experiments presented above satisfied one or more of these requirements. The features of these facilities which enable them to meet these have been identified and brought together into the MIT SSL Laboratory Design Philosophy. These features will drive the lower-level design of new testbeds, after a high-level design has been decided upon based on the project goals and TRLs to be met. The identified features of microgravity laboratories are:

Data Collection and Validation. A successful research environment must provide data collection of accuracy and precision scalable to the final system to demonstrate operation of the new algorithms or technologies. The collected data needs to ensure the technology is fully observable. The feedback from the research environment must be precise enough to validate the operation of the new technology. The facility must also ensure that the data is presented in a manner useful to demonstrate the validity of the results. Further, the data must be independently validated by a truth sensor.

Repeatability and Reliability. To demonstrate the repeatability of a new technologies, the research laboratory environment must have a better repeatability and reliability rate than the technologies to be tested. The environment must be able to provide similar test conditions through an extended period of time. Similarly, to demonstrate the reliability of a new controller, the environment should be easily changed so as to create different disturbances and commands. Therefore, the research environment must be a controlled setup, where interaction with the facility can easily recreate an environment or change it in a controlled manner.

Physical End-to-End Simulation. The test environment must provide a sufficiently realistic simulation of the expected operational environment and performance metrics. The environment must correctly simulate the hardware required for the actual mission, including the use of representative sensors, actuators, electronics, and other active hardware. Further, to fully capture the dynamics of the mission, the physical end-to-end simulation must allow its dynamics to be fully understood such that the results can be applied to the actual mission which may have different dynamics. Otherwise, important couplings and perturbations may be masked and the ability to achieve requisite performance levels is difficult to ascertain. The hardware simulation must also allow all essential operational steps of the mission to occur, either continuously or step-wise, so that all parts of the technology can be demonstrated.

Generic versus Specific Equipment. All laboratories distinguish between that which is being tested and the facilities needed to conduct those tests. Since it is difficult to modify hardware in the space environment, it is desired that laboratories based in the ISS have a set of generic equipment able to provide basic operation of the laboratory. Test-specific equipment can be attached to the generic equipment to better model a specific mission. In this way the laboratory can accommodate a multitude of research projects. This re-usability improves the cost-effectiveness of the research.

Hardware Reconfiguration. To demonstrate the reliability of a new algorithm or technology, it is desirable to manipulate the hardware configuration during a specific test to demonstrate increasingly complex geometry or components. Therefore, both the generic and specific hardware should allow easy reconfiguration.

Supporting Extended Investigations. The effectiveness of experimental research is generally correlated with the number of iterative research cycles completed. Sometimes, a test can reveal totally unexpected behavior. Under these circumstances, a cycle cannot closely follow the previous cycle since time needs to be spent re-exploring the theory before the original hypothesis can be appropriately refined. Therefore, there is a need to maintain access to the laboratory under repeatable test conditions following an extended period of no tests.

Risk Tolerant Environment. Laboratory tests are often conducted on immature and unproven technology. The environment must be designed to accommodate failure or unexpected behavior (e.g., control system instability). Such occurrences must not pose harm to the researcher, the test article or the test equipment. Furthermore, the researcher must expect such occurrences, otherwise they are not pushing the edge of knowledge and capability.

Software Reconfiguration. The ability to alter software provides much more versatility in manipulating test conditions. In particular, when the technology being tested is manifested as software (e.g., control, metrology, system identification, and autonomy algorithms), the ease with which that software can be altered directly impacts the productivity of the tests.

Human Observability and Manipulation. Research is a very human-in-the-loop process. The researcher's ability to observe behavior, refine a hypothesis, manipulate the test conditions, and observe new behavior is at the core of the iterative experimental research process.

Facilitating Iterative Research Process. While human interaction and laboratory reconfigurability are prerequisites for a laboratory, they alone are not sufficient to facilitate the iterative research process. The cycle time from posing an hypothesis to refining that hypothesis based upon correlation between experiment and theory must be sufficiently brief. This helps the researcher track the evolution of inquiry and offers the opportunity to explore alternatives more fully. Laboratory interfaces must be defined to minimize the resources consumed by each research cycle.

Supporting Multiple Investigators. Shared access to a research laboratory dramatically improves cost-effectiveness. Therefore, reconfigurability of the testbed should allow multiple investigators to participate in the program. Guest investigators must not only have access, but that access must be supported by the principal investigator, since the guest investigators may not be familiar with, or able to be present in, the laboratory environment.

3.4.1 Interactions Between the Features

The presented features of a laboratory are not independent of each other. A single characteristic of a system can help achieve multiple features, and success in some features helps to achieve success in others. Table 3.2 presents the interactions between the different features. The table shows when a feature in the rows helps a feature in columns; when an interaction between a feature in the rows exists with one in the columns, a check mark indicates this relationship. This section explains the interactions that occur as each feature in a row helps one or more of the other features.

Data Collection and Validation. The *iterative research process* depends on data analysis between iterations, therefore good data collection and validation is necessary. If the data quality is not precise enough, then the simulation will not achieve full *physical end-to-end simulation* of the experiment.

Repeatability and Reliability. The *iterative research process* depends on multiple iterations being carried out at different periods in time, with the guarantee that the test conditions will be similar. Otherwise, subsequent tests may waste resources trying to identify what has changed about the test environment. To support *extended investigations* the hardware must perform the same way over long periods of time, which cannot be done without a repeatable system. When a facility is known to be reliable scientists have greater confidence to push the limits of their technology towards the limits of the facility, aiding in creating a *risk-tolerant environment*.

TABLE 3.2 Interaction between the SSL Design Philosophy elements

These features ↓ support these features →	Data Collection	Repeat. / Reliab.	Iterative Process	Human Obs./Man.	End-to-End	Extended Invest.	Risk Tolerant	Generic/Specific	HW reconfig.	SW reconfig	Multiple Invest.
Data Collection and Validation			✓		✓						
Repeatability and Reliability			✓			✓	✓				
Facilitating Iterative Research Process											
Human Observability and Manipulation			✓			✓	✓		✓		✓
Physical End-to-End Simulation											✓
Supporting Extended Investigations			✓								✓
Risk Tolerant Environment			✓								
Generic versus Specific Equipment					✓				✓	✓	✓
Hardware Reconfiguration					✓						✓
Software Reconfiguration			✓								✓
Supporting Multiple Investigators											

Human Observability and Manipulation. Humans help the *iterative research process* by reducing the time to get feedback (data download and comments on observed behavior) on experiment runs. Humans aid *extended investigations* by enabling simple ways to resupply consumables and store hardware in between experiments. Humans provide for a *risk tolerant environment* in two ways: first, strict safety requirements reduce the risk of catastrophic failures; second, humans can intervene in the case of failures that would otherwise damage the facilities. Humans help support both *hardware reconfiguration* capabilities and *multiple investigators* by simplifying the methods to change the hardware and, in doing so, allowing the hardware to operate in different modes for different scientists.

Physical End-to-end Simulation. The participation of *multiple scientists* in a project usually implies that they are working on several areas of a technology. A system which achieves physical end-to-end simulation will provide better results for multiple scientists working on different areas of a technology, since the system behavior will be valid for all of them.

Supporting Extended Investigations. The *iterative research process* depends on the availability of sufficient time and data for scientists to analyze results and make modifications to their initial hypothesis. Operating for extended periods of time provides *multiple investigators* with sufficient time to run their tests.

Risk Tolerant Environment. The *iterative research process* is helped by a risk-tolerant environment since tests can be pushed to their limits, rather than taking conservative steps every time.

Generic vs. Specific Equipment. By creating a complete set of generic equipment, the facility can be later reconfigured with specific equipment to simulate all the different aspects of a technology being investigated to create a *physical end-to-end simulation*. Finding the correct interfaces between the generic and specific equipment facilitates the *reconfiguration* of both hardware and software. The creation of generic equipment helps *support multiple investigators*, who can create their own specific components rather than have to work with equipment that does not necessarily meet their needs.

Hardware Reconfiguration. A *physical end-to-end simulation* needs to cover all aspects of a technology to be demonstrated; hardware reconfiguration enables physical changes to demonstrate the technology under different environments. The ability to change the hardware enables *multiple scientists* to configure the facility as necessary for their specific objectives.

Software Reconfiguration. The ability of software to change *facilitates the iterative research process* since modified hypothesis can be tested via data transfers, rather than hardware deliveries. Further, *multiple scientists* will investigate different parts of a technology, which will require different software.

At this point we note that *facilitating the iterative research process* and *supporting multiple investigators* do not necessarily benefit the other features, but rather are beneficiaries of them. Therefore, these two features are considered of a higher level than the other ones; they are major features that require other lower-level features to be present, but which ultimately provide the capabilities that are most desired of a facility.

Table 3.3 shows features grouped into sets that take into account their interactions and their support for other features. Facilitating the iterative research process and supporting multiple investigators are left as independent features that require individual attention. The *experiment support* group includes those features that support the ability to conduct experiments; all of these support the iterative research process as lower-level features of the facilities. The *reconfiguration and modularity* group contains the low-level features that help support multiple investigators. The following sections present the theoretical background behind these features.

TABLE 3.3 Grouping of the SSL Design Philosophy features

Group	Feature
Facilitating Iterative Research Process	Facilitating Iterative Research Process
Experiment Support	Data Collection and Validation
	Repeatability and Reliability
	Human Observability and Manipulation
	Supporting Extended Investigations
	Risk Tolerant Environment
Supporting Multiple Investigators	Supporting Multiple Investigators
Reconfiguration and modularity	Generic versus Specific Equipment
	Hardware Reconfiguration
	Software Reconfiguration
	Physical End-to-End Simulation

3.4.2 Facilitating the Iterative Research Process

> "Research is the methodical procedure for satisfying human curiosity. It is more than merely reading the results of others' work; it is more than just observing one's surroundings. The element of research that imparts its

> descriptive power is the analysis and recombination, the "taking apart" and "putting together in a new way," of the information gained from one's observations." [Beach, 1992].

The MIT SSL Laboratory Design Philosophy guides the development of laboratories for space technology research. To ensure success of the laboratory, the research conducted within must be supported by formal research methods that guarantee valid results as expected by the scientific community at large. The methodical procedure most widely accepted, although by no means defined in one single manner, is the scientific method. The most basic interpretation of the scientific method can be found in its dictionary definition [Merriam-Webster, URL]:

> Main Entry: scientific method
>
> : principles and procedures for the systematic pursuit of knowledge involving the recognition and formulation of a problem, the collection of data through observation and experiment, and the formulation and testing of hypotheses

A wide range of research exists on the philosophy of the scientific method as demonstrated by the large number of publications that reference the Scientific Method. A quick review of these publications demonstrates that a large portion of literature on the design of experiments ([Fisher, 1935],[Mead, 1988],[Antony, 2003]) concentrates on the use of statistics to provide useful results. Yet, a single definition of the principles and procedures that constitute the method applicable to all sciences and research does not exist. Every reference presents a slightly different procedure for the scientific method, based on their expected application. From the start of the scientific revolution, the scientific method was applied on a case by case basis. The method began in the fields of anatomy and physiology in the 17th Century; two versions of the method each called for starting research based on facts/observations, or on the development of theory (models). In the 18th century Newton joined the two concepts together, showing how a well developed hypothesis (theory) leads to relevant experimentation that helps develop a coherent theory.

We shall build upon the concept introduced by Newton. The goal of the research process shall be to validate a hypothesis by experimentation and modification of the hypothesis until the theory matches the physical world. The basic steps of this process are encompassed in an elementary definition of the scientific method as presented by Gauch in his introduction:

"Elementary Scientific Method" [Gauch, 2003]

- Hypothesis formulation
- Testing
- Deductive and inductive logic
- Controlled experiments, replication, and repeatability
- Interaction between data and theory
- Limits to science's domain.

The basic method as presented above already supports our call to support the iterative research process, as it calls for the development of controlled experiments which can be replicated and repeated and the study between data and theory. But the basic method only implies the need for repetitions or iterations during the controlled experiments. As Gauch argues, the scientific method calls for a much deeper understanding of each step. He presents the steps shown in Figure 3.1 [Gauch, 2003] as the full scientific method. Of special importance to us is the fact that this advanced scientific method is iterative in its entirety. The development of the hypothesis leads to two paths: development of a model used in deduction of the science, and design of an experiment to observe and collect data from the physical world. His process introduces noise in data collection to remind the scientist that no observation is perfect, this step will be addressed in a later section. Next, Gauch calls for induction: the combination of the deductive theory and the observed data to determine the validity of the hypothesis. The last step closes the iterative loop: creating a hypothesis to test via deduction and observation.

The philosophy of science supports the need for iterations on the hypothesis and design of the experiment. The theory behind the design of experiments [Mead, 1988] calls for con-

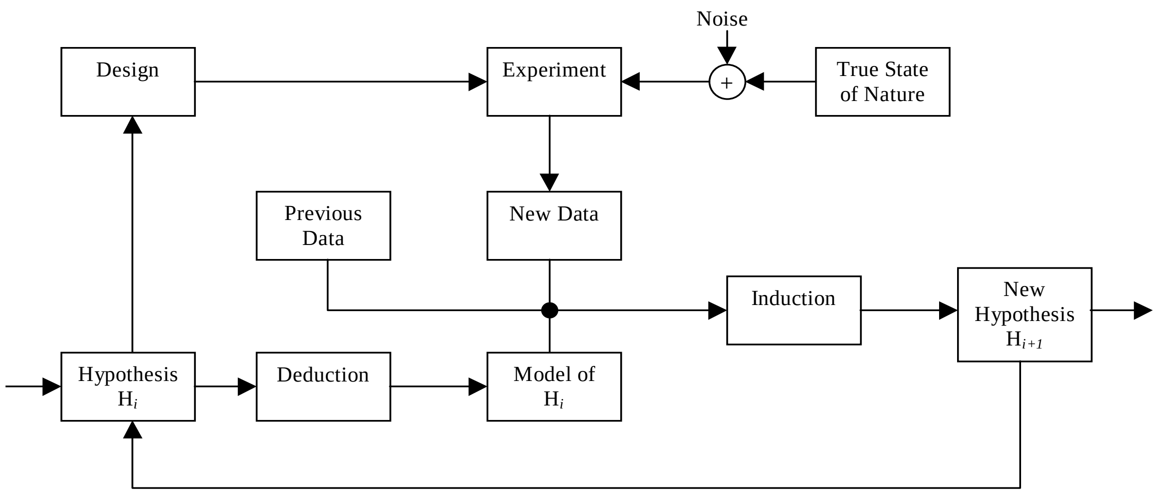

Figure 3.1 Overview of the scientific method by Gauch

ducting a number of experiments changing design variables in a controlled manner. The major references on the design of experiments concentrate on the topics of probability and the design of block methods [Fisher, 1935] [Montgomery, 1991] [Antony, 2003] to ensure full coverage of the design space. The concept of probability by itself implies the need to conduct multiple trials of experiments in order to obtain a meaningful set of data for analysis. Therefore, the design of a facility must allow researchers to conduct multiple tests in a repeatable environment with the ability to change the design variables of importance to the research:

> "The designer of an actual experiment is required to produce a design appropriate to a very particular set of circumstances. But, except where the designer is very experienced, he or she will not be able to assess the entire spectrum of design ideas, and make decisions about the design, from the basis of a comprehensive knowledge of how all the principles of design might relate to this particular problem." [Mead, 1988]

This concept further emphasizes the need to allow both a hypothesis and an experimental design to go through the iterative research process. Only through iterations will the hypothesis be understood and refined: "There are no hard and fast rules that lead to the selection of the best possible design for a given set of circumstances. The more one creates and evaluates designs, the better the chances of finding the best possible design. … We have observed that beginners require something in the vicinity of eight to ten redesigns before their comfort level is reached. Experts require four to five designs." [Lorenzen, 1993]. The iterative research process is essential to the true understanding of a research topic and the formulation of its hypotheses and models.

The philosophy of the scientific method and the design of experiments defines what it means to iterate a research experiment: to be able to repeat an experiment multiple times changing variables so that statistically relevant data is obtained and to have the ability to change the hypothesis behind the experiment and re-design the experiment to account of these changes. Therefore, to facilitate the iterative design process, a facility must ensure that both of these activities are as easy to perform as possible. An environment that truly facilitates the iterative research process allows experiments to be repeated with minimal overhead. This includes the full process of conducting each experiment run: resetting the facility in the same state, controlling the initial conditions; ensuring that the experiment behaves the same way given the same disturbances and actuation commands; collecting valid data continuously; and allowing the replacement of any consumables with ease. The design of the facility must account for the correct number of times an experiment must be repeated to obtain meaningful data and ensure that number of repetitions is possible.

The facility also needs to account for the different variables that are relevant to the research being conducted. But, as expressed by Mead, not all design variables will be known. Therefore, the design of the facility must contemplate the need to change the known variables and to expect the appearance of new variables. Conducting the iterative research process will result in the identification of those new variables, and will likely require the design of the experimental setup to change. A well designed facility must allow those changes to take place with ease.

The need for iterative design is well summarized by Ernst as it applies to our field of space technology:

> "Doing exhaustive design ahead of time may not be desirable, even if it were feasible, because of uncertainty - and because of the certainty of change. (The more successful the design and the more long-lived the resulting system, the more change there will be; thus, a successful design will eventually become less appropriate, less clear, and less true to its original conception.) … Few designs perfectly model the constructed system; artifact understanding and design recovery are crucial in such circumstances. … the implementation might have begun before design was complete, or might use pre-existing or separately constructed components that may not have their own designs or may not mesh perfectly with the overall system's design.
>
> "Iterative design encompasses design after part of an artifact has already been completed; re-design; design in the presence of changing requirements; and adjusting a design in response to changes to an artifact. … iterative design must take account of, and respect, existing components and their interactions. Iterative design goes further in comparing versions of requirements, designs, systems, and in being part of a continuing process…" [Ernst, 2003]

3.4.3 Experiment Support Features

The iterative research process depends on the ability to successfully perform experiments, collect data, interpret it, and then iterate on the hypothesis. Returning to the idea that the design of experiments is highly dependent on the statistical relevance of the collected data, it is further necessary that scientists be able to perform a relevant number of experiments in between each iteration. This group of features addresses the need to ensure individual experiment runs are effective and provide the right data.

Data Collection and Validation

The initial definition of this feature called specifically for the following requirements on data collection:

- Ensure data accuracy and precision scalable to the final system
- Ensure observability of the technology
- Provide a useful presentation of data
- Allow for a truth sensor

These requirements address a range of important practices in data collection. To ensure data accuracy and precision, the experimental setup must address the issues of frequency response/aliasing, bit depth/digital precision, and input/output ranges. The collection of data must be made at the necessary bandwidth to satisfy two goals: first, that the data is relevant to the technology being demonstrated. For example, saving data at 1Hz is not useful to demonstrate a controller for a 10Hz system, unless the frequency can be scaled, in which case scalability must be demonstrated. Second, the data sampling rate and/or hardware must ensure that aliasing does not occur. Scientists must also ensure to use the correct precision of the data. The bit depth affects two parts of the data collection process: conversion of analog signals and saving the data itself. The conversion to and from analog signals must be of sufficient bit depth to ensure that the single-bit precision of the data shows the necessary fluctuations in analog signals. When saving data, whether they originated in analog or digital form, the scientist must balance the number of bits used for each piece of data with the storage volume and communications bandwidth available to the experiment. It may not always be possible to save an analog measurement in floating-point format, and therefore the scientist must decide to what fixed-point precision the data should be saved. Lastly, the experiment must be such that the range of the inputs and outputs is able to both measure and actuate the system to ranges scalable to the final system. For example, if an experiment can only provide a limited amount of actuation from a reaction wheel, the scientist must ensure that the actuation is scalable to a larger satellite.

One of the characteristics of a mature technology is that it allows the identification of new physical phenomena that affects a system. To allow this identification the data must ensure that the system is fully observable, so that the scientists can demonstrate where the new phenomena originated. For example, in a dynamics and controls experiment, the scientist may be able to exactly reproduce the output (actuator commands) of a controller by knowing the inputs (sensor readings), since the controller is a deterministic mathematical algorithm. In developing that controller the scientist may have assumed some noise in the input. In models the scientists can use random noise generators, but the modeled noise may not correspond to the physical system. It is necessary that the saved data include the measured noise, otherwise the scientist would not be able to confirm their model. Further, the scientist may discover an unknown coupling with the noise observed during the experiment.

To truly support experiments and ultimately facilitate the iterative research process it is necessary to easily interpret the data. This means not only that the right data must be downloaded, but also that tools must be created a-priori to evaluate the results. While a scientist may not know exactly in what format the data will need to be presented to learn all the information contained within it, the scientists should be able to identify the basic requirements. During the data analysis time the scientist should only create new data analysis tools when new phenomena are identified that need further examination, and not to interpret the basic data.

Lastly, there is a need for a truth measure which can verify the validity of the data acquired by the system when the sensors in an experiment are part of the research itself. A truth measure helps to identify any couplings of the sensors with the system being tested and to ensure that these sensors are operating correctly. For this it is critical that the truth measurement systems operate independently of the experiment itself. For example, in a closed loop control experiment one should not use the feedback sensors to measure control performance; sensors outside of the control loop should be utilized as a truth measure.

The capabilities of the truth sensor in terms of accuracy and precision depend on the specifications and requirements of the sensors which need validation. Especially in those cases where the whole experiment is the development of new sensors with precision beyond existing systems, the truth sensor will not be able to verify the operation of the new sensor to its utmost precision. When a higher precision truth sensor is not available, the use of redundant sensors is desired. This would allow multiple ways to calculate performance and asses the variability in the performance estimates. Data from different sensors should correlate, helping to validate the data.

Repeatability & Reliability

The need for repeatability is directly supported by the theory behind the design of experiments (DOE). The goal of a DOE process is to select one of two methods: either have a large number of samples to show statistically useful results, or ensure that the small number of samples demonstrate the success of the technology. Repeatability is defined by the International Organization of Standards (ISO) as:

> The closeness of agreement between independent results obtained in the normal and correct operation of the same method on identical test material, in a short space of time, and under the same test conditions (such as the same operator, same apparatus, same laboratory).

Repeatability means more than the ability to run multiple tests. For the results to be statistically useful, each time a test is run the operating conditions must be the same. To further benefit an experiment, a facility should allow complete system identification and/or control of the operating conditions of the test. When a facility allows measurement of the operating conditions, the scientist can trade-off between obtaining samples for identical controlled initial conditions, which could utilize a large amount of consumables, and running multiple tests with a large number of known but different starting conditions.

The reliability of a system is defined by ISO as:

> The ability of an item to perform a required function under stated conditions for a stated period of time.

The number of samples needed for a successful demonstration is inversely proportional to the reliability of the test. If a test is expected to succeed with high reliability, during DOE a small number of samples are planned. Low reliability experiments will require more samples. A research facility must ensure that it is not the driver in the selection of the number of samples. The reliability accounted for in the DOE process must be that of the technology being tested, with the security that the reliability of the testing facility is high.

Because the goals of these facilities is to test the limits of the new technologies, the development of the facilities must assume that the technologies will fail and new tests will be needed. Therefore, the facility must be able to withstand failures of the technology without any critical failures of its equipment. The facility must be more repeatable and reliable than the technology being tested.

Human Observability and Manipulation

The review of antarctic and ocean research in Chapter 1 emphasized the need for humans to be present in the research environment. Humans in the Antarctic and below the sea are scientists, engineers, and mechanics; they ensure science occur and equipment works.

> "The most complex system cannot effect the simplest repair unless the particular failure mode has been foreseen and preprogrammed. An unmanned camera will happily shoot film when a dragging boom puts only bottom silt before the lens, and many manipulative functions are just best left for the human hand. There will always be the unexpected on a new frontier, and instruments are best regarded as extensions of man, reserved for areas where man cannot reach or function." [Penzias, 1973]

With the availability of humans, one must define what the human tasks should be. Human observability and manipulation of an experiment requires that humans control the experiment in several ways. The observation of an experiment means that there is a clear ability of the human to determine the progress of the test. In many cases it can be to visually observe the physical behavior of the system. Observation can also be the interpretation of results shown in real-time, such that the human can observe the progress of the experiment as it progresses. The critical element of human observation of an experiment is that the human obtains real-time feedback on the progress of the test, whether directly or indirectly. Manipulation of an experimental facility is composed of two parts. First, humans must control the operations of the experiment. While the facility's normal operations can be automated, the facility must allow override of such systems, so that a human can ultimately make the decisions on the progress and safety of a test. Because we are working with immature technology, which we expect to fail in many cases, a human should ultimately control when a test starts and ends, ensuring that the conditions to run the test are appropriate. Second, allowing humans to modify the system, either by reprogramming or changing hardware, can present considerable functionality and cost savings to the project.

Past experiences of the MIT SSL with microgravity experiments have demonstrated the success of human manipulation to help a mission. The SSL has benefited from the ability of humans to repair components of experiments which would otherwise have terminated the mission prematurely. The failure, an incorrectly wired connector which was not part of the original checkout procedure, was fixed on site by astronauts. The ability of humans to reconfigure the hardware of several experiments has allowed the SSL to proceed with those missions. Had the hardware needed automatic reconfiguration two problems would have occurred. First, the cost would be prohibitive for the program, forcing a substantial reduction in mission objectives. Second, the addition of motors and other physical elements would have complicated the structural components of the facility, changing the dynamics in ways incompatible with the mission goals.

Support Extended Investigations

The support of extended investigations does not refer to the ability to run individual tests for a long period of time. Referring back to the scientific process shown in Figure 3.1, the scientist needs time for induction - analysis of the data - and review of the hypothesis, with the ability to perform a new iteration shortly after the new hypothesis is created. Therefore, the support of extended investigations refers to the ability of a facility to allow storage of an experiment in safe conditions after a number of tests have provided enough data to iterate on the hypothesis. After the hypothesis has been modified, the experimental apparatus must be able to perform new tests in minimal time. Repeatability and reliability play a role in this feature, since it is expected that the new tests perform under conditions similar to those conducted originally.

Risk Tolerant Environment

The MIT SSL Laboratory Design Philosophy has been created for the maturation of new technologies. This implies that the technologies are not yet mature, and that before they are mature tests are likely to fail. The Innovation Network, when presenting the challenges of organizational innovation, provides a good summary of the need for a risk-tolerant environment to allow for maturation of untested technologies:

> "an environment that welcomes and continuously searches for opportunities -- one with a rich flow of ideas, information and interaction within and without the organization... among customers, the environment, competitors, suppliers and employees at all levels and functions. This is a risk-tolerant environment that celebrates successes as well as great tries that didn't work." [Wycoff, URL]

To truly allow for new technologies to be developed, the environment must be designed to accommodate failure or unexpected behavior; it should welcome failure as much as success. To achieve this, the environment must ensure that its operation never poses harm to the researcher, and that failures of the technology do not cause critical failure of the apparatus, while at the same time ensure that the controls put in place for this safety do not inhibit the research process.

3.4.4 Supporting Multiple Investigators

> "The most compelling rationale for engaging in collaborative relationships... is the advantage an organization accrues by gaining access to complementary areas of expertise, knowledge, skills, technology, or resources that it cannot produce on its own. Most researchers on strategic alliances concur that the value added from collaboration comes primarily when partners have complementary needs and assets... Consortia are advantageous when the knowledge base of an industry is both complex and expanding, the sources of expertise are widely dispersed, and the pathways for developing technology are largely uncharted." [Merrill-Sands, 1996]

Aerospace technology clearly lies within the industries that address complex problems. The advancement of microgravity technologies to full operational level, if we are to follow NASA TRLs, depends on the ability to demonstrate these technologies with a full system test in a relevant space environment. Therefore, the maturation of a space technology depends on the demonstration of its ability to integrate and operate with all the sub-systems of a spacecraft. For example, we can easily identify the needs for propulsion, avionics (navigation, control, and data processing), communications, thermal, and structures sub-systems. Advancing a technology in the area of dynamics and control may depend on advanced propulsion and structures technologies. Even a specific area may cover a wide range of studies; for example the area of controls, within avionics, requires sensors (metrology), data processing (and control theory), and actuators. The inter-dependence of all these areas are vast and deep. As such, collaboration has a high potential to benefit the advancement of space technologies and is essential to fully advance technologies for integration into new spacecraft.

Explaining how to best conduct collaborative research requires that the term be first defined in a concise and clear manner. One such definition is presented by the FENIX team: "*Collaborative research is defined as an emergent and systematic inquiry process embedded in a true partnership between researcher and members of a living system for the purpose of generating actionable scientific knowledge*" [Adler, 2004]. This definition consists of several parts, each of which presents its own challenges to collaborative research. The need for the process to be "emergent and systematic" requires that the collaborative process be in constant review and update. For the process to be embedded in a true partnership it must have been designed as an integral part of the research process at all levels, rather than only being a high-level process. Lastly, the definition calls for the results to produce actionable scientific knowledge; the results must provide the partners with new knowledge that have a practical use for each of the partners that entered into collaboration. Huxham illustrates this last point best:

> “Collaborative advantage will be achieved when something unusually creative is produced that no organization could have achieved on its own and when each organization, through the collaboration, is able to achieve its own objectives better than it could alone.” [Huxham, 1996]

With the concept defined, it is now possible to identify the challenges and different methods to enable collaborative research. Several past collaborative experiences [Merrill-Sands, 1996] [LeGris, 2000] demonstrated that an important challenge is that collaborative projects have higher management costs. Control of the project is shared among multiple entities, and division of responsibilities usually have to be negotiated. These challenges are best addressed at the start of the collaborative program. [LeGris, 2000] proposes the following steps to successfully initiate a collaborative effort:

1. Determining the relationship: define the goals, ensuring that they do not interfere with each organization's primary purposes. The definition also includes expected participation by staff of the different institutions.
2. Determine the structure: set meeting schedules and ensure visibility of the collaborative effort as appropriate through the organizations.
3. Assessing the organizational climate: before implementing the collaboration, ensure that the different parts scheduled to work together through 1 and 2 are ready to participate.
4. Recognize similarities and differences: take into account the different goals of the parties involved; researchers value the process, while industry values the product. Identify these differences and address them in the definition of the collaboration. Find common elements, such as quality management, to help bridge the differences.
5. Enhancing commitment through communication: ensure that the full staff of each organization which will be involved in the collaboration is aware of the project.

This process puts heavy emphasis on the need for all involved parties to be aware of the collaboration that will take place and be comfortable with it. [Davenport, 1999] condenses these ideas into the building of trust between the different organizations. Three types of trust are defined:

1. Contractual trust: adherence to agreements
2. Competence trust: adherence to expectations and performance
3. Goodwill trust: mutual commitment to the partnership

Only through goodwill trust can a relationship continue over the long term. "Cooperation between academic institutions and industry will be more likely to survive over time, the more there are initial assets of good will, trust, favourable prior beliefs, mutual psychological commitment and prior relations between the parties."

The need for substantial communications between the partners presents another challenge:

> "Collaboration requires frequent communication among all involved parties. The likelihood of success is greatly enhanced by the presence of a product or collaboration champion." [Littler, 1995]

[Kraut, 1988] presents a study on the effects of physical proximity on scientific collaboration. The study summarizes data on the amount of cooperation between researchers based on their physical location with respect to each other; next, it presents how the use of technology can help achieve that virtual presence. The study emphasizes the need for informal communications. The communication frequency and quality were proportional to the success of collaborations. On the other hand, high costs of communications greatly hindered the collaborative process. The study concludes that:

> "Omnipresent video might provide the low-cost and therefore frequent and spontaneous interactions that are crucial to initiating collaborations, monitoring and coordinating the project, and maintaining a smooth personal relationship. Multimedia meeting tools might provide the high quality communication to support planning and review. While many other specific tools have been proposed and could be built to support particular tasks that occur frequently in a collaborative project, most are likely to build from these two foundations."

Communications in a collaborative environment involves more than personal relationships, they also require successful data exchange. Therefore, further tools are required beyond video conference and multimedia. Projects such as the Electronic Laboratory Notebook (ELN) [Myers, 1996] [Myers, 2001], and Collaborative Experimental Research Environment (CORE) [Schur, 1998], and Jazz [Hupfer, 2004] are geared to support the data handling of collaborative research. The electronic lab notebook project is based on an important premise:

> "The laboratory notebook is a vital tool in scientific research. It is the central repository of information about the reasoning and preparation behind experiments, about the analyses done to obtain results, and about plans for future research. The notebook captures the scientific process that gives meaning to a scientist's observations. Sharing a notebook can help collaborating researchers build a common understanding of their work." [Myers, 1996]

The ELN consists of an internet based website which collects and presents data information as well as annotations. It can interface to data collection programs such that the data is placed directly in the website; the website handles threading of annotations, such that comments of a similar topic remain in the same thread, rather than being forced into a chronological pattern. The notebook also maintains a database of arbitrary electronic files, such that researchers can share data even with programs that did not exist during the development of the ELN. The ELN also provides query functions to provide concise reports by researcher, topic, etc.

CORE "provides a loosely integrated suit of Internet collaboration tools that appear as web-browser extensions... The goal... was to develop a system that would support the identified workflows, activities, and different collaboration types." The tools that form CORE are:

- Chat
- Audio/video conferencing
- Whiteboard
- File transfer
- Shared computer display (tele viewer)
- Electronic notebook
- Web browser synchronization
- Shared instrument control

CORE grows upon the ELN by not only providing space for results and procedures, but also the highly-interactive tools that enable inter-personal communications. CORE goes as far as to provide shared control of instruments.

The Jazz team bases their design on *contextual collaborations*, an approach where collaboration is enabled by expanding standard applications, rather than having to use special tools. The benefits of contextual collaborations include: reduced friction in the use of applications; enhanced collaborative work by easing the collection of collaborative artifacts: better informed collaborative work since researchers are more aware of the process while they conduct research, not only when they use the special tools; and reuse of collaborative components used on a wide range of standard applications. The Jazz project is based on the metaphor of an "open office", where developers communicate easily and use shared resources such as a whiteboard. The interface for the development environment integrates teams and team-members into standard one-user projects. Each team-member is immediately aware of the other team members with only minor changes to the interface, and without hindering their own work. The interface also integrates live-chat sessions into the IDE, but presents them in separate windows to prevent taking space from the main window. Through these simple but highly-integrated tools, Jazz allows a standard programming IDE to inherently support collaboration.

So far the challenges for collaborative research have concentrated on programmatic and inter-personal communications, but for space technology maturation there exists one other important aspect: sharing of the available facilities. The CORE project addressed the issue of sharing expensive/limited instruments by creating the toolkit for "secure collaborative instrument control" as part of the main application. Part of their research concluded that "some researchers were concerned about how their roles on research projects would change. For example researchers local to instruments voiced concerns about becoming technicians for remote users and no longer sharing physical maintenance tasks." The results of using CORE proved positive, and actually helped scientists have more time for research as the remote scientists used the tools without needing the constant help of local scientists. But the project concentrated on the creation of tools to control existing instruments rather than on the development of new instruments inherently designed to be shared by collaborating scientists. The development of new research facilities for the space station allows for new hardware designs that inherently support collaboration.

> "Would it not be better to build an entire family of... common product technologies, and a common set of highly automated production processes? Rather than have separate development teams each working on single products, wouldn't it be better to have them join forces in building a common *platform* or a design from which a host of *derivative products* could be effectively and efficiently created?" [Meyer, 1997]

The development of hardware to support multiple scientists must consider the common parts that will help all of the researchers, and allow for the development of specific equipment to support them. Following the idea of product platforms used in industry, this means that the main developer of the project must identify those common features and build them. Individual researchers should then be able to use this common equipment to implement their specific science. The basic common elements should define the overall architecture of the experiment, while individual experiments are derivative products. Ultimately, the goal is for developers of new ISS experiments to become the *supplier* of a *product platform*, while the collaborator scientists who use the experiment become the *customer* and create the *derivatives*. Note that the idea of product platforms is not limited to hardware; software can also become a platform. This idea is further explored in defining the concepts of modularity and reconfiguration.

Several key points arise from this review of collaborative science:

- For collaborative science to be effective it must allow each individual organization to achieve goals they would otherwise not be able to do on their own.
- A systematic approach to enabling collaborations is essential. This process must at the very least address:
  - Definition of the goals & structures of the collaboration
  - Trust between the parties
- Both inter-personal and data communications play an essential role in the success of collaborative endeavours
- New experiments developed for collaborative research must support multiple investigators by design; it is essential to identify the common elements of the project and allow individual scientists to add their own components

Successful collaboration provides benefits for all parties involved. If collaborative research is included as an integral part of a program, then it will have a high probability of success.

"**Everyone Wins**

> "Our open collaborative model provides benefits for all participants. It allows university researchers to amplify their thinking and their work - and potentially see it translated into commercial products - without having to leave academia. It enables Intel to accelerate research in areas we find interesting and worthy of exploration, by conducting research concurrently in the labs and deeper without our company. By facilitating synergy and open exchange of ideas, the model enables Intel and participating universities to jointly lead the industry toward breakthroughs that will continue to advance the state of the art. Under this new model of industry-university research, we believe everyone wins." [Intel, 2003]

3.4.5 Reconfiguration and Modularity

Reconfiguration and modularity affects both higher level tasks to support the iterative research process and multiple investigators. The need for reconfiguration and modularity is exhibited strongly by the philosophy of the scientific method, presented above, which includes as a critical element the need to revise the hypothesis and implement the changes for further experimentation. Supporting multiple investigators depends on the ability of the facilities to provide common parts and the individual researchers to create their specific equipment.

The idea of reconfiguration is closely linked with several studies on the need for flexibility of a system. [Saleh, 2002] proposes a definition of flexibility which applies to our case:

> "The property of a system that allows it to respond to changes in its initial objectives and requirements - both in terms of capabilities and attributes - occurring after the system has been fielded, i.e., is in operation, in a timely and cost-effective way."

That definition is further detailed by comparisons with other terms which are usually confused with flexibility, but which do not guide a products towards reconfiguration or modularity:

- Flexibility vs. Robustness - robustness is the ability of a system to satisfy a fixed set of requirements despite changes in the system’s environment. Flexibility satisfies changes in requirements after the system has been fielded.

- Flexibility vs. Universality - universality applies to a system that can be used in a wide range of situations without any changes. Flexibility implies the ability to change and adapt with ease.

These definitions clearly point towards a reconfigurable system, one which can adapt not only to changing conditions, but also to changing requirements. At the same time, the distinctions indicate that the goal is not to create a single facility that satisfies every foreseeable need, but rather one that can adapt to unforeseen needs.

The MIT SSL Laboratory Design Philosophy separates the concept of reconfiguration and modularity into four main areas: identification of generic and specific equipment, hardware reconfiguration, software reconfiguration, and physical end-to-end simulation.

Generic versus Specific Equipment

A ground-based laboratory usually includes a set of generic equipment used for the design and construction of multiple projects. For example, a laboratory for electronics includes oscilloscopes, multi meters, computers, soldering irons, wire, pliers, and even a set of generic electronic components such as resistors, amplifiers, and standard logic chips. The MIT SSL Laboratory Design Philosophy defines a laboratory as a place to enable a field of study, therefore the equipment referred to in the philosophy is that which enables the research. The ground-based generic equipment is utilized to create higher-order generic equipment specifically designed to aid in the research of the specified field in a microgravity environment.

The support of multiple investigators introduced the concept of a *product platform* as a model for the development of research facilities where the different researchers are the customers who decide the *derivative* products needed. This concept directly fits the idea of generic versus specific equipment. The definition of product platform as presented by *[Meyer, 1997]* is:

> A product platform is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced.

The definition first considers the subsystems and interfaces of a larger product. These subsystems are brought together to create a platform for the development of derivative products. The generic equipment of a microgravity laboratory should be composed of those sub-systems which can create such a platform, and provide a set of well-defined interfaces so that the specific equipment can be efficiently added to the generic equipment to form a complete product (experimental apparatus).

Meyer cautions on the distinction between platforming and standardization, a warning relevant to this philosophy. Standardization of all parts fixes too many aspects, ultimately resulting in an inflexible design of the platform. The use of standards should always be balanced with the ability to identify the special elements of a platform that add value to the overall project, and allow those parts to continuously be improved. In relation to the MIT SSL Laboratory Design Philosophy: selection and standardization of the generic equipment should not limit the capabilities of the specific equipment.

It is important to point out that generic/specific equipment can exist for both hardware and software; generic equipment is not limited to hardware implementations.

Hardware Reconfiguration

Hardware reconfiguration works in parallel with the concept of generic vs. specific equipment; still, they are different concepts. While the addition of specific hardware to the generic setup does in fact reconfigure the overall facility, hardware reconfiguration refers to the ability to change the hardware for a specific test. In the area of dynamics and control, for example, the hardware configuration of a test apparatus directly affects the results. Changing the hardware configuration means that the dynamics of the system being tested will change. This is sometimes desirable, for example, in order to demonstrate robustness of an algorithm. In these cases both the generic and specific equipment may change configuration, meaning that the ability to reconfigure hardware should be considered in the design of all parts of the facility.

Software Reconfiguration

The concepts of flexibility and platforming apply equally to software as they do to hardware. Software has become an important part in the implementation of algorithms. The software controls the behavior of the hardware, sometimes commanding the hardware itself to change. Therefore, in order to complete full cycles of the iterative research process and to support multiple investigators, the software of a system must be able to change.

Modular software or that used in collaborations is usually shared using the concept of data abstraction; each module is a *black box* with certain inputs and outputs, and the user does not know what happens inside the box. The interfaces to these black boxes are commonly called Application Programming Interfaces (APIs). An API explains the functionality of the module and defines the inputs and outputs for each module and allows a programmer to use those functions without knowing the actual implementation. There are both positive and negative aspects to this modularity.

The concept of data abstraction flows directly into the idea of product platforms, as long as one accounts for the programatic aspects. From the product platform point of view software should be based on a core set of modules which interface through API to plug-ins that provide the specific functionality. The APIs should be standardized, such that changes to the core system can be continuously performed to maintain the platform up to date, while not breaking the functionality of the more specific modules:

> "One set of... engineers has been constantly building new add-in modules for the current version of the product platform or engine. Concurrently, other teams have worked to renew the core platform and to embrace technological change occurring in the broader industry... The only way that such a smooth migration can be accomplished is to develop and sustain clear, robust interfaces between the underlying engine and the add-in modules" [Meyer, 1997]

[deSouza, 2004], on the other hand, points out how APIs can hinder collaboration of multiple scientists. Sustaining clear and robust APIs is a major challenge; real world experiences show that APIs are usually unstable. Current programming tools do not help account for changes in APIs, leaving programmers dependent on personal communications to account for the changes. APIs are also challenged by their inability to ever be truly complete. As one programmer works on their base function, the users work with previous versions. Lastly, the black box concept creates a lack of awareness among the different people working in the same project. Data abstraction causes people to make unsupported assumptions about the functionality implemented in other modules.

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 plug-ins for specific research. But this development must ensure that APIs do not hinder the collaboration efforts by abstracting too much information into an interface.

Physical End-to-End Simulation

The previous features allow multiple scientists to perform specific experiments in an iterative environment, but with what goal? The ultimate goal of the MIT SSL Laboratory Design Philosophy is to allow technology to maturate. A critical part of the technology maturation is to operate the experiments in a relevant environment:

> "Relevant environment" is a subset of all the "environments" to which the technology advance will be exposed. "Relevant environment" is defined to be that environment, operating condition, or combination of environments and operating conditions that most stresses the technology advance and is consistent with that expected in the spectrum of likely initial applications. It is to be delineated in detail with the appropriate NMP Project Manager and concurred by the NMP Program Manager. [NMP, 2003]

A review of TRLs [Graettinger, 2002] for software projects further defines what a relevant environment means. For example, in the case of TRL5 the following definition is used:

> SW: Reliability of software ensemble increases significantly. The basic software components are integrated with reasonably realistic supporting elements so that it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of software components.

> System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment. Software releases are "Alpha" versions and configuration control is initiated. Verification, Validation, and Accreditation (VV&A) initiated.

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.

To satisfy end-to-end simulation the other reconfiguration and modularity features can be used. As individual scientists create their specific equipment they are ensuring that the test apparatus simulates their experiment in a valid way. Allowing hardware and software reconfiguration allows scientists to test a wide range of operational environments and conditions. Being able to demonstrate that a facility allows end-to-end simulation ensures that successful tests lead to technology maturation.

3.5 SSL Experiments and the Laboratory Design Philosophy

Table 3.4 serves two purposes. First, it cross-indexes the past laboratories of the MIT SSL with the attributes that they contained. As shown in the table, the more basic attributes such as data collection, repeatability, separation of test-specific from generic hardware, and hardware reconfiguration were introduced in the earliest laboratories (MODE) and adopted in subsequent designs. The more advanced attributes such as software reconfigurability, facilitating the iterative research process through human observation and data downlink with uplink of refined algorithms, and multiple guest investigators were not introduced until later.

Second, the table shows the goal of the SPHERES project with respect to the principles. As shown, the requirements for SPHERES are to meet all the features: support experi-

TABLE 3.4 Past Experiments and the philosophy features

	Data Collection	Repeat. / Reliab.	Iterative Process	Human Obs./Man.	End-to-End	Extended Invest.	Risk Tolerant	Generic/Specific	HW reconfig.	SW reconfig	Multiple Invest.
MODE	✓	✓						✓	✓		
MODE Reflight	✓	✓						✓	✓		
DLS	✓	✓				✓		✓			
MACE	✓	✓	✓	✓			✓	✓	✓	✓	
MACE Reflight	✓	✓				✓	✓	✓	✓	✓	✓
SPHERES	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

ments and provide enough flexibility to ensure that the iterative research process is facilitated and multiple guest investigators are supported.