# Design and Operation of Micro-Gravity Dynamics and Controls Laboratories

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## ABSTRACT

The cost and complexity of maturing spacecraft dynamics and controls technology increases dramatically as the developer needs to demonstrate functionality in the space environment. Due to the high cost and infrequent opportunities to exercise such technology in space, dedicated free-flyers are developed which integrate a number of high risk technologies. As the budget expands and real or perceived risk is recognized, schedules extend and technologies are reduced or removed. Pushing advanced technology to its limits in an operational environment is fundamentally at odds with the risk-intolerant environment of space, leading to high costs and delayed testing. The MIT Space Systems Laboratory has taken an alternative approach by developing a family of dynamics and controls laboratories that have operated on Shuttle, Mir, and ISS. By designing the laboratories to not ensure safety through software design, as well as operating within the interior of these vehicles, the risk-tolerant and technically aggressive nature of a terrestrial laboratory has been emulated in the long duration micro-gravity of space. This paper will present the various laboratory design features that have led to the low cost of this technology maturation approach: including modularity; platforming; virtual presence; and facilitation of the iterative research process.

## 1.0 Introduction

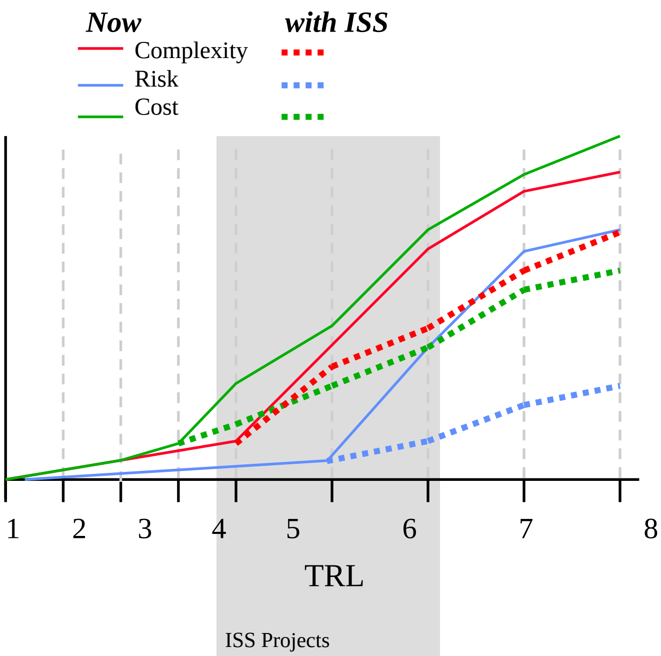
Space technology maturation is a challenging process. Substantial amounts of money, time, and human resources go into the development of new spacecraft. At every point in the design life of a new spacecraft there are substantial risks involved, especially as the complexity of new design increases. Over a decade ago NASA developed the Technology Readiness Levels[1] 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."[2]

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. In most cases when TRLs are used, these are refined for the specific application. The NASA NMP, for example, has made 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.

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."[3]. The amount of cost, complexity, and risk from one TRL level to the next are not always the same nor small; the definition of TRL 7 itself illustrates this point: "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 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. We wish to answer the question: *how can the ISS help mature technologies through the TRL scale? Can engineers and scientists utilize the ISS successfully to flatten the curves as shown in Figure 1?*




| | |
|---|---|
| TRL 1-2 | Basic principles & concept |
| TRL 3-4 | Proof-of-concept & laboratory breadboard |
| TRL 5 | Component validation in relevant environment |
| TRL 6 | System prototype demonstration in relevant environment |
| TRL 7 | System prototype demonstration in space environment (usually skipped due to cost) |
| TRL 8 | Flight system demonstration in relevant environment |
| TLR 9 | Mission Operations |

**Figure 1. Smoothing TRL Transitions**

## 2.0 Special resources of the ISS

In order to develop successful laboratory environments aboard the ISS, one must first understand the resources available for research. This section identifies the special resources of the ISS which can help reduce the sharp increases in risk, complexity, and cost usually seen as one proceeds through technology maturation. The following resources have been identified as most important:

**Crew -** The fact that humans are present in the space station to interact with and control different facilities is the most obvious and yet many times overlooked resource available in the ISS. Many times scientists put heavy emphasis on automation and independence from the crew, rather than trying to utilize their availability. Yet, the crew can help reduce the effects of many challenges: risk is reduced since humans can stop an experiment which is operating incorrectly; complexity and cost can be reduced by the need to remove automation tools. Therefore, any project that uses the ISS should actively use the humans to help the science and reduce risk, complexity, and cost. Further benefits of crew availability, such as the ability to iterate on hypotheses, are presented in the next section.

**Communications -** Correct use of the ISS communications system, and its constant expansion, is a priority for NASA[4] and a special resource which benefits all users of the ISS. The availability of continuous high-bandwidth communication to ground reduces the cost and complexity of missions which would otherwise need their own communications equipment. The availability of ever-increasing communications features will help with the issue of remote operation as real-time video and other teleconferencing options become increasingly available. Therefore, scientists should utilize the ISS as a direct communications link between them and their experiments.

**Long-term experimentation -** A unique features of the ISS is that it allows long-term microgravity experimentation in a laboratory environment. The long-term nature of the ISS helps to reduce the effects of high visibility as space research becomes part of daily life at NASA and the scientific community. The ISS allows space technology advances to come over longer periods of time, where specific one-time events (such as a landing or a docking) no longer need to mark the success or failure of a mission. Instead, the long-term nature of the ISS allows technology to mature over small steps in a low-visibility environment, allowing scientists to better concentrate on their research rather than outside factors.

**Power sources -** The ISS can provide several kilowatts of power to each experiment. Because power is usually traded-off with mass (i.e., larger batteries provide more power but have larger mass), utilizing the existing power sources of the ISS can help to substantially reduce the mass of an experiment, and in turn its cost. Because power sources are a constant safety concern, removal of power sources from an experiment also reduces the risk of the mission. Therefore, ISS supplied power should be utilized by the experiments.

**Atmosphere -** While sometimes an experiment intends to demonstrate the ability of its hardware to operate in a space environment, the development of ‘rad-hard’ techniques has been understood for several decades. Instead, many experiments wish to demonstrate the ability of their hardware and software to perform correctly in a microgravity environment without the need to worry about hardware failures. In these cases the pressurized environment of the ISS not only provides safety for humans, but also for electronics and structures. Experiments that can be performed inside the station can have a substantial reduction in cost, complexity, and risk, as compared to free-flyers in space, since they no longer need to worry about being exposed to the space environment radiation and vacuum. Cost is reduced directly by the use of standard components; complexity is reduced since protection equipment is no longer necessary; risk is reduced since the experiment is no longer exposed to the harsh conditions of space and therefore the probability of failure is lowered.

Table 1 summarizes the special resources of the ISS and their effects on the challenges of microgravity research.

**Table 1. Special resources of the ISS that facilitate microgravity research**

| Resource | Risk | Complexity | Cost |
|---|---|---|---|
| Crew | ↓ | ↓ | ↓ |
| Communications | | | ↓ |
| Long-term experimentation | ↓ | | |
| Power Sources | ↓ | ↓ | ↓ |
| Atmosphere | ↓ | ↓ | ↓ |

↓ = reduces impact of issue/challenge

## 3.0 Demonstrating new technologies aboard the ISS

This section proposes five main features to achieve the goal to reduce the *risk, complexity,* and *cost* of maturing space technology by utilizing the special resources of the ISS. Programs which fulfill the specifications of these proposals should enable scientists and engineers to mature their technologies *incrementally*, without substantial increases in the three measures between TRL levels. Because these features were developed based on the experiences of the MIT Space Systems Laboratory with dynamics and control laboratories which operated aboard manned facilities, the applicability of these features most directly affects those programs which operate aboard the ISS to demonstrate the development of space technologies. The features are:

1. Facilitating the iterative research process
2. Experiment Support
3. Support multiple investigators
4. Enable reconfiguration and modularity
5. Support Remote Operations

## 3.1. 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." [5]

To successfully perform the research necessary to demonstrate new space technologies, a project must enable the ability to iterate on different hypothesis of how to implement specific solutions. Through the successful iteration of increasingly complex problems one can incrementally mature technology. But, what does it mean to facilitate iterative research?

As presented by Gauch[6], the 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. This process introduces noise in data collection. Induction, the combination of the deductive theory and the observed data, is used to determine the validity of the hypothesis.

To iterate a research experiment one must:

- be able to repeat an experiment multiple times while changing variables, so that statistically relevant data is obtained
- have the ability to change the hypothesis behind the experiment
- re-design the experiment to account for these changes

Therefore, to facilitate the iterative design process, a facility must ensure that 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 ISS presents an environment which can promote the iterative research process. Astronauts can help to repeat experiments with controlled changes to obtain statistically relevant data. While it is not possible for astronauts aboard the ISS to fully re-design an experiment as would be possible in ground based laboratories, the availability of humans enables substantially more reconfiguration than what would be possible in an autonomous spacecraft.

## 3.2. Experiment Support

The iterative research process depends on the ability to successfully perform experiments, collect data, interpret it, and then iterate on the hypothesis. The design of experiments is highly dependent on the statistical relevance of the collected data; it is 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 -** This feature calls 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, and allow for a truth sensor. While the accuracy and precision of the system ultimately will depend on the science instruments aboard the spacecraft, the ISS helps to maintain the accuracy and precision of these instruments by providing a controlled and benign environment. The availability of high bandwidth communications helps scientists collect large amounts of data to guarantee obserbavility and format in a useful manner. Lastly, the availability of video and multiple measurement instruments aboard the ISS provide several methods to develop a truth sensor independently of the project.

**Repeatability & Reliability -** 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. 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 stability of the ISS, which operates in a fully controlled (or measured) environment helps the repeatability of tests. Scientists can safely reproduce initial conditions or make discrete changes with confidence that other states remain the same. Further, the ability to send supplies to the ISS and the availability of electrical power (as well as several basic gases) helps repeatability in cases where experiments have consumables

**Human Observability and Manipulation -** 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. 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.

**Support Extended Investigations -** The support of extended investigations does not refer to the ability to run individual tests for a long period of time. It means providing 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 to store 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. The ISS enables experiments to be stored for extended periods of times with less impact on the program than not utilizing a free flyer spacecraft.

**Risk Tolerant Environment** – This paper addresses the maturation of new technologies. This implies that the technologies are not yet mature, and therefore 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."[7]

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.

## 3.3. Supporting Multiple Investigators

The advancement of microgravity technologies to full operational level depends on the ability to demonstrate these in 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, 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.

To successfully enable collaborative research, the following points must be met:

- 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 endeavors
- 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.

The ISS program provides an environment highly beneficial to collaborations. First, it enables the development of multiple experiments to test individual areas which together form a complex technology (e.g., metrology, communications, and controls to demonstrate formation flight). In this manner, multiple scientists can work within the framework of the ISS program to develop individual technologies which together enable a space telescope program. Individual experiments aboard the ISS can also promote collaborative research by providing shared resources which are not a basic element of the ISS. For example, a project can provide a basic spacecraft bus system, while scientists can develop individual science-payload models for tests aboard the ISS.

## 3.4. Enabling Reconfiguration and Modularity

Reconfiguration and modularity affects the 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, which includes as a critical element the need to revise the hypothesis and implement changes to the design of the experiment for further iterations. 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[8] 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."

**Hardware Reconfiguration -** 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. The ISS provides multiple resources to benefit hardware reconfiguration. Astronauts can modify the hardware directly, without the need for complex automation tools. The ability to upload new parts to the ISS allows further modifications, even if they were not envisioned originally.

**Software Reconfiguration -** Software has become an important part in the implementation of algorithms. It 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. The availability of a direct data link to the ISS main computers, and the ability of experiments to connect to this network and access the files, enables software reconfiguration with minimal overhead for research scientists. A project can require an astronaut to manually update the software, or it could even be programmed to automatically fetch new files from the network (as long as NASA safety requirements are satisfied).

## 3.5. Support Remote Operations

Remote laboratories are based on remote locations because they offer a limited resource that researchers cannot obtain in their home locations. The design of remotely operated laboratories must account for the following facts about the operation:

- Operators
  - Are usually not experts in the specific field.
  - Are a limited resource.
- Research Scientists
  - Have little or no experience in the operational environment.
  - Are unable to modify the experiment in real-time.
  - Are usually an expert in the field but not in the development of facilities and testing environments.
  - May not have full knowledge of the facility design, especially when multiple scientists are invited to participate as part of a larger project.

The goal of a remote facility is to allow for a virtual presence of the research scientist in the operational environment. This includes the need for continuous communications between the operator and the research scientist, preferably in real-time. The availability of real-time two-way video is an important resource that benefits remote operations. In all cases, the use of high bandwidth communication systems, even if not real-time, should maximize the transfer of knowledge between the operator and researcher, especially when that is required to operate the facility successfully. In general the operator should have some idea of the expected results of each experiment in order to quickly transmit to the researcher information. In other words, the researcher should not solely depend on the communication of data, but also use the operator for feedback on the experiment.

Ultimately, the remote environment should allow a full virtual presence of the research scientist, where the operator becomes an extension of the scientist. Through its communications, astronaut availability and training, and benign environment the ISS provides research programs with the opportunity to enable a virtual presence of the scientist in space.

## 4.0 Experiment possibilities aboard the ISS

Experimental facilities which correctly utilize the resources of the ISS by enabling the features outlined above can conduct a wide range of experiments to demonstrate the maturity of new space technologies. This section outlines several types of these tests, those directly relevant to the MIT SSL concentration on the development of dynamics and control algorithms.

**Demonstration and Validation -** The ISS provides a microgravity environment with several resources (astronauts, communications, power) to ease in the demonstration of physical systems and provides substantial data and video collection.

**Repeatability and Reliability -** An experiments which successfully utilizes the ISS to enable iterative research and provides support of experiments would in turn demonstrate the repeatability and reliability of the technology. The ISS enables results to be obtained in the presence of the different disturbances and commands representative of those during a mission, therefore demonstrating the reliability of the algorithms.

**Determination of Simulation Accuracy -** The support of iterative research, which is benefited by multiple ISS resources, directly calls for the ability to create models (simulations) prior to tests for the deduction process. Therefore, correct utilization of the ISS inherently tests simulations and other analytical models 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 -** The risk tolerant environment which can be created aboard the ISS enables tests which can push new technologies and algorithms to their limits, until they fail. These tests enable scientists to identify most of the physical constraints of a system which may not be observable in a simulation or ground test.

**Operational Drivers** – Demonstration in a the space-relevant environment of the ISS allows scientistst to identify systems issues which are constraints to the technology. Issues such as sensor-actuator resolution, saturation, non-linearity, power consumption, roll-off dynamics, degradation, drift, and mounting techniques can be empirically determined and quantitative models created.

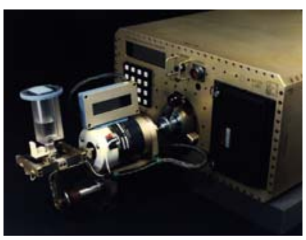
**Process Development** – The ISS enables scientists to carry varying portions of a mission during each tests. Initial tests can utilize only limited sub-systems; as tests progress incrementally, further parts of a mission can be simulated aboard the ISS to better understand the interactions of the different technologies at each step. Through experience scientists can refine system identification, refinement, and implementation processes to improve the development of new technologies.

## 5.0 Design Experiments of the MIT SSL

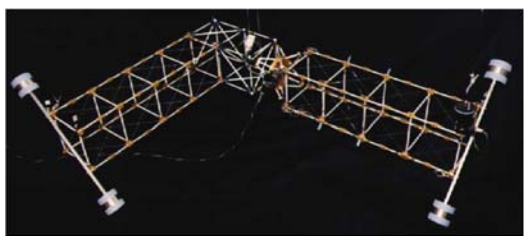
The MIT SSL has conducted microgravity experiments over the past two decades to demonstrate and validate dynamics and control algorithms and technologies for advanced spacecraft missions. While these experiments covered different areas of research (non-linear dynamics, fluid slosh, load sensors, robust control), each of them attempted to demonstrate each of these characteristics in the technology they tested. Each of these mission exhibited some aspects of the features proposed in this paper. The current mission, SPHERES, is expected to exhibit all the features presented above, once it operates aboard the ISS. The past experiments (pictured in Figure 2) 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.

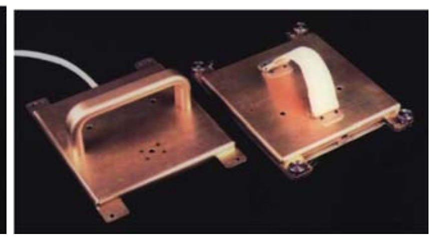
Table 2 presents a summary of the past MIT SSL microgravity experiments and the upcoming SPHERES program aboard the ISS. The table summarizes the mission and its areas of study. The table also shows the total cost of the mission and the time to flight. Re-flight opportunities clearly lowered both metrics. 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,



MODE



MODE



DLS

MACE

MACE-R

**Figure 2. Past MIT SSL Experiments**

MACE allowed algorithms to be selected and modified during the mission, allowing a larger number of areas of study to be investigated.

Table 3 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, 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.

**Table 2. Summary of MIT SSL microgravity experiments**

| **Experiment** | **Cost ($M)** | **Contract to Start to Flight (years)** | **On-Orbit Time (weeks)** | **Technology Research Area** |
|---|---|---|---|---|
| MODE | 2 | 3 | 1 | Microgravity fluid and structural dynamics tested on scaled test articles |
| MODE-R | 1 | 2 | 1.7 | Non-linear structural dynamics on truss structure |
| DLS | 0.75 | 1 | 40 | Crew-induced dynamic disturbance isolation |
| MACE | 4 | 3 | 2 | Advance control design on non-linear structure |
| MACE-R | 1 | 1.5 | 36 | Neural net, non-linear control design |
| SPHERES | 2.1 | 3 * | 40+ ** | Rendezvous and docking, satellite constellation ops. |

* not including STS downtime
** expected

**Table 3. Past MIT SSL experiments and their features**

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

Second, the table shows the goal of the SPHERES project, illustrated in Figure 3. The goals for SPHERES are to meet all the features: support experiments and provide enough flexibility to ensure that the iterative research process is facilitated and multiple guest investigators are supported. Table 4 presents the current lines of research which have been conducted with the SPHERES project. SPHERES has attracted multiple scientists, who have performed dozens of iterations in critical areas for formation flight and docking.

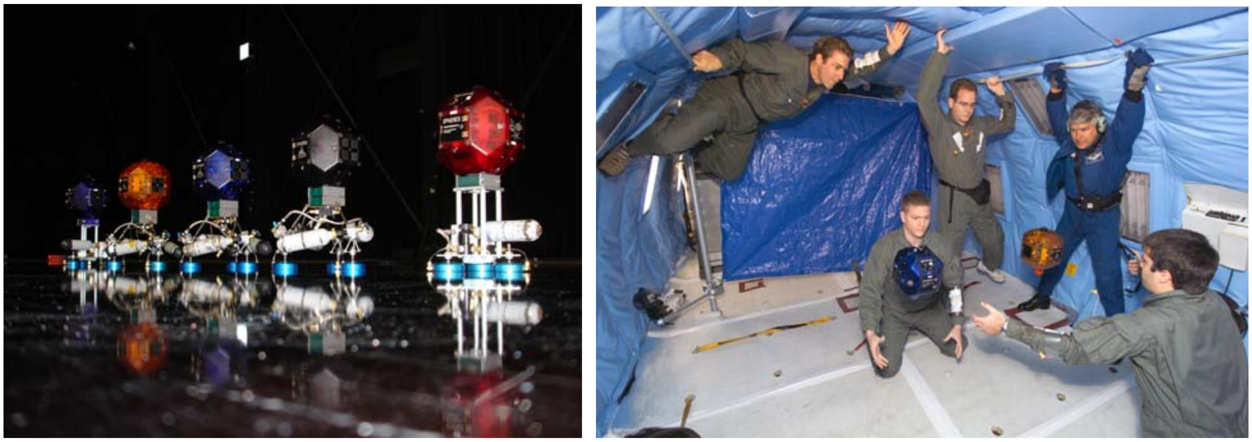


**Figure 3. SPHERES Operations at the MSFC Flat Floor and NASA RGA KC-135**

**Table 4. Current Results of the SPHERES Formation Flight Laboratory**

| Research | Year | Application | Guest Scientist |
|---|---|---|---|
| F.F. Communications | 2000 | DSS | |
| F.F. Control | 2000 | TPF | JPL |
| Docking Control | 2002 + | Orbital Express (DARPA) | |
| Mass ID / FDIR | 2003 + | Modeling | Ames |
| Tethers | 2003 + | SPECS | Goddard |
| MOSR | 2004 + | Mars Sample Return | |

## 6.0 Summary

Development of new space technologies remains a substantial challenge. Continuously scientists and engineers must trade-off between the use of proven but limited technologies and the use of new powerful yet risky tools. A major obstacle in enabling scientists to utilize new technologies are the steep increases in risk, complexity, and cost associated with maturing them through the NASA TRL's or similar measures. As a project requires testing in a *relevant* environment, that is, a space environment, many programs are unable to perform incremental tests due to the unavailability of easy access to such an environment.

The ISS, though, provides such an environment with multiple resources which can greatly benefit the maturation of new technologies. The availability of crew, communications, power, long-term experimentation, and possibility to create virtual presence of the scientist in space all can help reduce the steep jumps in risk, complexity, and cost normally associated with testing in a relevant environment. To successfully utilize the resources available aboard the ISS, the MIT SSL proposes that programs exhibit the following five features:

1. Facilitating the iterative research process –experiments must support the ability to modify the hypothesis on which they are based and can be reconfigured to incrementally test more complex theories.
2. Experiment Support –programs must provide the necessary precision and accuracy of data

acquisition, repeatability, reliability, and manipulation, while ensuring that long term operations are possible in a risk-tolerant environment.

3. Support multiple investigators – to ensure that a technology is demonstrated, programs must enable the necessary number of scientists to participate in the experimentation so that all areas of the technology are validated.
4. Enable reconfiguration and modularity – during the design of a facility, scientists and engineers should decide which parts of the experiment can be reconfigured in the future and identify those parts which represent general equipment which can be used as a platform for future experiments.
5. Support Remote Operations – all programs must ensure that the availability of astronauts and communications tends towards creating a virtual presence of the scientist in space.

By enabling these features in technology maturation programs, scientists can then conduct experiments to: demonstrate new technologies, ensure repeatability and reliability, determine simulation accuracy, identify performance limitations and operational drivers, and test process development.

The MIT SSL has conducted a wide range of experiments which exhibit a varying range of these features, to demonstrate the development of dynamics and control algorithms for spacecraft. These experiments include MODE (2 STS Flights), DLS (MIR), MACE (STS & ISS), and SPHERES (future ISS). The past experiments have demonstrated the ability to mature control algorithms in a space environment for microgravity fluid and spacecraft structural dynamics, astronaut interactions, truss structures, advanced non-linear controls, and neural network. By testing these technologies in a space relevant environment, these past tests meet the definition of a TRL5 at greatly reduced costs from other technology demonstrators. Even before flight SPHERES has demonstrated technologies in formation flight and docking. Once aboard the ISS, these tests can reach maturity to TRL6, while the costs remain significantly lower than any demonstration by free-flyer spacecraft.

## 7.0 References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