Appendix E

MIT SSL PREVIOUS MICROGRAVITY 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 MIT SSL Laboratory Design Philosophy presented in Chapter 3. The experiments utilized to reach the philosophy are:

- 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.

This appendix describes each family of experiments in further detail, with emphasis on the identification of the features of the MIT SSL Laboratory Design Philosophy.

E.1 MODE & MODE Re-Flight

MODE. The Middeck 0-Gravity Dynamics Experiment (MODE) flew as a facility for measuring the nonlinear dynamics of fluid slosh and jointed truss structures. Scaled deployable trusses of different geometries, developed by ABLE Engineering, were excited at different forcing levels to measure the amplitude-dependent shifts in frequencies and damping as compared to equivalent 1-g tests. McDonnell Douglas Astronautics collaborated with MIT on this part of the experiments.

The fluid slosh portion of the experiments were conducted to determine the predictability of nonlinear fluid slosh in 0-g, where surface tension provides the stiffness terms in the governing equations, based upon models and tests in 1-g where gravity provides the displacement-dependent restoring forces. Silicon oil and water, contained in different geometry tanks, were excited at different amplitudes. Both experiments calibrated the ability to predict 0-g nonlinear behavior from 1-g tests and analyses. [Miller, 1992] and [van Schoor, 1993] present the objectives and results of the MODE project.

The first laboratory attribute incorporated in MODE was the separation of test-specific hardware from generic infrastructure. The test-specific hardware consisted of the truss segments and the tanks that contained the silicon oil and water. Since the objectives of the tests required that these elements be tested in different configurations, the generic test equipment was placed in an Electronic Support Module (ESM in Figure E.1 with fluid tank and shaker attached). This included data storage media, the operator interface, power amplifiers used to drive actuators, sensor signal conditioning, power conditioning, and experiment control computers. The ESM was designed to fit into one standard mid-deck locker. The ESM design was versatile enough to not only test different truss and fluid tank geometries, but to also allow testing of other as yet unforeseen test-specific hardware on subsequent Shuttle flights.

Hardware reconfigurability was the second laboratory attribute built into MODE. The truss segments included two four-bay deployable segments, an erectable segment, and a rotary alpha joint with operator-selectable friction (Figure E.2). These segments were attached by the Shuttle crew in different combinations and geometries to allow tests on increasingly complex and nonlinear systems. Furthermore, a total of four fluid slosh tanks allowed two different fluids to be tested in tanks with flat and hemispherical bottoms. The ability of the crew to reconfigure the hardware was instrumental in enabling the test of a

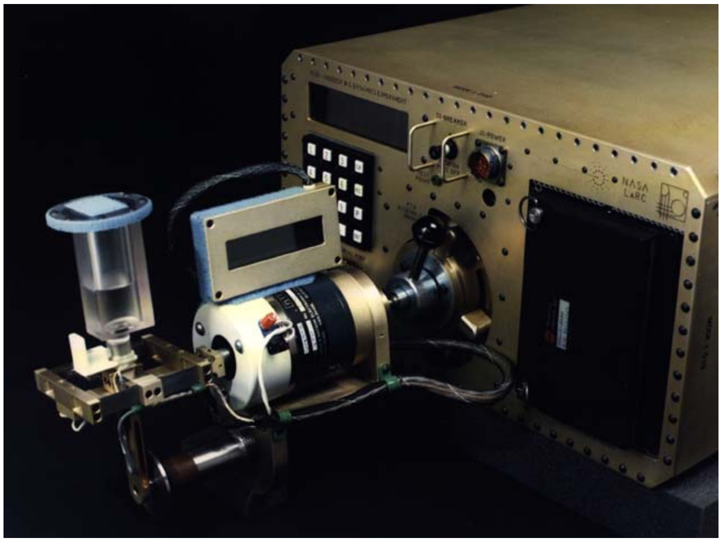

Figure E.1 MODE Experiment Support Module w/ Fluid Test Article

range of test articles that was much wider than can be tested in non-human rated on-orbit facilities. The crew facilitated the changes of test articles and reconfigured the Structural Test Article with Alpha joint without the need for costly automation equipment which would have been required to perfom these tasks remotely. Even with such equipment, it may not have been possible to develop the ESM in the modular fashion it was designed. Instead, the ESM would have been special equipment for a single automated mission.

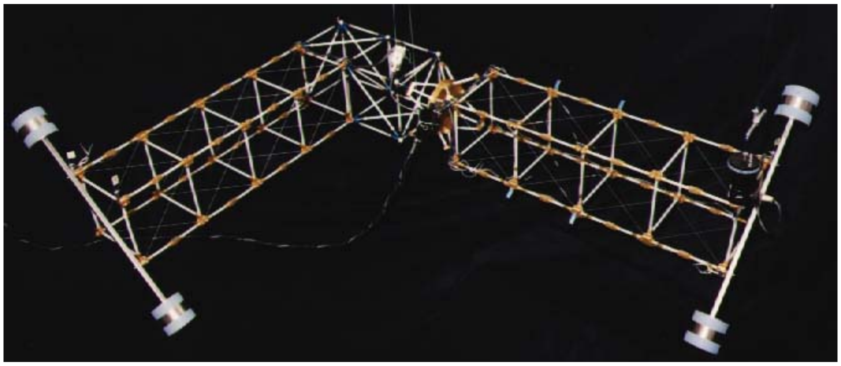

Figure E.2 MODE Structural Test Article with Alpha joint

MODE-re-flight. MODE-re-flight flew on STS-62 in March 1994 to perform additional truss structure tests and initiate the testing of the Dynamic Load Sensors (DLS, pictured in Figure E.3). DLS consisted of a hand hold, foot restraint, and push pad each instrumented to measure the forces and torques that a crew member imparts on the vehicle as they move through the Mid-deck using these devices. This provided a database for quantifying the loads that crew members would impart on the International Space Station (ISS).

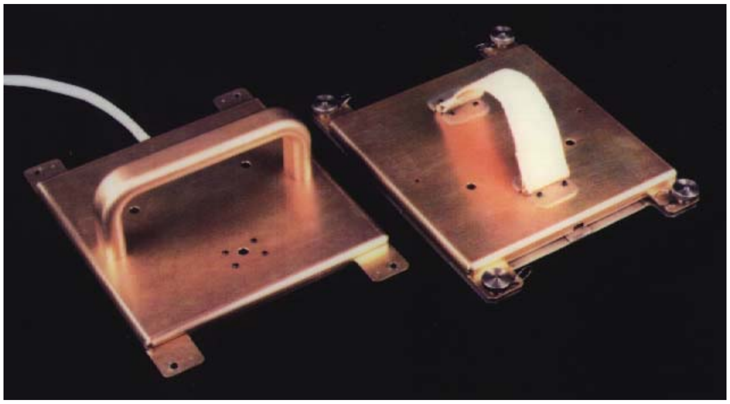

Figure E.3 DLS handhold and foot restraint

The generic versus specific nature of the MODE design was exploited in two ways during re-flight. First, the fact that the MODE hardware flown on the original flight was retrievable allowed it to be refurbished and reflown to support additional tests at a fraction of its original cost. Second, MODE-re-flight saw the introduction of a new series of test articles known as the Dynamic Load Sensors. Since only the DLS test articles, and not the entire test support equipment, needed to be built, the data collected on the DLS test articles was acquired very cost-effectively. The MODE design enabled reusability by containing the generic test equipment in the ESM.

E.2 DLS

The MODE ESM and DLS test articles re-flew on MIR for about three years as a part NASA's ISS Risk Mitigation program. Re-flight allowed a more extensive database to be acquired. This allowed crew motion force and torque statistics to be correlated with crew flight experience as well as with current time on orbit. By testing over weeks to months, rather than days on MODE-re-flight, crew adaptation time constants could be identified. [Amir, 1999], [Amir, 2000], and [Newman, 2001] present the methodology and results obtained over the 40 weeks of DLS operations aboard MIR.

DLS on MIR was the first introduction of extended duration testing in the MODE family of dynamics and controls laboratories. Extended duration testing allows long time constant dynamics to be identified (e.g., crew adaptation), many cycles of the iterative research process to be completed, and new test article configurations to be introduced (e.g., different crew members conducting maneuvers using DLS).

DLS on MIR was the MIT-SSL's first experience with space station operations. Shuttle science operations are typically characterized by the science team traveling to the NASA Johnson Space Center and assisting in the operation of the experiment while residing in one of the Customer Support Rooms. Essentially, the science team needs to travel to Houston and constantly be "on call" for the duration of the flight. This is an expensive process. For DLS on MIR, no such travel was conducted, and the crew and science team were given days to weeks, rather than minutes or hours, to work through test anomalies. This more relaxed operational environment allowed anomalies and their solutions to be analyzed more carefully. Unfortunately, the remote nature of the communication made it difficult for the science team to clearly understand the issues with the tests, particularly when the communication was by email and through several layers of flight operations.

E.3 MACE & MACE-re-flight

MACE. The Mid-deck Active Control Experiment (MACE) flew on STS-67 in March, 1995 to develop dynamics and controls tools for predicting as well as refining robust, multi-variable control algorithms on systems that cannot be realistically tested in 1-g due to gravity couplings. [Grocott, 1994], [Campbell, 1995], [Miller, 1996], and [How, 1997] present the methodologies used to develop and verify controllers during the mission. [Miller, 1998] and [Campbell, 1999] presents the results of the mission. [Miller, 1995] present the high-level design goals of MACE to build upon the design of the MODE family.

Figure E.4 shows the MACE multi-body platform test article being operated on the mid-deck of the Shuttle. The test article consisted of a reaction wheel triax attached to a flexible backbone over a meter and a half in length. A two axis motorized gimbal was attached at both ends of the backbone to perform pointing and slewing maneuvers. MACE consisted of twenty sensors, nine actuators, an ability for the crew to reconfigure its geometry into three different shapes, and a system for connecting the MACE ESM with the Shuttle's Ku-Band communication system.

The Ku-Band Interface System (KIS) gave the ability to downlink test results and uplink new control algorithms. Five times during the mission, the crew downlinked system identification and closed-loop test data, the science team refined dynamic models and control algorithms, and uplinked the new algorithms for test.

MACE continued the design philosophy developed under MODE by separating the test article from the generic laboratory equipment. Again, an ESM (Figure E.5) was built to house the generic equipment in a standard mid-deck locker. This ESM, however, included a high speed real-time computer, an interface for a laptop, and an interface for the Ku-band system. MACE also incorporated hardware reconfigurability in the test article design to maximize the science return.

Figure E.4 MACE operations on shuttle mid-deck

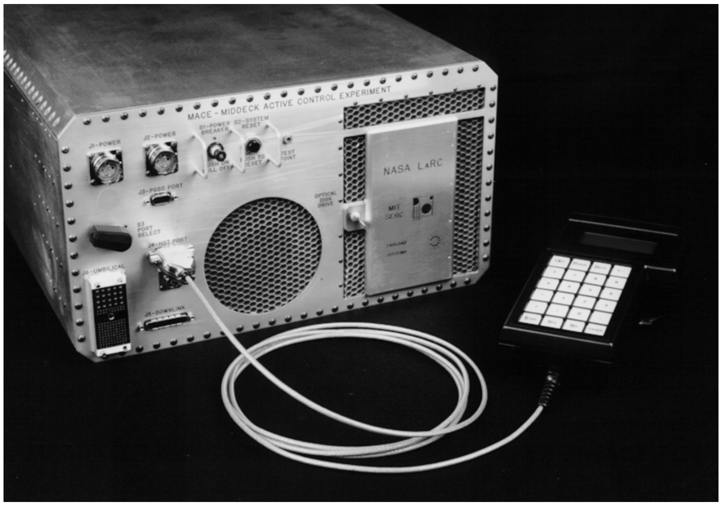

Figure E.5 MACE Experiment Support Module

MACE also introduced a number of important and advanced laboratory attributes. MACE was designed to be risk-tolerant. Unlike dynamics experiments, control experiments have the potential to result in unstable behavior leading to large amplitude motion. The team realized that since the technology being investigated was control and that the desire to explore the limits of control capability dramatically increased the probability that instability would occur, safety assurance through software was not an option. Instead, the MACE team took the approach of ensuring that instability could not break the hardware and that the crew member was provided with a switch that could immediately cut off power to the test article. These features allowed the boundaries of instability to be explored using a test article that was tolerant of the associated risk. Few if any other on-orbit systems could view unstable behavior as routine operation.

Unlike the MODE laboratory, MACE allowed the science team to change the software during the mission. Software reconfiguration gives the researcher many more degrees of freedom that can be manipulated to alter the conditions of the test. Software that performs dynamic characterization of the test article can be changed in order to investigate unforeseen phenomena in more detail. Control algorithms can be modified based upon models of the unforeseen phenomena. Sensor and actuator groupings can be changed to explore new disturbance and performance topologies. Furthermore, it allows experimental research into methodologies that facilitate on-orbit validation for precision space systems that cannot be accurately tested prior to launch.

The MACE design was the first in the MODE family to exploit human observation and manipulation of the test. Through training and on-orbit documentation, the crew developed the capability to identify, describe, and alter test conditions. In the event that the crew observed unexpected motion of the test article, they described the motion to the science team. A nomenclature was developed to allow the crew to describe the behavior. The crew was asked to estimate whether it exhibited broad or narrow-band frequency content, the frequency range in which the dominant motion occurred, and any directional preference in terms of an agreed upon coordinate system.

Since MACE verbal communications only occurred twice a day and data down-links occurred once a day, the crew then needed the ability to manipulate the test sequence if a clear instability or hardware failure was observed. The training and on-orbit documentation allowed the crew to maximize the number of successful algorithms tested between communication opportunities. To this end, the Flight Data File, used by the crew to guide them through experiment operations, contained families of algorithms. Each family corresponded to a specific geometric axis of motion, sensor-actuator suite, control design approach, and designation as to whether that family was a primary family or a backup. Each family consisted of six to eight algorithms or individual tests. Each succeeding algorithm would have slightly higher control gain.

Backup families would be tested if its corresponding primary family exhibited hardware problems (e.g., failed actuator or sensor). This allowed them to explore the same control features while isolating failed hardware from the control.

When a clear instability was observed during two successive tests within a family, the crew could ignore all remaining higher gain algorithms in that family. This allowed the crew to maximize science productivity.

The last important attribute introduced in MACE was the facilitation of the iterative research process. The science team used the verbal observations communicated by the crew to prepare a plan of attack for the next control redesign phase that would start after the next down-link of data. In addition, they would assist the crew in re-planning their next sequence of tests as well as selecting data files that should be down-linked during the next opportunity. Data down-links occurred once every one to two days. Dynamic characterization data was used to generate models and closed-loop response data was used to alter control parameters. During a single crew sleep period, the science team built models, developed new families of control algorithms, and wrote updates to the Flight Data File. The latter two were up-linked with the morning mail. The existence of the KIS interface for (up)down-link, crew observations and test sequence manipulation, and science team facilities were instrumental in shortening the research "question & answer" cycle time to one day.

One day cycle time was a little too short. The team basically had enough time to regurgitate algorithm refinements in response to features observed by the crew and in the data. Allowing several days to weeks to digest the downlinked test results and develop updates to algorithms would allow a more methodical approach to posing new research questions and putting test plans in place to address those questions. Clearly, this requires the laboratory to reside on orbit for longer periods of time.

MACE-re-flight. On MACE's second flight, it was launched to the International Space Station in September 2000. Operations started in December of that year with the arrival of the Expeditionary One Crew making MACE-re-flight the first crew-interactive experiment on ISS. Figure E.6 shows operations of the MACE article inside the ISS US Node. MACE-re-flight was a collaborative effort between the Air Force Research Laboratory (AFRL) and the MIT-SSL. Each brought with them a team of researchers studying dynamics and controls technologies ranging from neural networks to nonlinear dynamic characterization to adaptive reaction wheel isolation. Modifications for re-flight included an upgraded real-time control computer and operating system, upgraded data storage media, and meter long flexible appendages attached to the gimbal faces giving the test article an appearance of a free-floating, multi-link robot. MACE-re-flight returned to the ground in August 2001. [Blaurock, 1999] presents the modeling of MACE-re-flight prior to deployment, while [Yung, 2001] uses the results of the mission.

The laboratory attribute first featured in MACE-re-flight was opening the laboratory to multiple investigators. A number of government research agencies, industries, and academic institutions participated in MACE-re-flight. Unfortunately, due to the early stage of ISS assembly, data downlink and crew time were limited. This severely limited the iterative research process.

Figure E.6 MACE operations aboard the ISS