Control Testbeds and Flight Demonstrations: Transitioning Theory to Application

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Abstract

Over the past decade, the Space Engineering Research Center (SERC) and Space Systems Laboratory (SSL) at the Massachusetts Institute of Technology (MIT) have developed and operated numerous dynamics and controls testbeds and flight experiments in university laboratories, government facilities and Shuttle/MIR. These programs have been in support of multi-instrument pointing platforms, acoustic control, and space-based optical interferometry. Experiencing a diverse combination of experiments in a wide variety of environments and at many levels of technology maturity has given the SERC/SSL insights into the benefits and drawbacks of conducting such programs. This paper will elaborate upon the manner in which experimental objectives were developed, what lessons were learned in the design and operation of these experiments, as well as the experiences of how such experiments have changed the posture of the associated controls technology from the perspective of readiness for insertion into various applications.

1. Introduction

This paper addresses the issues of transitioning control research from the mind of the researcher to operational and commercial systems. Control research tends to be mathematically rich with experiment underemphasized. It is, however, only through validation on realistic physical systems that a technology can go from 'theoretical' to 'applied.' In physics, a theory is supported when it is verified experimentally, or rejected when it is experimentally shown incorrect. The same paradigm should apply to engineering research.

There are several key areas where control experimentation is crucial in the research and development cycle:

1. Demonstration and Validation: Demonstrating a research result on a physical system, in its operational environment, often provides the only acceptable information to a person who needs to make a go/no-go decision but who may not be fluent in the details of the technology.

2. Repeatability and Reliability: To develop the necessary heritage for critical applications, a control technology must demonstrate reliable and repeatable behavior in its interactions with other foreseeable subsystems. It must work more than once.

3. Determination of Simulation Accuracy: The results of control experiments can be compared with simulations, thereby providing credibility in control system simulation techniques and measuring the simulation accuracy.

4. Identification of Performance Limitations: Tests provide insights into, and prioritization of, the various physical constraints that limit a control system's performance.

5. Operational Drivers: Systems issues such as sensor-actuator resolution, saturation, nonlinearity, power consumption, roll-off dynamics, degradation, drift, and mounting techniques are most often constraints rather than design variables. Experiments uncover their inter-relations.

6. Investigation of New Physical Phenomena: New physical phenomena can be discovered and modeled through observation of physical systems. For example, the action of thermal snap as a disturbance source for a high precision spacecraft can be characterized through experiment [1].

There are many implementation issues that must be considered. Simulations only address issues that the control engineer remembers to consider. Implementation on hardware forces the engineer to prioritize issues in a way that may not be obvious a priori. Implementation and experiment is particularly important for the education of engineers, who may not appreciate the real-world limitations of the theory that they are taught.

This paper discusses the importance of experiments in controls research, and in the design of particular control systems for application. Common hardware issues will be outlined based on a sample control experiment. Lastly, a family of experimental control testbeds developed over the last decade at the MIT SERC/SSL will be presented, emphasizing the role of these experiments in control research.

2. Background and Notation

In general, compensators for the control of a physical system are designed with the use of a model. Modeling a real-world system presents a trade-off between the capture of the relevant features of the system and the complexity of the model. On one hand, the physics of a system can be represented with a finite element model (FEM). If the characteristics of the system are measured experimentally, then a measurement model can be fit to the acquired data. Hybrids of these two model types are common, with experimental data allowing parameter updates of the FEM.

The elements of a modern control system design are shown in Fig. 1. The design plant, G_T, is a model of the physical system, G. The uncertainty block, Δ, contains bounds on the uncertainty of G_T, bounding the error between the true system, G, and the design model, G_T. This error results from purposely neglected (unmodeled) dynamics, and from modeling inaccuracies in the frequencies and shapes of system modes. Often, complex systems are modeled with linear time-invariant (LTI) models and the uncertainty includes linear bounds on the effects of

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the neglected nonlinearities, and on the range of variation in a time-varying system. An important consideration is the determination of $\Delta$. Can a non-conservative bound on $\Delta$ be determined from the physics of the plant and from the specifications of the sensors and actuators? Can experimental measurements be used to reduce the ‘size’ of the uncertainty, reducing conservatism and increasing performance?

![Figure 1. Control System](image)

3. Control Experimentation

Through the implementation of control techniques on testbeds, the control engineer is exposed to hardware issues. Often, these hardware issues provide the fundamental limitations to performance. From an aerospace perspective, flight demonstrations provide the additional opportunity to test control techniques in an extreme/operational environment, and generate heritage.

3.1 The Role of Testbeds

The role of control testbeds can be roughly classified into five categories according to their research objective:

- **Educational**: An educational testbed provides a simple platform for demonstration of control concepts typically taught in an undergraduate curriculum. A common example is the inverted pendulum. The simplicity of such testbeds allows quick demonstrations of concepts, but limits their usefulness for traceability to complex real-world plants.

- **Investigation of unknown phenomena**: Testbed’s can be constructed for the observation of unknown phenomena such as microdynamics or other nonlinear phenomena.

- **Generic methodology development platforms**: These testbed’s provide an extension of educational testbeds, but tend to be considerably more complex. They provide realistic (suitably complex) platforms for the development and evaluation of modeling and control methodologies.

- **General capability calibration**: The goal of this type of testbed is to achieve a requirement, and to investigate the resulting implications of the necessary control techniques. JPL’s Micro-Precision Interferometer (MPI) testbed provides such an example. MPI has demonstrated that the stringent control requirement of the Space Interferometry Mission (SIM) can be met in a laboratory environment [2].

3.2 Hardware Issues

There is a set of common hardware issues that a control engineer must address before a controller can be implemented. Fig. 3 is a block diagram of the hardware for a typical control system. Due to its common occurrence in modern control applications, and its special hardware issues, a digital compensator is examined in this example. This section details common hardware implementation issues.

The system $G$ is controlled by a discrete compensator $K$, which is implemented on a computer (labeled as μP). The plant can be considered the components from the actuator inputs $u$ to the sensors $y$. The computer receives analog signals through a bank of analog to digital converters (A/D), and generates analog control signals through a bank of digital to analog converters (D/A). The sampling A/D requires the use of antialiasing filters, $F$.

![Figure 3. Control Experiment Hardware](image)
delay to be modeled with the required fidelity. If a measurement model is to be used, then delay can be included in the model by including the \( \mu P \) in the identification loop.

The quantization of the A/D and D/A provide fundamental limits to the resolution of the system sensors and actuators. For example, a sensor with a range of \( \pm 10 \text{ V} \) sampled with a 12 bit A/D, will be binned in \( 4 \text{ mV} \) quanta. That is, if 12 bit quantization is used then it is not economic to purchase sensors with resolutions better than \( 4 \text{ mV} \). Quantization often determines the fundamental noise floor. The resolution of actuators is treated in an identical way.

In an analogous fashion, quantization also provides a fundamental stroke/resolution trade. For example, if a force actuator is set up to have a 1 mN resolution then 12 bit quantization will limit the stroke to \( \pm 2 \text{ N} \). Improving the stroke or resolution requires higher resolution A/D and D/A converters or the use of multiple/staged actuators (sensors). For example a coarse actuator can be used for large stroke control, while a fine actuator is added to compensate for the coarse stage’s quantization error.

Quantization limits the dynamic range of the compensator. Quantization effects on the compensator, \( \hat{H}(z) \), are minimized if the full quantized range (i.e. \( \pm 10 \text{ V} \) in the example above) is utilized. It is useful for the system, \( G \), to include variable gains on each of the sensor and actuator channels. Gain can then be distributed around the loop allowing the compensator to fill the quantized range. Frequency dependent sensor and actuator gains can further refine this gain distribution, showing that physical considerations can influence the selection of the gains and frequency characteristics of the sensors and actuators.

The compensator can be represented in state space form as \( (A,B,C) \). This form is not unique and presents a trade between computational efficiency and numerical conditioning. For example, the matrix \( A \) can be tri-diagonalized, allowing sparse computation, whereas a numerically balanced realization tends to be fully populated.

High gain and unstable compensators can kick the system with strong startup transients. In fact, unstable compensators can be very difficult to implement in practice, a fact not easily recognized without experimental hardware.

Model inaccuracies and nonlinearities limit the performance of a physical system. Uncertainty bounds placed on a model should be based on the system to be controlled. These bounds can be measured with a careful identification of the plant.

4. MIT SERC/SSL Control Experiments

The MIT SERC/SSL has been very active in control experimentation during the last decade. A family of laboratory test articles and flight demonstrations have been developed. Figure 4 is a block diagram of the set of control experiments that will be discussed.

Each test article has been developed with specific research objectives, and the knowledge gained from each has influenced the design of subsequent testbeds. Fig. 4 shows the interconnections of the test articles. The combination of testbeds and the associated tools developed for each has provided the SERC/SSL with considerable experience in the area of experimental structural control.

**4.1 Multi-Point Alignment Testbed**

The MIT multi-point alignment testbed [5] was designed to investigate the precision control of optical elements on a lightweight structure. Experiments were performed on this laboratory test article from 1988-1996.

![Multi Point Alignment Testbed](image)

**Table 1:** Contains the elements of the multi-point alignment testbed for a control system using the notation of Fig. 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>Aluminum truss structure</td>
</tr>
<tr>
<td>z</td>
<td>Differential optical path (OPD)</td>
</tr>
<tr>
<td>w</td>
<td>Shakers simulating physical disturbances</td>
</tr>
<tr>
<td>y</td>
<td>OPD interferometer, accelerometers</td>
</tr>
<tr>
<td>u</td>
<td>Active struts, active isolators</td>
</tr>
</tbody>
</table>

Control research investigated on this test article are listed below. This list also includes the role, indicated with a letter in parentheses, of the testbed in the context of Section 3.1.

- Structural control to visible wavelength precision (d)
- MIMO precision control, adaptive control, robust control, isolation [6] (c)
- Sensor/actuator optimization and identification. Passive damping and system design (c)
- FEM modeling and model updating for control design (c)
• Microdynamics (b)

This testbed provided a platform for validation of modern control techniques on a complex flexible system, and provided experience with the implementation issues of Section 3.2. The testbed demonstrated that an FEM of the fidelity required for control was not possible to generate for this closed-topology, lattice structure. Instead, a measurement model methodology was developed consisting of Markov techniques combined with model reduction and logarithmic least squares fine tuning. The complexity of the test article demonstrated that minimal models are required for efficient control.

4.2 Middeck 0-Gravity Dynamics Experiment (MODE)

Though this experiment was not an active control experiment, it investigated the dynamics of a spacecraft-like truss structure in the 0-g environment. MODE [7] flew on the Shuttle during STS-48, in September 1991, and again on STS-62, in March 1994. Research is continuing on the MODE truss, with the investigation of disturbance phenomena like thermal snap and microdynamic behavior at nano-strain levels.

Figure 5: MODE

The control system elements of the MODE experiment are listed in Table 2.

Table 2: MODE Control System Elements

<table>
<thead>
<tr>
<th>Plant</th>
<th>Composite flexible struts</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>None</td>
</tr>
<tr>
<td>w</td>
<td>Shakers simulating physical disturbances, environment (thermal)</td>
</tr>
<tr>
<td>y</td>
<td>Accelerometers</td>
</tr>
<tr>
<td>u</td>
<td>None</td>
</tr>
</tbody>
</table>

Control research in the context of role (b) of section 3.2 has been conducted with the MODE truss as well as system identification research.

4.3 Middeck Active Control Experiment (MACE)

The objective of the MACE [8] program is to develop a set of methods and approaches for modeling and control of flexible structures that will increase the confidence of the designers of the \textit{in situ} performance of future spacecraft. MACE flew on the Shuttle during STS-67, March 1995, and has a planned reflight. Table 3 shows the control system elements for MACE.

Figure 6: MACE

Table 3 contains the control system elements of the MACE test article.

Table 3: MACE Control System Elements

<table>
<thead>
<tr>
<th>Plant</th>
<th>Composite flexible struts</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>Pointing</td>
</tr>
<tr>
<td>w</td>
<td>Gimble shaker, reaction wheel disturbances</td>
</tr>
<tr>
<td>y</td>
<td>Encoder positions, accelerometers, rate gyro, strain gauges</td>
</tr>
<tr>
<td>u</td>
<td>Gimbal motors, reaction wheels</td>
</tr>
</tbody>
</table>

Control research programs that are investigated with MACE include:

• Demonstration that active control can provide a two order of magnitude improvement in pointing jitter (c)
• MIMO precision control, adaptive control, robust control, isolation [9] (c)
• FEM modeling, including the prediction of the effect of environmental factors such as gravity (c)
• Control redesign with measurement models (c)
• Nonlinear control and modeling (c)

While not developing a new control technique, MACE did develop a synthesis and evaluation methodology exploiting optimal techniques (LQG) to identify robustness problems, desensitizing techniques (SWLQG) to identify key uncertainties, and bounding techniques to provide high performance robust control. The first flight of MACE demonstrated that the effects of gravity can be accounted for during control design. Further, for systems that are weakly nonlinear, the accurate fit of measurement models can be deceptive. The identification of a system should be conducted at signal levels expected during operation of the closed loop system. MACE provided valuable flight experience for modern $H_2$ and $H_{\infty}$ control techniques. Before these control techniques will be transferred to high-risk applications it is necessary that experiments like MACE build up a heritage.

4.4 Single Axis Interferometer Textbed

An interferometer testbed was developed in 1996 to investigate the optimal design of a controlled structure [10]. Though simpler than the multipoint alignment testbed, the single axis testbed includes an external reference which simulates the role...
of the science or guide stars of future space telescopes. This testbed fulfills role (c) from Section 3.1.

Figure 7: Single Axis Interferometer Testbed

The control system elements for the single axis interferometer testbed are:

Table 4: Single Axis Interferometer Testbed Control System Elements

<table>
<thead>
<tr>
<th>Plant</th>
<th>Aluminum truss structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>Optical Pathlength Difference (OPD)</td>
</tr>
<tr>
<td>w</td>
<td>Shaker simulating physical disturbance</td>
</tr>
<tr>
<td>y</td>
<td>OPD interferometer</td>
</tr>
<tr>
<td>u</td>
<td>Voice coil and piezo driven mirrors, active struts</td>
</tr>
</tbody>
</table>

Modern structural control was combined with classically designed optical control and structural optimization to achieve a three order of magnitude reduction in the measured OPD. The necessity for a well designed pole/zero structure in the plant and the usefulness of physical insight were demonstrated for high bandwidth control.

4.5 Origins Testbed

The Origins Testbed has a structural response traceable to planned space telescopes like SIM. This is the first spacecraft-like testbed to combine large angle slew control with fine phasing and pointing control in the presence of realistic disturbances. The test article was constructed in 1997 [11].

Control system elements of the Origins Testbed are found in the following table:

Table 5: Origins Testbed, Control System Elements

<table>
<thead>
<tr>
<th>Plant</th>
<th>z</th>
<th>w</th>
<th>y</th>
<th>u</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OPD, optical pointing</td>
<td>Reaction wheel disturbance, slew motion disturbance</td>
<td>OPD interferometer, angle encoder, CCD wavefront tilt, accelerometers</td>
<td>Voice coil and piezo driven mirrors, active struts, reaction wheels, FSM mirrors</td>
</tr>
</tbody>
</table>

The current and planned control research programs on the Origins Testbed include:

- Development of global MIMO controllers on a complex structure with many sensors and actuators (c)
- Develop vibration and isolation suppression schemes to meet SIM and Next Generation Space Telescope (NGST) performance specifications (c,d)
- Characterize microdynamics of an integrated structure (b)
- Develop techniques to properly scale a dynamic system (c)
- Investigate automation issues for complex optical systems (c)

Initial slew control experiments (linear and nonlinear controllers) have been conducted. Figure 3 is based on the control system set-up for this test article. Many of the hardware issues outlined in Section 3.2 have been encountered in the preliminary control experiments with this test article.

4.6 Active Acoustic Launch Load Alleviation (AALLA)

The objective of this program is the reduction of the acoustic loads on payloads during launch by controlling transmission and reflection of sound through the payload fairing. An experiment has been operational in the SSL since 1996 [12].

Figure 8: Origins Testbed

Figure 9: AALLA
The control system elements for the AALLA testbed are listed below:

<table>
<thead>
<tr>
<th>Plant</th>
<th>Steel acoustic chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>Acoustic level</td>
</tr>
<tr>
<td>w</td>
<td>Speakers simulating physical disturbances</td>
</tr>
<tr>
<td>y</td>
<td>Microphones and PVDF</td>
</tr>
<tr>
<td>u</td>
<td>Speakers and piezo</td>
</tr>
</tbody>
</table>

This testbed provides role (c) to the acoustic control program. Impedance matching and $H_2$ compensators have been run on the testbed. The testbed has demonstrated the challenge of acoustic control when no disturbance feedforward is allowed.

4.7 FLEX

Currently in development is a robotic testbed with the objective to demonstrate task level control on a scaled arm representing the Space Station Remote Manipulator System (SSRMS). FLEX will be operated on the station. The control system elements of FLEX are listed in Table 8.

![Figure 10: FLEX, Envisioned on International Space Station](image)

Control system elements for FLEX are found in Table 8.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Flexible robotic arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>End effector position and jitter</td>
</tr>
<tr>
<td>w</td>
<td>Environment</td>
</tr>
<tr>
<td>y</td>
<td>Joint angle encoders, CCD vision</td>
</tr>
<tr>
<td>u</td>
<td>Joint motors</td>
</tr>
</tbody>
</table>

5. Conclusion

Control experiments are fundamental for the advancement of control research. Experiments emphasize physical limitations and problems in the hardware that all control research ultimately needs to address. It is only through encountering these issues that a control engineer can appreciate the complications they bring to the controller design. The MIT SERC/SSL family of control experiments and flight demonstrations has advanced the field of practical control research by producing control techniques and graduates with the tools to implement control on real-world systems.

References


