Design and Operation of Micro-Gravity Dynamics and Controls Laboratories

Georgia Institute of Technology
Space Systems Engineering Conference
Atlanta, GA
GT-SSEC.F.4

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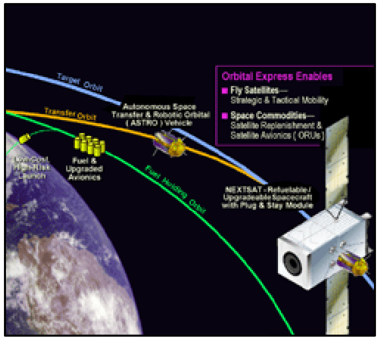
Motivation

- A large number of upcoming programs require the development of new space technologies
  - Advanced structural control
  - High precision staged optical control
  - Docking and rendezvous
  - Formation flight
  - Tethered flight
- How can one demonstrate the maturity of these technologies?
  - Is it possible to have demonstrations and validation of models prior to flight?
  - Where can one not only demonstrate, but also research these technologies?

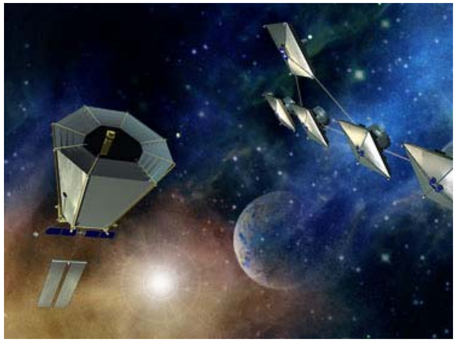
JPL

SIM

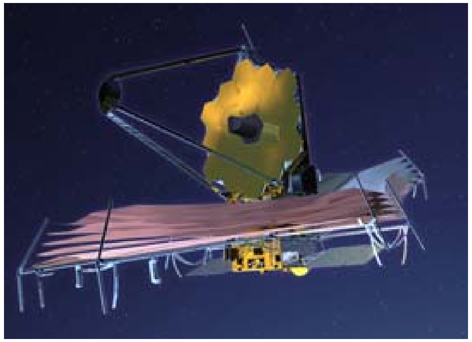


DARPA

Orbital Express


ESA

Darwin

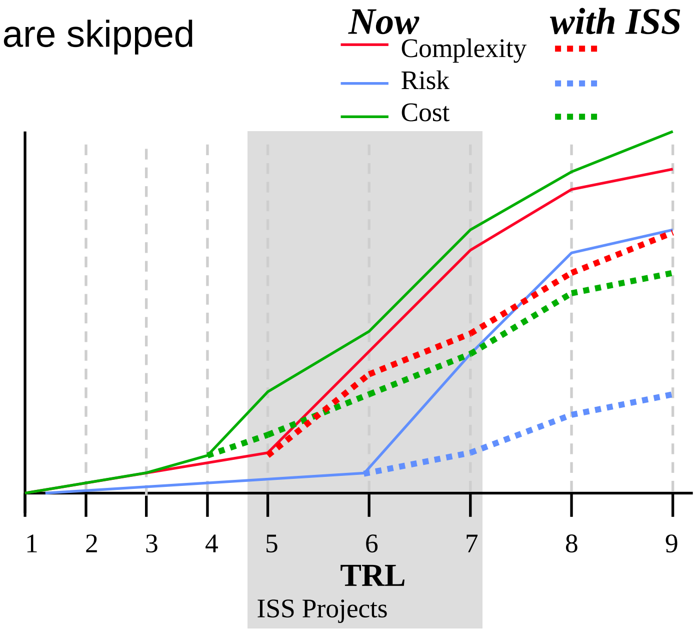

NASA

JWST

Introduction

- Space technology maturation is a challenging process
  - Complexity, risk, and cost increase substantially as a program progresses from ground-based research and development to space-based demonstrations
- NASA's Technology Readiness Levels (TRLs) provide a guideline to determine the state of development of a technology
  - Nine levels of readiness are defined
  - But the advancement between levels is not necessarily linear nor is it necessary to go through each level
  - Many times complex/expensive levels (e.g. TRL 7) are skipped

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



Can the ISS provide a research environment to advance smoothly through TRLs?

Special Resources of the ISS

- The International Space Station provides a wide range of existing resources to reduce the challenges of space technology maturation with no development costs of the scientists to utilize these resources
  - **Crew** - astronauts can control/oversee experiments reducing risk (lower probability of failure), as well as complexity and cost due to automation
  - **Communications** - scientists can download large amounts of data (including video) to account for remote operations without special communications equipment
  - **Long-term experimentation** - allows scientists to incrementally mature the technologies rather than depend on a single demonstration mission (reduced risk)
  - **Power sources** - reduces the safety concerns of power sources, and reduces the mass (and therefore cost) of the project
  - **Atmosphere** - allows the use of standard COTS equipment (reduced cost) without the need for special protections (reduced complexity) in a controlled environment (reduced risk)

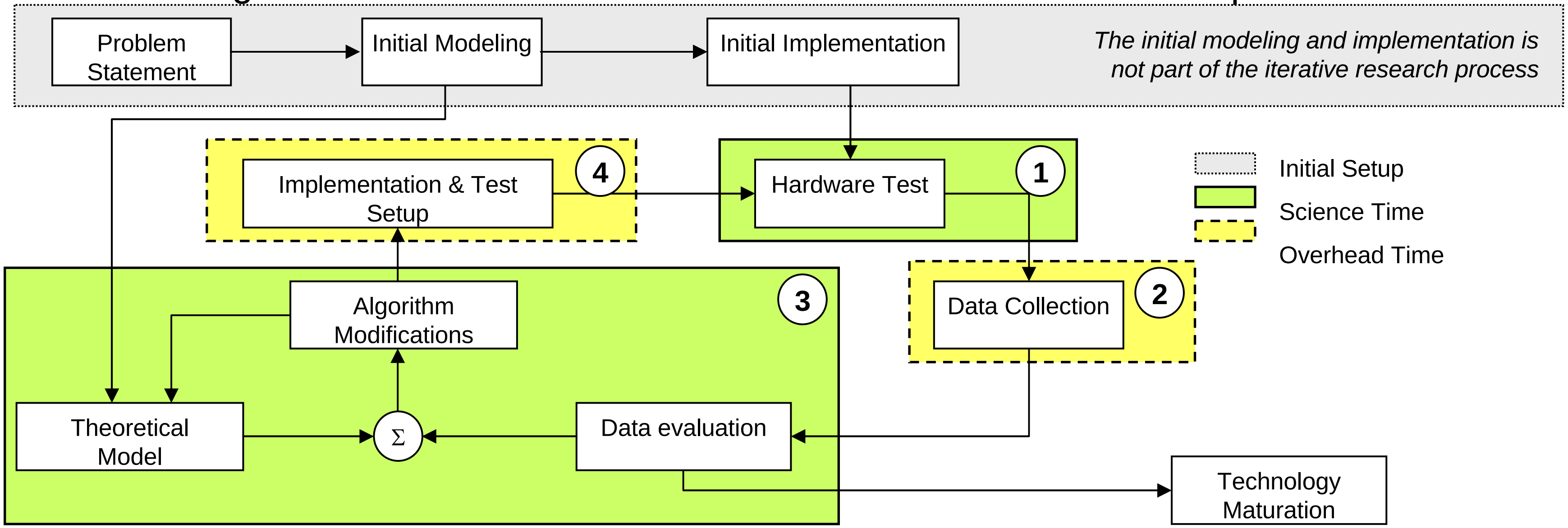
Resource	Risk	Complexity	Cost
Crew	↓	↓	↓
Communications			↓
Long-term experimentation	↓		
Power Sources	↓	↓	↓
Atmosphere	↓	↓	↓

Maturing Technologies aboard the ISS

- Develop new space technology demonstration programs following these guidelines:
  - 1) Facilitate the Iterative Research Process
  - 2) Provide support of experiments
  - 3) Support multiple investigators
  - 4) Enable reconfiguration and modularity
  - 5) Support Remote Operations

Facilitate the Iterative Research Process

- Program must support:
  - Repetitions of an experiment multiple times changing variables so that statistically relevant data is obtained
  - Changes to the hypothesis behind the experiment
  - Re-design of the experiment to account for these changes
- ISS
  - Crew, atmosphere
  - Communications
  - Long term exp., power



Four major steps which support the iterative process:

1. Test execution (science time: allow enough time)

2. Data collection and delivery to researcher (overhead time: minimize)

3. Data evaluation and algorithm modification by researcher (science time: allow enough time)

4. Modification to tests and new program upload (overhead time: minimize)

Provide Support of Experiments

- The facilities must provide:
  - **Data Collection and Validation** - enable collection of both visual and numerical data to support the experiment; enable validation of measurements
  - **Repeatability & Reliability** - allow repetition of experiments with ease; ensure reliability of the experimental apparatus to operate through multiple tests
  - **Human Observability and Manipulation** - enable humans to determine the progress of the test and reconfigure its operational environment
  - **Support Extended Investigations** - allow scientists the necessary time not only to collect data, but also to determine new configurations and/or tests to demonstrate the technology
  - **Risk Tolerant Environment** - allow scientists to develop tests which push the functional capabilities of the technologies, such that failures in the theory do not cause a mission-critical failure

- ISS
  - Communications
  - Crew, atmosphere, power
  - Crew
  - Long term exp.
  - Crew, atmosphere

Support Multiple Investigators

- The program must accomplish:
  - 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
  - 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.

- ISS
  - Crew, long term exp.
  - Communications
  - Communications, crew (inc. training), long term exp.

- *The ISS is an inherently cooperative environment*

Enable Reconfiguration and Modularity

- The program must:
  - Identify those aspects of the experiment that are generic in nature and allows its future use
  - Focus the modularity to ensure that the initial research goals are met
    - The original immediate research should not be compromised
  - Not try to design a "do-everything" system
  - Tend towards the development of modules which create a platform for future research
  - Enable Hardware reconfiguration
    - Allow controlled hardware changes for specific tests
  - Enable Software reconfiguration
    - Enable scientists to program different algorithms at multiple levels of control
    - *Ensure* software changes cannot cause a mission-critical failure
    - *Ensure* software is **not** part of the safety requirements for missions

- ISS
  - Crew
  - Communications

Support Remote Operations

- Consider the fact that remote operators perform the everyday experiments while research scientists, who do not have direct access to the hardware, are examining data and creating hypotheses and experiments for use with the facility

- Remote facilities are remote because they offer a limited resource that the researcher cannot obtain in their location

- Operators
  - are usually not an expert in the specific field
  - are an inherent part of the ‘feedback’ loop to provide researchers with results and information
  - are a limited resource

- Research Scientists
  - have little or no experience on the operational environment
  - are unable to modify the experiment in real-time
  - are usually an expert in the field but not in implementation
  - may not have direct contact with the facility

- Therefore the operations and interface of a remote facility must
  - Enable effective communications between operator and research scientist
  - Enable prediction of results
  - Ultimately: create a virtual presence of the scientist through the operator

Experiment Fields aboard the ISS

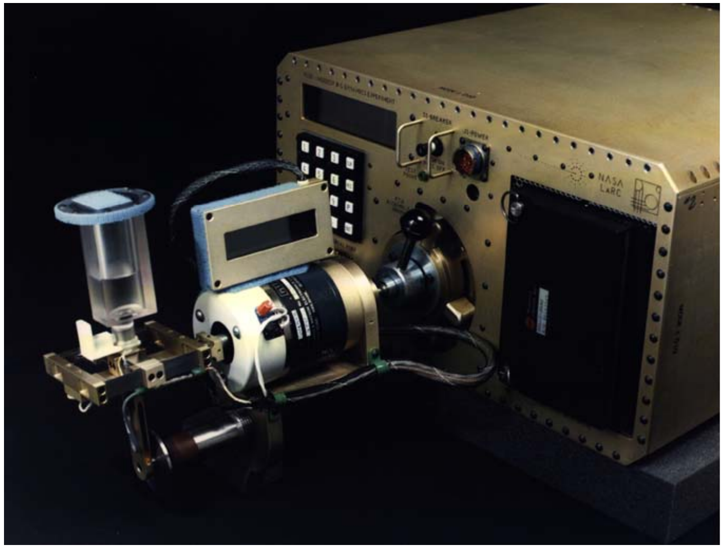
- In the area of dynamics and control, the ISS provides a beneficial environment to conduct the following experiments:
  - **Demonstration and Validation** - demonstration of physical systems with data and video collection.
  - **Repeatability and Reliability** - demonstration of the repeatability and reliability of the technology in the presence of different disturbances and commands.
  - **Determination of Simulation Accuracy** - comparison of ISS results with simulations to provide confidence in simulation techniques and accuracy.
  - **Identification of Performance Limitations** - risk tolerant environment enables tests which can push new technologies and algorithms to their limits.
  - **Operational Drivers** – identification of systems issues which are constraints to the technology.
  - **Process Development** – refinement of system identification and implementation processes to improve the development of new technologies.

Space Technology Programs of the MIT SSL

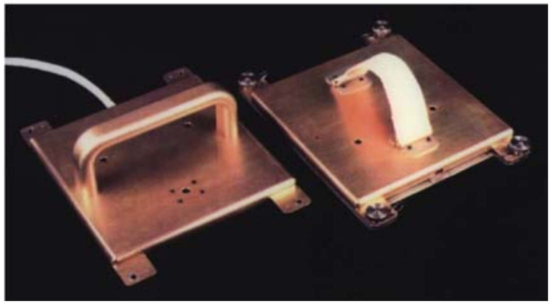
	Acronym	Flight	Date	Technology
Middeck 0-g Dynamics Experiment	MODE	STS-48	Sep ‘91	Microgravity fluid and structural dynamics tested on scaled test articles
Middeck 0-g Dynamics Experiment Reflight	MODE-R	STS-62	Mar ‘94	Non-linear structural dynamics on truss structure
Dynamic Load Sensors	DLS	MIR	‘98-‘99	Crew-induced dynamic disturbance isolation
Middeck Active Control Experiment	MACE	STS-67	Mar ‘95	Advance control design on non-linear structure
Middeck Active Control Experiment Reflight	MACE-R	ISS	Sep ‘00	Neural net, non-linear control design
Synchronized Position, Hold, Engage, Reorient Experimental Satellites	SPHERES	ISS (STS-121)	‘05/’06	Rendezvous and docking, satellite constellation ops.

MODE & DLS

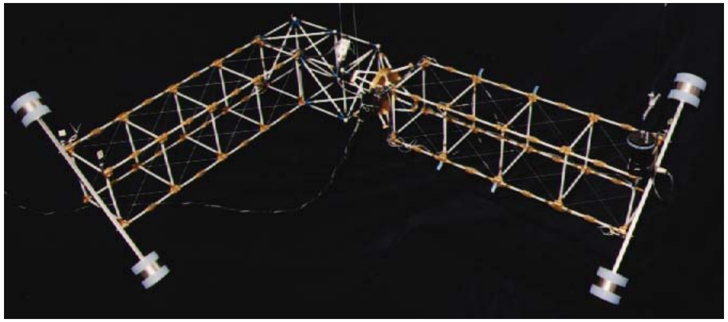
- MODE- STS-48 & 62
  - Support of experiments
    - Data collection, repeatability
  - Hardware reconfiguration
    - Development of the ESM and several test articles
    - Individual test articles support hardware changes
- DLS - MIR
  - Support of experiments
  - Hardware reconfiguration
    - Re-uses MODE ESM
  - Long-term experimentation
    - Enabled scientists to collect different types of data based on analysis throughout the program



MODE Experiment Support Module (ESM) & Fluid Test Article (FTA)



DLS Sensors



MODE Structural Test Article (STA)

MACE

- MACE: STS-67
  - Enabled iterative research
  - Direct human observation and manipulation: enabled human feedback
  - Risk tolerant environment
  - HW and SW reconfiguration

MACE aboard STS-67

MACE Re-flight aboard the ISS

- MACE Re-flight - ISS
  - Enabled extended investigations aboard the ISS
  - Supported multiple investigators from MIT SSL and AFRL
  - A hardware malfunction prevented iterative research, but successful reconfiguration of hardware and software allowed multiple research areas

SPHERES

- SPHERES - ISS (manifested on STS-121 & 116)
  - Intended to satisfy all of the guidelines
  - Enable iterative research by allowing scientists to review their data and upload new algorithms
  - Support experiments through all features: data collection, repeatability and reliability, fully human observable and controlled, risk tolerant environment
  - Supports multiple scientists through both programmatic planning and modular software development
  - Enables software reconfiguration and hardware changes both with and without new deliveries to the ISS

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	

SPHERES flight hardware validation

Results Summary

	Cost	Time to Flight (years)	Orbit Time (weeks)	Data Collection	Repeat. / Reliab.	Iterative Process	Human Obs./Man.	End-to-End	Extended Invest.	Risk Tolerant	HW reconfig.	SW reconfig	Multiple Invest.
MODE	$2M	3	1	✓	✓						✓		
MODE Reflight	$1M	2	1.7	✓	✓						✓		
DLS	$0.75 M	1	40	✓	✓				✓				
MACE	$4M	3	2	✓	✓	✓	✓			✓	✓	✓	
MACE Reflight	$1M	1.5	36	✓	✓				✓	✓	✓	✓	✓
SPHERES*	$2.1M	3	40+	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

* SPHERES Time-to-flight does not include shuttle down time; estimated on-orbit time

Conclusions

- The International Space Stations provides a wide range of existing resources which help reduce the challenges of space technology demonstration without adding costs to the mission
  - The ISS provides crew, communications, power, an atmosphere and long-term experimentation facilities
  - New programs to demonstrate space technologies aboard the ISS should utilize those resources correctly so as to:
    - Facilitate the Iterative Research Process
    - Provide support of experiments
    - Support multiple investigators
    - Enable reconfiguration and modularity
    - Support remote operations
- The MIT Space Systems Laboratory has demonstrated the use of space-based facilities (STS, Mir, and ISS) to accomplish technology maturation at relatively low costs
  - Previous projects demonstrate technologies to TRL 4/5
  - SPHERES is expected to demonstrate TRL 6
  - All programs are under $5M