

Sloshing Platform for In-orbit Controller Experimentation (**SPICEsat**)

Low-G Slosh Workshop 2026

June 11, 2026

Laurent Burlion

Michael Fogel & Devan Kapur



Background



1/2019-present, Faculty at Rutgers

9/2017-8/2018, Visiting Researcher at the University of Michigan

4/2010-12/2018, Research Scientist at Onera, the French Aerospace Lab, Toulouse, FR



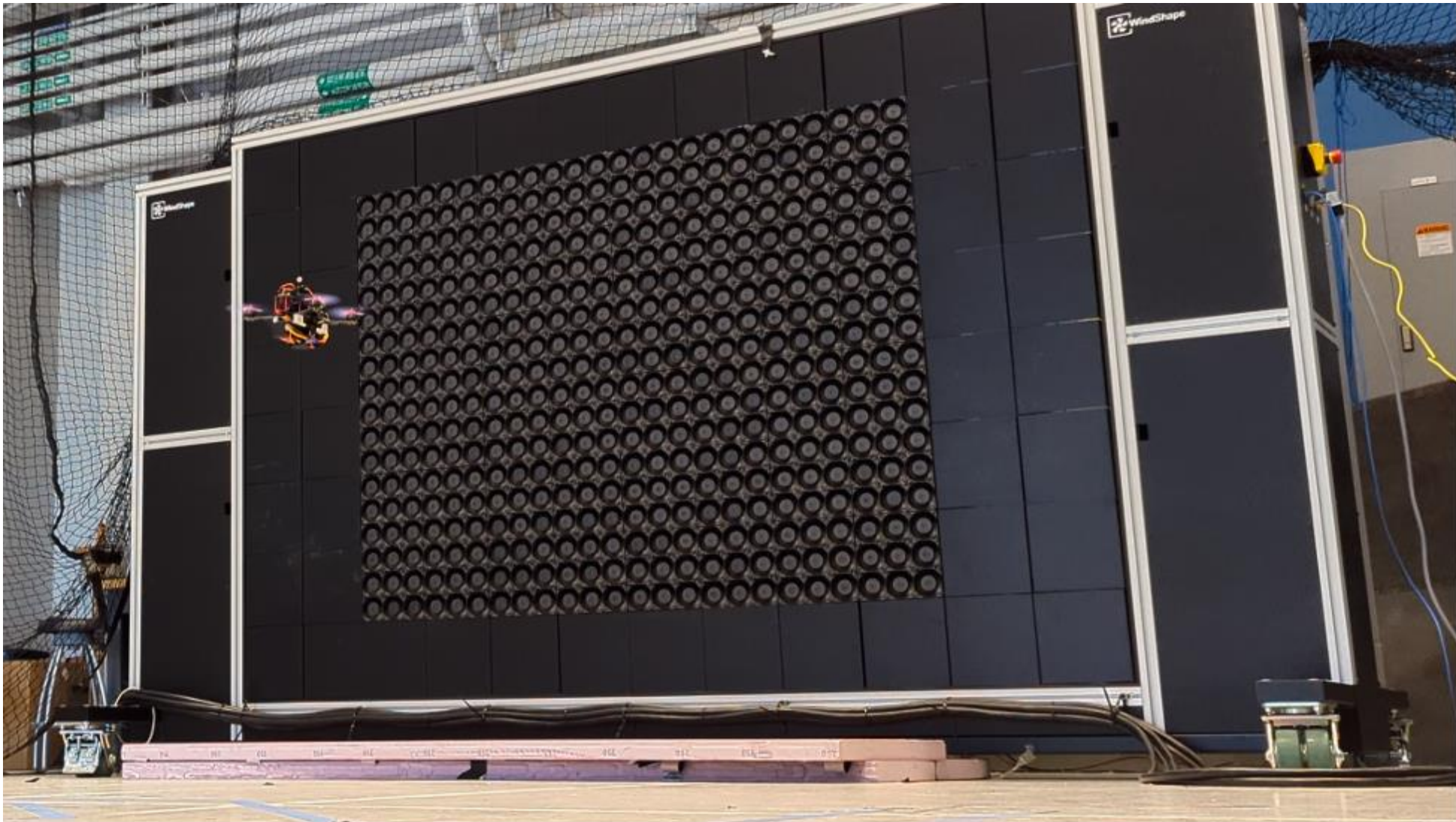
Toulouse, FR, the center of the European aerospace industry





Research Topic

R
ENGINEERING





Acknowledgement



Collaborators:



J-M. Biannic
M. Cassaro

Anthony Bourdelle (ONERA, Ph.D, Toulouse, 2021)

- LPV Modelling
- Observer design
- Anti-windup and Reference Governor designs

Guido Magnani (ONERA, Ph.D, Toulouse, 2024)

- H_∞ Controller + Multi-Model Reference Governor
- MRAC + Adaptive Reference Governor

Manav Jadeja (Rutgers, M.S 2024)

- Closed-loop CFD simulator (then joined SpaceX)

Tamar Leiser (Rutgers, M.S 2025)

- Hexapod-enabled Investigation of Sloshing

Ashish Kumar Shakya (IIT Roorkee, Visitor, summer 2024)

- Spill-Free Liquid Container Control

Mike Fogel (Rutgers, Ph.D. in progress)

- Machine learning controller (M.S, 2022)
- CFD closed-loop simulation studies (Flow3d, STARCCM)
- Cubesat Payload development

Devan Kapur (Rutgers M.Eng in progress)

- Satellite manipulator
- Closed-loop CFD simulator (OpenFoam)



C. Pittet
E. Evain
J. Mignot



Presentation Overview

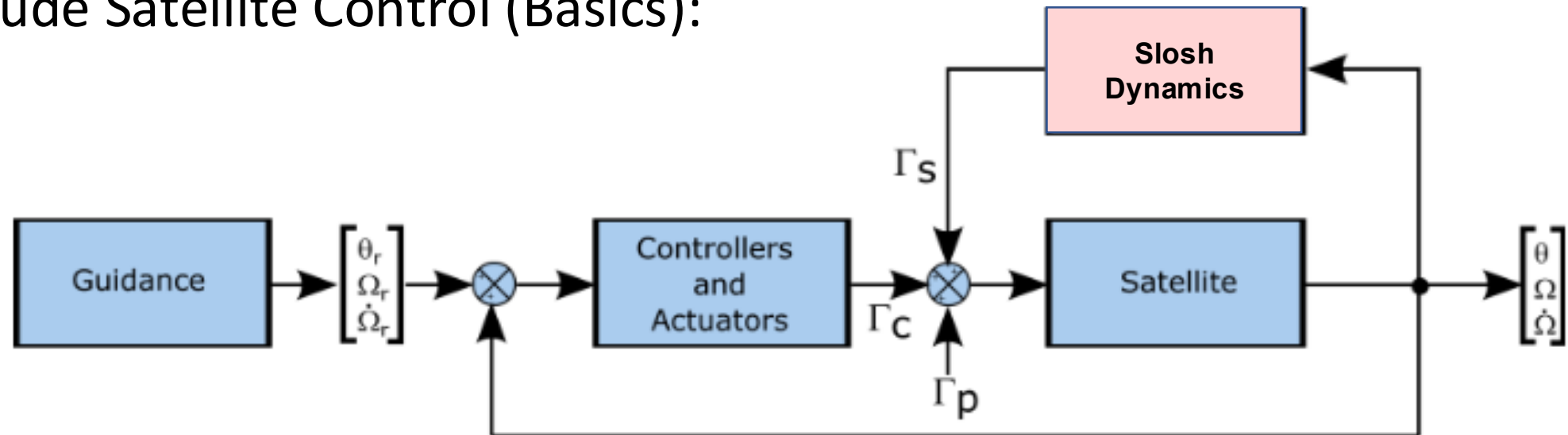


1. Motivation: Research in Control
2. Application: The SPICEsat mission
 - Expected outcomes
 - Design and feasibility analysis using CFD
3. Next Steps



1- Motivation: Research in Control

Attitude Satellite Control (Basics):



θ Angular position

Ω Angular velocity

$\dot{\Omega}$ Angular acceleration

θ_r Desired reference angular position

Ω_r Desired reference angular velocity

$\dot{\Omega}_r$ Desired reference angular accel

Γ_c Input control torque

Γ_s Sloshing torque

Γ_p Other perturbing torques



Problem Statement



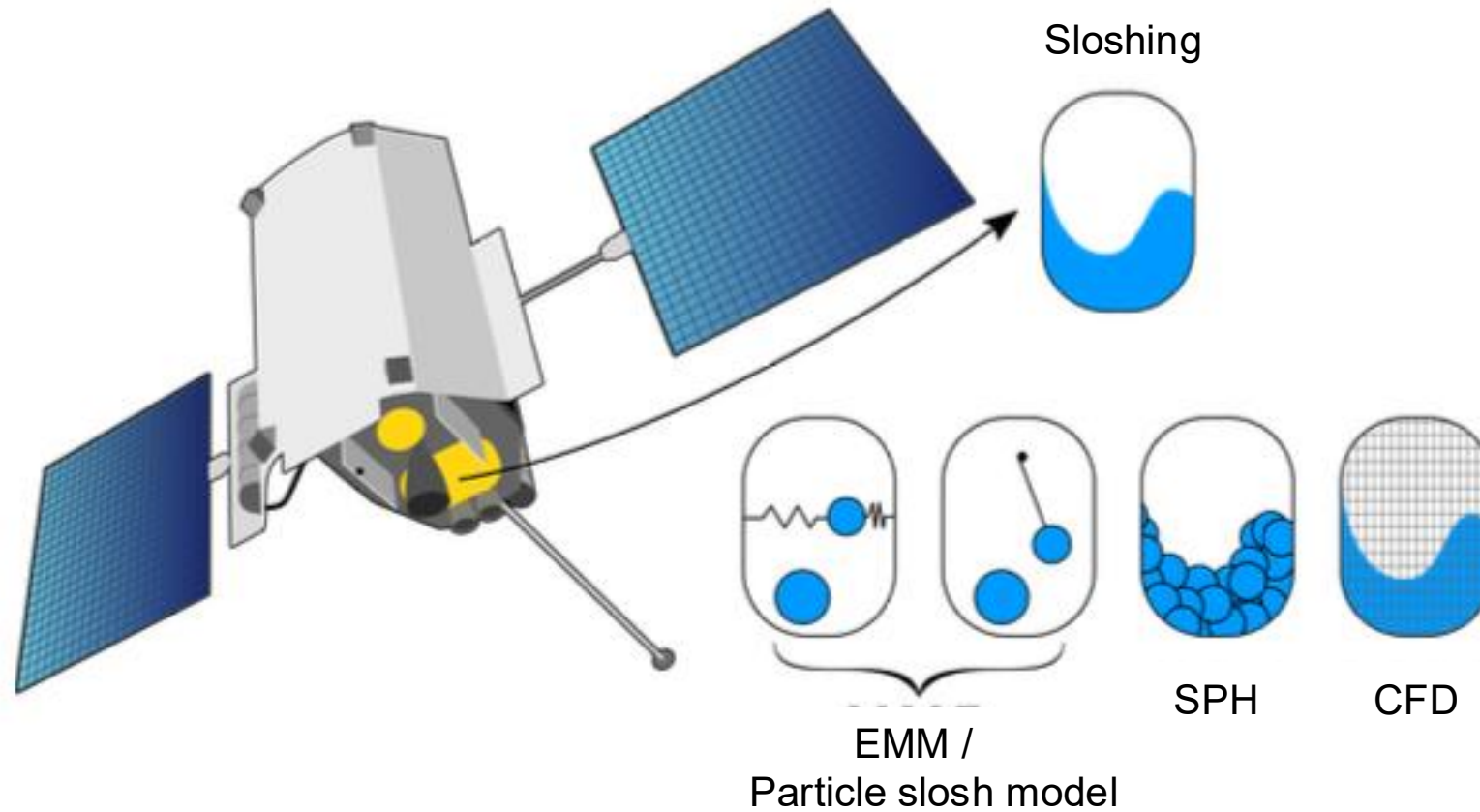
Required Attitude Control Performances (Demeter benchmark)

- Pointing steady-state error ≤ 0.04 deg
- Pointing rate steady-state error ≤ 0.1 deg/s
- Control torque error ≤ 0.007 Nm (saturation)
- Angular momentum ≤ 0.1 Nms (saturation)

C. Pittet, D. Arzelier, “*DEMETER: A Benchmark For Robust Analysis and Control of the Attitude of Flexible Micro Satellites*,” IFAC Rocond, 2006.

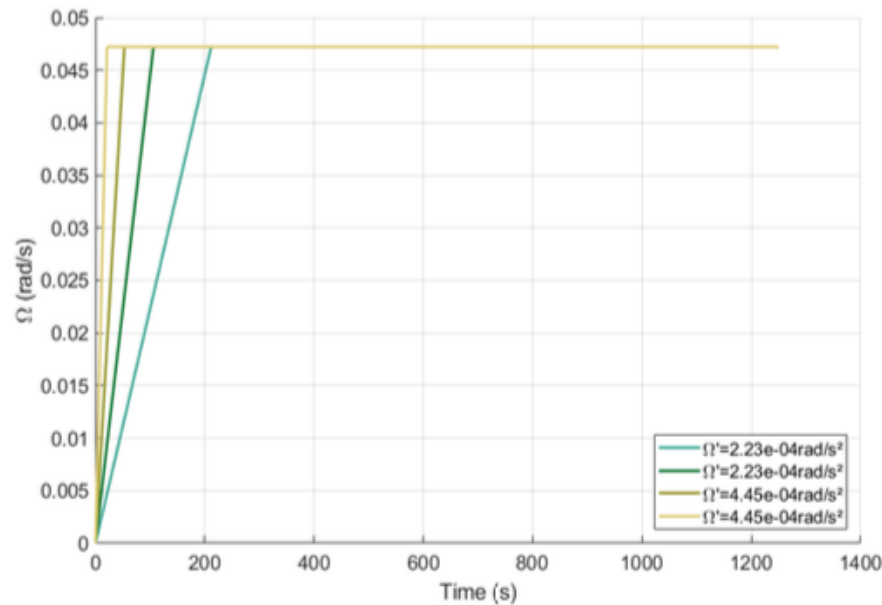


Slosh Dynamics Modeling

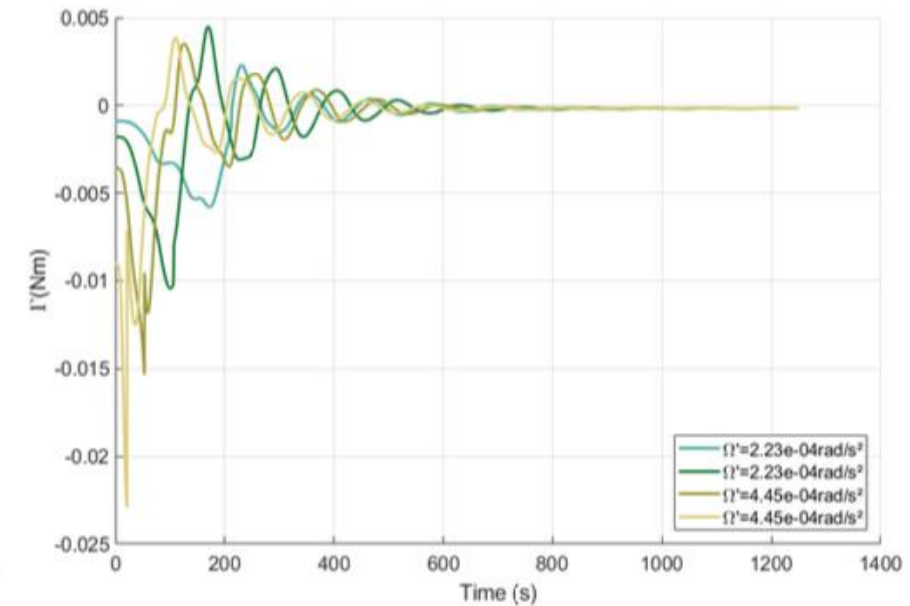




Uncertain LPV Model



(a) Tank enforced angular velocity



(b) Torque Γ_Z along the Z-axis

$$\ddot{\Gamma}_s = -\alpha_c(\Omega, \dot{\Omega})\dot{\Gamma}_s - \alpha_K(\Omega, \dot{\Omega})\Gamma_s - \alpha_a(\Omega, \dot{\Omega})\Omega - \alpha_b(\Omega, \dot{\Omega})\dot{\Omega}$$

A. Bourdelle, et al. "Towards New Controller Design Oriented Models of Propellant Sloshing in Observation Spacecraft," *AIAA Scitech 2019 Forum*.

A. Bourdelle, et al, "Modeling and Control of Propellant SLOSH Dynamics in Observation Spacecraft with Actuator Saturations," *EUCASS 2019*, best student paper award.



Approaches to Sloshing Control



Controller Designs for sloshing compensation (in collaboration with ONERA):

1. Simple compensation: measure the sloshing torque and apply a compensating torque.

When you cannot directly measure it:

- Design a LPV/LTV Observer (or a neural network)

A. Bourdelle, et al., "Propellant Sloshing Torque H_∞ – based Observer Design for Enhanced Attitude Control," IFAC LPVS, 2019.

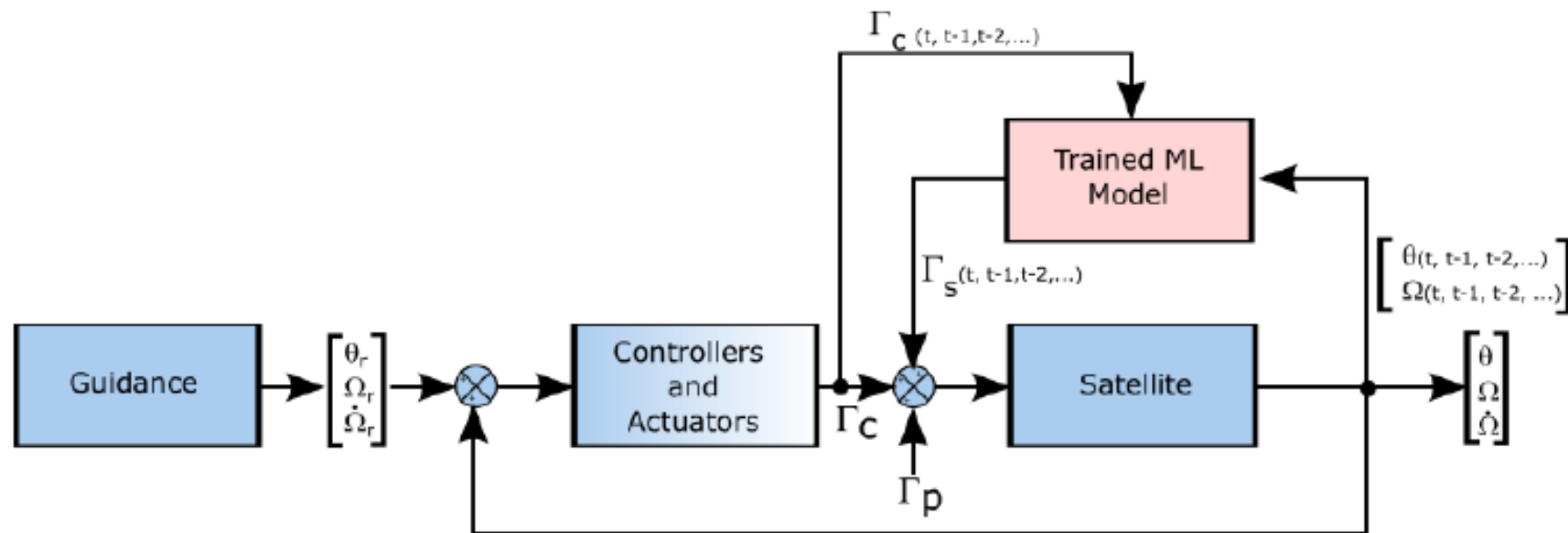
- Use a Model Reference Adaptive Control:

M. Cassaro, J. -M. Biannic and H. Evain, "Adaptive Minimal Control Synthesis for Satellite Attitude Control in Presence of Propellant Sloshing and Flexible Appendices," ECC, 2022.

2. Advanced control methods: synthesize a Structured H_∞ controller

G. Magnani et al., "Reference Governor Based Solution for Satellite Attitude Control in Presence of Multiple Disturbances and Actuator Saturations," EUCASS, 2022.

- Machine Learning controller can be treated as a true “Black Box”
 - Neural Network model trained using satellite data and used as a “Black Box”
 - Train on data downloaded from satellite
 - Upload new training algorithm
 - Impart same reference and measure for reduced slosh mitigation

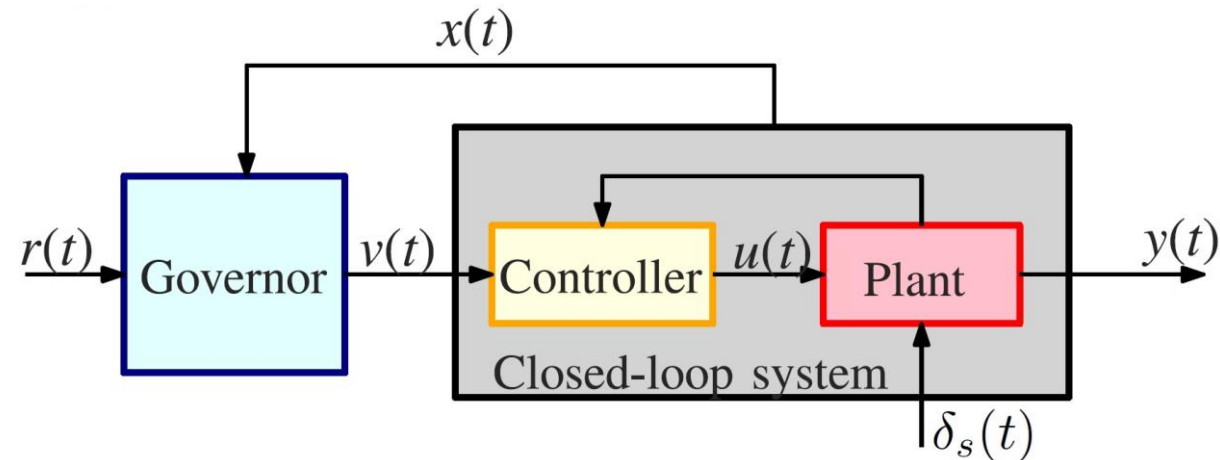




Note that if you exactly compensate Γ_s then the planned attitude maneuver is executed as if sloshing were absent.

However, this performance is ultimately restricted by the system's torque and momentum saturation limits, as well as the need to avoid forbidden orientations.

(See e.g. [M.M. Nicotra, D. Liao-McPherson, L. Burlion and I.V. Kolmanovsky, "Spacecraft Attitude Control with Nonconvex Constraints: An Explicit Reference Governor Approach," IEEE TAC, vol 65\(8\), 2020.](#))



E. Garone et al. / Automatica 75 (2017)

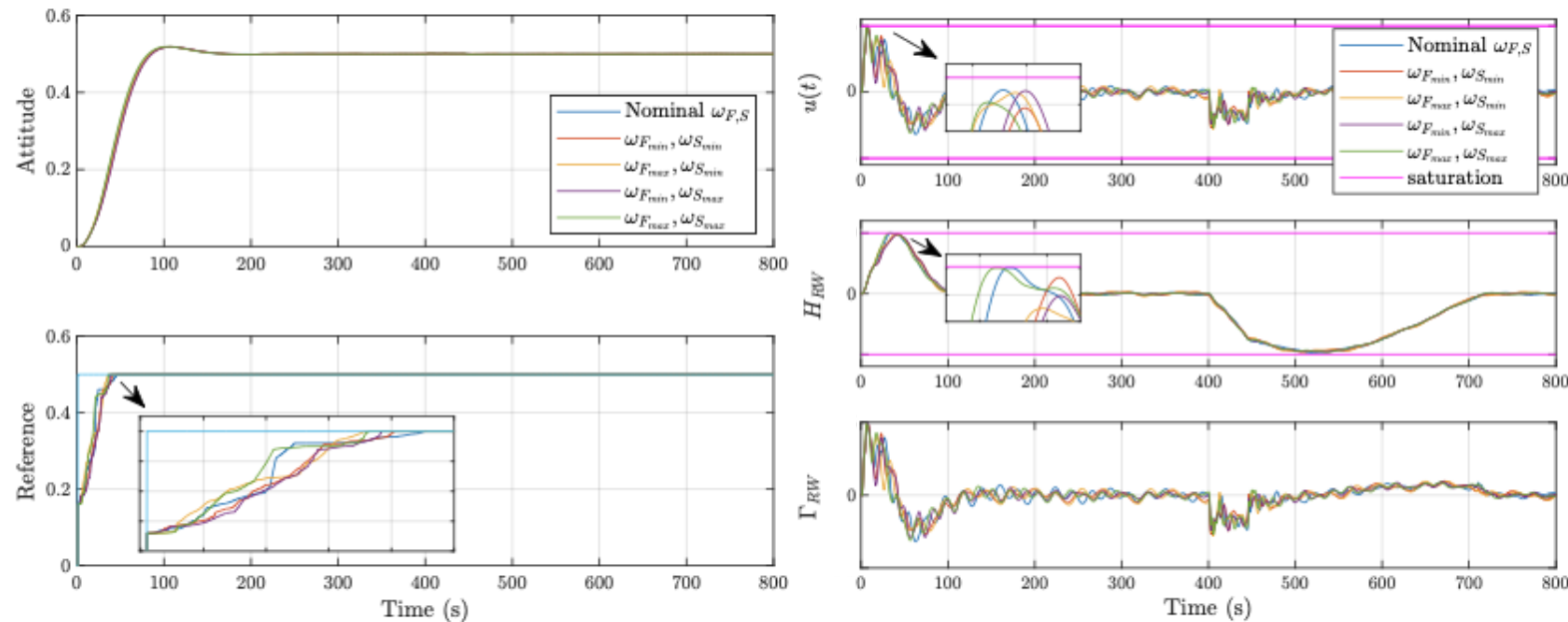
1. Augment rather than replace an existing nominal controller.
2. Inactive if no danger of constraint violation.
3. 'Easy' to implement / Fast online computations.
4. Special properties.

But a few challenges, e.g nonlinearities, uncertain parameters

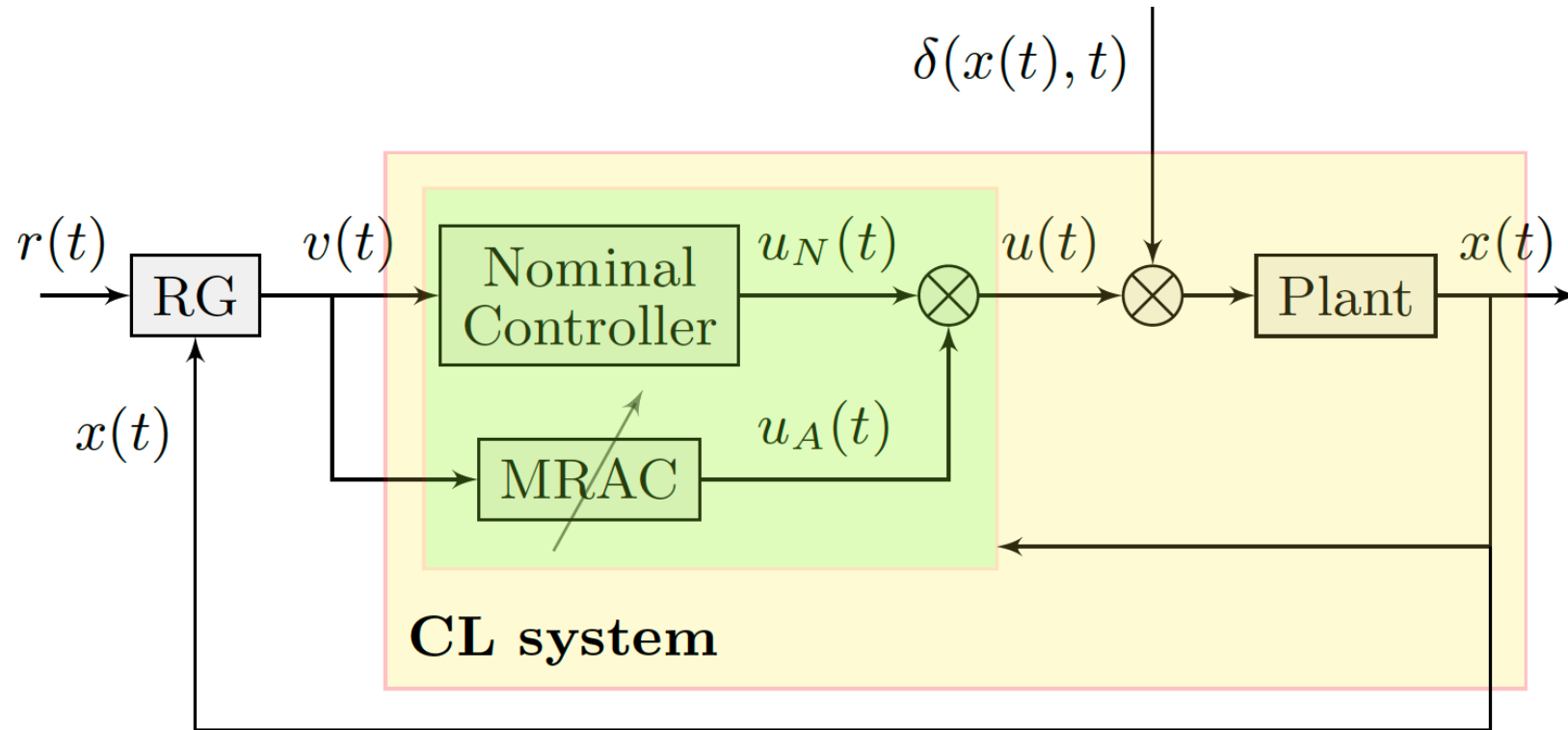


Extension#1: Multi-Model Reference Governor

1. A dynamic controller $K(s)$ was designed to minimize the attitude error in presence of disturbances and actuator delay
2. A multi-model reference governor was added to avoid the system control loss and enlarge the set of reachable angles in presence of sloshing/flexible modes variations



G. Magnani et al., "Reference Governor Based Solution for Satellite Attitude Control in Presence of Multiple Disturbances and Actuator Saturations," EUCASS, 2022



- G. Magnani, et al., "Command governor-based adaptive control for constrained linear systems in presence of unmodelled dynamics", American Control Conference, 2023.
- G. Magnani, et al., "Quadrotor Fault-Tolerant Control Using Model Reference Adaptive Control and Adaptive Reference Governor", IEEE TAES, vol. 61, 2025.
- G. Magnani, et al., "Slosh attenuation via Reference Governor-based adaptive control for space operations under actuators constraints", IFAC Journal of Systems and Control, vol. 33, 2025.



Model vs Method Overview

Method Model	Baseline	Adaptive	Machine Learning	RG	Combination
LTI	★	★	★	★	★
Nonlinear/LTV	★	★	★	★	★
CFD/RGBD	★	—	—	★	—
Real satellite	—	—	—	—	—



2- Application: the SPICESat Mission



- What is SPICESat ?
 - A project to develop Rutgers University's first Cube Satellite
 - A project that applies advanced control methods to a challenging control problem
 - Undergraduate student proposed, led, and implemented by the Space Technology Association at Rutgers (STAR)

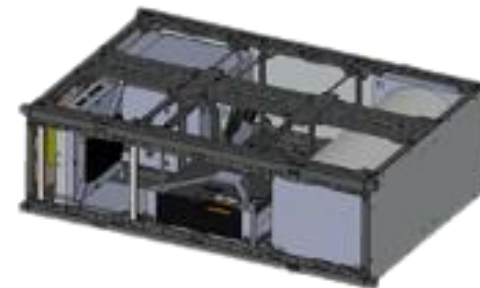


- Sloshing Platform for In-orbit Controller Experimentation = SPICESat



- University Nanosatellite Program – US AFRL Funded

- PI Laurent Burlion – Rutgers University





Educational Program Sponsorship



- The University Nanosatellite Program (UNP) funds U.S. university students and programs to design, build, launch, and operate small satellites.
- UNP's objective is to train the next generation of space professionals by providing a rigorous concept-to-flight-ready spacecraft development process centered on systems engineering principles and practices.

Phase	Description
SCR	System Concept Review
SRR	System Requirements Review
PMR	Program Management Review
PDR	Preliminary Design Review
CDR	Critical Design Review
FSR	Flight Selection Review



SPICEsat Mission Overview



Mission Statement

Capture zero-gravity fuel sloshing dynamics and implement novel active control stabilization algorithms to optimize satellite functionality.

Mission Objective

The Rutgers team will investigate and **characterize the fluid sloshing motion** in zero-g environments to **validate equivalent mechanical models** and **create** more representative ones.

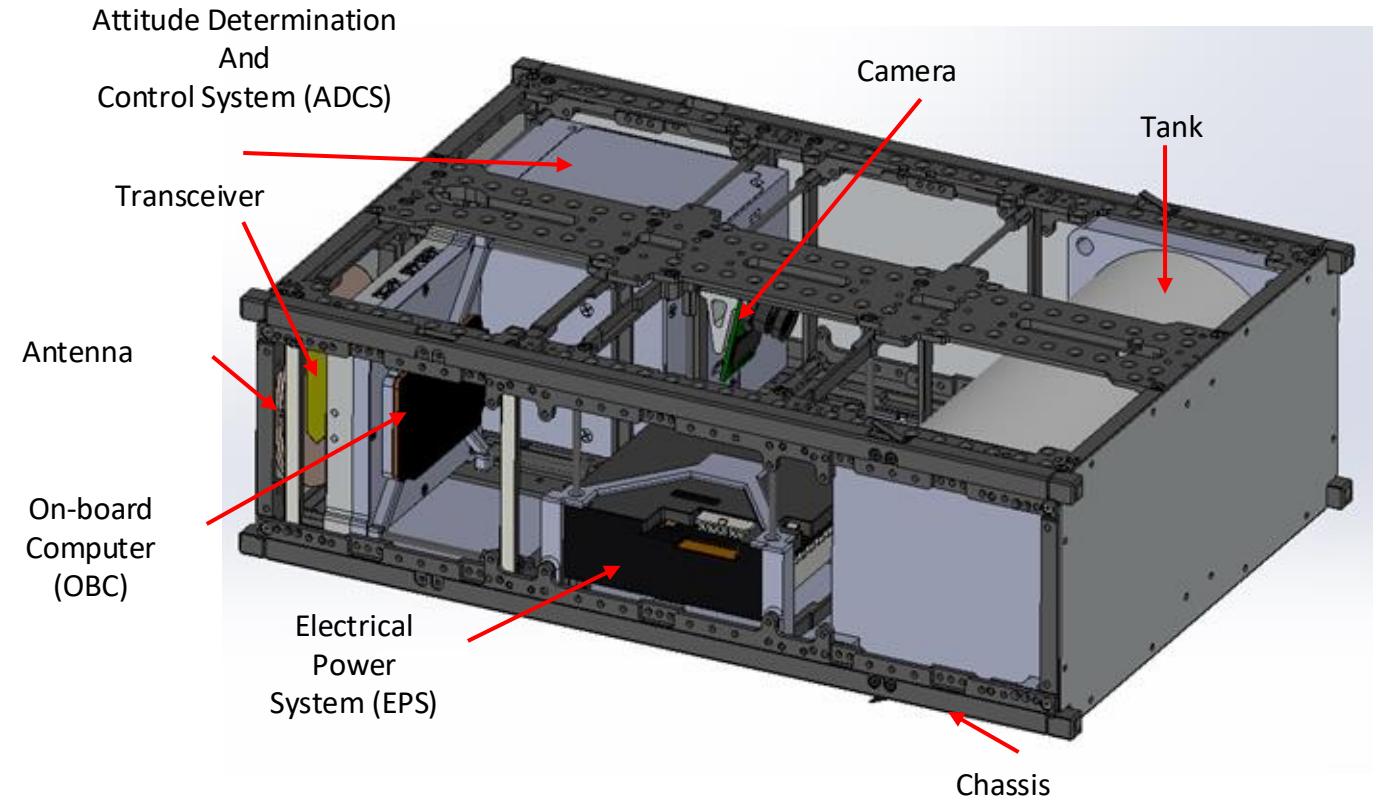
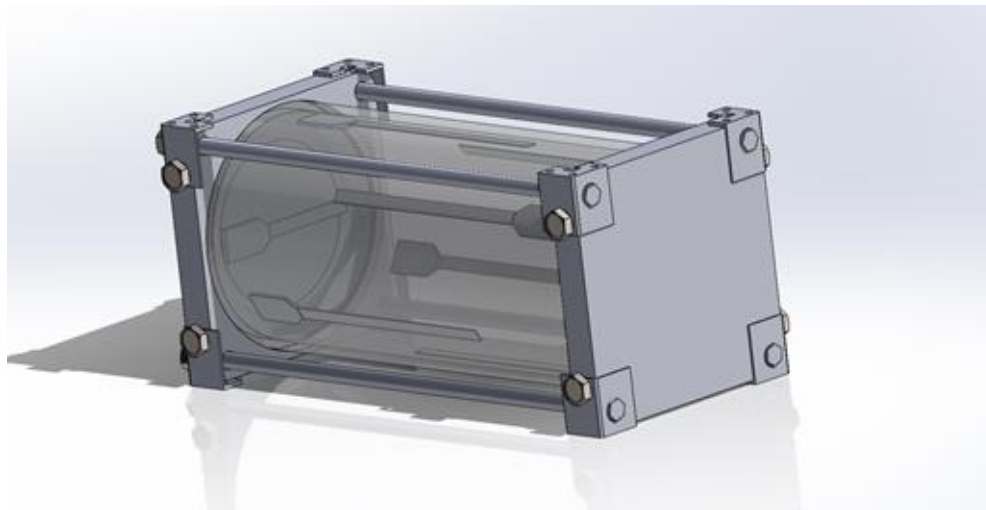
Mission Objective

The Rutgers team will develop **active control stabilization** algorithms to **mitigate sloshing** more efficiently.

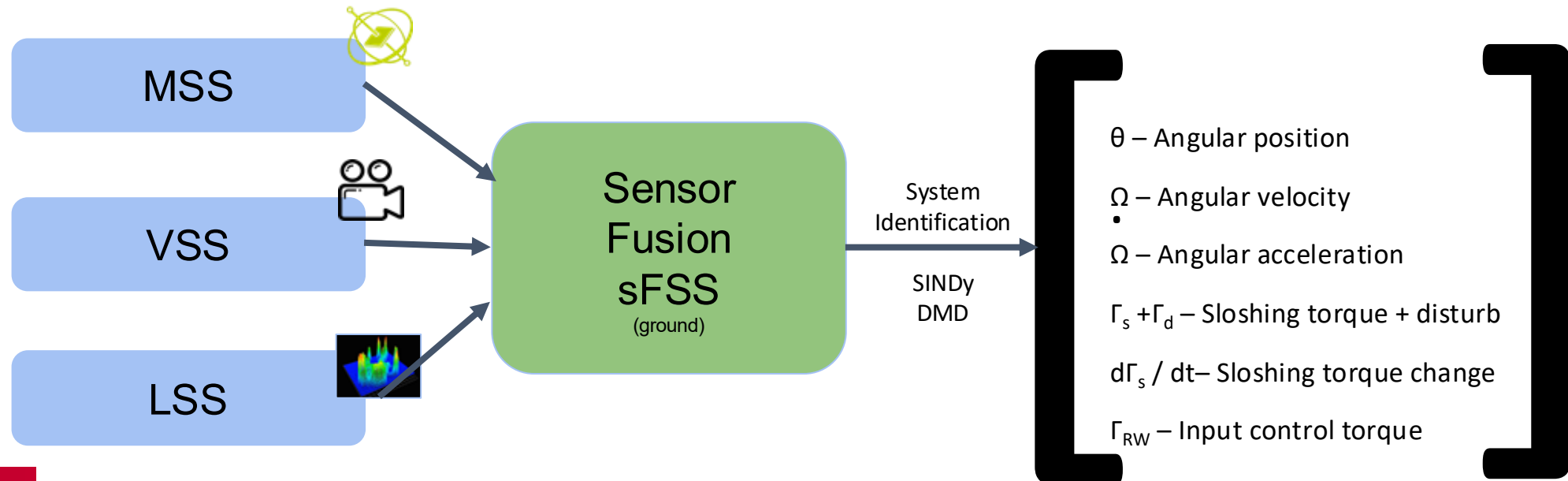


SPICEsat Satellite Design

Component	Description	Vendor
ADCS (MSS)	Satellite attitude and control	Blue Canyon XACT-50
Camera (VSS)	Sloshing video recording	ArduCam OV5647
Tank	Primary experiment with fluid	Polycarbonate
Pressure Sensors (LSS)	Pressure sensor mapping	Sensitronics
Chassis & Panel	Satellite main chassis	SpaceMind 6U
Electrical Power	Power for satellite	SpaceMind
Payload Computer	Payload computer / control	RaspberryPi 4B+
Onboard Computer	Flight computer	GOMSpace NanoMind A3200
UHF Transceiver	Omni-directional comms	UHF Transceiver
S-band Transceiver	High data rate comms	GOMSpace Software Defined Radio (SDR)

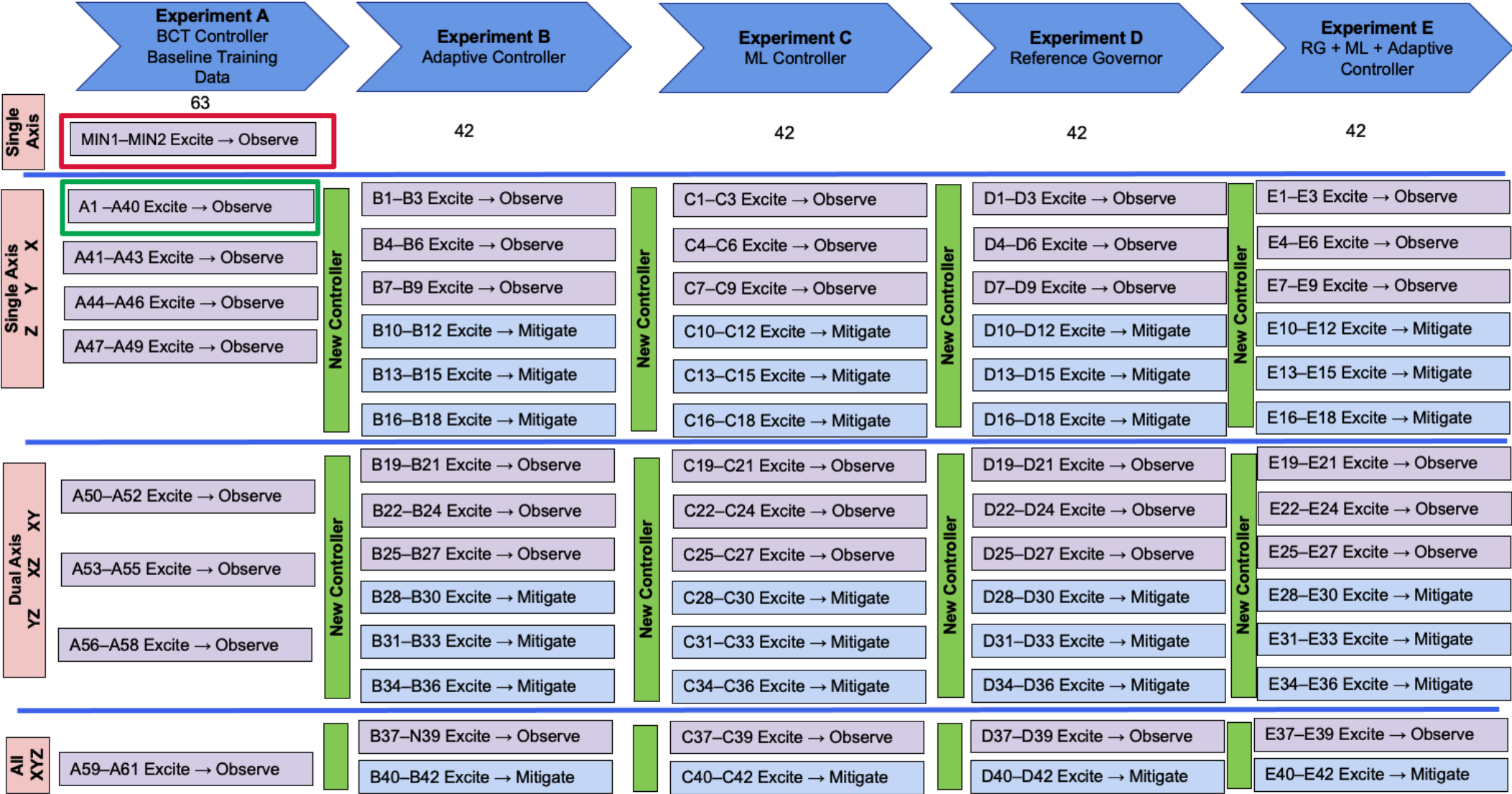


- Implement multiple methods to detect and measure sloshing
 - Motion Sensing Suite (MSS) – highly accurate gyroscopes
 - Vision Sensing Suite (VSS) – camera to record sloshing
 - Liquid Sensing Suite (LSS) – force torque sensors
 - Sensor Fusion Sensing Suite (sFSS) – ground software state space reconstruction





Slosh Mode Excitations



231 Experiments Total – Min Success: 40 Experiments
Each Experiment $d\theta/dt$ (angular velocity of spin) and θ (duration of rotation)



Satellite Design - Feasibility & Verification



- **Key Challenge:** Verifying SPICESat's design
 - How do we make sure that the design is flyable ?
 - The experiment incorporates a unique liquid-filled tank and advanced control me
 - Neither have that flight heritage



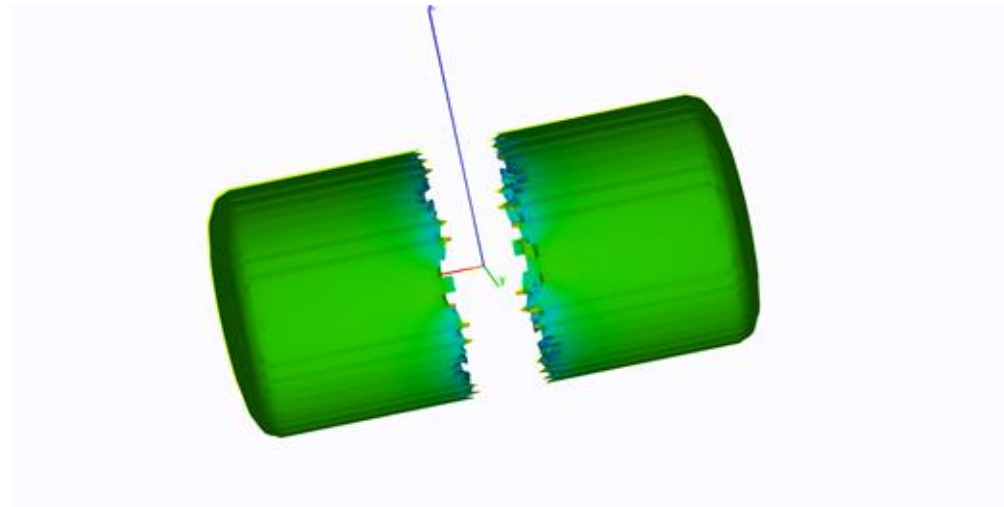
- **Solution:** Analyze satellite sloshing disturbance in open and closed-loop responses
- 1- Initial Feasibility: Use Open Loop CFD analysis to validate sensor designs
- 2- Design Verification: Use Rigid Body Dynamics + Closed Loop Control + CFD to validate design
- 3- Flat Sat Verification: Independently perform experiment verification



3.1- Initial Feasibility & Sensor Thresholds



- Open Loop CFD Analysis
 - CFD models using manufacturer reaction wheel torque input and angular velocity
 - $\Gamma_{rw} < 6 \text{ mN-m}$
 - $\Omega_{rw} = 16 \text{ }^\circ/\text{sec}$ (max $26 \text{ }^\circ/\text{sec}$)
- Spin tank around the CG of the satellite

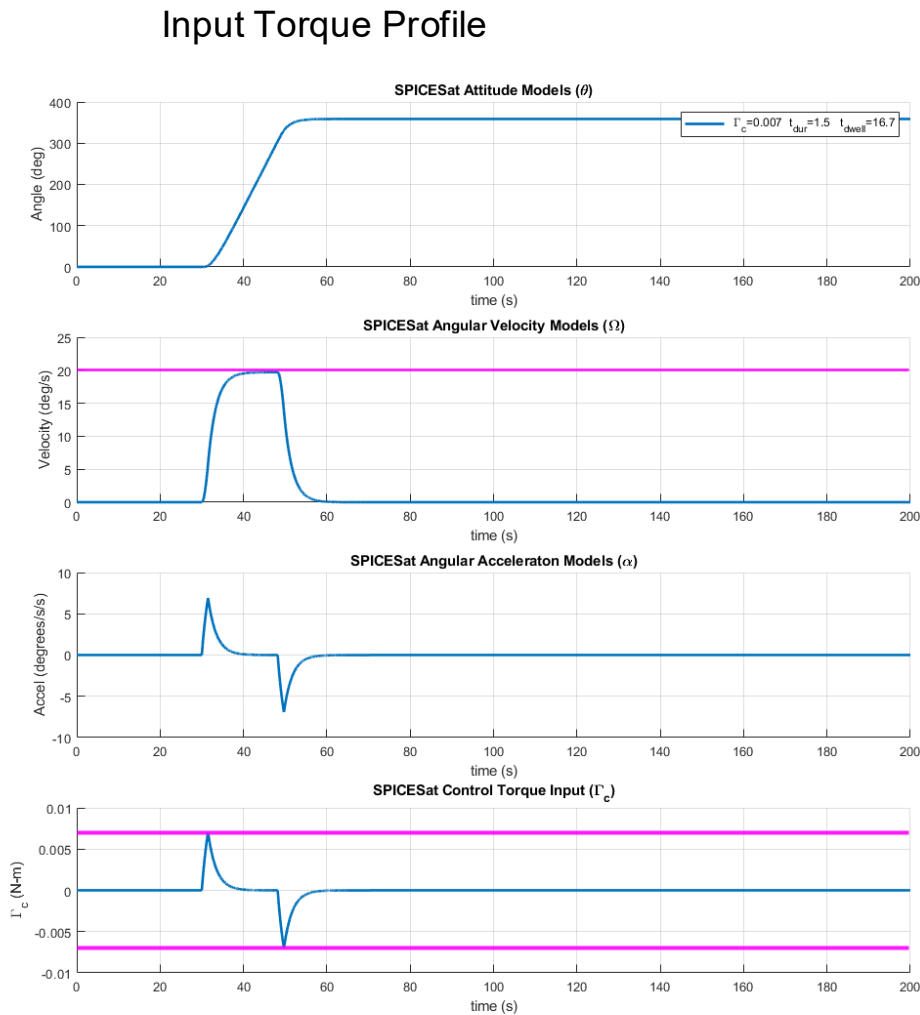




SPICEsat Open-Loop Results



- Input control torque profile chosen
- Flow-3D uses angular accelerations to model slosh



Slosh Disturbance Torque

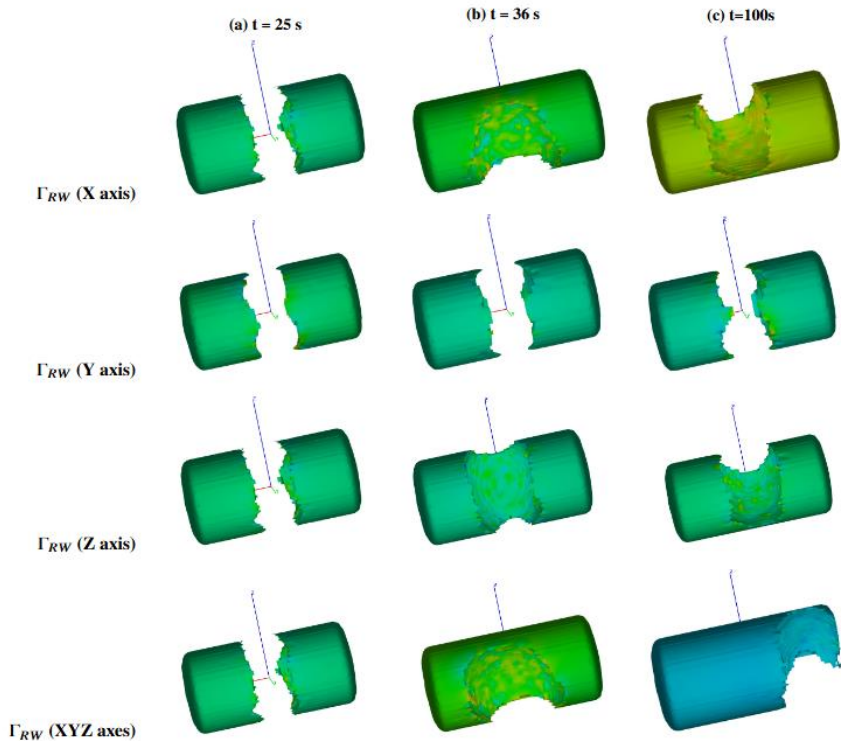


Fig. 18 CFD Results at $t = 25$ s (initial state), $t = 36$ s (Max Γ_{RW}), and $t = 100$ s for input torques along the X,Y,Z, and XYZ axes.

Sloshing Disturbance Forces and Torques Derived from CFD Calculations

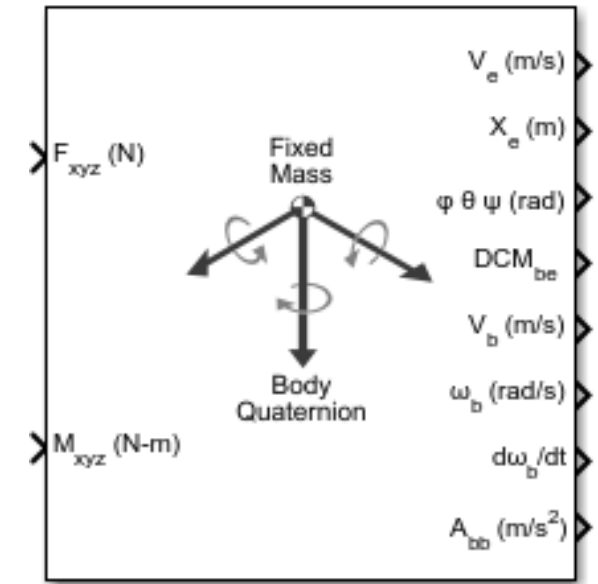
Γ_{RW} Direction	Max F(N)	Max Γ_s (N-m)
X-Axis	4.75E-2	5.77E-3
Y-Axis	9.35E-3	1.44E-3
Z-Axis	1.48E-2	4.17E-3
XYZ-Axis	5.99E-2	7.56E-3

Fogel et. al, “Nanosatellite Design Considerations for a Mission to Explore the Propellant Sloshing Problem,” AIAA Journal of Spacecraft and Rockets, 2024.



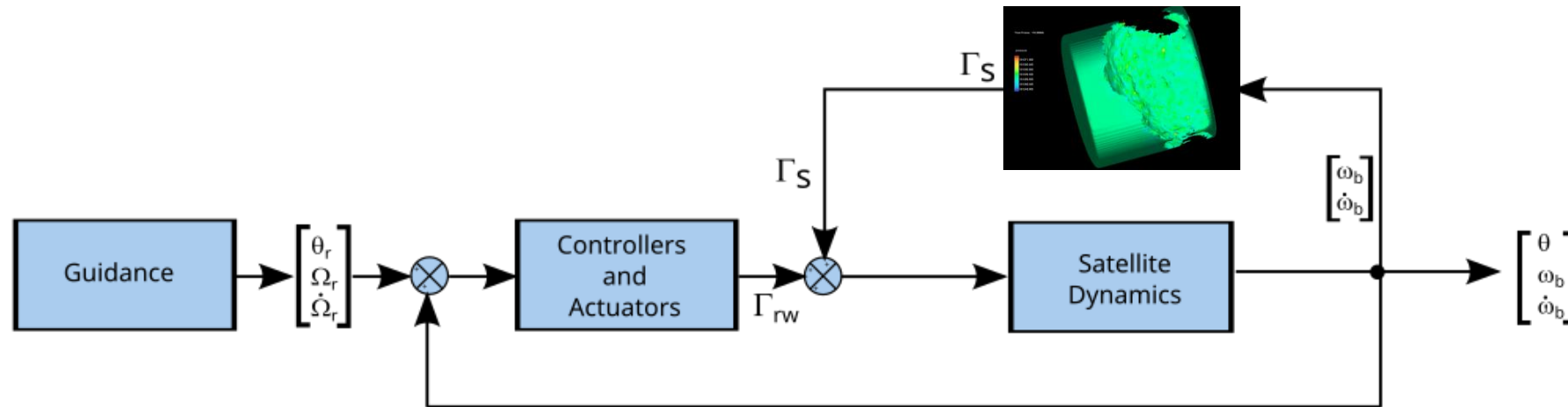
3.2- Design Verification

- Rigid Body Dynamics + CFD
 - Two-way exchange of sloshing effects
- Features
 - Rigid Body Dynamics
 - Simulink 6-DoF Aerospace Blockset Module
 - Magnetorquers
 - Simulate satellite detumbling
 - Modular Control Algorithm Implementation
 - Current PD controller
 - B-dot controller
 - Modular Sloshing Module
 - EMM
 - Flow3D CFD





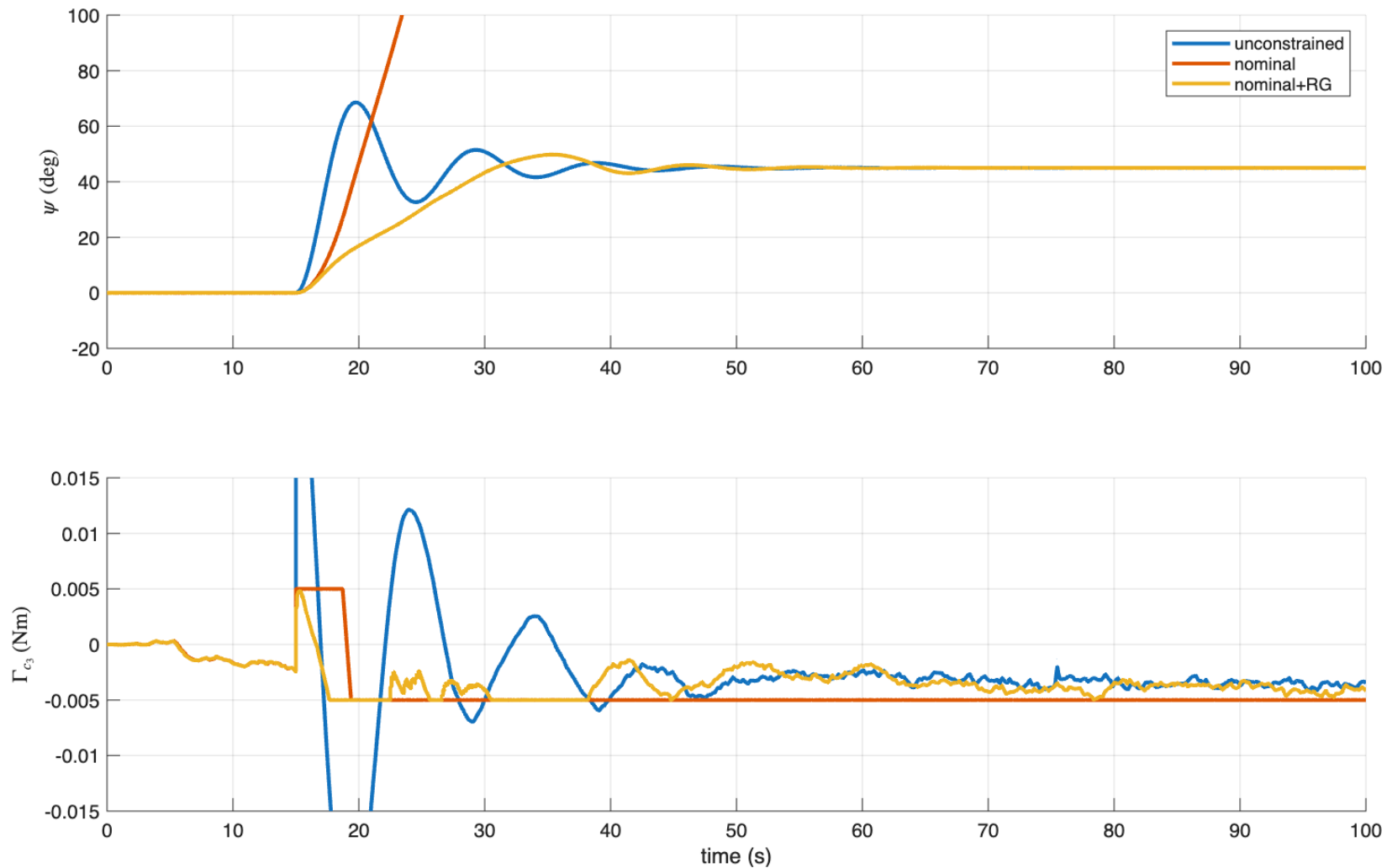
Closed-loop CFD simulator



1. Generating the data of the 231 experiments of our mission using this benchmark,
2. Analyzing this data to determine when linear models are inadequate (such as during large angular velocities or accelerations),
3. Developing Linear Parameter-Varying (LPV), or quasi-LPV models, or ML models for more accurate representation



Closed-loop CFD results (Example)





What we learnt so far



This is early stage work with several issues we need to fix:

- The torques and forces coming from Flow3D are too noisy. They need to be initially at zero and have zero steady-state values.
- The "numerical noise" is even larger when we close the loop.

Before doing a more extensive campaign, we need to figure out the link between the:

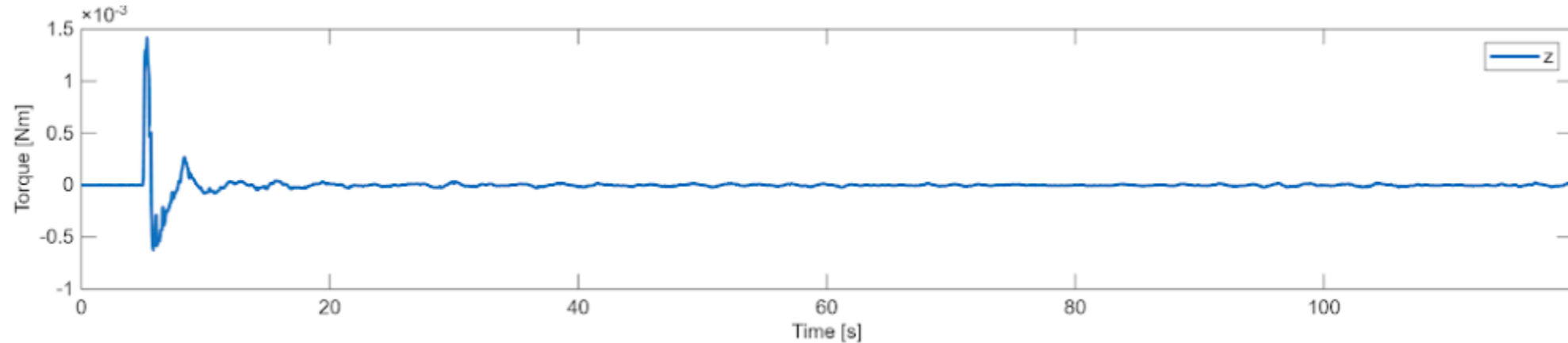
velocities / gravity value, and the mesh resolution

This is a multi-disciplinary problem and we need to collaborate more closely with the fluids experts.

Other software is being considered: STAR-CCM+ and OpenFOAM

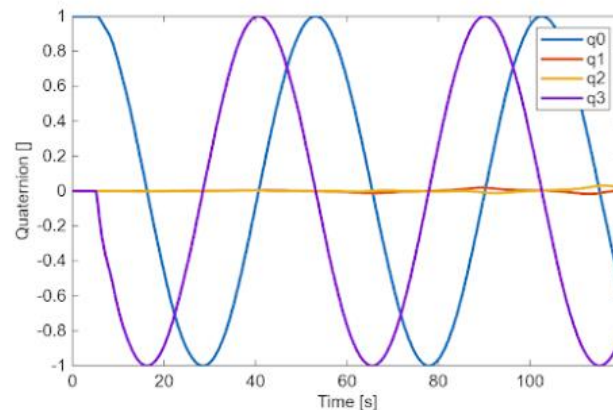
(Contact angle hysteresis is not available in Flow3D, but is available in STAR-CCM+)

- The "numerical noise" is way smaller when we use OpenFOAM.

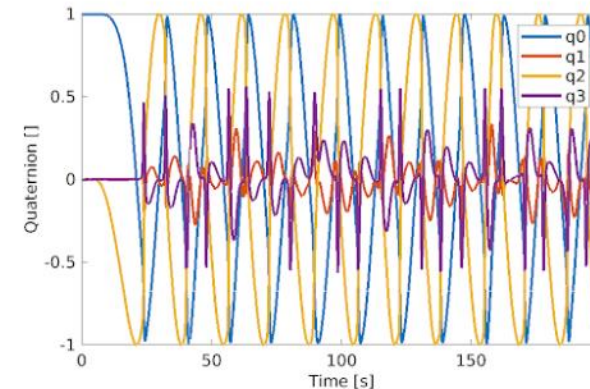


Bang Stop about z: Sloshing disturbance torque

- Fuel sloshing can indeed alter the attitude maneuver (the attitude is very sensitive to the initial position of the fluid relative to the axis of rotation)



Left: Bang Stop about z-axis



Right: Bang Stop about y-axis



- Detumbling Simulations
 - Open-loop / Closed-loop CFD simulator
 - Effect of sloshing on SPICESat ejection
 - $B_{\dot{}}$ magnetorquer model at ISS altitude



3.3- FLATsat Verification

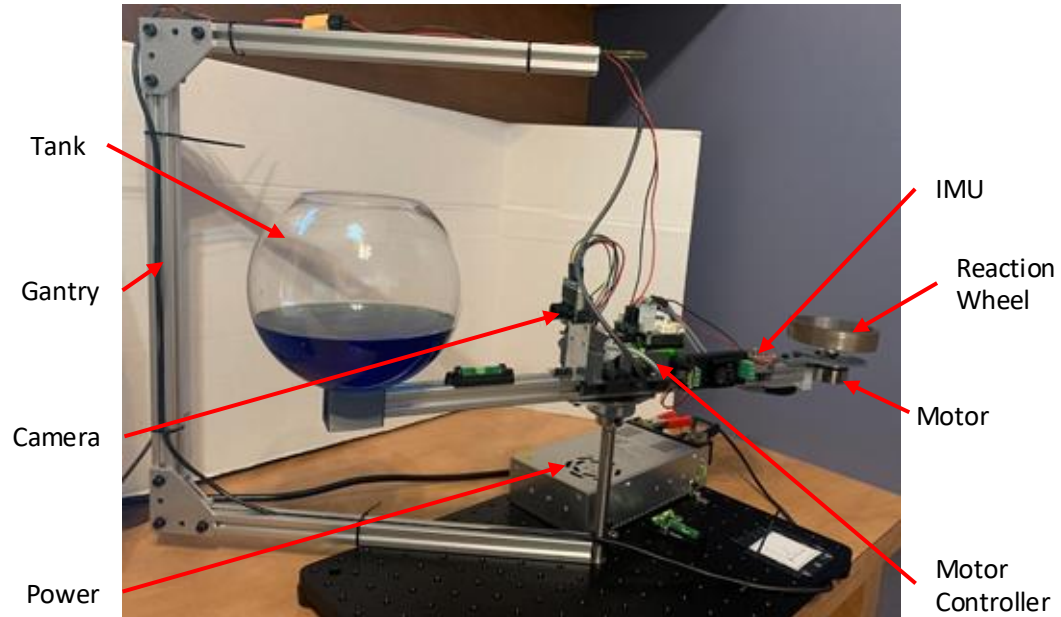


- Student Built Test Bench Projects
 - Students led experienced design iterations → Enhanced educational processes
 - 3U Satellite Initial Design
 - CAD Modeling of 6U Design
 - Construction of a Testbench
 - Construction of a Working "FlatSat"

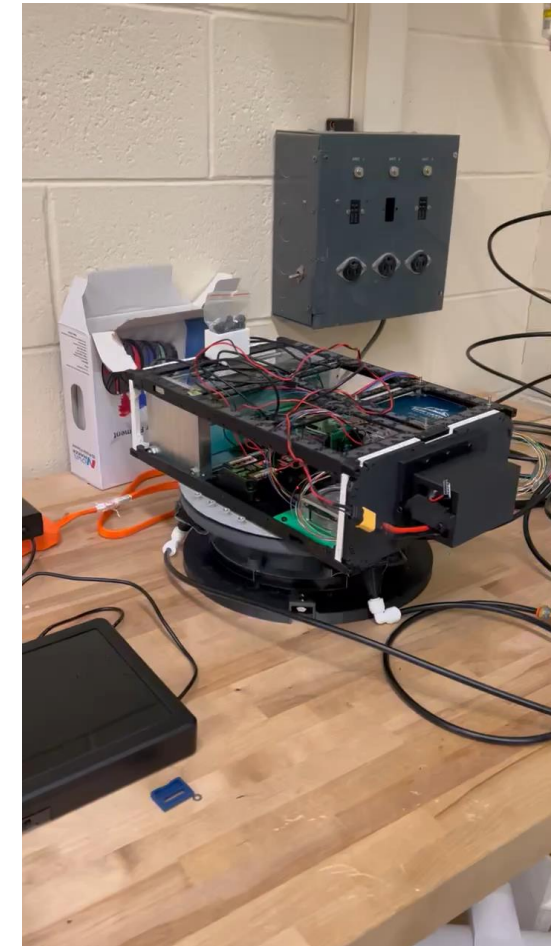


From the First to the Final Design

Initial testbench



FLATsat

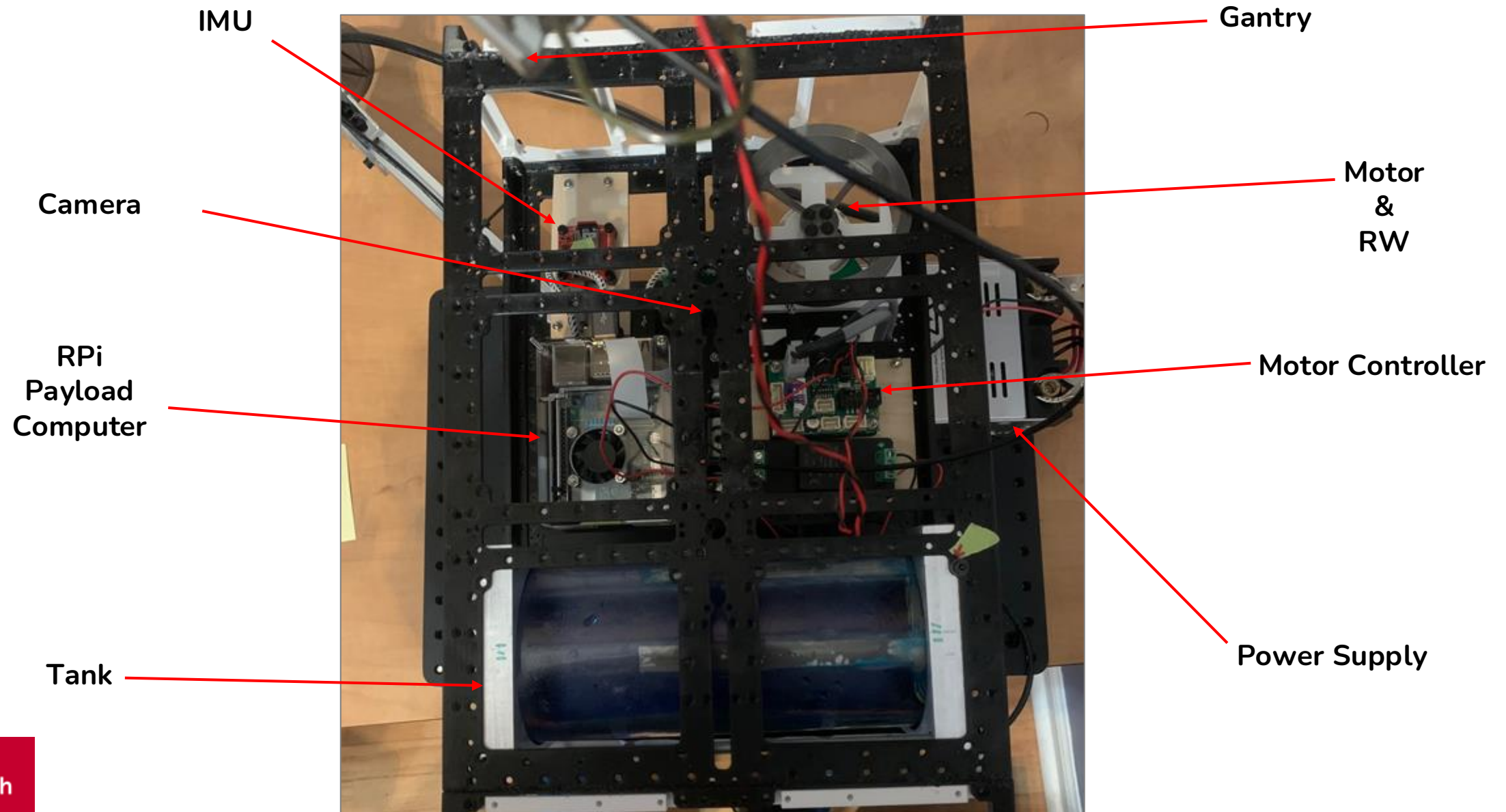


Testing

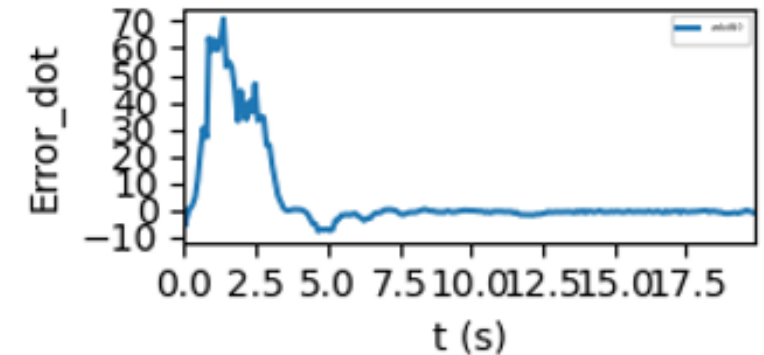
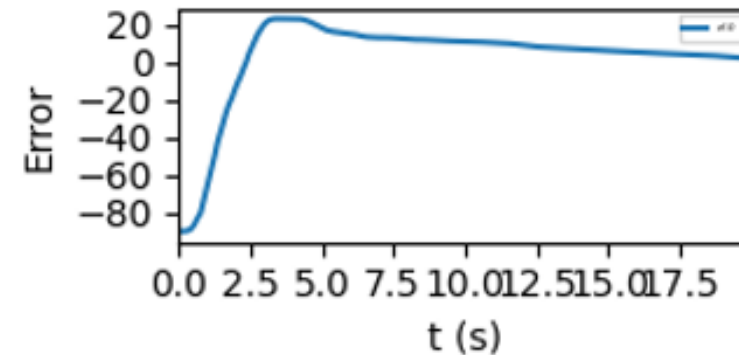
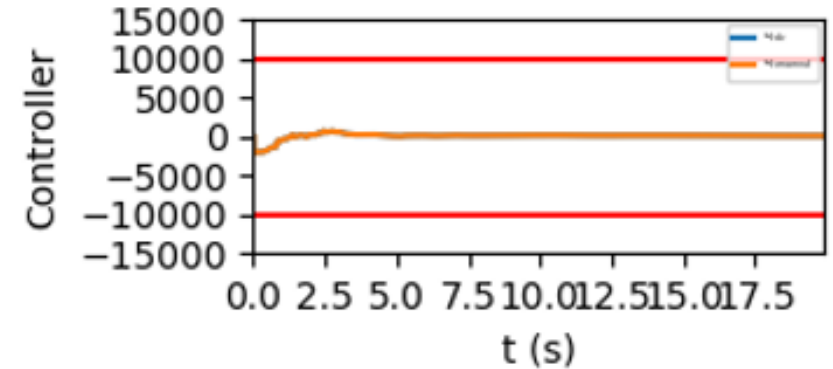
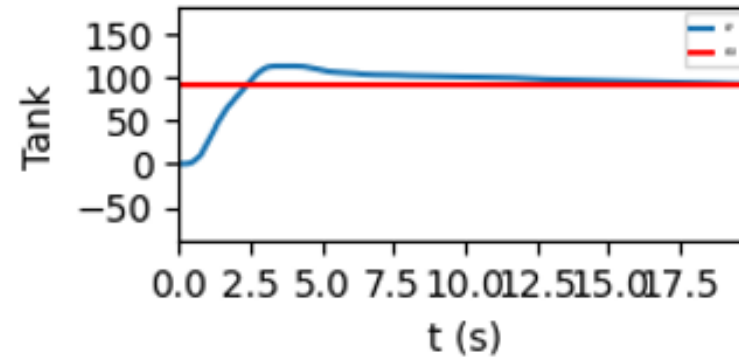
Controller software
Pressure sensor software
OBC
Control algorithms
Tank
Camera



FLATsat



- Commanded 90°
- PID Controller
 - Commands within safety limits
 - P-error $\rightarrow$ zero
 - D-error $\rightarrow$ zero
 - I-error $\rightarrow$ zero





Other Testbenches with more DoFs

Toward a 3 DoF FLATsat





Other Testbenches with more DoFs

Hexapod





3-Next Steps and Conclusions



- Research
 - Improve the Closed-loop CFD simulators
 - Implement all the controllers and run the Closed-loop CFD simulations of the mission
- Launch a Cubesat (NS-12)
 - Acquire and share the data!
- Control Education
 - Propose some educational activities for each testbench (modeling/identification/control)



Next Steps and Conclusions



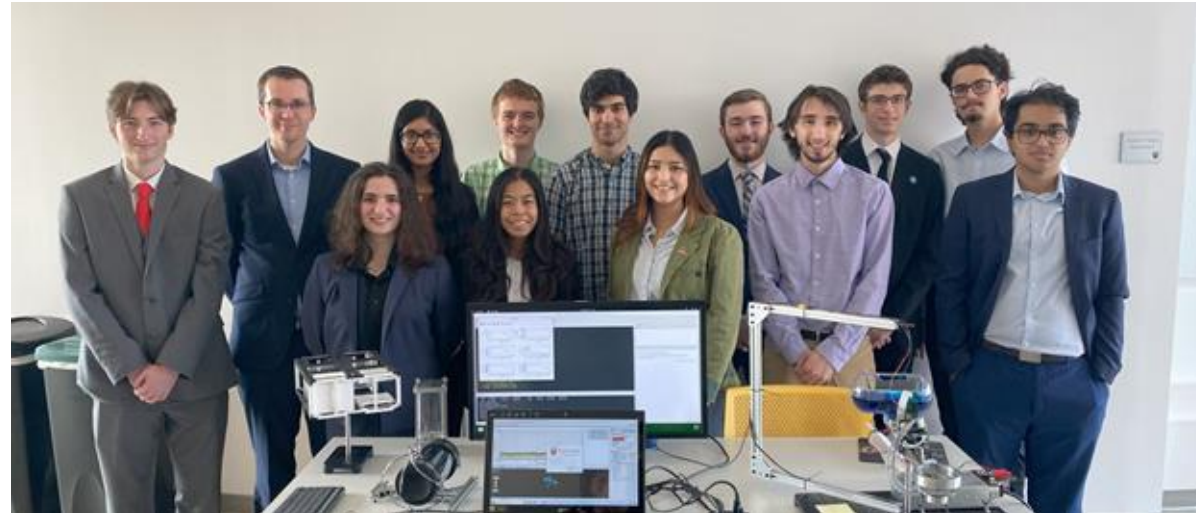
- Extremely rewarding experience for students
 - No substitute for hands-on skills
- Real life skills
 - Project management is tough
 - Project turnover challenges
- Interestingly, students who applied to a graduate prgm specialized in “GNC”
- Awesome Employment Opps: Boeing, JPL, SpaceX, Rocket Lab, Draper, Relativity Space, Blue Origin...





Thank you !

R
ENGINEERING



Questions / feedback ?



Bibliography & Appendix



B. Marsell et al. "Integrated CFD and Controls Analysis Interface for High Accuracy Liquid Propellant Slosh Predictions." In: 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. doi: 10.2514/6.2012-308. eprint: <https://arc.aiaa.org/doi/abs/10.2514/6.2012-308>.

M. Fogel, S. Sushil Mishra, and L. Burlion, "Nanosatellite Design Considerations for a Mission to Explore the Propellant Sloshing Problem," 2025, Journal of Spacecraft and Rocket, Vol 62, No 2, pp 510-527, doi: 10.2514/1.A35871. eprint: <https://arc.aiaa.org/doi/abs/10.2514/1.A35871>.

W. Benson et al, "Low-G Slosh Workshop Results From 2023: State of the Art, Gaps and Forward Work," in Proc. of the 46th Annual AAS Guidance, Navigation and Control (GN&C) Conference, 2024. eprint: <https://ntrs.nasa.gov/citations/20240000625>

G. Magnani, et al., "Slosh attenuation via Reference Governor-based adaptive control for space operations under actuators constraints", IFAC Journal of Systems and Control, vol. 33, 2025. <https://doi.org/10.1016/j.ifacsc.2025.100321>