Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 58-16 (2024) 83–88

Engaging Students in Control Engineering through Sloshing Experiments

Michael Fogel * **Laurent Burlion** *

* *Rutgers, the State University of New Jersey, Piscataway, NJ 08854 USA (e-mails: mikefogelny(at)gmail.com, laurent.burlion(at)rutgers.edu)*

Abstract: This paper describes how Rutgers University's SPICEsat (Sloshing Platform for In-Orbit Controller Experimentation) CubeSat mission is being used to excite student interest in control engineering. Many spacecraft rely on large propellant tanks that can slosh, affecting their control. SPICEsat aims to be the first CubeSat to study this phenomenon in zero gravity. The primary mission is to improve our understanding of sloshing dynamics through novel experiments. This will lead to better control systems for future spacecraft. A secondary mission is to provide educational and outreach opportunities throughout the project. Students will gain hands-on experience in modeling, identification, and control by working with SPICEsat data and test-benches specifically developed for this mission.

Keywords: Control Education, Laboratory Equipment, Aerospace Control Systems Technology, Project-based Education, Experiences outside the classroom.

1. INTRODUCTION

Fuel motion in a partially filled spacecraft's tank can disrupt the spacecraft's orientation, necessitating a redesign of its attitude control algorithms (Bourdelle et al. (2019a,b,c)). This "fuel sloshing" is a major concern, affecting everything from telescope pointing (e.g., James Webb requiring extreme position accuracy of 6 milliarcseconds (JWST ACS documentation (2017))) to spacecraft maneuvers (like the NEAR anomaly in 1998 attributed to slosh (Hoffman et al. (1998))). Space agencies have been testing how liquids behave in low gravity using zero-G airplanes, spacecraft, and even the International Space Station (ISS). One example is a mini-satellite called SloshSat-FLEVO, built to study fluid movement (Vreeburg (2005)). Another one is the FLUIDICS experiment that was run by the ESA astronaut Thomas Pesquet during his Proxima mission in 2016. NASA has also invested significant resources in understanding slosh dynamics through experiments on the ISS, including the 'SPHERES-Slosh" and "SPHERES-Slosh Tether" experiments.

A collaborative effort in 1999 by Cal Poly and Stanford resulted in the CubeSat standard. This standard was created to make space research more achievable for university students. With CubeSats becoming more and more affordable since then, students might soon be able to collect fluid data in micro-gravity environments too. Rutgers University is currently taking on the challenge of developing a CubeSat mission called SPICESat (Sloshing Platform for In-Orbit Controller Experimentation) to collect fluid data and test advanced slosh mitigation control methods. More specifically, using pressure sensors and cameras, the satellite will gather data to improve simulations and understand fluid mechanics better. This will help students test new algorithms to control and stabilize fluids in spacecraft tanks.

* This research was supported by United States Air Force Research Lab University Nanosatellite Program through award number CP0072457 and by the US National Science Foundation under award 2308283.

This paper aims to discuss this Rutgers student project that combined the challenge of building a CubeSat with the practical application of control engineering principles for its future in-orbit operations. In sections 2 and 3, the scientific goals of the mission are presented, along with the studies that validate it. These studies include the use of computational fluid dynamics (CFD) simulations. The sensor requirements needed to achieve the mission objectives are discussed too. Then, section 3 presents a few test benches designed by the students. Section 4 presents the various control methods that are expected to be tested on these test benches in the future in a 1-g environment and subsequently in a 0-g environment on the CubeSat. Finally, section 6 dives into the educational benefits that are inherent to such a project.

2. RESEARCH MISSION OVERVIEW

2.1 Overview of the SPICEsat nanosatellite mission

This CubeSat mission, named SPICEsat (Sloshing Platform for In-Orbit Controller Experimentation), aims to tackle the challenge of propellant sloshing in spacecraft. When liquid fuel moves freely inside a spacecraft's tank due to microgravity, it can significantly disrupt the spacecraft's attitude. SPICEsat's main objectives are twofold:

(1) Test new sensor technology for sloshing detection: Pressure sensors will map the pressure variations inside the tank caused by sloshing whereas video

10.1016/j.ifacol.2024.08.466

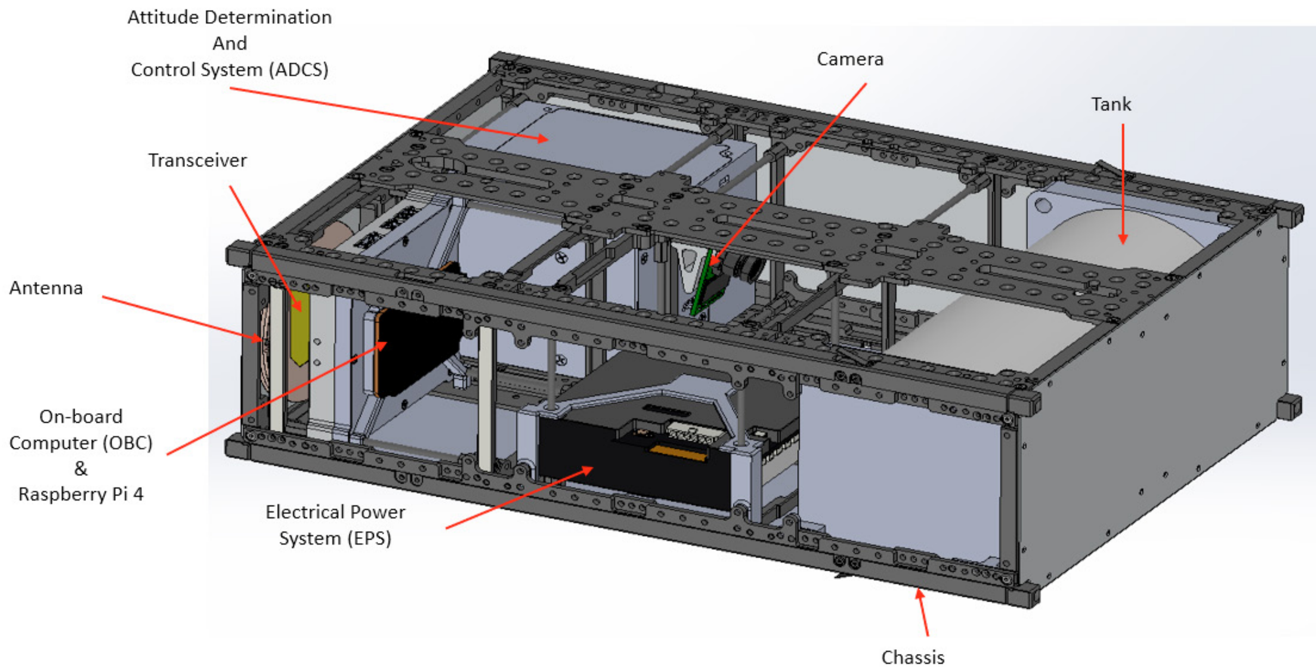

Fig. 1. Satellite Preliminary Design Concept

cameras will record video footage of the sloshing liquid.

(2) Develop methods to mitigate the effects of fuel sloshing: the mission will test different control algorithms to mitigate the effects of sloshing on the spacecraft. In particular, machine learning will be used to predict and counteract sloshing disturbances (Fogel (2022)).

2.2 Cubesat preliminary design

SPICEsat was designed to be a 6U, standardized CubeSat carrying a sealed tank filled with a propellant analogous liquid (See Fig. 1).

Once in orbit, SPICEsat will perform a series of maneuvers to induce sloshing at various intensities. High-precision sensors will measure the spacecraft's motion and the forces exerted by the sloshing liquid. The mission will explore seven different excitation modes to gather comprehensive data. The data collected will be used to improve existing models and validate sloshing mitigation techniques. SPICEsat's findings will be crucial for designing future spacecraft that can operate more precisely and efficiently in the microgravity environment of space.

2.3 In orbit experiments

SPICEsat's mission is to gather data on propellant sloshing in space. It will run 229 experiments, repeating each three times for reliable results. During these experiments, the satellite will be spun in different directions using its reaction wheels. Mid-range Bond numbers $1 < B_o < 10$ are intended to be explored. The data collected will include satellite state, pressure readings, and camera footage. A ground station will receive and process the collected data and then upload new control algorithms to the spacecraft for testing.

3. SPICESAT FEASIBILITY ANALYSIS

To ensure the success of the mission (and also to convince potential donors to invest in it), the students must address a few challenging questions.

3.1 Measuring sloshing in zero-g

A key challenge for the students throughout the mission design was to prove that sloshing can be detected in a 6U Cubesatellite. The ability to sense sloshing behavior in zero-g became one of the central questions as long as the students were designing the mission. This process started with theoretical and simulated modeling of sloshing. For simulating sloshing behavior, the fuel problem has been studied numerically using computationally expensive CFD methods. CFD modeling is complex and computationally intense, especially in the controls arena, where the inputs can change at each time step, introducing new dynamics into the problem and therefore requiring recalculation of the CFD solution.

CFD results have been reported in (Fogel et al. (2022)) and demonstrated that the design of SPICEsat and its payload measurements are well within detection limits, placing upper and lower bounds on the sensitivity of each sensor.

3.2 Avoiding fluid leaks

Another key challenge was to demonstrate that the sealed tank would not have any leakage once in a space environment. To this end, a master's student studied pressurization techniques and leak test technology to identify and extrapolate a known leak rate that exceeds the Cubesat mission duration. Fig. 2 shows a pressurization test.

Fig. 2. Tank vacuum testing

3.3 Being able to detumble

Finally, the last major challenge identified was to demonstrate that the satellite would be capable of detumbling after being ejected. This is clearly a control problem that specifically requires showing that the magnetorquers will be able to stabilize the satellite's attitude under a given set of initial conditions. To this end, closed-loop CFD and rigid body dynamcis simulations are currently in preparation at Rutgers. This problem not only keeps students awake, but pushes them beyond their comfort zone to tackle a critical control problem.

4. TEST BENCHES DEVELOPMENT

To understand how some key components would interact, get a clearer understanding of the control algorithms, or begin system identification, the students built several 1-g sloshing test benches following an iterative design approach.

1 DoF Test Bench (Fig. 3). The students built a single degree of freedom (DoF) test bench to put together several satellite parts for the first time. This allowed them to test different functionalities. Here's what they accomplished with this test bench:

- They created a mathematical model describing the satellite's rotation and used a standard control method (PID controller) to precisely turn the reaction wheel to a desired angle.
- They learned how to interpret data from the inertial measurement unit (IMU) and control brushless motors.
- They used the camera to capture data and developed a computer vision program to detect the level of sloshing in the fuel tank, proving the initial functionality of the vision system.
- Early tests showed the sensors could detect slosh, but incorporating that data into the control system required future development.

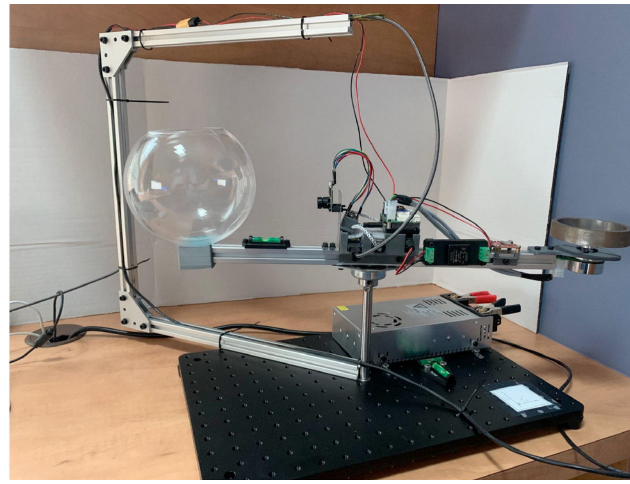

Fig. 3. 1g, 1DoF Sloshing testbench

FlatSat The next stage was building a FlatSat. FlatSat, or "flat satellite" development started in the Fall of 2023 (Fig. 4). This is basically a practice version of the entire satellite, where all the parts (hardware, wires, power systems, and software) come together for testing. Building the FlatSat involved several challenges for the students:

- They had to design and build a 'dust-free' workspace following strict university guidelines.
- They needed to work with university maintenance staff, outside suppliers, and the purchasing department to get everything they needed. Teamwork was crucial here, as different teams had to figure out how their parts would fit together in the final satellite.
- The students even got experience with how universities negotiate contracts with vendors, which is an important part of any engineering project

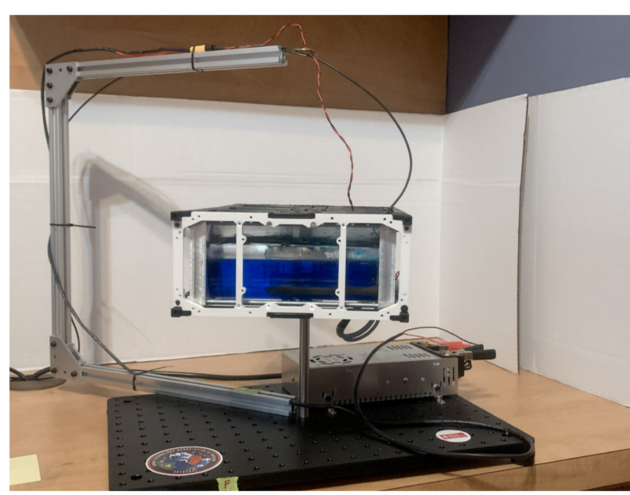

Fig. 4. FlatSat

3 DoF Test Bench Capitalizing upon their previous experience, some students built a three-degree of freedom (DoF) test bench (Fig. 5). These undergraduate students won the best aerospace project award at the MAE senior design expo in the Spring of 2024. The next step could be to develop a 3DoF FlatSat by adding nanosatellite components.

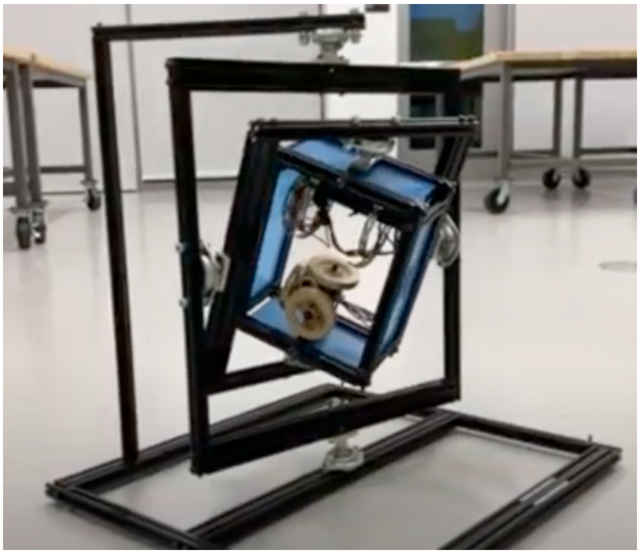

Fig. 5. 1g, 3DoF Sloshing testbench

Hexapod Test Bench In parallel and most recently, a Stewart Platform was purchased (Fig. 6). This platform uses powerful linear actuators to move in any direction and precisely control its position and orientation. It also has built-in sensors to track its movement. A large tank was mounted on top of this platform. The liquid movement is monitored using the platform's sensors and cameras developed for the SPICEsat mission. This allows the students to test different control algorithms and computer vision programs to see how well they handle sloshing liquids in a safe and controlled environment. An additional benefit for students is learning about inverse and forward kinematics.

5. CONTROL SYNTHESIS

Through the SPICEsat mission, several modeling methods and control algorithms will be thoroughly tested.

5.1 Modeling and identification

Reaction wheel control inputs similar to those shown in Fig. 7 can be used to turn the tank and excite the fluid. These control inputs, along with the satellite mass moment of inertia, act as key parameters for modeling the satellite's and fluid's behavior. Equivalent Mechanical Models (EMM) and Computational Fluid Dynamics (CFD) can be used to simulate the dynamics.

5.2 EMM and CFD Results

EMM Results EMMs have been studied extensively in books and journal articles such as (Sidi (1997)), (Dodge (2000)), and used for control synthesis, as demonstrated in works like (Reyhanoglu and Hervas (2012)) and (Sopasakis et al. (2015)).

Fig. 6. Hexapod sloshing tank

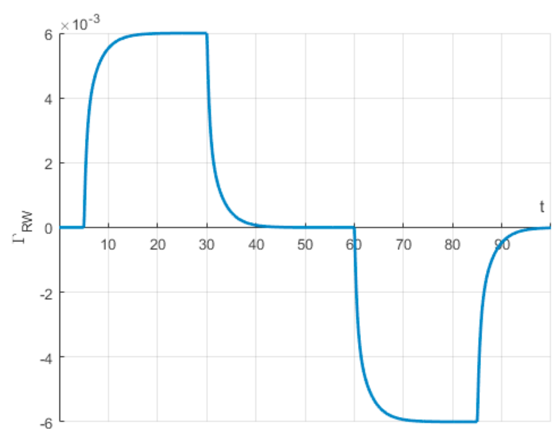

Fig. 7. Typical Reaction Wheel Torque Profile

A satellite motion sensing system consisting of high-precision accelerometers and gyroscopes will be used to measure satellite motion including the effect of sloshing fluid.

Given a typical input control torque of $\Gamma_{RW} = 0.006$ N-m and a typical 6U satellite moment of inertia $I_{sat} = 0.0542$ kg-m^2, the equivalent mechanical models indicate a sloshing torque of $1.0 \times 10^{-4} < \Gamma_s < 1.0 \times 10^{-3}$ N-m. Assuming the ADCS is located at $r = 10$ cm from the center of the tank the angular and linear accelerations are:

$$\dot{\Omega}_{min} = \frac{\Gamma_s}{I_{sat}} = \frac{0.000134}{0.0542} = 2.47 \times 10^{-3} \text{ rads}/s^2 \quad (1)$$

Table 1. Sloshing Disturbances Derived from CFD Calculations

Γ_{RW} **Direction**	**Max F(N)**	**Max** Γ_s**(N-m)**
X-Axis	4.75×10^{-2}	5.77×10^{-3}
Y-Axis	9.35×10^{-3}	1.44×10^{-3}
Z-Axis	1.48×10^{-2}	4.17×10^{-3}
XYZ-Axis	5.99×10^{-2}	7.56×10^{-3}

$$a_{min} = \dot{\Omega}_{min} r = (2.47 \times 10^{-3})(0.1) = 25.2\mu g \quad (2)$$

Assuming the same sloshing torques, we use EMM and CFD models to estimate the order of magnitude of the angular acceleration ($\dot{\Omega}$) and angular velocity (Ω) disturbances caused by the sloshing to give us an order-of-magnitude measurement of the disturbance, which we will require the gyroscopes to detect.

CFD Results We also model the sloshing torque using Computational Fluid Dynamics calculations using Flow3D software for the same size tank and reaction wheel torque studied in the EMMs (Fogel et al. (2022)). The CFD models show similar sloshing torques of $1.4 \times 10^{-3} < \Gamma_s < 7.6 \times 10^{-3}$ N-m, consistent with the EMMs. CFD force and disturbance results for excitation on X, Y, and Z axes individually and then all three axes simultaneously are given in Table 1.

5.3 Control methods

The experiment will test different ways to control a satellite's motion and counteract the sloshing of its fuel.

- Start with a baseline control system that will also be used for safety if needed.
- Next, use past data values to build an estimator and reject sloshing disturbance torques.
- Use machine learning to predict sloshing and adjust the satellite's motion accordingly.
- Add a reference governor to ensure the satellite stays within safe limits.
- Finally, combine machine learning and reference governors and test them together. Previous research has confirmed that the mathematical models used for this experiment are accurate (Bourdelle et al. (2019b),Bourdelle et al. (2019c), and Bourdelle et al. (2019a)). It has also been shown that machine learning can be used to predict the sloshing torques (Fogel (2022)).

5.4 Interval Contractors

Model-based and data-based control methods are intended to be tested on the test benches and subsequently on the Cubesatellite. The first one requires an EMM while the second one does not. Another avenue of research is the ability to learn the uncertainty bounds of an uncertain parametric model while performing some maneuvers.

6. STUDENTS OUTCOMES AND OPPORTUNITIES

6.1 Educational Benefits

In October 2021, the Air Force Research Lab's University Nanosatellite Program (UNP) selected Rutgers University's proposal to study this propellant sloshing problem. During those two years, the SPICEsat team was held to a tight schedule, similar to a commercial satellite design program. The development follows the well-established process used by NASA, the military, and the commercial industry today, called the "V-Model" of Systems Engineering (UNP User Guide (2023)).

6.2 Technical Skills

SPICEsat and the UNP Program follow the V-Model of systems engineering. This method was an important template for developing new technical skills in the undergraduates participating in the program. This is where the majority of the hands-on and technical skills were developed. Classroom instruction on systems engineering exposes students to the concepts. Each month, the UNP held deep-dive seminars with aerospace industry experts on a variety of topics, extending theory into the practical application of building a satellite.

Students were subjected to regular critical reviews and given direct feedback by the UNP team at each stage. These reviews included detailed day-long presentations covering key Systems Engineering Skills, including:

Systems Engineering Skills

- Mission Design
- Mission Objectives
- Mission Requirements
- Mass Budgets
- Data Budgets
- Pointing Budget
- Link Budget
- Power Budget
- Thermal Budget
- Concept of Operations

Technical skills were developed further through the multidisciplinary nature of the project itself. SPICEsat required students to work across disciplines of engineering (mechanical, electrical, and aerospace), computer science, and physics, bringing together many different departments at the university.

Leadership / Management Skills About one-third of all university-class satellite missions do not meet their minimum mission objectives (Berthoud et al. (2023)). The difference between flagship universities that successfully launch at least four satellite missions and regular independent programs is a matter of perseverance and learning from mistakes, rather than initial success.

As a student team, every cube satellite program is challenged with inconsistent funding, inconsistent staffing, and a transient unpaid workforce. In response, Rutgers student leaders took a strategic approach to project management, interpersonal skills, problem management, and staffing management. Each semester, surveys were completed by every member of the team in order to generate a Personnel Budget - essentially treating manpower as another resource of the satellite. Using the systems engineering approach, people and time were allocated to reach a balance and meet project demands as they varied throughout the mission life cycle.

Over the course of one year, adjustments were made to evenly distribute workload across students, with leaders (Project Manager/Chief Engineer) delegating more broadly. This had the benefits of decreased stress, greater productivity, and transfer of knowledge as more students were involved in decision-making and stakeholder communication.

Program Management methods to sustain progress and increase retention throughout the mission life-cycle include distributing the workload across as many students as possible, implementing a “deputy” role to transfer knowledge, and tasking via the SCRUM method to give students ownership and flexibility. Students who sense a strong support system are eager to motivate each other toward mission goals.

6.3 Focus on the payload subteam

The payload subteam played a crucial role in developing most of the test benches, software, and control methods. This subteam was led by a graduate student specializing in control. Engineering students are not software developers! This has become clear as the team started to implement the image processing and control algorithms. Recruiting students with a background in software architecture and software engineering early in the project is a key lesson learned. Every control engineer should be aware of the hidden difficulties in implementing their algorithms in realtime.

7. CONCLUSIONS

SPICEsat is perhaps the first Cubesat dedicated to studying and mitigating fuel sloshing using a variety of control methods. SPICEsat is based on a successful partnership between Burlion’s Advanced Control Lab and an undergraduate student club at the University.

Since undergraduate volunteers don’t receive grades for participating, the project experiences a continuous flow of students. Graduating students, fluctuating interest levels, and other semester pressures cause this turnover. This ebb and flow leads to uneven project progress. Recognizing this challenge, early participants established a system of detailed records in spreadsheets and notebooks to smoothen future transitions.

Participation in the Rutgers SPICEsat program has directly led its graduates to obtain aerospace internships and full-time positions at U.S. industry leaders like Boeing, Lockheed Martin, and SpaceX. This success is a direct result of the program’s focus on Systems Engineering, ensuring graduates possess the hands-on experience to be immediately productive from day one.

REFERENCES

A. Bourdelle, J.-M. Biannic, E. Evain, C. Pittet, S. Moreno, and L. Burlion, ”Modeling and Control of Propellant Slosh Dynamics in Observation Spacecraft with Actuators Saturations”, Proceedings of *EUCASS 2019*, Madrid, Spain, July, 2019.

A. Bourdelle, L. Burlion, J.-M. Biannic, H. Evain, S. Moreno, C. Pittet, A. Dalmon, S. Tanguy and T. Ahmed-Ali, ”Towards New Controller Design Oriented Models of Propellant Sloshing in Observation Spacecraft”, *AIAA Scitech 2019 Forum*, 2019.

A. Bourdelle, and J.-M. Biannic, H. Evain, S. Moreno, C. Pittet and L. Burlion, ”Propellant Sloshing Torque H_∞ – Based Observer Design for Enhanced Attitude Control”, in *IFAC-PapersOnLine*, Vol 52, pp 286 - 291, 2019.

F.T. Dodge, ”The new dynamic behavior of liquids in moving containers”, Technical report, *Southwest Research Institute*, 2000.

James Webb Space Telescope Attitude Control Subsystem User Documentation, 2017, https://jwst-docs.stsci.edu/jwst-observatory-hardware/jwst-attitude-control-subsystem.

Hoffman, E.J. and Ebert, W.L. and Femiano, M.D. and Freeman, H.R. and Gay, C.J. and Jones, C.P. and Luers, P.J. and Palmer, J.G., The NEAR Rendezvous Burn Anomaly of December 1998, *Technical Report, Applied Physics Laboratory, Johns Hopkins University*, 1999, https://spacese.spacegrant.org/Failure Reports/NEAR_Rendezvous_BurnMIB.pdf.

J. Vreeburg, Measured States of Sloshsat FLEVO, *Royal National Research Lab Report*, The Netherlands (NLR-TP-2005-518), 2005.

M. Fogel, ”Applying Machine Learning to the Satellite Sloshing Problem”, Masters Thesis, *Rutgers University*, Department of Mechanical and Aerospace Engineering, 98 Brett Road, Piscataway, NJ 08854, USA., 2022.

M. Fogel, S. S. Mishra, and L. Burlion, ”SPICEsat: Nanosatellite Design Considerations for a Mission to Explore the Propellant Sloshing Problem”, to appear in *AIAA Journal of Rockets and Spacecraft*, 2024.

M.J. Sidi, ”Spacecraft Dynamics and Control: A Practical Engineering Approach,” Cambridge Aerospace Series, *Cambridge University Press*, 1997.

M. Reyhanoglu and J. Rubio Hervas, ”Nonlinear dynamics and control of space vehicles with multiple fuel slosh modes”, *Control Engineering Practice*, pp.912-918, vol.20(9), 2012.

P. Sopasakis, D. Bernardini, H. Strauch, S. Bennani and A. Bemporad, ”Sloshing-aware attitude control of impulsively actuated spacecraft,” in Proc. of the 2015 *European Control Conference* (ECC), pp. 1376-1381, 2015.

Mission Concept User Guide, *University Nanosatellite Program*, Initial Release, May 2023, pg. 27. https://universitynanosat.org/resources/assets/user-guides-and-technical-documents/UNP Mission Concept User Guide.pdf

L. Berthoud, M. Swartwout, J. Cutler, D. Klumpar, J. Larsen, and J. Nielsen, ”University CubeSat Project Management for Success”, in 33rd Annual AIAA/USU Conference on Small Satellites, 2023.