1. Signature Page

2. Project Summary

The objective of this proposal is to develop a nonlinear adaptive estimation and control (AEC) theory for spacecraft' mass properties identification and manipulation for attitude control in Low Earth Orbit (LEO) using mass moving control (MMC). This objective will be achieved by **(1)** using dynamic formulation that consists of dual quaternions, **(2)** developing and verifying novel AEC theory, and **(3)** validating the theory using a state-of-the-art 5-degree-of-freedom (5-DOF) spacecraft testbed that is currently being developed by the Advanced Autonomous Multiple Spacecraft (ADAMUS) laboratory at Embry-Riddle Aeronautical University (ERAU).

RELEVANCE TO NASA - The advances proposed herein lie in the ability to autonomously characterize, compensate, and alter spacecraft's mass properties through MMC. Furthermore, improvements in ground testing of spacecraft AEC algorithms are proposed in this work. This project will directly support NASA's TX04 (Robotic Systems), TX10 (Autonomous Systems), TX13 (Ground, Test, and Surface Systems), and TX17 (Guidance, Navigation, and Control).

3. Significance of Project

Estimating the center of mass (CoM) and moment of inertia (MoI) of spacecraft is critical for many autonomous space missions where changes in mass distribution occur during the mission. A clear example is NASA's GRACE missions, where the CoM must be aligned to the onboard accelerometer's geometrical center to avoid measuring disturbance accelerations. Yet, current attitude control methods require knowledge of the initial MoI, and they are not robust in the case of gravity gradient torques acting as disturbances. These calibration maneuvers require dedicated actuators or the use of limited sources, which can add unwanted weight to the system and reduce mission lifetime, respectively [1]. Thus, designing novel, trustable AEC algorithms is required to complete an LEO mission. Moreover, their validation on the 5-DOF testbed will bridge the gap between theory and practice.

Collaborations - The proposed effort will foster collaboration among the PI, Co-PI, and Nhan Nguyen (Technical Group Lead, Advanced Control and Evolvable Systems, Intelligent Systems Division). In addition, NASA Goddard Spaceflight Center will be interested in the application of dual-quaternion-based control. The PI is collaborating with Mr. Huaizu You at GSFC, and the results of this effort will lead to joint proposals for GRACE follow-on missions.

External Funding Opportunities - Finally, the PI and Co-PI plan to use the initial results from this project to apply for external funds from NASA and DoD agencies that target both basic and application-specific proposals (details in Section 6). This project will also have impacts in other industries, such as civil engineering, for the design of earthquake-resistant buildings, through an adaptive adjustment of internal dedicated masses (NSF Dynamics, Control and Systems Diagnostics Program).

Commercialization - If successful, the new theory and testing procedures will be published and available to the space community open source.

4. Work Plan

Given a spacecraft with unknown mass properties: **(i)** unknown CoM and **(ii)** unknown MoI, we *first* would like to estimate and modify both parameters to control the orientation of the spacecraft, using only MMC. Preliminary estimation-based work has already been performed by our research team on the challenge given in **(i)** for compensating for the gravity torque experienced due to the offset between the center of rotation (CoR) and CoM of a 5-DOF testbed. Furthermore, our novel controller aims to reduce the error of the angular velocities between a reference model that describes the torque-free motion and the testbed's real motion while dealing with the challenge given in **(i)**. However, the work done so far assumes that the initial MoI is known, which might not be the case for most spacecraft. *Second*, we will design an adaptive controller to deal with the challenge given in **(ii)** such that our controller will not require the knowledge of MoI.

The controller correction of the angular rates between both trajectories ensures the persistence of excitation requirements in adaptive control to obtain convergence of the estimated parameters with their true values. This excitation is due to the magnitude of gravitational acceleration on Earth's surface. However, its magnitude diminishes as altitude increases, and its effects are relatively low once in LEO. However, spacecraft are still affected by Earth's gravitational field, which can alter their attitude through gravity gradient torque. *Third*, we will use this attitude disturbance with AEC and MMC to control the spacecraft's attitude resiliently. *Later*, we will improve the performance of the designed controller by minimizing the high-frequency oscillations resulting from the control input. *Finally,* we will implement our theory on AEC and MMC to the 5-DOF spacecraft testbed.

Note that all these concepts of the proposed theory are presented in the following subsection. Specifically, the dynamics and controller based on the 5-DOF testbed and the basis for the adaptation to spacecraft in LEO are demonstrated.

A. Ground Model Dynamics

The dynamics of the 5-DOF testbed, including external torques, are presented using Euler's rotational equations as in Eq. (1). For notation simplicity, vector variables will first be introduced with proper notation ($\vec{\cdot}$). The variables shall only be referenced for subsequent equations with its symbol ($\cdot$).

$$\vec{\tau}^{B}_{ext} = \dot{\vec{H}}^{B} + \vec{\omega}^{B}_{B/I} \times \vec{H}^{B} \quad , \quad H^{B} = J^{B}\vec{\omega}^{B}_{B/I} \tag{1}$$

Here, ($\vec{H}$) represents the angular momentum and ($\vec{\omega}$) represents the angular velocity. The MoI about CoR, (J^B), is obtained using the parallel axis theorem given in Eq. (2). The main external torque ($\vec{\tau}_{ext}$) acting on the body is the result of the gravity force plus the control input ($\vec{u}$) to be designed, all defined in Eq. (3).

$$J^{B} = J^{CoM} - M(r^{B}_{off})^{\times}(r^{B}_{off})^{\times} \tag{2}$$

$$\tau^{B}_{ext} = \vec{r}^{B}_{off} \times M\vec{g}^{I} + \vec{u} \tag{3}$$

In Eq. (2), J^{CoM} represents MoI about CoM, the superscript $(\ \cdot\ )^{\times}$ indicates the skew-symmetric matrix, M is the total mass of the spacecraft simulator (including all three sliding masses), $(\vec{g}^{I})$ represents the gravity in the inertial frame, and $\vec{r}_{off}^{B} = [r_{off_x}\, r_{off_y}\, r_{off_z}]^T$ is the unknown offset between CoM and CoR, as seen in Fig. 1. Sharing the naming convention

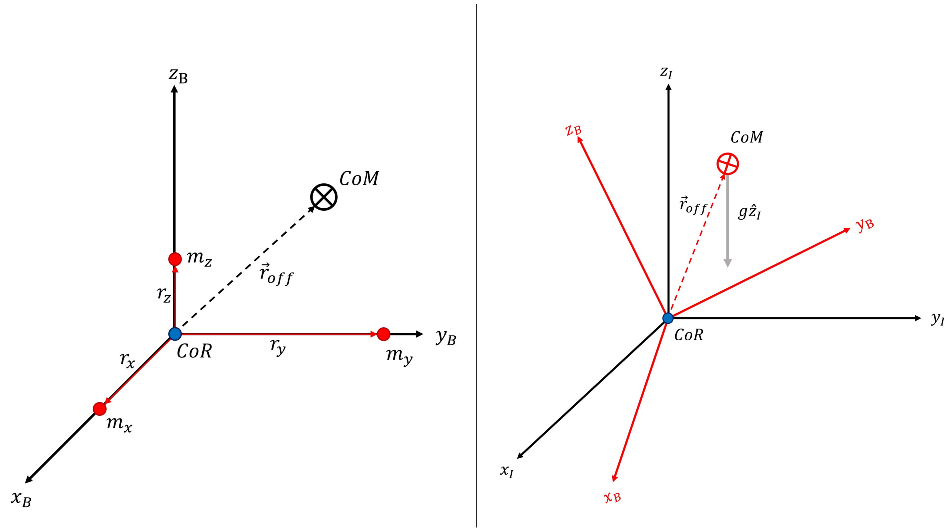

Figure 1: (Left) Diagram of Mass Balancing System (MBS) in 5-DOF ground model. (Right) Reference frames used in EOM modeling (Ground Model (GM) environment) with gravity vector direction.

defined in [2], $\vec{r}_{off}^{B}$ can be defined at the initial time ($t = 0$) as Θ. Then, one can define Φ, such that the following relationship holds.

$$\Phi\Theta = \Theta \times M g^B \quad , \quad \Phi = -\ M \left(g^B\right)^{\times} \tag{4}$$

Combining Eq. (1), Eq. (3), Eq. (4), and solving for $\dot{\omega}_{B/I}$, one can obtain Eq. (5).

$$\dot{\omega}_{B/I}^{B} = \left(J^B\right)^{-1}\left(-\omega_{B/I}^{B} \times J^B \omega_{B/I}^{B} + \Phi\Theta + u\right) \tag{5}$$

Next, to obtain the gravity vector in the testbed's body fixed frame, it is required to know the relative attitude of the body with respect to the inertial frame. This can be obtained with the kinematics equations using quaternions as shown below.

$$\dot{\breve{q}}_{B/I} = \frac{1}{2}\breve{q}_{B/I}\breve{\omega}_{B/I} \tag{6}$$

Here, $\breve{\omega}_{B/I} = [0 \ \ \vec{\omega}_{B/I}]^T$ is the quaternion representing the angular velocity of the testbed in the body fixed frame, with scalar part equal to zero. Then following the quaternion formulation, the Earth's gravity vector is projected from the inertial frame to the spacecraft's body fixed frame, using Eq. (7).

$$\breve{g}^B = \breve{q}_{B/I}^{*}\breve{g}^I\breve{q}_{B/I} \tag{7}$$

Where $\breve{g}^I = [\vec{0}_{3\times1} \ \ -g]^T$ is the quaternion representing the gravity field vector in the inertial frame, and $\breve{g}^B$ its transformation into the spacecraft simulator body fixed frame to be used to properly simulate the dynamics in Eq. (5).

B. Nonlinear AEC

The nonlinear adaptive control law objective is to follow a reference state trajectory defined by a free rotation body with the same mass properties as the testbed while updating the adaptive parameter $\hat{\Theta}(t)$ and bringing the estimation error $\tilde{\Theta}(t) = \Theta - \hat{\Theta}(t)$ to 0.

Trajectory Error Design

As mentioned, the equations of motion for a body under free rotation are defined with the same mass properties as the testbed. Thus, by setting $\tau_{ext} = \vec{0}$, that is desired external torque, the desired attitude is propagated using the structure in Eq. (6), and adding the subscript d to all variables. Then, one can define the tracking error between the desired and real trajectories, $\tilde{\omega}_{B/I} = \omega_{B/I_d} - \omega_{B/I}$, and taking the derivative with respect to time, its dynamics are obtained as:

$$\dot{\tilde{\omega}}_{B/I} = \left(J^B\right)^{-1} \left(-\ \tilde{\omega}^B_{B/I} \times J^B \omega^B_{B/I_d} -\ \omega^B_{B/I_d} \times J^B \tilde{\omega}^B_{B/I} + \Phi\Theta + u\right) \tag{8}$$

Adaptive Law and Control Input

The control law objective is to reduce the angular velocity error ($\tilde{\omega}_{B/I}$) to zero. The adaptive control law is obtained through Lyapunov analysis, using Eq. (9) as the Lyapunov candidate. The Lyapunov function is a variation of the work proposed in [2]. In this work, the angular rate error is used instead of the testbed angular rates. For notation simplicity, we assume all variables in the body-fixed frame and lose the superscript B.

$$V(x) = \frac{1}{2}\tilde{\omega}^T_{B/I} J \tilde{\omega}_{B/I} + \frac{1}{2\sigma}\tilde{\Theta}^T\tilde{\Theta} + \breve{q}^T_{B/I}\breve{q}_{B/I} \tag{9}$$

Where σ is the positive learning rate for the adaptive law. The first derivative of the Lyapunov function with respect to time is shown in Eq. (10).

$$\begin{aligned}\dot{V}(x) = &\ \tilde{\omega}^T_{B/I}\Big(-\ \tilde{\omega}_{B/I} \times J\omega_{B/I_d} -\ \omega_{B/I_d} \times J\tilde{\omega}_{B/I} + \Phi\hat{\Theta} + u\Big) \\ &+ \tilde{\Theta}^T \left(\Phi^T \tilde{\omega}_{B/I} +\ \tfrac{1}{\sigma}\dot{\tilde{\Theta}}\right)\end{aligned} \tag{10}$$

Using Eq. (10), the selection for the adaptive update law as well as control input u can be defined to obtain Lyapunov stability. Both parameters are defined in Eq. (11) and Eq. (12) respectively.

$$\dot{\hat{\Theta}} \equiv \sigma \Phi^T \tilde{\omega}_{B/I} \tag{11}$$

$$u \equiv \tilde{\omega}_{B/I} \times J\omega_{B/I_d} +\ \omega_{B/I_d} \times J\tilde{\omega}_{B/I} -\ \Phi\hat{\Theta} -\ K\tilde{\omega}_{B/I} \tag{12}$$

In Eq. (12), K is the positive definite proportional gain used to tune the performance of the controller. Substituting Eqs. (11) and (12) into Eq. (10), the later becomes:

$$\dot{V}(x) = -K\tilde{\omega}^T_{B/I}\tilde{\omega}_{B/I} + \tilde{\Theta}^T\left(\Phi^T\tilde{\omega}_{B/I} +\ \frac{1}{\sigma}\dot{\tilde{\Theta}}\right) = -K\|\tilde{\omega}_{B/I}\|^2 \leq 0 \tag{13}$$

Thus the stability of $(\tilde{\omega}_{B/I}, \tilde{\Theta}, \breve{q}_{B/I})$ in the Lyapunov sense can be concluded. Moreover, by Barbalat's Lemma, one can show that $\lim_{t\to\infty}\tilde{\omega}_{B/I} = 0$

Estimation Parameter Convergence

Using LaSalle's Invariance Principle, the convergence of the estimation error can further be proved. Since $\tilde{\omega}_{B/I} = 0$ as $t \to \infty$, and recalling Eq. (11), the following holds.

$$\dot{\tilde{\Theta}} = -\sigma \Phi^T \tilde{\omega}_{B/I} = \vec{0} \implies \tilde{\Theta} = \vec{C} \tag{14}$$

Here, $\vec{C}$ is any constant vector. Recalling that $J \neq 0$ and $\Phi \neq 0$, then $C = \tilde{\Theta} = 0$. That is the estimated parameters converge to the true values. With this, it has been shown that CoM can be estimated to its true values if the initial MoI is known using only MMC, which has not been achieved with previous estimation algorithms, as shown in **Section 5**.

C. Spacecraft Application

With the basis of the work shown in **Subsections A** and **B**, modifications to the controller to account for actuator saturation and time-varying moment of inertia are to be investigated, which will improve the controller's performance through robustness and model accuracy. These improvements are then to be applied to a spacecraft model to obtain attitude control in LEO through shifting masses only.

The main difference between the GM and LEO dynamics is the magnitude of the disturbances acting on the spacecraft. For the LEO application, the new EOM are derived as follows. First, we must redefine the reference frames as in Fig. 2. The subscript I indicates the canonical Earth-Centered Inertial Frame and the desired and body-fixed frames are defined by D and B respectively.

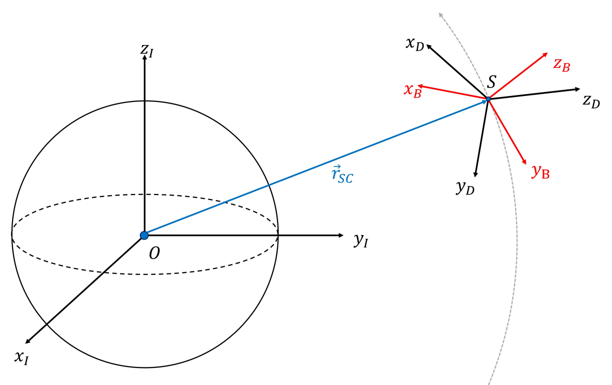

Figure 2: Reference frames used in EOM modeling (LEO environment).

In the LEO environment, the dynamics must encapsulate both the translational and rotational motion of the spacecraft. Dual quaternions have been proven to provide more accurate results due to the coupling of translational and rotational motion in [3, 4, 5]. The coupled EOM using dual quaternions for the relative pose for a spacecraft with a time-varying moment of inertia are formulated in [3] as follows.

$$\begin{aligned}\left(\dot{\check{\omega}}^B_{B/D}\right)^S = \left(M^B(t)\right)^{-1}\left[\check{f}^B - \left(\check{\omega}^B_{B/D} + \check{\omega}^B_{D/I}\right) \times \left(M^B(t)\left(\left(\check{\omega}^B_{B/D}\right)^S + \left(\check{\omega}^B_{D/I}\right)^S\right)\right)\right] \\ - \left(\check{q}^*_{B/D}\dot{\check{\omega}}^D_{D/I}\check{q}_{B/D}\right)^S - \left(\check{\omega}^B_{D/I} \times \check{\omega}^B_{B/D}\right)^S\end{aligned} \tag{15}$$

Where $\check{f}^B$ represents the dual forces (DF) acting on the spacecraft, and are depicted in [3] as follows:

$$\check{f}^B = \check{f}^B_g + \check{f}^B_{\nabla g} + \check{f}^B_{J_2} + \check{f}^B_d + \check{f}^B_u \tag{16}$$

Here, $(\check{f}^B_g)$ is the gravity DF, $(\check{f}^B_{\nabla g})$ is the gravity gradient DF, $(\check{f}^B_{J_2})$ is the J_2 DF, $(\check{f}^B_d)$ are disturbance DF (drag, solar radiation pressure, magnetic field), and $(\check{f}^B_u)$ are input DF. In dual-quaternion form, forces are represented by a translational real part and a rotational dual part multiplied by (ϵ), the dual parameter. One can further expand the forces acting on the spacecraft as follows:

$$\check{f}_g^B = M\begin{bmatrix} 0 \\ -\mu\frac{\vec{r}^B_{B/I}}{\|\vec{r}^B_{B/I}\|^3}\end{bmatrix} + \epsilon 0\ ,\ \check{f}_{J_2}^B = M\begin{bmatrix} 0 \\ \frac{3\mu J_2 R_e^2}{2\|\vec{r}^I_{B/I}\|^4}\begin{pmatrix}\left(1-5\left(\frac{z^I_{B/I}}{\|\vec{r}^I_{B/I}\|}\right)^2\right)\frac{x^I_{B/I}}{\|\vec{r}^I_{B/I}\|} \\ \left(1-5\left(\frac{z^I_{B/I}}{\|\vec{r}^I_{B/I}\|}\right)^2\right)\frac{y^I_{B/I}}{\|\vec{r}^I_{B/I}\|} \\ \left(3-5\left(\frac{z^I_{B/I}}{\|\vec{r}^I_{B/I}\|}\right)^2\right)\frac{z^I_{B/I}}{\|\vec{r}^I_{B/I}\|}\end{pmatrix}\end{bmatrix} + \epsilon 0 \quad (17)$$

$$\check{f}_{\nabla g}^B = 0 + \epsilon\begin{bmatrix} 0 \\ 3\mu\frac{\vec{r}^B_{B/I}\times\left(J^B(t)\vec{r}^B_{B/I}\right)}{\|\vec{r}^B_{B/I}\|^5}\end{bmatrix} \quad (18)$$

Here,($R_e = 6378.137$ km) is the Earth's mean equatorial radius, ($\mu = 398600.4418$ km^3/s^2) is Earth's gravitational parameter, ($\check{f}_d^B$) is not modeled, and ($\check{f}_u^B$) shall be similarly designed as in **Subsection B**, through Lyapunov analysis. Using the EOM presented above, we aim to design an AEC framework that can estimate the **(i)** and **(ii)** of the spacecraft using the relationship defined in Eq. (2). By defining a desired state trajectory and reducing the angular rate errors due to a MOI error between real and desired trajectories, the CoM shall be estimated and compensated, eventually suppressing the second term in Eq. (2), thus making $J^D = J^M$. Note that in this case, while the MOI of the spacecraft is time-varying, the mass of the body remains unchanged; thus $\check{f}_g^B$ and $\check{f}_{J_2}^B$, which affects the translational motion of the body, remain unchanged between desired and real trajectories. Furthermore, we can define the rate of change in the spacecraft's moment of inertia by taking the first-time derivative of Eq. (2). In addition, we will consider the case where (M), the dual moment of inertia matrix is unknown. Finally, we plan to increase the performance and robustness of the proposed controller by using a low-frequency method and accounting for MMC actuator limitations. As shown in **Section 5**, this combination of control techniques has not yet been developed and shall bring significant advances to AEC using MMC with unknown M and CoM.

Challenges, Risk, and Mitigation Plans - Since the proposed work is mostly theoretical and simulation-based, we do not envision critical risks. Laboratory experimentation will demonstrate the capabilities of the algorithms with hardware in the loop and real-time, and the risks will be minimal, being the laboratory environment entirely controlled.

Technology Readiness Level (TRL) - At the end of this effort, we envision a TRL 4.

5. Prior State of Knowledge and Proposed Advances

Spacecraft simulators and testbeds are a recurring resource used in the aerospace industry. When launching a satellite, testing is essential to increase the chances of mission success.

With the increasing trend of low-budget small satellites, especially present in academia, having access to a relatively low-cost manner of validating new autonomous estimation and control algorithms is key to maintaining high mission success without exceeding the budget. To be able to simulate space-like conditions, two major disturbances must be mitigated: friction and gravity torque. The first is generally eliminated with the use of granite tables, epoxy floors, and air bearings, that is, by creating a thin film of air between two contact surfaces, virtually eliminating the friction forces generated between them. The air bearings allow frictionless translational motion (flat air bearings) as well as rotational motion (spherical air bearings) for a total of up to 6-DOF frictionless motion. The second is caused by the offset vector between the CoM and the CoR. The second disturbance has been solved through multiple methods, which are presented in [6], altogether with their major benefits and drawbacks. To mitigate the effects of gravity torque, manual compensation, batch estimation, filtering, and active control techniques are used.

Specifically, manual balancing has been used in multiple testbeds, and although it can reduce the gravity torque up to 0.01 Nm [7], the disturbance is still significant when performing precision testing. Furthermore, it is a time-consuming process, subject to human error, and must be performed before each experiment. [8] Batch estimation techniques are commonly used for MBS. Unknown parameters are estimated through observation and data recording of the free oscillating body, which behaves as a three-dimensional pendulum under gravity torque. This process leads to higher precision, with a final offset of 2×10^{-6} m for a 14.24 kg testbed. [9] However, this approach requires large data-storing capabilities and an iterative process which may prove time-consuming. [10] The Kalman filter approach, and its extensions, are currently the most used [6] for MBS. The major benefits are handling process noise, lower computational efforts, and the ability to handle both linear and non-linear dynamical systems. However, this approach is usually used with momentum exchange devices.

The last technique used for MBS is active control [2, 11, 12]. The majority of these approaches use external actuators to generate the control torque necessary to compensate for or estimate the gravity effects. The only found case of using only sliding masses is [2], where the CoM offset is compensated with a combination of active estimation and control maneuvers. *The work presented in this proposal* reduces the controller to a single maneuver by modifying the adaptive control law approach and allowing for the estimation of all three vector components while using only sliding masses to generate the control torque. Furthermore, we aim to improve the robustness and performance of the system by adding saturation limits and low-frequency adaptation into our model and eliminating the assumption of a known moment of inertia. The work reviewed for this proposal does not take these two additions into account. Then, we aim to adapt the controller to an LEO space model using MMC.

Attitude control using MMC technology is studied in [13]. In this work, MMC finds application in a wide variety of fields, such as spacecraft, spinning projectiles, underwater vehicles, aerial vehicles, and reentry vehicles. Previous work has been done regarding mass properties estimation and attitude control using MMC for spacecraft. Most of this work uses the changing torque generated by drag in LEO. However, it is known that as altitude is increased, the effects of drag are diminished. For this reason, *our proposal* aims to use

MMC by using the effects of gravity gradient torque in LEO. Some previous work has been done in this field [14, 15, 16]. However, in [14] a simplified linear model with assumptions such as instantaneous mass shifting is assumed. Furthermore, it is mentioned in [14] that the controlling maneuver might require an iterative process of repeated maneuvers to obtain attitude control success. On the other hand, [15] presents a detumbling non-linear control maneuver in LEO using MMC with a gravity gradient. However, it assumes known mass distribution properties and does not extend on attitude control after detumbling has been achieved. The work presented in [16] shows full-domain attitude reorientation using MMC in a combination of sequence rotation with small angle maneuver by assuming that the system properties and dynamics are fully known.

Motivating by the above-mentioned research gaps, the proposed advances for our proposal include **(I)** estimating the moment of inertia and center of mass of a spacecraft in LEO using MMC only, **(II)** extending the results of [14, 15] using MMC under gravity gradient torque with a non-linear adaptive control law for attitude control after detumbling, **(III)** adding robustness and performance guarantees to the spacecraft model by applying saturation limits and low-frequency adaptation, and **(IV)** verifying the theoretical advances through testing with a 5-DOF testbed.

6. Extent to which the proposed work supports NASA's four Mission Directorates and/or the State's goals of building the space industry in Florida

The proposed project aligns with NASA's Space Technology Mission Directorate (STMD) by advancing technologies highly important for autonomous spacecraft estimation, control, and mass properties manipulation. Proposed work is set to enhance capabilities in robotics, autonomous systems, and ground testing, pivotal for STMD's goal of propelling technological innovation to expedite future space missions and ensure leadership in aerospace technology. It directly supports NASA's objectives under TX04, TX10, TX13, and TX17, thereby addressing critical areas in robotic systems, autonomous estimation and control essential for the Artemis missions and beyond.

Moreover, this project holds the potential to significantly boost the space industry in Florida by fostering advancements in space technology and creating opportunities for local aerospace businesses and research institutions. Companies like Terran Orbital, Space Perspective, Sidus Space, and Moon Express, based in Florida, might directly benefit from the advancements of our proposed work. By increasing Florida's robust space infrastructure, the project can contribute to the state's economy and reinforce its status as a leading hub for space exploration and technology development. Collaboration with NASA and the infusion of cutting-edge research and innovation from this project is aimed at enhancing Florida's competitiveness in the global space industry.

7. Potential Sources for Continued Support

Specific plans for external funding will be fleshed out during the conversations between PI, Co-PI, NASA, and industry collaborators on developing, verifying, and validating autonomous AEC system. Furthermore, for application-specific proposals targeting theoretical and technological developments, the project will also be sustained by collaborating with the industry through SBIR/ STTR-like research activities and seeking funding from DoD. The likelihood of obtaining funding is very high.

8. Key Personnel and Levels of Commitment

Level of Commitment

Drs. Bevilacqua and Dogan will work with research students (RS) in this project. To accomplish the **Tasks 1-3** given below, the PI, Co-PI, and RS will perform necessary theoretical developments. For **Task 4 and 5**, the RS will perform necessary simulation and experimental studies. Note that weekly face-to-face/online meetings will be organized within the PI, Co-PI, and RS to successfully accomplish the tasks of this proposal.

Finally, as noted earlier, this project will be executed in close collaboration with **Dr. Nhan Nguyen** from NASA Ames (**letter** attached). Specifically, the PI and Co-PI will collaborate with him in developing algorithms for AEC, in which Dr. Nguyen has a significant interest. Our results will also be publicly available at the premier journals and conferences of the IEEE, ASME, AIAA, and IFAC.

Expertise of Teams

Dr. Bevilacqua has published over 150 journal and conference articles on spacecraft guidance, navigation, and control. He is and has been the lead PI for several DoD and NASA projects, including the flight operations of two CubeSats. He has received multiple DoD prestigious awards over his career.

Dr. Dogan has published over 80 papers, with the majority focused on the verification and validation of control systems in the presence of uncertainties and unknown terms. She has received several awards on resilient control design, including several STTR/SBIR projects and two FAA projects. She has supervised several PhD, MSc, and undergrad students.

Prior Relevant Work

Dr. Bevilacqua is an expert on nonlinear, adaptive, and machine learning based control for orbital systems. His CV contains additional information.

Dr. Dogan has previously designed, verified, and validated adaptive controls in the presence of uncertainties, actuator constraints, and performance constraints. The journal papers [2]-[14], and the conference papers [6]-[49] & [53]-[60] on her CV are related to this proposal.

Tasks Summary

1. Theoretical developments of novel AEC controller that can deal with unknown MOI as well as modifying the controller to estimate the MoI of the 5-DOF testbed.

2. Theoretical developments of the novel controller using gravity gradient disturbance for LEO spacecraft using MMC. This includes modeling the EOM for the LEO environment using dual-quaternion dynamics representations.
3. Providing robustness of the AEC controller by considering actuator dynamics and ensuring saturation bounds in terms of position and velocities of the MMC.
4. Numerical simulations of the theoretical results obtained through Tasks 1-3 using MATLAB, Simulink, and Python.
5. Experimentation of the novel controller using a 5-DOF testbed with a dedicated MBS for gravity torque compensation.

Facilities, Software Tools, and Equipment

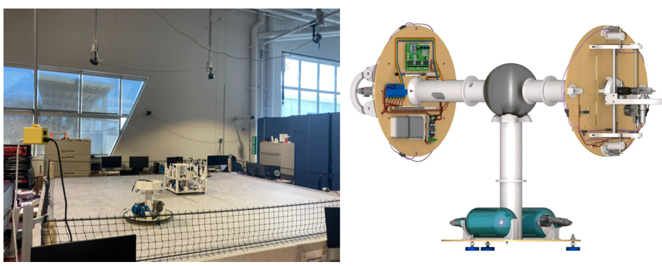

Figure 3: (Left) Family of current spacecraft test beds on 14×14 ft granite table in ADAMUS laboratory. (Right) CAD Model of dumbbell 5-DOF with mass balancing system currently being assembled by the ADAMUS team.

The work presented in this proposal will take place at the **ADAMUS** laboratory at **ERAU (DB)**. The ADAMUS laboratory operates with state-of-the-art computers equipped with Windows, macOS, and Linux OS, and industry-focused software tools such as MATLAB, STK, CATIA, SOLIDWORKS, and other open-source software. Furthermore, the laboratory has a 14×14 ft granite table and a fleet of spacecraft testbeds that allow for simulation of space-like motion in 3-DOF and 5-DOF using state-of-the-art air bearing technology. The testbeds can be equipped with actuators and sensors such as thrusters, reaction wheels, sliding masses, IMUs, etc., and use PhaseSpace infrared cameras to obtain real-time pose data. The ADAMUS team is currently assembling a new state-of-the-art dumbbell 5-DOF testbed that allows planar motion, full rotational motion about two axes, and restricted motion to $\pm 40^o$ about the third axis, see Fig. 3. This new testbed shall be used for this work. The PI and Co-PI have access to undergraduate student participation as needed for assistance with setting up the experiments in the Facilities, Software Tools, and Equipment.

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9. Budget

See attachment for the budget excel sheet completed by the Office of Sponsored Research Administration with the detailed cost sharing document.

10. Support Letters

This attachment includes:

- Collaboration/support letter of the Dr. Nhan Nguyen from NASA Ames Research Center.

11. PI and Co-PI's Standard Curriculum Vitae (CV)

Please see the attached CVs of PI and Co-PI.