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Mitigating fuel sloshing disturbance in on-orbit satellite refueling: an Experimental study

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Abstract

In this study, a control strategy for on-orbit satellite refueling is proposed and experimentally evaluated, with a particular focus on mitigating the fuel sloshing disturbance during the docking phase. The ability to refuel satellites in orbit is a crucial aspect of satellite operations, as it can extend their lifespan and improve their overall performance. The proposed strategy combines model predictive control and linear quadratic gaussian control techniques to address the fuel sloshing disturbance, modeled using a spherical pendulum. Specifically, a stationary target satellite is to be refueled by a tanker satellite in the scenario. The fuel sloshing disturbance is induced by two 3DOF floating platforms, one of which carries a large fuel tank and acts as the tanker, while the other platform carries a small tank and serves as the target satellite. Experimental evaluations of the proposed control strategy were conducted in the Zero-G Lab facilities of the University of Luxembourg. The experiments involved the control of the tanker satellite to approach and dock with the target satellite while simultaneously compensating for the fuel sloshing disturbance. The performance of the proposed control strategy was evaluated in terms of the accuracy and safety of the docking process, as well as the fuel efficiency of the refueling mission. The results of the experimental evaluations demonstrate the effectiveness and feasibility of the proposed control strategy for mitigating the fuel sloshing disturbance during the docking phase of an on-orbit satellite refueling mission. Specifically, the proposed strategy achieved a safe and fuel-efficient docking trajectory in the presence of the fuel-sloshing disturbance induced by the floating platforms. These findings validate the simulation-based results and contribute to advancing on-orbit satellite refueling technology. Moreover, the proposed strategy has the potential to pave the way for more extended and more efficient on-orbit satellite missions.

Keywords: satellite docking, orbital refuelling, model predictive control, floating platform

1. Introduction

Satellites play a critical role in various space missions, but their finite lifespan and the absence of maintenance and repair infrastructure in space result in costly satellite deterioration and the generation of space debris. As the demand for satellite-based services increases and ambitious missions to destinations like the Moon, Mars, and deep space loom on the horizon, extending the lifespan of satellites has emerged as a crucial research endeavor. In-orbit satellite servicing, particularly orbital refueling, has the potential to revolutionize space missions by enhancing mission flexibility and resilience, reducing launch costs, and prolonging satellite operation [1-3]. By enabling satellites to undertake new or supplementary missions such as servicing other satellites, removing debris, and constructing space-based infrastructure, on-orbit refueling offers a pathway to sustainable and efficient space resource utilization, as well as space exploration and colonization [4, 5].

Considerable research efforts have been dedicated to developing the essential technologies required for in-orbit refueling, including advanced propulsion systems, robotic servicing technologies, and control systems. However, the reliability of these technologies remains uncertain due to the lack of comprehensive operational testing [6]. Refueling strategies and corresponding algorithms have been devised for refueling multiple satellites, encompassing various approaches such as one-to-one (O2O) [7], one-to-many (O2M) [7], many-to-many (M2M) [8], peer-to-peer (P2P) [9], egalitarian P2P [10], cooperative P2P [11], and mixed refueling strategies [12].

Although most studies have focused on refueling multiple geosynchronous orbit (GEO) satellites [13, 14], less attention has been given to refueling satellites in low Earth orbit (LEO). Nonetheless, some investigations have proposed formation flight solutions for refueling circular satellite constellations and explored the P2P strategy for refueling LEO constellations while considering factors such as perturbations, communication links, sun illumination, hold points for different rendezvous phases, and sensor switching [15, 16]. Furthermore, the study in [17] addresses the intricate scheduling problem concerning the refueling of numerous Sun-synchronous orbit satellites using multiple resupply spacecraft while accounting for J2 perturbation. Research efforts have examined optimized strategies for both P2P and mixed refueling within circular constellations [12]. Similarly, circular constellation refueling employing the P2P strategy has been explored in [18] with the aim of equitably distributing fuel among constellation satellites. A comparative analysis between S2M and P2P refueling strategies has been conducted in [19], revealing that a hybrid strategy incorporating a P2P component yields superior overall fuel efficiency.

However, it's essential to note that the implementation of orbital refueling hinges on the successful execution of rendezvous and docking maneuvers. As orbital refueling missions entail the risk of unwanted collisions due to even minor velocity discrepancies during docking, the associated control algorithm is paramount for ensuring both safety and precision. While various proposed control methodologies satisfy the requisite performance criteria for satellite docking, they may not seamlessly translate to orbital refueling missions. This is attributed to the significant influence of fuel sloshing, a complex dynamic phenomenon whose model is imprecisely defined, on satellite dynamics during orbital refueling. Consequently, the development of a robust control scheme becomes imperative to guarantee smooth satellite docking while accommodating the disruptive effects of fuel sloshing disturbances. Furthermore, incorporating a collision avoidance constraint is crucial to upholding the safety of all satellites involved.

This study aims to propose a control strategy for on-orbit satellite refueling that specifically targets the mitigation of fuel sloshing disturbances during the docking phase. The proposed strategy combines model predictive control and linear quadratic Gaussian control techniques to effectively address the fuel sloshing disturbance, which is modeled using a spherical pendulum. Specifically, the scenario involves the refueling of a stationary target satellite by a tanker satellite. The fuel sloshing disturbance is induced by two three-degree-of-freedom (3DOF) floating platforms, with one platform carrying a large fuel tank and acting as the tanker, while the other platform carries a smaller tank and serves as the target satellite.

To evaluate the effectiveness of the proposed control strategy, experimental evaluations were conducted in the Zero-G Lab facilities at the University of Luxembourg [20]. These facilities provide a microgravity environment that simulates the docking and relative dynamics of satellites in space. Similar to an air hockey platform, the lab allows for the observation of how spacecraft, orbital robotics, and other spacecraft can be controlled or perform with decoupled systems in this unique environment. Within this laboratory setting, the control of the tanker satellite to approach and dock with the target satellite, while compensating for the fuel sloshing disturbance, was examined.

The performance of the proposed control strategy was assessed based on the accuracy and safety of the docking process, as well as the fuel efficiency of the refueling mission. The results of the experimental evaluations demonstrate the efficacy and feasibility of the proposed control strategy in mitigating the fuel sloshing disturbance during the docking phase of an on-orbit satellite refueling mission. Specifically, the proposed strategy achieved a safe and fuel-efficient docking trajectory in the presence of the fuel sloshing disturbance induced by the floating platforms. These findings validate the simulation-based results and contribute to the advancement of on-orbit satellite refueling technology. Moreover, the proposed strategy holds the potential to pave the way for more extensive and efficient on-orbit satellite missions.

Following the introduction, the subsequent section will introduce the Zero-G Lab facilities at the University of Luxembourg, where the experimental evaluations were conducted. In Chapter 3, we will present the comprehensive modeling of the on-orbit satellite refueling system, which includes the representation of the fuel sloshing disturbance and the control inputs. Chapter 4 will focus on detailing the control algorithm, which proposes a combination of model predictive control and linear quadratic Gaussian control techniques to address the fuel sloshing disturbance. In Chapter 5, we will present the results obtained from the experimental evaluations, further demonstrating the effectiveness and feasibility of the proposed control strategy in mitigating the fuel sloshing disturbance during the docking phase of an on-orbit satellite refueling mission. Finally, the conclusion will provide remarks on the significance of our findings and discuss the potential of the proposed strategy to enable more extensive and efficient on-orbit satellite missions.

2. Zero G lab

The Zero-G Lab at the University of Luxembourg, shown in Figure 1, features an advanced mechatronic system known as a floating platform, which has proven to be an essential tool for conducting research on on-orbit satellite operations. The lab is a collaboration between different groups of the university, including SpaceR, SpaSys, CVI2, and ARG. The floating platform is designed to simulate the microgravity environment of space and enable the testing and validation of various space technologies and systems [21].

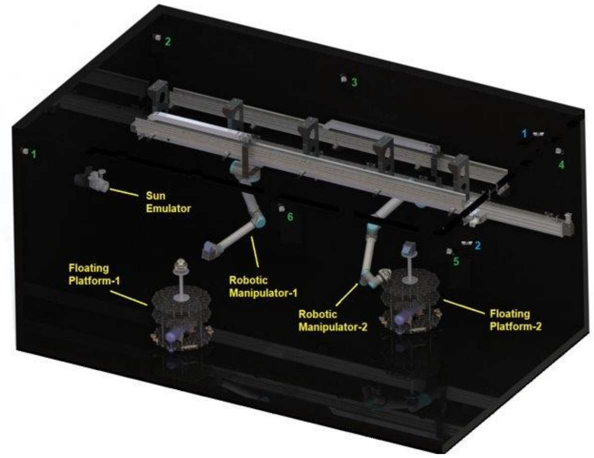

Figure 1 The schematic outline of the Zero-G Lab.

The floating platform consists of several components, including a power source, computation board, solenoid valves, air-bearings, pressure tank, and sensors. The air-bearings, in particular, play a crucial role in the functioning of the floating platform. They are pneumatic components that blow high-pressurized air towards the epoxy floor to remove the mechanical contact between the air-bearing mounted beneath the floating platform and the floor, creating a near-frictionless environment that simulates microgravity.

The floating platform is integrated into the Robot Operating System (ROS) network of the Zero-G Lab, which means that any data generated by the platform is published to the topics/nodes that the UR10 robots of the lab can access. This integration provides an opportunity for both the floating platforms and UR10 robots to synchronize and realize any type of orbital scenario, such as rendezvous, docking, and capture.

To enable programming of the floating platform, a ROS-MATLAB bridge has been created, allowing the platform to be programmed using the popular MATLAB environment. Two main experiments have been defined to test the capabilities of the floating platform: holding its position under mechanical disturbances and tracking a user-defined trajectory. Figure 2 shows how system works.

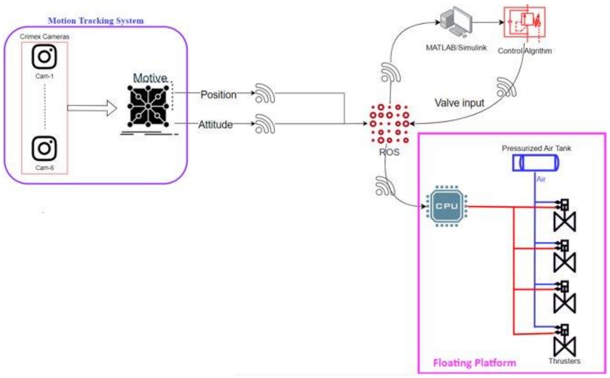

Figure 2 The system data flow in the Zero-G Lab.

In this study, the floating platform is used to simulate the fuel sloshing disturbance that occurs during the docking phase of on-orbit satellite refueling. The configuration is shown in Figure 3.

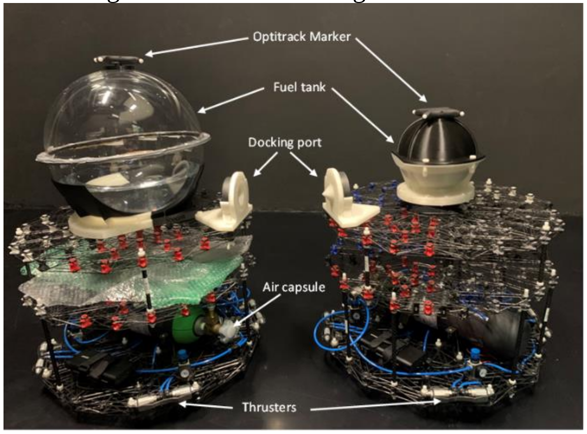

Figure 3 The floating platform configuration for the fuel sloshing test.

3. Dynamics

The phenomenon of sloshing occurs when a liquid inside a container undergoes oscillating movements, primarily influenced by the shape of the container and the applied accelerations, including gravity. The first mode of sloshing exhibits the most significant disruption in the liquid's center of mass, resulting in system-wide oscillations. To analyze sloshing dynamics, it is common to employ mechanical equivalents that capture the forces and torques acting on the system, thereby simplifying the motion analysis compared to complex fluid dynamics equations.

In the context of this study, the sloshing dynamics are approximated using a mechanical system represented by a spherical pendulum. Consider a rigid spacecraft, referred to as the tanker, moving within a fixed plane corresponding to the orbital plane of the target satellite. The tanker incorporates a spherical fuel tank, and Figure 4 illustrates the tanker model in its corresponding body frame. The slosh dynamics are analogously represented by a spherical pendulum with a length denoted as l. In this model, it is assumed that the tanker's motion is restricted to a planar movement and rotation around the Z-axis.

The total mass of the spacecraft, regardless of the fuel, is denoted by M, while the mass equivalent of the fuel is represented as m. Describing the free surface of the liquid requires two angles: the polar angle, θ, and the azimuthal angle, ϕ. The tanker is equipped with eight on/off thrusters, facilitating the necessary attitude control around the Z-axis, ψ, and planar motion control within the $X-Y$ plane, which coincides with the orbital plane.

By employing this mechanical representation and considering the system's characteristics, the sloshing dynamics during the docking phase of on-orbit satellite refueling can be studied, enabling the development of effective control strategies to mitigate the disruptive effects of sloshing.

The equation of motion for the tanker in the inertial reference frame can be derived using Lagrange's equations [22]:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\boldsymbol{p}}} - \frac{\partial L}{\partial \boldsymbol{p}} = \boldsymbol{\Sigma_p} \tag{1}$$

Here, $L = T - U$ represents the Lagrangian of the system, where $\boldsymbol{p} = [X\ Y\ \theta\ \phi\ \psi]^T$ denotes the vector of generalized coordinates, and $\boldsymbol{\Sigma_p}$ is the vector of generalized forces acting on the system. T and U correspond to the kinetic and potential energy of the system, respectively. The equations of motion of the system can be derived as follows:

$$\begin{aligned}
(m+M)\ddot{X} &= f_x + f_{g_X} \\
&\quad + ml\big(\sin\theta\cos\phi\,(\dot{\theta}^2 \\
&\quad + \dot{\phi}^2) + 2\cos\theta\sin\phi\,\dot{\theta}\dot{\phi}\big) \\
&\quad - ml\big(\cos\theta\cos\phi\,\ddot{\theta} \\
&\quad - \sin\theta\sin\phi\,\ddot{\phi}\big) \\
(m+M)\ddot{Y} &= f_y + f_{g_Y} \\
&\quad + ml\big(\sin\theta\sin\phi\,(\dot{\theta}^2 \\
&\quad + \dot{\phi}^2) - 2\cos\theta\cos\phi\,\dot{\theta}\dot{\phi}\big) \\
&\quad - ml\big(\cos\theta\sin\phi\,\ddot{\theta} \\
&\quad + \sin\theta\cos\phi\,\ddot{\phi}\big) \\
l\ddot{\theta} &= l\sin\theta\cos\theta\,\dot{\phi}^2 - g\sin\theta \\
&\quad - \big(\ddot{X}\cos\theta\cos\phi \\
&\quad + \ddot{Y}\cos\theta\sin\phi\big) \\
l\sin\theta\,\ddot{\phi} &= \ddot{X}\sin\phi - \ddot{Y}\cos\phi - 2l\cos\theta\,\dot{\theta}\dot{\phi} \\
\mathbf{I}\ddot{\psi} &= \tau
\end{aligned} \tag{2}$$

In the given equations, the control moment generated by thrusters is denoted by τ, and $\mathbf{I}$ represents the moment of inertia of the floating platform. Furthermore, f_g represents the Earth's gravitational force acting on the tanker with respect to the target satellite, which can be calculated using the Clohessy–Wiltshire equations [23].

This model forms the basis for the development and implementation of control strategies to mitigate fuel sloshing disturbances during on-orbit satellite refueling operations.

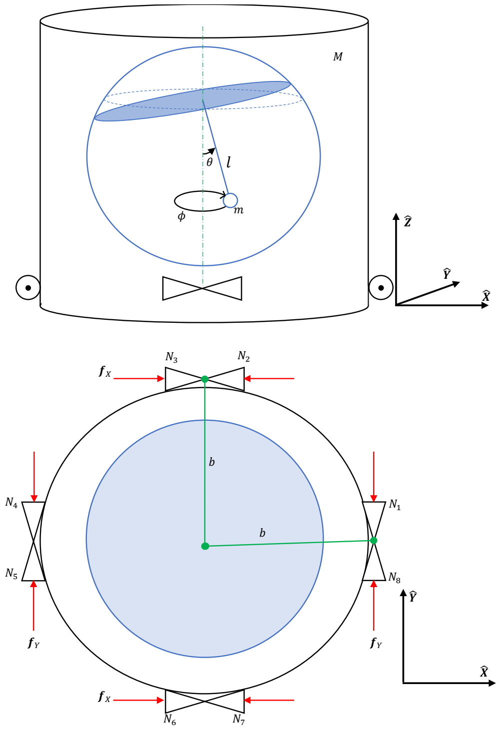

Figure 4 Parameters of the system dynamics.

4. Control

In this section, we present the control scheme designed to mitigate fuel sloshing disturbances during the docking phase of on-orbit satellite refueling. The control scheme incorporates two main components: Model Predictive Control (MPC) for path planning and Proportional-Derivative (PD) control for trajectory following. The schematic diagram of the control loop is shown in **Figure 5**, which will be discussed in detail in the rest of the section.

4.1 Model Predictive Control for Path Planning

The path planning component employs MPC to optimize the trajectory for safe and efficient docking. The distinctive characteristics of MPC that render it well-suited for diverse aerospace applications, including space tether control [24], path planning [25], satellite formation flight control [26, 27], spacecraft rendezvous control [28], satellite attitude control [29], satellite maneuvering planning [30] , and asteroid landing control [31-33], establish MPC as a compelling choice for the path generation for floating platforms.

The optimization problem is formulated as a finite-time horizon optimal control problem, aiming to minimize a cost function representing the deviation of the satellite's state (position and velocity) from the desired final docking states, $\boldsymbol{\eta}_f$, and the control inputs (thrust) applied during the trajectory. Subject to the dynamics of the system and constraints on control inputs and states, MPC solves this optimization problem iteratively at each time step. The resulting sequence of control inputs adapts in real-time to the evolving system dynamics, enabling precise trajectory planning that considers fuel sloshing disturbances and system uncertainties.

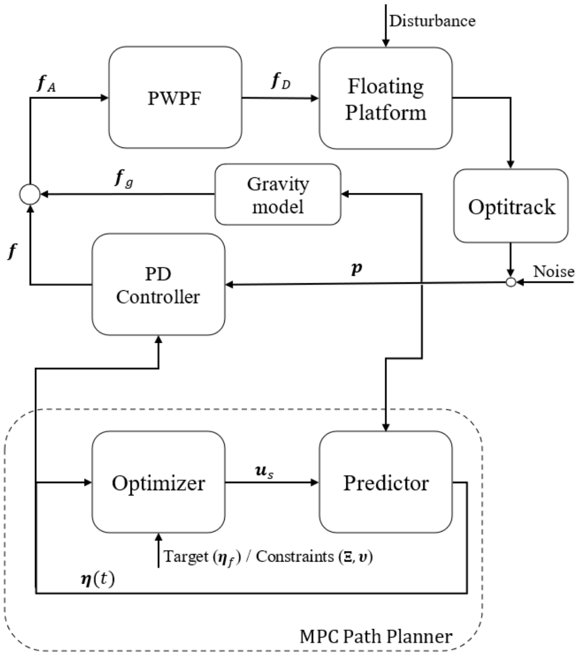

Figure 5 Schematic structure of the control system.

The optimization problem for path planning using MPC is expressed as follows:

$$\text{Minimize}_{u_s} \int_{t=t_0}^{t_f} \left[\left\| \boldsymbol{\eta}(t) - \boldsymbol{\eta}_f \right\|_{\Omega}^{2} + \left\| \boldsymbol{u}_{s(t)} \right\|_{\omega}^{2} \right] dt$$

$$\begin{gathered} \text{Subject to:} \\ \dot{\boldsymbol{\eta}}(t) = A\boldsymbol{\eta}(t) + B\boldsymbol{u}_{s(t)} \\ \boldsymbol{\eta}(t) \in \Xi \\ \boldsymbol{u}_s(t) \in \upsilon \\ \boldsymbol{\eta}(t_0) = \boldsymbol{p}(t_0) \end{gathered} \tag{3}$$

where t_f represents the final docking time, t_0 represents the current time instant, $\eta(t)$ represents the state vector of the linearized system, η_f represents the desired final docking states, $\|.\|_{\Omega}^{2}$ denotes the weighted norm of a quantity defined by $(.)^T \Omega (.)$, with Ω being a positive definite matrix, $u_s(t)$ represents the control input (thrust), A and B are system matrices representing the linearized dynamics of the satellite, Ξ is the set of feasible states representing constraints, υ is the set of feasible control inputs representing constraints, and $\boldsymbol{p}(t_0)$ represents the initial state of the system.

4.2 PD Control for Trajectory Following

The PD control component ensures accurate trajectory following during the docking phase. The control law is expressed as a linear combination of the error, $\boldsymbol{e}(t)$, between the desired trajectory, $\boldsymbol{\eta}(t)$, and the actual trajectory, $\boldsymbol{p}(t)$, of the satellite. The control input (thrust) at each time step is determined by the proportional gain, K_p, and derivative gain, K_d. The proportional term drives the system towards the desired trajectory, while the derivative term dampens any oscillations around the desired path.

4.3 Integration of MPC and PD Control

The integration of MPC and PD control within the proposed scheme allows for effective trajectory planning and responsive trajectory tracking, essential during the docking process, particularly in the presence of fuel sloshing disturbances.

MPC's predictive capabilities optimize the trajectory by accounting for future system behavior and considering uncertainties and disturbances. PD control complements MPC by providing immediate corrective actions, ensuring precise trajectory following in real-time. The hybrid control approach enhances the overall performance of the docking process, guaranteeing safety, accuracy, and efficiency in on-orbit satellite refueling missions.

4.4 Practical Implementation and On/Off Control

In practical satellite missions, thrusters often operate in an on/off manner. To implement control commands generated by the combined MPC and PD controller, we employ a Pulse-Width Pulse-Frequency (PWPF) modulator. This modulation technique converts continuous analog control commands, $\boldsymbol{f}_A$, into discrete on/off signals for the thrusters, $\boldsymbol{f}_D$.

The PWPF modulator incorporates a Schmidt trigger and a first-order filter, adjusting the width and frequency of control pulses to regulate the thrust amplitude efficiently. This modulation technique offers advantages, such as reduced fuel consumption and improved accuracy compared to classical on/off controllers [34].

5. Simulation results

In this section, we present the comprehensive results obtained from the experiments conducted in the Zero-G Lab facilities at the University of Luxembourg. The experiments aimed to rigorously evaluate the efficacy and feasibility of the proposed control scheme for mitigating fuel sloshing disturbances during the docking phase of on-orbit satellite refueling.

The simulation experiments were conducted based on the following system specifications, as shown in Table 1. In the docking scenario, the tanker (Floating platform-A) should dock with the target satellite (Floating platform-B) at the desired docking state $[x, y, \theta] = [1m, 1m, 20^o]$. MPC with a prediction horizon of 10 s and a time step of 0.1 s is employed to generate the reference trajectory. Moreover, $\mathbf{\Omega}$ is a diagonal matrix whose position- and angle-related diagonal elements are 1, and the time derivative-related elements are 100. In addition, $\boldsymbol{\omega}$ refers to a diagonal matrix with all diagonal elements equal to 1000.

The time histories of the reference position are illustrated in **Figure 6**, demonstrating the successful achievement of the desired docking point. Throughout the trajectory, the control scheme precisely guides the tanker satellite, maintaining alignment with the reference trajectory.

Table 1. System specification of the fuel sloshing experiment.

Parameter	Value
Floating Platform Mass	5 kg
Liquid Mass	10 kg
Tank Diameter	0.4 m
System Frequency	10 Hz
Nozzle Thrust Level	1 N
Moment of Inertia of Floating Platform	$5 \text{ kg} \cdot \text{m}^2$

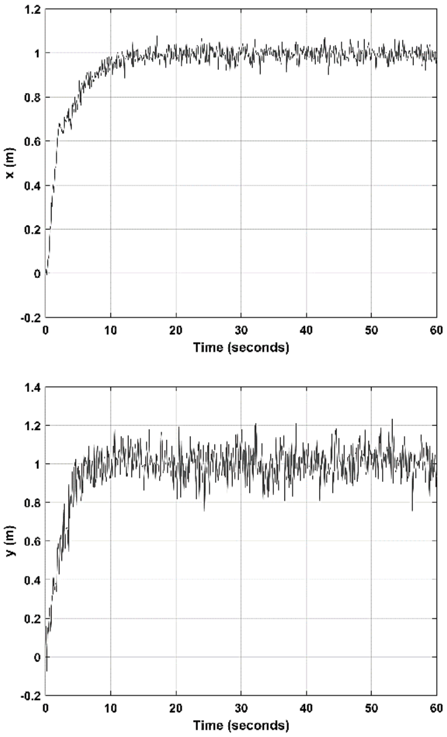

Figure 6 Time Histories of Position

Figure 7 showcases the attitude control of the tanker during the docking phase. The control scheme effectively commands the desired attitude, ensuring the proper alignment of the spacecraft. However, due to the impulsive nature of thruster activations, some fluctuations are observed in the angular behavior. The time histories of the thrusters' activity are presented in **Figure 8**, illustrating their on/off behavior during the docking process. Notably, the thrusters are predominantly off for most of the docking duration. This is attributed to the optimization achieved by MPC's trajectory planner, resulting in minimal thruster activations and reduced fuel consumption. Therefore, the control scheme effectively mitigates fuel-sloshing excitation, leading to improved fuel efficiency.

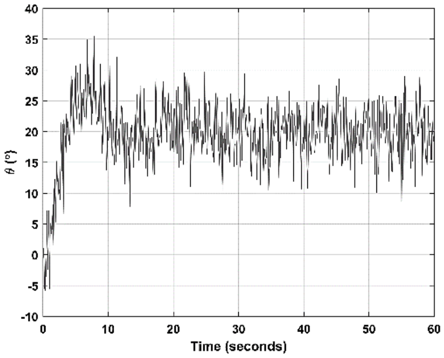

Figure 7 Attitude of the Tanker

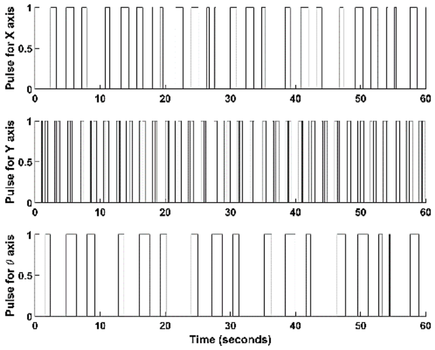

Figure 8 Time Histories of Thrusters' Activity.

The observed variations in controlled behavior are primarily attributed to disruptive factors such as Optitrack sensor noise, laboratory ground inclinations, fuel sloshing disturbances, and unaccounted-for dynamic irregularities, notably nozzle misalignments. Nevertheless, the outcomes of comprehensive simulations serve to underscore the robustness inherent in the advanced control strategy proposed in this study, specifically when confronted with disruptive influences and uncertainties. Notably, this control strategy effectively overcomes formidable challenges, including those arising from the intricate dynamics associated with fuel sloshing disturbances and the inherent non-continuous nature of thruster operations.

These accomplishments are instrumental in achieving precision and stability throughout the trajectory tracking process, culminating in the secure docking of the tanker spacecraft with its designated target satellite.

6. Conclusion

The simulation results presented herein underscore the effectiveness and feasibility of the proposed control scheme for mitigating fuel sloshing disturbances during on-orbit satellite refueling. The control scheme demonstrates exceptional trajectory planning and tracking performance, resulting in accurate and safe docking maneuvers. By efficiently managing thruster activations and fuel consumption, the proposed control scheme contributes to enhanced fuel efficiency, enabling extended on-orbit satellite missions. The robustness of the control scheme against various disturbances reinforces its potential to advance on-orbit satellite refueling technology, paving the way for more efficient and reliable space missions in the future.

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