Advances in Control Techniques for Floating Platform Stabilization in the Zero-G Lab

Barış Can Yalçın(1), **M. Amin Alandihallaj**(2), **Andreas Hein**(3), **Miguel Olivares-Mendez**(4)
(1) *Space Robotics (SpaceR) Research Group, Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg, Email: bariscan.yalcin@uni.lu*
(2) *Space Systems Engineering (SpaSys) Research Group, Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg, Email: amin.hallaj@uni.lu*
(3) *Space Systems Engineering (SpaSys) Research Group, Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg, Email: andreas.hein@uni.lu*
(4) *Space Robotics (SpaceR) Research Group, Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg, Email: miguel.olivaresmendez@uni.lu*

ABSTRACT

The study presents a novel control approach for managing floating platforms in the unique environment of a zero-gravity laboratory (Zero-G Lab) of University of Luxembourg. These platforms are pivotal for diverse experiments and technologies in space. Our solution combines Model Predictive Control (MPC) and Proportional-Derivative (PD) control techniques to ensure precise positioning and stability. The MPC algorithm generates optimal trajectories based on predictive platform models, adjusting paths for minimal effort. Augmented by a PD controller using feedback from the Optitrack motion system, real-time adjustments maintain stability by considering platform state, position, and orientation data. Extensive simulations and experiments within the Zero-G Lab demonstrate the effectiveness of our approach. The MPC-PD strategy accurately controls platforms, making them resilient against external disturbances and human interactions. This strategy holds promise for space exploration, microgravity experiments, and beyond, offering adaptable control in zero-gravity conditions.

1. INTRODUCTION

The pursuit of space exploration continues to push the boundaries of human understanding, presenting a plethora of challenges that demand innovative solutions. A pivotal aspect of this endeavor is the emulation of zero-gravity conditions and the replication of intricate orbital scenarios within controlled laboratory environments. Such laboratories serve as crucibles for advancing our comprehension of orbital dynamics, spacecraft interactions, and autonomous systems. This introduction provides an overview of the current landscape of similar laboratories around the world, highlighting their diverse approaches and contributions, and subsequently introduces the distinct contribution of the Zero-G Lab at the University of Luxembourg.

In the tapestry of laboratories dedicated to space exploration, several institutions have emerged as pioneers, each with a unique focus on emulating microgravity conditions and simulating various aspects of space scenarios. For instance, the Georgia Institute of Technology's ASTROS facility leverages robotic arms to replicate spacecraft Autonomous Rendezvous and Docking (ARD) maneuvers [1]. European Space Research and Technology Centre (ESA-ESTEC), Netherlands, hosts the ORBIT facility, employing air-bearing platforms for orbital robotics simulations [2]. The University of Florida's ADAMUS employs a 6-DoFs spacecraft simulator testbed [3], while the German Aeronautics Centre (DLR) encompasses multiple testbeds for descent, docking, and formation flight studies [4]. GMV's platform-art dynamic test facility in Spain explores the potential of Guidance, Navigation, and Control (GNC) technologies [5], and Caltech's Aerospace Robotics and Control Lab employs multi-spacecraft testbeds for trajectory attitude profile studies [6].

Amidst this global landscape of laboratories, the Zero-G Lab at the University of Luxembourg stands out with a unique mission: to investigate and manage floating platforms in the absence of gravity. The facility strives to emulate space-like conditions, making it a hub for research in space exploration, microgravity experiments, and beyond, which has been utilized for different scientific and industrial projects [7-10]. The core challenge in this environment is the precise control and stabilization of these floating platforms, which are central to diverse experiments and technologies.

The distinctive characteristics of Model Predictive Control (MPC) that render it well-suited for diverse aerospace applications, including space tether control [11], path planning [12], satellite formation flight control [13, 14], spacecraft rendezvous control [15], satellite attitude control [16], satellite maneuvering planning [17] , and asteroid landing control [18-20], establish MPC as a compelling choice for the control of floating platforms.

In this context, our study embarks on a novel exploration, addressing the challenges of managing floating platforms within the unique environment of the Zero-G Lab. This paper presents a sophisticated control approach that merges the power of MPC with the agility of Proportional-Derivative (PD) control techniques. The overarching goal of our strategy is to ensure precise positioning and stability of these floating platforms, which play a pivotal role in enabling a myriad of experiments and technologies tailored for space applications. Through the integration of MPC, our solution generates optimal trajectories for the floating platforms by leveraging predictive models of their behavior. This predictive aspect empowers the platforms to execute movements with minimal energy expenditure, optimizing their paths to meet the desired objectives. Augmenting this approach, a PD controller, informed by real-time feedback from the Optitrack motion system, enhances stability by considering the current state, position, and orientation data of the platforms.

This study encompasses a dual-fold contribution: the adaptation of advanced control techniques to the unique context of the Zero-G Lab, and the synthesis of a comprehensive strategy that harnesses the strengths of both MPC and PD control. Our approach is designed to address the challenges posed by external disturbances and human interactions, ensuring the platforms' resilience and stability.

In the subsequent sections of this paper, an in-depth exploration of our methodology is undertaken, which encompasses the intricacies of both design and implementation within the distinctive environment of the Zero-G Lab. This journey is initiated by acquainting the reader with the fundamental aspects of the laboratory and the underlying system model. The simulations and experiments that validate the efficacy of our approach are subsequently presented. Through this study, the potential impact of the proposed strategy on diverse space exploration endeavors is highlighted, offering adaptable and precise control mechanisms in the unique microgravity conditions that define the cosmos.

2. ZERO-G LAB OVERVIEW

The Zero-G Lab, situated at the Interdisciplinary Centre for Security, Reliability, and Trust (SnT) within the University of Luxembourg's Kirchberg campus, stands as a remarkable fusion of cutting-edge technology designed to emulate on-orbit scenarios from a Guidance, Navigation, and Control (GNC) perspective. This innovative facility leverages a combination of robotic arms mounted on robotic rails, a super-flat epoxy-floor, and floating platforms (shown in Figure 1) to faithfully replicate microgravity conditions and support a diverse range of space-oriented experiments and research endeavors.

The laboratory's primary objective is to replicate crucial aspects of orbital scenarios such as spacecraft proximity maneuvers, rendezvous operations, on-orbit maintenance, and operations. By meticulously simulating these scenarios, the Zero-G Lab serves as a valuable platform for generating datasets to train perception algorithms, validate close control-loop approaches, and test various navigation and control strategies.

At its core, the Zero-G Lab comprises a spacious room with dimensions of 7m x 6m x 2.30m, within which the experiments are conducted. This controlled environment features an additional 5m x 3m x 2.3m experiments room, painted entirely with non-reflective black paint to minimize optical reflections. Equipped with small windows for monitoring, the lab space is also surveilled through IP cameras connected to the laboratory network to enable remote observation of experiments.

Central to the lab's capability are two 6-degree-of-freedom robotic arms mounted on separate rails — one on the wall with a length of 5m and the other on the ceiling with a length of 4.6m. These robotic arms emulate dynamic motion in six dimensions, effectively replicating the movement of space assets during various space operations. Additionally, the lab's flat-floor setup is critical for simulating vehicle dynamics. The 3m x 5m epoxy floor, installed with micron-scale precision, enables two floating platforms to glide frictionlessly, each equipped with an air-pressured system generating an air cushion. This novel approach emulates free-floating dynamics in space, effectively replicating microgravity conditions [21]. A comprehensive motion capture system, operating at a frequency of 240Hz, allows precise estimation of pose, providing accurate data on object positions [22].

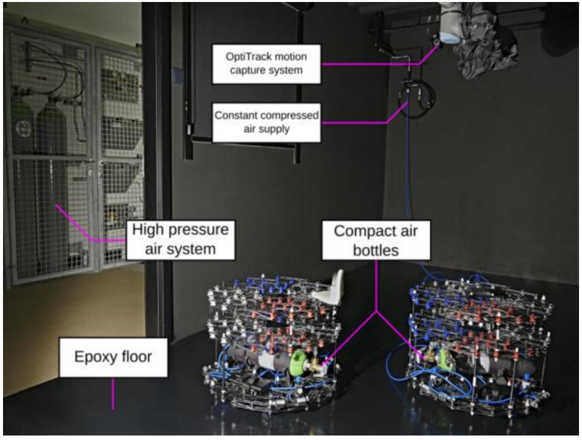

Figure 1. The major components of the Zero-G Lab.

The Zero-G Lab's floating platform is meticulously designed to create a near-frictionless environment. The air-bearings integrated into the platform are instrumental in achieving this by directing high-pressurized air toward the epoxy floor, effectively eliminating mechanical contact. This platform is seamlessly integrated into the ROS network, and a ROS-MATLAB bridge facilitates platform programming using MATLAB, enabling experimentation and assessment of its capabilities, including maintaining position under disturbances and trajectory tracking.

It should be noted that a patent application for the floating platform, titled “Pneumatic floating systems for performing zero-gravity experiments,” has been submitted to the national patent agency in Luxembourg and is presently undergoing evaluation, with the patent application file number recorded as LU503146. Additional details pertaining to the Zero-G Lab facility can be accessed in [23]. A comprehensive overview of the Zero-G Lab is also provided in [24].

3. CONTROL APPROACH

In this section, we introduce the control scheme employed for precise control of the floating platform during the docking phase in on-orbit satellite operations. The control scheme encompasses two distinct methodologies: PD control and integrated MPC-PD control, which will be explained in the rest of the paper.

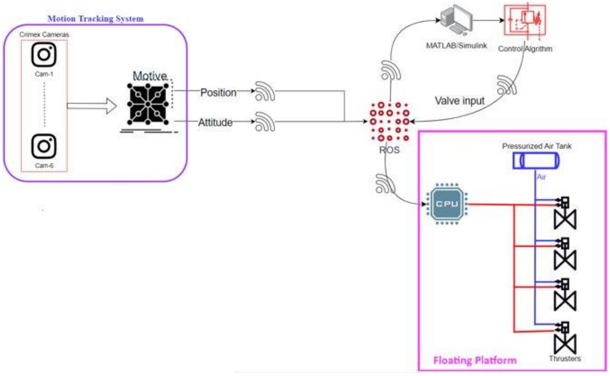

Figure 2. The system data flow in the Zero-G Lab.

3.1. PD Control

In the first approach, we exclusively utilize PD control to govern the floating platform’s behavior. The PD control gains, which are critical for the system’s stability and performance, are derived through a technique known as pole placement, as detailed in reference. Specific values and the comprehensive procedures for gain determination can be found in reference **[25]**. This approach ensures precise control of the floating platform, guaranteeing accurate and stable trajectory following during the docking process.

To translate the continuous analog control commands into discrete digital signals suitable for the control of the floating platform, we incorporate a saturation module. This module efficiently limits the control commands’ amplitude within a predefined range. This approach enhances control accuracy and stability, especially in scenarios where the floating platform operates with discrete on/off control signals.

3.2. Integrated MPC-PD Control

The second approach combines MPC with PD control to enhance the precision and responsiveness of the floating platform’s control. Within this framework, MPC is responsible for generating a reference trajectory tailored for efficient docking. The PD controller is then employed to track this reference trajectory. This integrated approach enhances the control system’s performance during docking operations.

MPC entails the minimization of a cost function that quantifies the disparities between the state of the floating platform, denoted as $\boldsymbol{x}(t)$, and the desired final states, represented as $\boldsymbol{x}_d$, in conjunction with the control inputs, denoted as $\boldsymbol{u}(t)$. This optimization process takes into account system dynamics and constraints, and it is solved iteratively by MPC to dynamically adjust control inputs in response to uncertainties and disturbances. The formal representation of the MPC cost function is as follows [18]:

$$\min_{\boldsymbol{u}} \int_{t=t_0}^{t_f} [\|\boldsymbol{x}(t) - \boldsymbol{x}_d\|_{\Omega}^2 + \|\boldsymbol{u}(t)\|_{\omega}^2] dt \qquad (1)$$

where t_f and t_0 represent the initial and final time prediction window, respectively. The matrices $\boldsymbol{\Omega}$ and $\boldsymbol{\omega}$ are both positive definite weighting matrices, contributing to the optimization process.

During the experimental phase, we utilized MPC with a prediction horizon of 10 seconds and a time step of 0.1 seconds to compute the reference trajectory. Furthermore, $\boldsymbol{\Omega}$ took the form of a diagonal matrix, with its diagonal elements associated with position and angles set to 1, while the diagonal elements linked to time derivatives were established at 100. Additionally, $\boldsymbol{\omega}$ was configured as a diagonal matrix where all diagonal elements were uniformly set to 1000. These parameters were instrumental in our control scheme's performance during the experiments.

4. THE CASE STUDY

The case study consists of three-fold simulations; 1- Disturbance rejection, 2- Set-point tracking with PD controller, 3 Set-point tracking with PD controller in which set-points determined by MPC. In Figure 3, Figure 4 and Figure 5, the disturbance value applied to the floating platform is 1 N for each translational x and y axes, and 1 Nm for rotational z axis. The floating platform gets back to its initial position [0, 0, 0] after the disturbance vector is applied. Since there is no specific trajectory generation, MPC does not play a role in this particular scenario.

The comparison between PD and MPC controllers is given in Figure 6, Figure 7, and Figure 8. The desired set-point is [1 m, 0.5 m, 20 degrees] Compared with set-point tracking with PD controller, using the trajectory generated by the MPC controller provides slightly less overshoot, while rise time decreased for all axes.

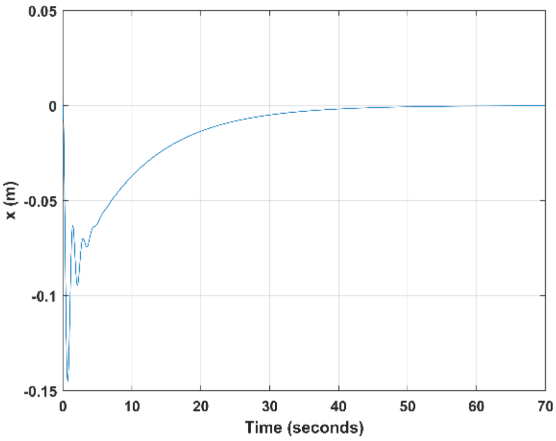

Figure 3.Disturbance rejection on translational x axis.

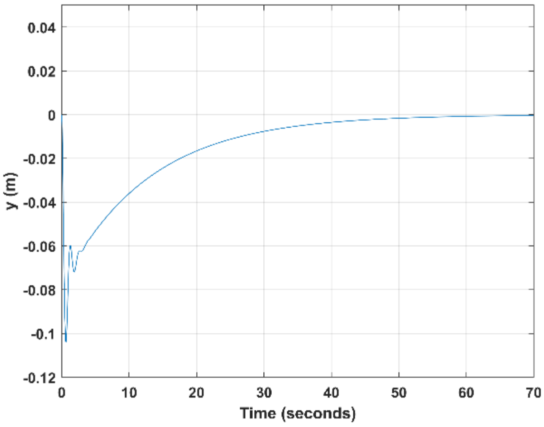

Figure 4. Disturbance rejection on translational y axis.

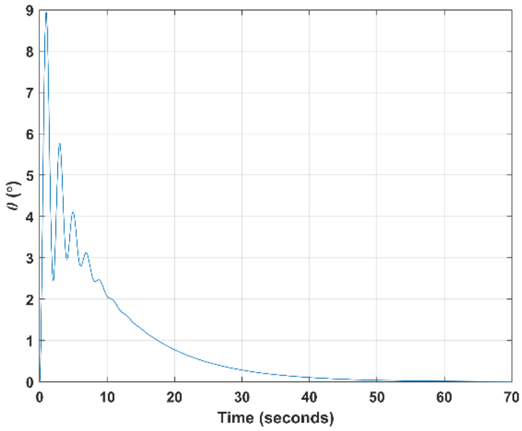

Figure 5. Disturbance rejection on rotational z axis.

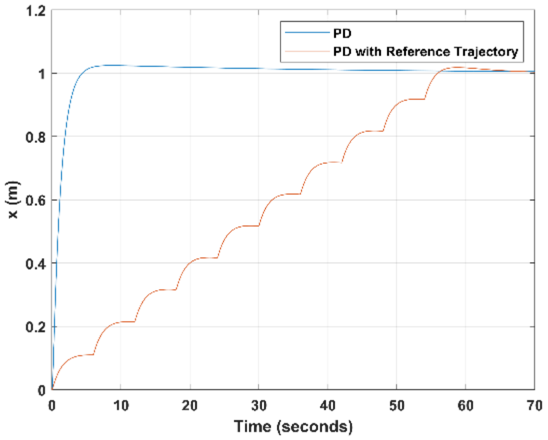

Figure 6. Comparison between PD and MPC on x axis.

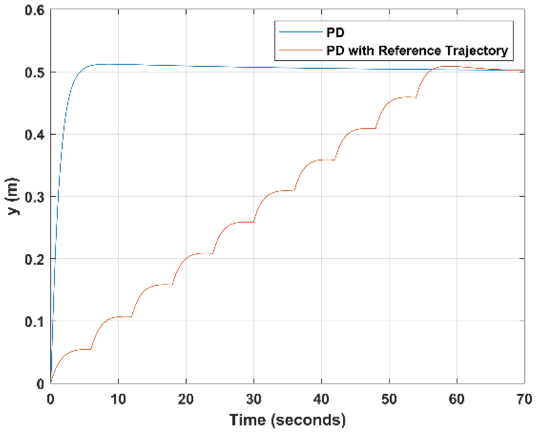

Figure 7. Comparison between PD and MPC on y axis.

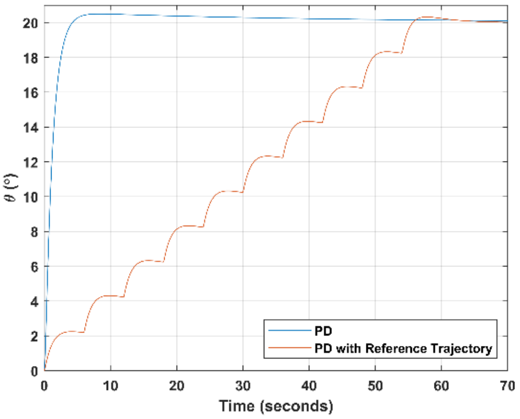

Figure 8. Comparison between PD and MPC on z axis.

5. CONCLUSION

In this study, we rigorously explored disturbance rejection within a basic PD controller and conducted a preliminary comparison with the MPC controller for position control of the floating platform. Our simulations affirm the PD controller’s robustness in mitigating disturbances. Additionally, when utilizing the trajectory generated by MPC, we observed reduced overshoot compared to the PD controller, which gives certain advantages for particular cases, such as contact dynamics, close proximity, and docking. These findings hold significant implications for control theory and applications in space exploration, pointing to the potential benefits of combining PD and MPC for enhanced precision and reliability in microgravity control.

References

[1] P. Tsiotras, "ASTROS: A 5DOF experimental facility for research in space proximity operations," *Advances in the Astronautical Sciences*, vol. 151, pp. 717-730, 2014.

[2] T. Rybus *et al.*, "New planar air-bearing microgravity simulator for verification of space robotics numerical simulations and control algorithms," in *12th ESA Symposium on Advanced Space Technologies in Robotics and Automation*, 2013, p. 8.

[3] D. Gallardo, R. Bevilacqua, and R. Rasmussen, "Advances on a 6 degrees of freedom testbed for autonomous satellites operations," in *AIAA Guidance, Navigation, and Control Conference*, 2011, p. 6591.

[4] M. Schlotterer, E. Edlerman, F. Fumenti, P. Gurfil, S. Theil, and H. Zhang, "On-ground testing of autonomous guidance for multiple satellites in a cluster," in *8th International Workshop on Satellite Constellations and Formation Flying*, 2015.

[5] P. Colmenarejo, E. di Sotto, and J. A. Béjar, "Dynamic test facilities as ultimate ground validation step for space robotics and GNC system," *6th ICATT*, 2016.

[6] R. C. Foust, E. S. Lupu, Y. K. Nakka, S.-J. Chung, and F. Y. Hadaegh, "Ultra-soft electromagnetic docking with applications to in-orbit assembly," 2018.

[7] X. Li *et al.*, "Emulating Active Space Debris Removal Scenarios in Zero-G Lab," 2022.

[8] X. Li *et al.*, "Exploring NVIDIA Omniverse for Future Space Resources Missions," 2022.

[9] K. Aggarwal *et al.*, "Enabling Elements of Simulations Digital Twins and its Applicability for Information Superiority in Defence Domain," 2022.

[10] X. Li *et al.*, "Nvidia Omniverse for Active Space Debris Removal Missions, an Overview," 2022.

[11] M. AlandiHallaj and N. Assadian, "Multiple-horizon multiple-model predictive control of electromagnetic tethered satellite system," *Acta Astronautica*, vol. 157, pp. 250-262, 2019.

[12] M. Ramezani, H. Habibi, J. L. Sanchez-Lopez, and H. Voos, "UAV Path Planning Employing MPC-Reinforcement Learning Method Considering Collision Avoidance," in *2023 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2023: IEEE, pp. 507-514.

[13] N. R. Esfahani and K. Khorasani, "A distributed model predictive control (MPC) fault reconfiguration strategy for formation flying satellites," *International Journal of Control*, vol. 89, no. 5, pp. 960-983, 2016.

[14] A. Richards, L. Breger, and J. P. How, "Analytical performance prediction for robust constrained model predictive control," *International Journal of Control*, vol. 79, no. 8, pp. 877–894, 2006.

[15] E. N. Hartley, M. Gallieri, and J. M. Maciejowski, "Terminal spacecraft rendezvous and capture with LASSO model predictive control," *International Journal of Control*, vol. 86, no. 11, pp. 2104-2113, 2013.

[16] O. Hegrenaes, J. Gravdahl, and P. Tondel, "Spacecraft attitude control using explicit model predictive control," *Automatica*, vol. 41, no. 12, pp. 2107-2114, 2005.

[17] M. Amin Alandihallaj, N. Assadian, and K. Khorasani, "Stochastic model predictive control-based countermeasure methodology for satellites against indirect kinetic cyber-attacks," *International Journal of Control*, vol. 96, no. 7, pp. 1895-1908, 2023.

[18] M. AlandiHallaj and N. Assadian, "Soft landing on an irregular shape asteroid using Multiple-Horizon Multiple-Model Predictive Control," *Acta Astronautica*, vol. 140, pp. 225-234, 2017.

[19] M. AlandiHallaj and N. Assadian, "Asteroid precision landing via Probabilistic Multiple-Horizon Multiple-Model Predictive Control," *Acta Astronautica*, vol. 161, pp. 531-541, 2019.

[20] M. A. Alandihallaj, N. Assadian, and R. Varatharajoo, "Finite-time asteroid hovering via multiple-overlapping-horizon multiple-model predictive control," *Advances in Space Research*, vol. 71, no. 1, pp. 645-653, 2023.

[21] W. F. Ribeiro *et al.*, "Mobility Strategy of Multi-Limbed Climbing Robots for Asteroid Exploration," *arXiv preprint arXiv:2306.07688*, 2023.

[22] B. C. Yalcin, C. Martinez Luna, S. Coloma Chacon, E. Skrzypczyk, and M. A. Olivares Mendez, "Ultra-Light Floating Platform: An Orbital Emulator for Space Applications," presented at the IEEE International Conference on Robotics and Automation 2023 (ICRA), London, 29-5-2023 to 02-06-2023, 2023

[23] "Zero-G Lab." University of Luxembourg https://ism.uni.lu/facility/zero-gravity-lab (accessed.

[24] The Zero-G Lab: Testing in a Micro-Gravity Environment. Available:

https://www.youtube.com/watch?v=kFhv9fGXk8w&t=1s.

[25] B. C. Yalçin, C. Martinez, S. Coloma, E. Skrzypczyk, and M. Olivares-Mendez, "Lightweight Floating Platform for Ground-based Emulation of On-orbit Scenarios," *IEEE Access*, 2023.