Model Predictive Control in Hardware in the Loop Simulation for the OnBoard Attitude Determination Control System

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***Abstract*—Rocket flight tests invariably serve a purpose, one of which involves area monitoring or aerial photography. Consequently, the rocket necessitates the installation of a camera that remains consistently oriented toward the Earth's surface throughout its trajectory. Thus, ensuring the rocket's stability and preventing any rotation becomes imperative. To achieve this, the Onboard Attitude Determination Control System (OADCS) was researched and developed, fully controlled by NI myRIO with Labview as the programming language, ensures the rocket's attitude control and maintains a rolling angle of 0 degrees during flight. The MyRIO oversees the retrieval of attitude and position data from the X-Plane flight simulator, offering feedback through actuator control. The development of the OADCS proceeded incrementally through stages utilizing the Software in the Loop Simulation (SILS) and Hardware in the Loop Simulation (HILS) techniques, to ensure the verification of the system's functionality before its application to the rocket for real flight testing. In the OADCS control scheme, Model Predictive Control (MPC) is chosen, and it is compared with a PID controller to serve as a benchmark for processing speed. Because the rocket's flight time is short and its speeds of up to Mach 4. The simulation results indicate that MPC can halt the rocket's rotation 12 times more rapidly than PID control. Additionally, the MPC's ability to maintain a zero-degree rotation can persist throughout the rocket's flight time. Employing SILS and HILS enhances the OADCS rocket development process by incorporating MPC, which holds promise for application in real rockets.**

Keywords*—Hardware in the Loop Simulation; Hardware in the Loop Simulation; Model Predictive Control; OnBoard Attitude Determination Control System.

I. Introduction

The intensive development of sounding rockets by the Indonesian National Institute of Aeronautics and Space (LAPAN) dates back to the '90s, predating its affiliation with BRIN. This ongoing effort serves the purpose of advancing aerospace technology and space exploration [1]-[3], involving interdisciplinary research in areas such as vehicle design, structure, propellant (solid rocket fuel), rocket motor, electronic systems, and ground stations. The development of this sounding rocket started from a small rocket of 70 mm caliber to the largest currently 450 mm, which is equipped with an avionics/electronics and flight control system as generally applied to various sounding rocket missions [4]-[7], encompassing the main on-board control unit, control scheme and actuator, power module and management [8], [9], pulse code modulation (PCM) module to organize the transmission of communication data, radio telemetry system [10], [11], and utilization of wrapped around micro strip antenna [12]-[14], are several scientific disciplines connected to this research.

Sounding rockets typically carry a payload and a health monitoring system (HMS) [15]-[17] or avionics system upon launch. Certain rocket payloads frequently feature cameras for specific missions [18]-[21], including observing the separation process between the payload and the rocket, particularly in multi-stage rocket scenarios. Additionally, there are rockets designated to carry cameras that capture flight visuals from the rocket's perspective or maintain a constant view of the Earth's surface. Therefore, it is imperative to guarantee the rocket's stability for this purpose, as any rotation of the rocket could adversely affect the clarity of the captured images or videos.

To overcome the above challenges, considerable efforts have been invested in the development of an OnBoard Attitude Determination Control System (OADCS) [22]-[24], as carried out in several researches concerning rocket trajectory correction and control. The OADCS can take various forms, including the release of a mass object as a YoYo despin device, a geomagnetic field sensors assembly (GA), and a sun angle sensor, as demonstrated in Japan's JAXA/ISAS sounding rocket (Fig. 1 (a)). Alternatively, the OADCS may involve a gyro inertial sensor with an extended Kalman Filter, as seen in the S-250-30 configuration [25], [26]. This paper will explore a similar methodology, examining the progress of the HTTP-3S sounding rocket (depicted in Fig. 1 (b)), as well as the successful implementation of OADCS in Taiwan using the National Instrument module as the main controller. Typically, sounding rockets come with OADCS serving as an avionics system, similar to what Taiwan possesses. However, this research integrates avionics and flight control systems to prevent rocket rotation and maintain the camera's Earth-oriented orientation, employing Model Predictive Control (MPC) as a control strategy.

Rocket development inherently entails considerable risks and costs. Therefore, it is essential to engage in research stages that include simulations at every developmental phase to minimize the risk of critical errors during the rocket's manufacturing process. Historically, such simulations and procedures utilizing Software in the Loop Simulation (SILS) and Hardware in the Loop Simulation (HILS) were predominantly conducted using Matlab/Simulink [27]-[29]. However, Matlab's application to HILS and embedded hardware directly used for rocket operations presents many challenges, necessitating the adoption of alternative hardware and software solutions.

(a) (b)

Fig. 1. Sounding rocket: (a) Japan's S-520-29; and (b) Taiwan's HTTP-3S

In addition to devising the appropriate control scheme for the rocket mission, careful consideration must be given to the selection and utilization of the primary onboard controller unit during the developmental phase. Factors such as ease of programming, universal connectivity to support peripheral devices, and simulation with various robust control strategies and connection capabilities should be prioritized. Incorporating the NI (National Instrument) module, which relies on FPGA (Field Programmable Gate Array) technology [30]-[32], alongside the XSense Inertial Navigation System (INS) and a range of other sensors, is aimed at addressing the requirements of rocket avionics and flight control systems. This integration caters to the diverse complexities of disturbances encountered during rocket flight, including velocity, shock, gravitational forces, atmospheric pressure, and more.

This research focuses on constructing a real-time Onboard Attitude Determination and Control System (OADCS), fully governed by the NI myRIO module and programmed in LabView. The objective is to enhance the development of the sounding rocket, particularly its avionics system, by simulating real-time OADCS operations to stabilize the rocket's orientation, ensuring that the camera payload consistently faces downward toward the Earth. The utilization of the NI myRIO module with its LabView as the main controller of the OADCS equipped with INS as well as a function of the rocket avionics and flight control system represents a new insight, which has not been fully documented in the literature.

The OADCS development, encompassing both software and hardware, is set to advance incrementally through SILS and HILS stages, incorporating appropriate control strategies. The objective is to fulfill the mission goal of sustaining the rocket's camera orientation towards Earth throughout the flight. Additionally, the aim is to establish and implement the complete OADCS system equipped with MPC control strategy, alongside connectivity to all supporting peripheral systems, onto a physical rocket.

II. Methods

As outlined earlier, the research and development of rocket technology entail substantial costs, risks, time commitments, and the involvement of numerous skilled professionals. It is imperative to conduct thorough and focused research to prevent undesirable outcomes during flight testing. Among the areas requiring meticulous research is the avionics and flight control system, which significantly contributes to the success of rocket development missions. Every stage and procedure, including Software In-the-Loop Simulation (SILS) extensively employed across various scientific domains [33]-[35], Hardware In-the-Loop Simulation (HILS) utilized to simulate cost-related concerns and high-risk scenarios [36]-[39], and the deployment of the Ready to Flight System (RTFS) as the subsequent phase, all necessitate flawless sequential execution, involves testing the application of MPC control strategies to achieve mission objectives.

A. OnBoard Attitude Determination Control System

The complete control of this Onboard Attitude Determination and Control System (OADCS) will be facilitated by the main control unit, utilizing the NI myRIO-1950. This controller is based on the FPGA Xilinx Zynq-7010 and ARM Cortex A9 processor, boasting a speed of 667 MHz, 512 MB of nonvolatile memory, and 256 MB of DDR3 memory. It is also outfitted with 8 analog inputs, 4 analog outputs, and 32 I/O lines. The myRIO module proves instrumental in managing the entire flight process, from liftoff to touchdown on Earth, and is adept at controlling the rocket's rotation, even employing memory-intensive algorithms like the Model Predictive Control (MPC).

Fig. 2 illustrates the operational concept of the OADCS, comprising the myRIO module and programmed in LabView, supported by the power system and electrical sensors for attitude and position detection, serving as input for the controller. This input undergoes processing to ascertain the rocket's trajectory and flight position through the canard actuator system, with all flight data transmitted via telemetry. Additionally, imagery or video footage captured by the camera is transmitted through this telemetry channel. It is pertinent to mention that this simulation exclusively addresses the rocket's attitude adjustment, achieved through canard control to maintain the camera's downward-facing orientation. Further details regarding the electrical and power systems, telemetry, and camera functionalities will be addressed separately.

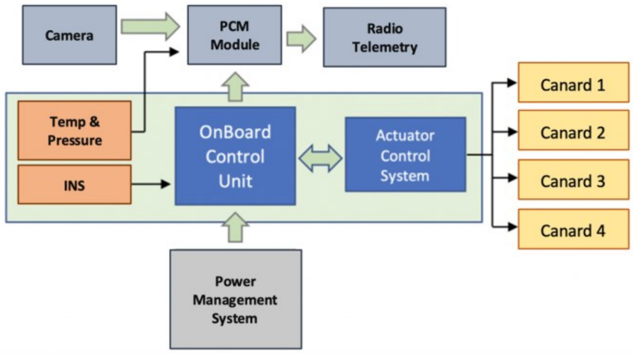


Fig. 2. OADCS block diagram which is fully controlled by NI myRIO module and LabView as the programming language

B. *Modelling and Flight Simulator*

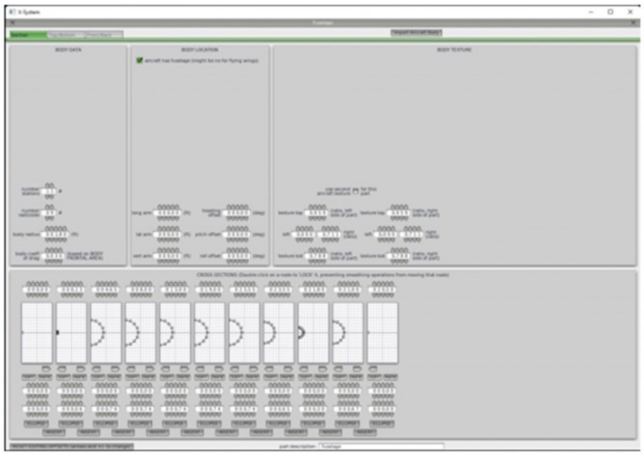
One of the pivotal stages in the research and development of rockets involves simulation [40]. In this context, a flight simulator software capable of closely emulating real flight dynamics is indispensable. Additionally, this software should offer a User Datagram Protocol (UDP) connection, enabling data transmission to and from other software components for control program execution. Consequently, X-Plane version 10.51 was selected as the flight simulator environment, paired with LabView version 2018 as the control program, given its extensive utilization as a simulation tool in laboratory research endeavors [41]-[43]. The X-Plane, serving as a 'black box' vehicle model, offers comprehensive real-time output concerning attitude and positional data during flight, enabling its direct integration into the closed-loop control program by Labview in this simulation.

Subsequently, utilizing the LAPAN-developed single-stage sounding rocket as the basis for this simulation, a corresponding single-stage rocket model was constructed within X-Plane (refer to Fig. 3), with an extra canard appended to manage the rocket's rotation, as illustrated in Fig. 4 (a).

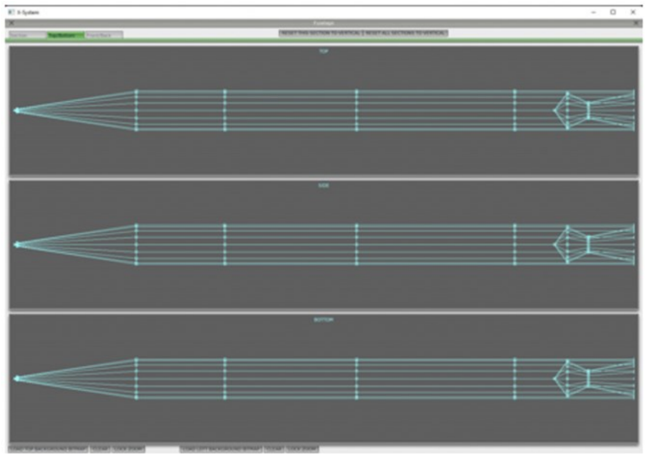
Utilizing X-Plane Maker which is part of X-Plane [44]-[46], we crafted the rocket's fuselage and nose cone in accordance with the original design, as shown in Fig. 3. The tube's diameter and length, along with the nose cone's shape, were fashioned using the fuselage tool (Fig. 3 (a) and (b)), while the tail fin and canard were sculpted using the wings or misc wings tool (Fig. 3 (c)). Engine specifications, including thrust and propellant properties, were configured within the engine specs section.

Furthermore, adjustments to the control canard and determination of the center of gravity were made, delineated within the control geometry and weight and balance parameters. While X-Plane Maker serves as a representative tool for creating intricate rocket models suitable for simulation purposes, it is not tailored for production applications.

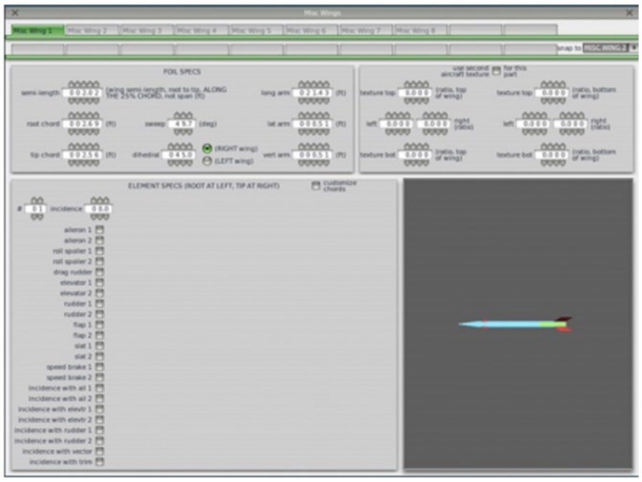
Please note that this paper exclusively focuses on the development of the Onboard Attitude Determination and Control System (OADCS) and the corresponding control scheme, omitting in-depth discussions on aerodynamics, structural aspects, or the rocket motor. Consequently, we proceed under the assumption that the rocket design adheres to an ideal configuration and maintains perfect stability during flight. Furthermore, our objective is to replicate the simulation as closely as possible to the actual flight test of the rocket. This entails selecting the LAPAN launch facility in Pameungpeuk, Garut as the launch site and programming the rocket's trajectory southward, mirroring the real flight test trajectory, utilizing the WED (WorldEditor) software, as depicted in Fig. 4 (b).



(a) Nose and tube design

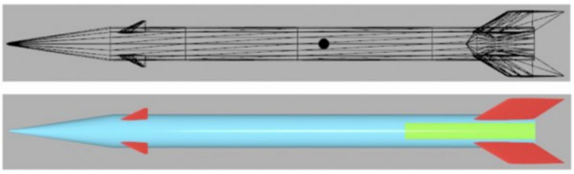


(b) Design in 3D frame

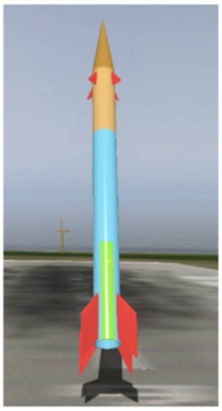


(c) Fin design

Fig. 3. Rocket modelling by X-Plane Maker



(a)



(b)

Fig. 4. The rocket model, augmented with an extra canard for managing the rocket's rotation, and the simulation

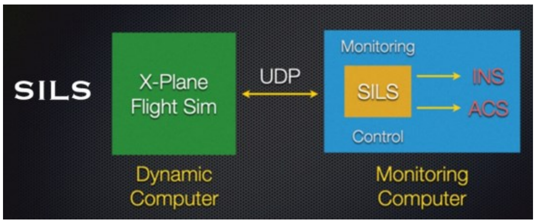
C. *Software in the Loop Simulation (SILS)*

The initial phase of this simulation involves implementing the Software In-the-Loop Simulation (SILS) as in block diagram Fig. 5 (a). This is achieved by establishing a UDP connection (operating at a 50Hz data rate) between the Dynamic Computer (X-Plane is installed on this computer equipped with high specifications optimized for rendering within the simulation) and the Monitorng Computer (contains LabView), with the respective IP addresses configured for the designated ports for mutual communication. The closed-loop system operates by X-Plane providing attitude and positional data to LabView, which in turn processes this data to generate control signals for the canard, subsequently transmitting them back to X-Plane.

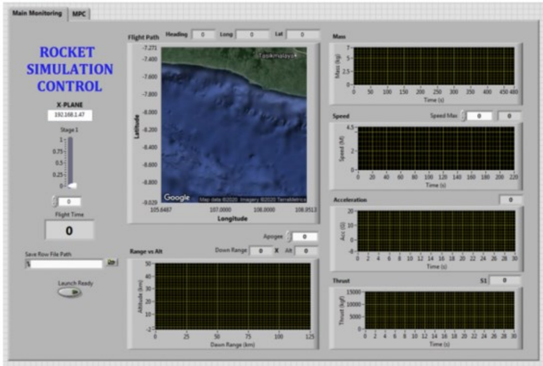
In this setup, Labview serves two main functions: firstly, it presents comprehensive flight data encompassing position, longitude, latitude, altitude, downrange, as well as rocket attitude parameters such as thrust, speed, and acceleration, illustrated in Fig. 5 (b), flight data from liftoff to touchdown is both displayed and logged in the Ground Control Station (GCS). Secondly, it generates control commands utilizing the Model Predictive Control (MPC) scheme to counteract rocket spin and ensure the camera maintains a downward-facing orientation toward the Earth. Throughout this Software In-the-Loop Simulation, it is imperative to verify that all components operate according to plan.

D. *Hardware in the Loop Simulation (HILS)*

Following the successful execution of the SILS, we proceeded to the Hardware In-the-Loop Simulation (HILS) stage which has been widely used by researchers in their laboratories [47]-[50]. In this HILS, the physical controller hardware has been incorporated for subsequent utilization as a rocket avionics and flight control system, specifically the NI myRIO. The programming aspect was segmented into two parts: one part manages communication with X-Plane, while the other part oversees the onboard rocket controller. Both parts are interconnected via shared memory, as illustrated in Fig. 6 (a).

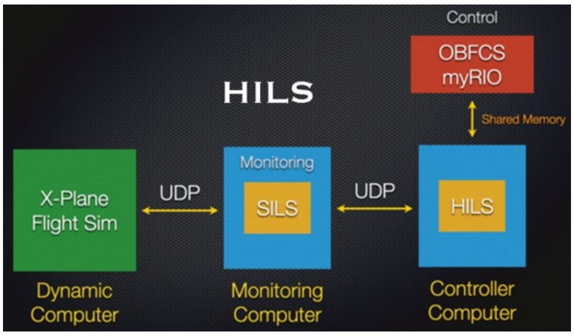


(a) SILS block diagram

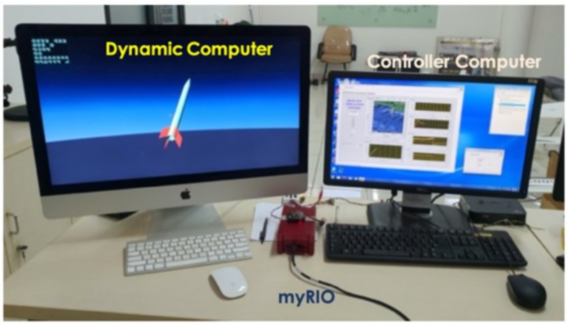


(b) SILS monitoring

Fig. 5. SILS diagram and rocket simulation control window



(a) HILS block diagram



(b) Real time simulation in HILS

Fig. 6. HILS diagram and its simulation

The HILS configuration comprises the myRIO as the controller and two computers: a dynamic computer responsible for rendering the flight simulation via X-Plane and a controller computer that acts as an intermediary between the dynamic computer and myRIO. Additionally, the controller computer serves as a monitoring platform, presenting real-time test data. This implies that during the HILS stage, the main controller intended for use in the subsequent real flight test is directly engaged, functioning as both an avionics system and flight control system within the simulation (Fig. 6 (b)). The next stage, Ready to Flight System (RTFS) will not be described in this paper because it requires integration of the OADCS into the rocket body along with other components, thus requiring a separate test procedure.

E. Control Strategy

Rockets represent flying vehicles with six degrees of freedom (6-DOF) [51]-[53], enabling unhindered motion across three axes of translation and three axes of rotation. Although PID is a conventional control strategy extensively employed across diverse industries, its practical application poses challenges in the realm of developing avionics and flight control systems for rockets, particularly those operating within a 6-DOF environment at speeds reaching up to Mach 4. The intricate nature of Proportional, Integral, and Derivative (PID) elements, typically requiring precise fractional adjustments, renders them impractical as controllers for rockets in flight.

In contrast, modern control strategies such as robustness or optimal control offer promising alternatives for managing the Onboard Attitude Determination and Control System (OADCS) of rockets. Among these, Model Predictive Control (MPC) emerges as a viable option for controlling rockets during flight. MPC boasts several advantages over PID, including superior constraint handling, optimization of control actions to approach target values, simplified control parameter adjustments using integer values, and the capability to manage multivariable control scenarios.

MPC is founded upon multivariable control principles (Fig. 7), specifically tailored for multi-input multi-output (MIMO) systems, by incorporating constraints on either input or output variables. Aligned with the rocket control model, it is segregated into Lateral control (involving two inputs, aileron, and rudder, affecting roll and yaw dynamics) and Longitudinal control (with one input, elevator, governing pitch dynamics during flight). However, this study prioritizes the examination of roll dynamics.

Incorporating PID Control and MPC into the OADCS, which utilizes an NI myRIO main controller, is relatively straightforward with LabVIEW, as both functionalities are supported by the provided functions.

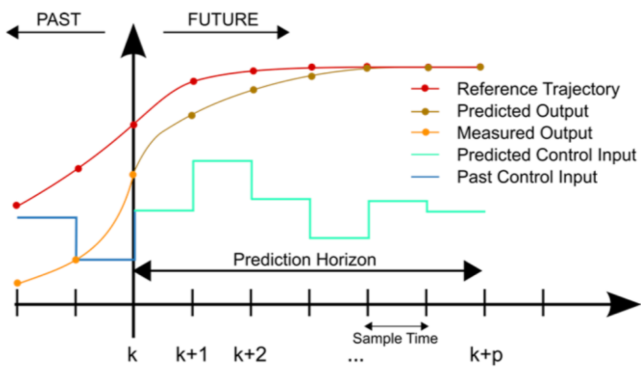


Fig. 7. MPC working principle [54]

III. Result and Discussion

Following the step-by-step approach outlined earlier, which involves simulation using SILS and direct hardware integration through HILS, the rocket flight simulation in this research was conducted by comparing two control strategies: PID and MPC. As previously mentioned, the simulated rocket in this research if there is no interference is assumed to be ideal and perfectly stable (no roll, pitch and yaw), designed for an 18-second burnout period with a maximum speed of up to 4.07 Mach Number (4985.93 km/h). The stability of a rocket is affected by various factors. Internally, these factors include the placement and dimensions of the fins, the center of gravity, rocket mass and the thrust generated by the rocket. Externally, factors such as drag, weather conditions and gusts of wind (wind turbulence) can also impact the rocket's trajectory, causing deviations. The rear fin primarily serves for stabilization, while the front fin (canard) facilitates maneuvering. Moreover, misalignment of the fins during rocket fabrication can lead to unwanted rolling. The rocket has been engineered to maximize stability, ensuring minimal rolling throughout its 230-second flight time.

Therefore, for the purpose of this paper, a spinning disturbance was intentionally introduced between T+2 and T+8 during the flight, achieved by triggering a 0.02-degree deflection of the canard, resulting in the rocket spinning up to 48 degrees. Following T+8 in the flight, the control program initiates an attempt to halt the roll.

A. Conventional PID Control

Initially, the program to halt the spinning was executed using conventional PID control methods [55-58], starting from T+8 and continuing until T+20 during the flight. Under these conditions, the PID gains were configured as follows: P= 7; I= 0.7; and D= 0.001. The output signal undergoes testing with two distinct division factors to discern its PID sensitivity: divided by 5 and divided by 10. The outcomes are depicted in Fig. 8.

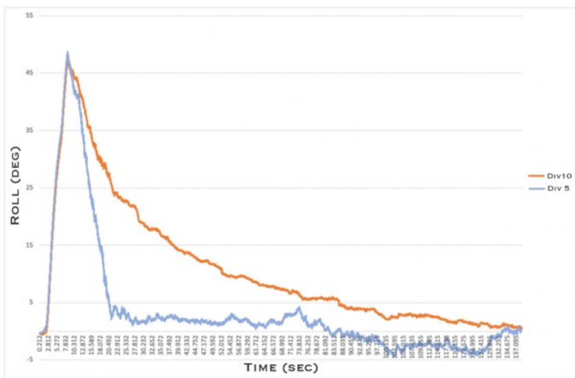


Fig. 8. Stop spinning using PID control

The PID output divided by 5 (illustrated by the blue line) exhibits rapid roll increase over time, reaching a peak around 10 seconds (T+10). Subsequently, the OADCS gradually reduces the roll, ultimately stabilizing it at 0 degrees within 83 seconds. Notably, the graph displays fluctuations between 20 seconds and 83 seconds before reaching 0 degrees. After 83 seconds, the graph fluctuates within negative values, returning to positive values after 134 seconds (T+134).

In contrast, the PID output divided by 10 (represented by the red line) yields a more consistent outcome: even after 132 seconds following the initiation of the control program, the roll remains considerably distant from 0 degrees. Based on these findings, it is evident that reducing the division factor below 5 might expedite the attainment of 0 degrees, albeit with pronounced oscillations. Such performance in a real flight scenario could render the rocket unstable and unsuitable for camera applications. Conversely, increasing the division factor beyond 10 would significantly prolong the time required to reach 0 degrees. Consequently, it was decided not to pursue further iterations and to explore alternative approaches instead.

B. Model Predictive Control (MPC)

The primary focus of this paper does not center on rocket modeling. Utilizing a design developed by the aerodynamic and flight dynamics team, a stable rocket is produced. Parameters such as rocket dimensions, thrust, fin configuration, center of gravity, and others are then inputted into X-Plane according to the guidelines outlined in point II.B. Conversely, due to X-Plane's 'black box' nature in this simulation, lacking a concrete mathematical model, it cannot be directly applied to real rockets intended for physical flights in the future. Hence, this paper predominantly highlights feedback control as a response to the rocket's attitude in X-Plane within the hardware utilized. Therefore, the model employed in this Model Predictive Control (MPC) is deliberately simplified, and even so, the outcomes are still juxtaposed with those obtained using PID.

Model Predictive Control (MPC) represents a modern optimal control methodology wherein predictive algorithms formulate control signals. As its name implies, these output signals are fine-tuned through optimization, utilizing forecasts of the plant's state in the subsequent time step. This leverages the process model to anticipate the future dynamics of the controlled system [59]-[62]. While MPC typically necessitates a mathematical model of the system (state-space), for the purpose of halting the spinning in this paper, we employ a basic state-space model as an illustrative example.

$$x\_(k+1) = [0.93]\, x\_k + [1]\, u\_k \quad (1)$$

$$y_k = [1]x_k + [0]u_k \quad (2)$$

To validate formulas (1) and (2), we utilized a sample program built in LabView, namely 'CDX MPC Base Case with Model Mismatch'. The program employs the following parameter settings:

- Prediction horizon for the MPC controller parameter set to 10, with a control horizon of 2.
- Output error weighting set to 0.11528.
- Control action changing weighting adjusted to 10.
- Model gain difference set to 0.172946.
- The closed-loop response is depicted in Fig. 9, demonstrating a smoother curve with minimal ripple compared to the default value.

Subsequently, the optimized parameters outlined above are incorporated into the MPC configuration within the Rocket Simulation Control, scheduled to activate after T+8 seconds into the flight. The simulation outcome, displayed in Fig. 10, illustrates the effectiveness of the MPC algorithm in halting the rocket's spinning motion (green line).

Combining the stop-spinning simulation outcomes using MPC with the PID results, as depicted in Fig. 10, reveals a notable contrast. The MPC algorithm swiftly mitigated the rocket's roll from 48 degrees to 0 degrees within a mere 11 seconds following the activation of MPC control, marking a remarkable improvement compared to the PID results. This reduction occurred approximately 12 times faster than with PID control. Moreover, the MPC maintained the roll at 0 degrees for the remainder of the flight until touchdown at T+230 seconds.

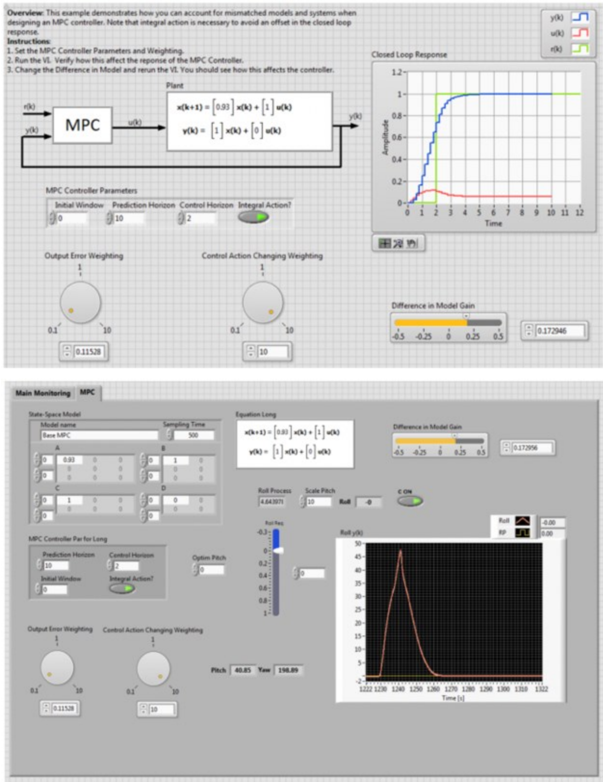


Fig. 9. MPC parameter settings and close loop program results

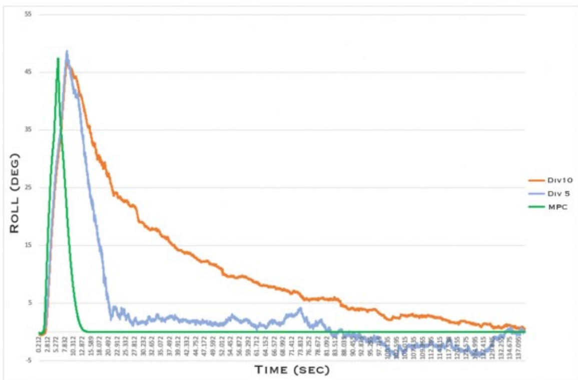


Fig. 10. OADCS simulation by MPC and PID

C. Discussion

Both PID and MPC control strategies underwent rigorous testing in the Hardware In-the-Loop Simulation (HILS), directly engaging the myRIO hardware slated for flight testing. This comprehensive testing confirms the efficacy of the Onboard Attitude Determination and Control System (OADCS) main controller when implementing MPC, successfully mitigating.

In the realm of actual rocket development, an accurate mathematical model is imperative for ensuring that MPC can adeptly address all rocket attitudes. Hence, conducting further comprehensive research on potential rocket models, possibly developed using Matlab/Simulink and integrated with MPC in Labview, followed by validation through direct flight tests, gain significance and leading to novel challenges on the future. At the very least, in this research, MPC has been successfully embedded in the OADCS main processor by utilizing NI myRIO, demonstrating its capability to effectively mitigate the rocket's rotation according to the mission in this research.

IV. Conclusion

The implementation of rocket Onboard Attitude Determination and Control System (OADCS) for single-stage rocket management using NI myRIO as the main controller has demonstrated its ability to effectively address all demands of the rocket's avionic and flight control system. Through the developmental phases, including Software in the Loop simulation (SILS) and Hardware in the Loop simulation (HILS), significant progress has been made toward achieving OADCS objectives. These simulations have also streamlined to the pre-launch development of sounding rocket. In this research, the performance of MPC significantly surpassed that of the PID controller, achieving almost a 12-fold improvement in stopping the rocket's spinning motion. Furthermore, our discoveries affirm that the OADCS simulation, employing the MPC control scheme, effectively halts the rocket's rotational movement promptly and sustains stability until touchdown, thereby validating the comprehensive suitability of the software and hardware development of the OADCS for rocket camera payload applications, ensuring continuous earth-facing orientation. Moving forward, this research has the potential for advancement by utilizing Matlab/Simulink as the provider for the rocket model instead of X-Plane. This would involve integrating Matlab/Simulink with the OADCS, which is equipped with MPC in Labview, along with all sensors, peripherals, power management, and data communication systems. Such integration aims to yield more realistic outcomes for missions involving the utilization of cameras on real rockets.

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References

[1] S. Trowitzsch, E. Artono, H. Gantina, W. Pasadena, R. Sunarya, L. Mariani, "An atmospheric sensor payload for the Indonesian RX-320 sounding rocket," in *Proceedings of the International Astronautical Congress*, 2018.

[2] G. Tan *et al*., "Experimental Investigation into Closed-Loop Control for HTPB-Based Hybrid Rocket Motors," *Aerospace*, vol. 10, no. 5, 2023.

[3] A. I. Torres, "Reusable Rockets and the Environment," *UC Merced Undergraduate Research Journal*, vol. 12, no. 2, 2020.

[4] A. Fedaravičius, S. Kilikevičius, A. Survila, and S. Račkauskas, "Short range rocket-target: research, development and implementation," *Aircraft Engineering and Aerospace Technology*, vol. 91, no. 7, 2019.

[5] F. M. Villanueva, "Sounding Rocket Development Program for Peru," in *IEEE Aerospace Conference Proceedings*, p. 1–9, 2018.

[6] Y. Yun, J. Seo, K. Park, J. Huh, J. Lim, and S. Kwon, "Integration validation of key components for small sounding rockets," *Aerospace Science and Technology*, vol. 100, p. 105823 2020.

[7] A. Okninski, "Multidisciplinary optimisation of single-stage sounding rockets using solid propulsion," *Aerospace Science and Technology*, vol. 71, 2017.

[8] T. Zhang, X. Zhao, R. Hu, and W. Fu, "A method for fault diagnosis of power system of carrier rocket engine based on linear-quadratic receding time-domain algorithm," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, vol. 236, no. 4, 2022.

[9] D. C. Walther and J. Ahn, "Advances and challenges in the development of power-generation systems at small scales," in *Progress in Energy and Combustion Science*, vol. 37, no. 5, 2011.

[10] M. Lin, J. Zhang, L. Xu, W. Zhu, and N. Ren, "Development of Large Capacity FM Telemetry System for Long March 5 Launch Vehicle," *Journal of Deep Space Exploration*, vol. 8, no. 4, 2021.

[11] A. T. Nugraha and D. Priyambodo, "Development of Rocket Telemetry in Chamber Gas Pressure Monitoring with the MPXV7002DP Gas Pressure Sensor," *Journal of Electronics, Electromedical Engineering, and Medical Informatics*, vol. 2, no. 3, 2020.

[12] A. Mohammed, W. A. G. Al-Tumah, and R. Malallah, "Design of Wraparound Microstrip Antenna using the Method of Moment," *Open Journal of Science and Technology*, vol. 3, no. 3, 2020.

[13] N. T. Markad, R. D. Kanphade, and D. G. Wakade, "Design of Cavity Model Microstrip Patch Antenna," *Computer Engineering and Intelligent Systems*, vol. 6, no. 4, 2015.

[14] A. Mohammed, A. Wa'il, and R. Malallah, "Design of Wraparound Microstrip Antenna using the Method of Moment," *Open Journal of Science and Technology*, vol. 3, no. 3, pp. 266-273, 2020.

[15] A. Vennitti, T. Schmiel, C. Bach, and M. Tajmar, "Health Monitoring of Reuseable Rockets: Basics for Sensor Selection," *Aerotecnica Missili & Spazio*, vol. 101, no. 3, 2022.

[16] J. J. Wu, X. Zhu, Y. Q. Cheng, and M. Y. Cui, "Research Progress of Intelligent Health Monitoring Technology for Liquid-Propellant Rocket Engines," in *Tuijin Jishu/Journal of Propulsion Technology*, vol. 43, no. 1, 2022.

[17] W. Yin, X. Qu, Z. Wu, D. Gao, and Z. Lei, "Design of the Structural Health Monitoring Sensor System for the Rocket Tank," *Yadian Yu Shengguang/Piezoelectrics and Acoustooptics*, vol. 39, no. 1, 2017.

[18] G. Fox *et al*., *Design and Construction of a High-Powered Rocket with a Camera Placed in the Nosecone*. John Heinrichs Scholarly & Creative Activities Day, 2023.

[19] H. Kojima, T. Okawara, and P. M. Trivailo, "Ellipse detection-based visual servo control for capturing upper-stage rocket body," *Acta Astronautica*, vol. 182, 2021.

[20] A. C. Pamungkas, A. A. Putra, P. Puspitaningayu, Y. Fransisca, and A. Widodo, "Multi-Parameter Wireless Monitoring and Telecommand of

a Rocket Payload: Design and Implementation," *IOP Conference Series: Materials Science and Engineering*, vol. 336, no. 1, 2018.

[21] C. E. Constantinescu, "A reactive control system for a partially guided small sounding rocket," *MATEC Web of Conferences*, vol. 304, 2019.

[22] W. Jingyu, J. Yansheng, Z. Jinfeng, W. Yanqing, W. Yabin, and G. Siyan, "Analysis and correction method of stellar aberration for high-resolution satellites," in *Advances in the Astronautical Sciences,* pp. 2347–2356, 2018.

[23] F. Mingireanu, L. Baschir, S. Miclos, D. Savastru, and N. Jula, "Proportional and bang-bang controller for space vehicle de-tumbling using quaternion-based attitude determination," *UPB Scientific Bulletin, Series A: Applied Mathematics and Physics*, vol. 82, no. 3, 2020.

[24] W. Zhang, C. Wen, and T. Zhou, "An effective flight attitude and trajectory control scheme for sounding rocket," in *Journal of Physics: Conference Series*, vol. 2472, no. 1, p. 012023, 2023.

[25] Y. Fukushima, "Onboard 7DOF motion stage as an inertial platform for payloads on sounding rockets," *2018 IEEE 15th International Workshop on Advanced Motion Control (AMC)*, pp. 240-245, 2018.

[26] Y. Fukushima, "Onboard 7DOF motion stage as an inertial platform for payloads on sounding rockets, in *Proceedings - 2018 IEEE 15th International Workshop on Advanced Motion Control, AMC 2018,* pp. 240–245, 2018.

[27] D. C. Shin and D. M. Lee, "Development of real-time implementation of a wind power generation system with modular multilevel converters for hardware in the loop simulation using matlab/simulink," *Electronics (Switzerland)*, vol. 9, no. 4, 2020.

[28] P. Pa Aye, "Analysis on Control System Design of Plant Simulator for Hardware-In-The-Loop Simulation Using MATLAB," *International Journal of Sensors and Sensor Networks*, vol. 6, no. 1, 2018.

[29] A. Kharbouch *et al*., "Internet-of-Things Based Hardware-in-the-Loop Framework for Model-Predictive-Control of Smart Building Ventilation," *Sensors*, vol. 22, no. 20, 2022.

[30] Y. K. Chen, Y. C. Lee, and V. C. Koo, "Design and Implementation of Synthetic Aperture Radar (SAR) Field-Programmable Gate Array (FPGA)-Based Processor," *Applied Sciences*, vol. 12, no. 4, 2022.

[31] S. A. Bamerni and A. K. Al-Sulaifanie, "Field programmable gate arrays implementation of different standard deviation estimation techniques," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 27, no. 1, 2022.

[32] W. A. Al-Musawi, M. A. A. Al-Ibadi, and W. A. Wali, "Artificial intelligence techniques for encrypt images based on the chaotic system implemented on field-programmable gate array," *International Journal of Artificial Intelligence*, vol. 12, no. 1, 2023.

[33] D. Wang, Z. Tian, A. Gholami, and G. Yang, "Evaluation of virtual controller interface device and software-in-the-loop simulation," *Proceedings of the Institution of Civil Engineers: Transport*, vol. 174, no. 6, 2021.

[34] J. Yang, X. Wang, S. Baldi, S. Singh, and S. Fari, "A software-in-the-loop implementation of adaptive formation control for fixed-wing UAVs," *IEEE/CAA Journal of Automatica Sinica*, vol. 6, no. 5, 2019.

[35] S. Elanchezhian and G. Anitha, "Software In-Loop Simulation of a Quad Tilt Rotor Unmanned Aerial Vehicle for Transition Control," *Transactions of Famena*, vol. 47, no. 1, 2023.

[36] W. Zhao, Y. Guo, J. Yang, W. Xue, X. Wu, "Design of liquid rocket engine fault diagnosis device and its HIL verification," *Beijing Hangkong Hangtian Daxue Xuebao/Journal Beijing University Aeronautics and Astronautics,* vol. 45, no. 10, pp. 1995–2002, 2019.

[37] J. Yang, A. Konno, S. Abiko, and M. Uchiyama, "Hardware-in-the-loop simulation of massive-payload manipulation on orbit," *ROBOMECH Journal*, vol. 5, no. 1, 2018.

[38] T. Koo, R. Ko, D. Ha, and J. Han, "Development of Model-Based PEM Water Electrolysis HILS (Hardware-in-the-Loop Simulation) System for State Evaluation and Fault Detection," *Energies*, vol. 16, no. 8, 2023.

[39] H. Y. Irwanto and E. Artono, "Correlation of Hardware in the Loop Simulation (HILS) and real control vehicle flight test for reducing flight failures," *Journal of Physics: Conference Series*, vol. 1130, no. 1, p. 012014, 2018.

[40] Y. Gao, J. Wang, S. Gao, and J. Ding, "A General Integrated Design and Control Strategy Considering System Decomposition with Application to a Rocket Flight Attitude Control System," *IEEE/ASME Transactions on Mechatronics*, vol. 25, no. 6, 2020.

[41] M. Bouziane, A. E. M. Bertoldi, P. Milova, P. Hendrick, and M. Lefebvre, "Development and testing of a lab-scale test-bench for hybrid rocket motors," *15th International Conference on Space Operations*, p. 2722, 2018.

[42] N. N. Deshmukh *et al*., "Suppression of thermo-acoustic instabilities in horizontal Rijke tube using pulsating radial jets," *MethodsX*, vol. 11, 2023.

[43] H. Y. Irwanto, I. E. Putro, and S. Saeri, "HILS of FPV-2600 UAV using MyRIO-1950 as Optimal Flight Control System," *International Journal on Advanced Science, Engineering and Information Technology*, vol. 11, no. 5, pp. 1780–1786, 2021.

[44] H. Shin, J. Lee, H. Kim, and D. Hyunchul Shim, "An autonomous aerial combat framework for two-on-two engagements based on basic fighter maneuvers," *Aerospace Science and Technology*, vol. 72, 2018.

[45] A. Kumar, S. Yoon, and V. R. S. Kumar, "Mixed reality simulation of high-endurance unmanned aerial vehicle with dual-head electromagnetic propulsion devices for earth and other planetary explorations," *Applied Sciences*, vol. 10, no. 11, 2020.

[46] S. Lee, C. Park, Y. Park, and D. Lee, "Development of Simulation Environment for Proximity Flight Using Simulink and X-Plane," *Journal of the Korean Society for Aeronautical and Space Sciences*, vol. 49, no. 6, 2021.

[47] H. Y. Irwanto, "HILS of auto take off system: For High Speed UAV using booster rocket," *Proceeding - 2016 International Seminar on Intelligent Technology and Its Application, ISITIA 2016: Recent Trends in Intelligent Computational Technologies for Sustainable Energy*, pp. 373–80, 2016.

[48] W. Zhao, Y. Guo, J. Yang, and H. Sun, "Hardware-in-the-loop simulation platform for fault diagnosis of rocket engines," *2019 IEEE 10th International Conference on Mechanical and Aerospace Engineering, ICMAE 2019*, 2019.

[49] F. M. Cantri, M. H. Bisri, and H. Y. Irwanto, "Realtime Simulation for Rocket Using Visual Programming," *Proceeding - IEEE 8th Information Technology International Seminar*, 2022.

[50] Y. W. Hadi, R. T. Bambang, "Development of hardware-in-the-loop simultion for rocket guidance system," *Proceedings - 5th International Conference on Electrical Engineering and Informatics: Bridging the Knowledge between Academic, Industry, and Community*, pp. 229–34, 2015.

[51] M. Sagliano, D. Seelbinder, S. Theil, and P. Lu, "Six-Degree-of-Freedom Rocket Landing Optimization via Augmented Convex–Concave Decomposition," *Journal of Guidance, Control, and Dynamics*, 2023.

[52] A. Ünal, K. Yaman, E. Okur, and M. A. Adlı, "Design and Implementation of a Thrust Vector Control (TVC) Test System," *Politeknik Dergisi*, vol. 21, no. 2, pp. 497-505 2018.

[53] G. H. Ceotto, R. N. Schmitt, G. F. Alves, L. A. Pezente, and B. S. Carmo, "RocketPy: Six Degree-of-Freedom Rocket Trajectory Simulator," *Journal of Aerospace Engineering*, vol. 34, no. 6, 2021.

[54] X. Yang, G. Liu, A. Li, and V. D. Le, "A Predictive Power Control Strategy for DFIGs Based on a Wind Energy Converter System," *Energies*, vol. 10, no. 8, p. 1098 2017.

[55] D. Lastomo, H. Setiadi, and M. R. Djalal, "Optimization pitch angle controller of rocket system using improved differential evolution algorithm," *Int. J. Adv. Intell. Informatics,* vol. 3, no. 1, pp. 27–34, 2017.

[56] I. Khan, I. Hussain, M. Z. A. Shah, K. Kazi, and A. A. Patoli, "Design and simulation of anti-lock braking system based on electromagnetic damping phenomena," *2017 1st International Conference on Latest Trends in Electrical Engineering and Computing Technologies, INTELLECT 2017*, 2018.

[57] A. Bhadran, J. G. Manathara, and P. A. Ramakrishna, "Thrust Control of Lab-Scale Hybrid Rocket Motor with Wax-Aluminum Fuel and Air as Oxidizer," *Aerospace*, vol. 9, no. 9, 2022.

[58] L. Sopegno, P. Livreri, M. Stefanovic, and K. P. Valavanis, "Thrust Vector Controller Comparison for a Finless Rocket," *Machines*, vol. 11, no. 3, 2023.

[59] S. Pérez-Roca *et al*., "An MPC approach to transient control of liquid-propellant rocket engines," *IFAC-PapersOnLine*, pp. 268–73, 2019.

[60] C. Wang and Z. Song, "Convex Model Predictive Control for Rocket Vertical Landing," *37th Chinese Control Conference*, pp. 9837–9842, 2018.

[61] I. McInerney, L. Nita, Y. Nie, A. Oliveri, and E. C. Kerrigan, "Towards a framework for nonlinear predictive control using derivative-free optimization," *IFAC-PapersOnLine*, vol. 54, no. 6, 2021.

[62] Z. Bojun, L. Zhanchao, and L. Gang, "High-precision adaptive predictive entry guidance for vertical rocket landing," *Journal of Spacecraft and Rockets*, vol. 56, no. 6, 2019.