The International Journal of Energy & Engineering Sciences, 2023, 8 (2) 28-39
ISSN: 2602-294X - Gaziantep University

COMPARATIVE STUDY OF PID AND MPC CONTROLLERS FOR VERTICAL TAKE-OFF AND VERTICAL LANDING (VTVL) ROCKET CONTROL

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ABSTRACT

This study explores the intricacies of designing a controller for simulating environments dedicated to rocket flight and vertical landing. The primary focus is on evaluating two prominent control mechanisms: the Proportional-Integral-Derivative (PID) controller and the Model Predictive Control (MPC) controller. The study systematically explores the performance of these controllers in the context of vertical descent, revealing that the PID controller effectively enhances the rocket's vertical descent capabilities. Additionally, the research underscores the MPC controller's remarkable potential in augmenting vertical descent performance through the adept coordination of various control mechanisms and its ability to adapt to external disturbances. The findings of this study not only contribute significantly to the field of rocket control but also establish a foundational framework for future endeavours and advancements in this dynamic and crucial domain.

Keywords: VTVL Rocket Control, PID, MPC, Optimization

1. INTRODUCTION

Rocket technology holds a pivotal role in numerous fields, including manned and unmanned space exploration, telecommunications satellites, space tourism, scientific research, satellite deployment, and military defence. However, the high costs associated with rocket technology have driven the need for innovations in system reusability, particularly in the domain of first-stage rockets. SpaceX and Blue Origin's successful vertical landing trials using Vertical Take-off and Vertical Landing (VTVL) have marked significant progress towards achieving autonomous rocket engine recovery and reusability [1]. Achieving precise control of rockets is essential to ensure their safe navigation towards their intended destinations. This demands the execution of complex control algorithms in real-time on the rocket [2][3]. Hence, it is imperative to accurately model and control rockets and optimize them using advanced algorithms and techniques [4].

The evolving rocket and control technologies, particularly the algorithms used in the vertical landing phase, constitute a significant area of research. Vertical landing requires the use of precise control algorithms to ensure the rocket safely returns to the

Earth's surface. During this phase, the interaction of the rocket with factors such as changing atmospheric conditions, aerodynamic derivatives, propulsion systems, and control systems increases the complexity of mathematical modelling [5]. The applicability of these algorithms is of great importance to ensure the rocket safely lands at the intended location. In this context, the simplicity and widespread use of the Proportional-Integral-Derivative (PID) controller, as opposed to the more sophisticated strategy of Model Predictive Control (MPC), will be subject to a comparative evaluation in terms of controlling the complex systems of the rocket. This study aims to provide a valuable perspective on the development and applicability of algorithms in the vertical landing phase, focusing on the challenges posed by these algorithms.

This study aims to establish a rocket flight and vertical landing simulation environment through controller design, allowing for the dynamic modelling and control of rockets during various phases. The research delves into rocket control, particularly modelling and an analysis of control mechanisms, namely the PID (Proportional-Integral-Derivative) and MPC (Model Predictive Control) controllers. Rocket modelling involves translating physical characteristics into mathematical expressions, including aerodynamic derivatives, atmospheric parameters, propulsion, control systems (e.g., gimbal engines and cold gas thrusters), and considerations such as fuel consumption and changes in inertia. These elements combine to compute the rocket's equations of motion.

The PID controller, known for its simplicity and wide usage, operates through a feedback loop to generate control signals based on the difference between system output and the desired target. The study highlights the PID controller's role in rocket control, discussing its advantages and limitations.

Conversely, the MPC controller represents a more sophisticated strategy that determines optimal control signals by using a mathematical model and considering the system state, future predictions, and predefined constraints. It excels in managing complex systems with precision and adaptability [6]. The study explores the application of the MPC controller in rocket control, presenting its merits, demerits, and inherent limitations. Evaluations about advantages and disadvantages of required flight controllers for a drone to be able to remain stable in the air and fulfill its mission and variable pitch mechanism of a RC Helicopter tail in terms of the structural analysis are been presented [7][8].

In addition to addressing the challenges of high costs associated with rocket technology and emphasizing the advancements made in rocket reusability through vertical landing trials, this research aims to contribute to the broader landscape of autonomous rocket control. The establishment of a comprehensive simulation environment for rocket flight and vertical landing, coupled with a focus on controller design, serves as the cornerstone for dynamic modelling and control during various phases of rocket operations. The study further underscores the significance of achieving precise control in rocket navigation through the real-time execution of complex control algorithms, highlighting the need for accurate modelling and optimization using advanced techniques. By delving into the nuances of rocket control, with a specific emphasis on PID and MPC controllers, this research seeks to provide valuable insights that can potentially revolutionize not only the efficiency of rocket operations but also pave the way for broader applications in space exploration, satellite deployment, and beyond.

2. METHODOLOGY

This thesis centres on the modelling and control of vertical landing rockets. The methodology section outlines the core approach, commencing with a detailed explanation of the mathematical modelling process. Here, the focus is on scrutinizing the rocket's equations of motion and dynamic properties, laying the groundwork for understanding its behaviour.

The foundation of this study rests upon a meticulously designed rocket model, with a primary focus on comprehensive Computational Fluid Dynamics (CFD) analysis and the detailed extraction of all necessary parameters. The engineered rocket model has been scrutinized from various perspectives, encompassing its aerodynamic performance, propulsion system efficiency, and integration of control mechanisms. CFD simulations have been conducted to gain insights into the rocket's behaviour within the atmosphere and identify potential challenges during the vertical landing phase. This model serves as a crucial groundwork for understanding the complexities involved in the rocket's vertical landing stage. The mathematical modelling of the rocket, considering aerodynamic derivatives, atmospheric conditions, and interaction with control systems, has been employed to evaluate the performance of PID and MPC controllers. In this manner, the designed rocket model acts as a reference point to ensure the reliability and applicability of the simulation environment that forms the basis of this study. In the subsequent sections of the research, a detailed analysis of the data obtained from this model, efforts to optimize control algorithms, and endeavours to enhance the performance of the rocket during the vertical landing phase will be thoroughly discussed.

2.1. Rocket Mathematical Model

Mathematical models elucidate rockets' functioning and behaviour, grounded in fundamental physics laws and equations of motion, as shown in Figure 1. These models, primarily based on Newton's laws of motion and the principle of mass conservation, provide a concise representation of rocket dynamics.

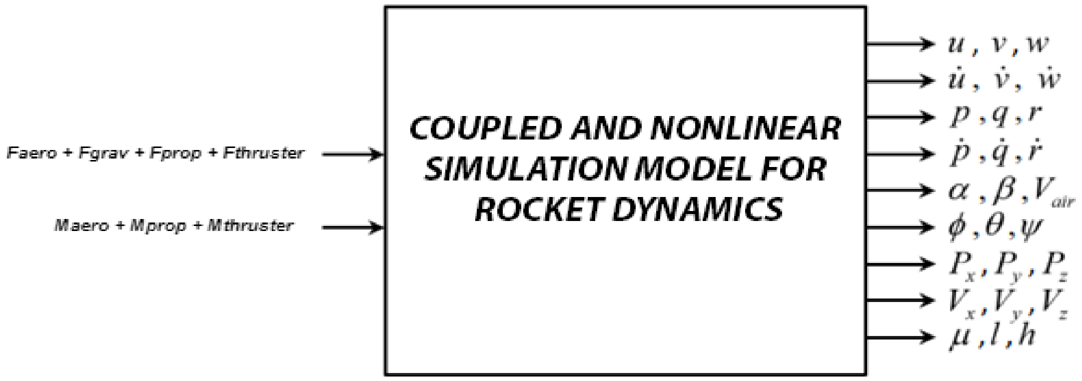

Figure 1. Coupled and Nonlinear Simulation Model for Rocket Dynamics

Initially, employing Newton's second law of motion, formulas are derived to calculate the net force of the system by combining mass and angular velocities to define linear motion equation values. Subsequently, the time derivatives of linear velocities (u, v, w) are directly obtained from the force equations, and calculating the linear velocities merely requires derivatizing them with respect to time [9].

$$X = m * (\dot{u} + wq - vr)$$
$$Y = m * (\dot{v} + ur - wp)$$
$$Z = m * (\dot{w} + vp - uq)$$

The derivation takes into account the plane of symmetry assumption for the moment equations, assuming symmetrical production of the rocket. As a result, inertial components I_{XY} and I_{YZ} are considered zero due to this symmetry, while the impact of I_{XZ} is factored into the ensuing calculations [9].

$$M = I_y\dot{q} + (I_x - I_z)pr + I_{xz}(p^2 - r^2)$$

$$L = I_x\dot{p} - I_{xz}\dot{r} + qr\left(I_z - I_y\right)pr - I_{xz}pq$$

$$N = -I_{xz}\dot{p} - I_z\dot{r} + pq\left(I_y - I_x\right) + I_{xz}qr$$

2.1.1. Forces and Moments

The design phase of a rocket involves modelling the six degrees of freedom (6 DOF) equations, considering various elements such as aerodynamics, propulsion, surface model, cold gas thruster, and gravitational forces and moments. These elements collectively shape the rocket's flight behaviour, crucial for ensuring a safe and successful mission.

Aerodynamic forces and moments play a pivotal role, determined by factors like the aircraft's shape, angle of attack, size, airspeed, air density, Reynolds number, and Mach number.

The movement of air around the rocket generates pressure and velocity variations, resulting in aerodynamic forces and moments. Forces acting on a rocket during flight include aerodynamic forces, thrust, and gravity, resolved along the body-axis system and referenced to the centre of gravity (Cg). The reference coordinate system for rockets is typically fixed to the body and cantered on the Cg [10].

During flight, multiple forces and moments act on the rocket, including gravitational force, aerodynamic forces, propulsion forces and moments, and nitrogen thruster forces and moments. The gravitational force, dependent on the rocket's mass and height, pulls the rocket towards the ground with a constant value. Aerodynamic forces depend on the rocket's stance, shape, angle of attack, and flight speed, influencing stability and direction [11]. Propulsion forces propel the rocket forward, accelerating and altering its trajectory, with moments arising from the difference between thrust vector and centre of gravity.

The combination of these forces and moments determines the rocket's flight behaviour and trajectory. Proper control and stabilization are essential for mission success, allowing the rocket to reach its intended trajectory. Below is a simplified explanation of the different forces:

- **Gravitational Force:** Gravity, a constant force, pulls the rocket towards the ground, dependent on mass and height.
- **Aerodynamic Forces:** Depending on the rocket's stance, shape, angle of attack, and flight speed, aerodynamic forces influence stability and direction.
- **Propulsion Forces and Moments:** Rocket engines produce propulsion forces that propel the rocket forward, altering its trajectory. Moments arise from the thrust vector and the rocket's centre of gravity.
- **Nitrogen Gas Propulsion Engines:** Small thrusters correct the rocket's direction and control rotational movements, stabilizing it for the desired trajectory.

In summary, a meticulous analysis of the various forces and moments is indispensable in the rocket's design phase to guarantee a well-controlled and stable flight, ultimately paving the way for a successful mission.

2.2. Control Algorithms

The system's behaviour is typically complex, and in controller design, two essential steps, linearization, and trimming, are employed to establish a linear model at the desired operational point of the system. Linearization entails the transformation of intricate systems into a linear model at a specified operational point. These steps are instrumental in gaining a deeper insight into the system's behaviour and determining the necessary coefficients for controller design.

In controller design, the processes of linearization and trimming serve as crucial tools for achieving a comprehensive understanding of the system's dynamics and facilitating the design of effective control strategies.

2.2.1. Linearization

Linearization simplifies complex nonlinear systems by approximating their equations with linear ones, often using the Taylor series expansion method. This technique is crucial in rocket modelling, aiding in the control, stabilization, and analysis of these intricate systems affected by factors like aerodynamics and engine thrust [12]. Linearization establishes a mathematical link between linear and nonlinear systems at a specific operating point, enhancing our understanding and control capabilities.

Jacobian linearization is a numerical approach that approximates nonlinear functions through derivatives at a specific point, leading to matrices A, B, C, and D. These matrices describe the linearized system in state space form. The state space formula is as follows:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

In rocket controller design, linearizing the nonlinear system equations is essential. This process simplifies the analysis and control tasks by converting the rocket into a linear approximation around a chosen operating point [13]. This enables the design of linear controllers that are suitable for stability analysis.

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \qquad B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} \\ \vdots \\ \frac{\partial f_1}{\partial u_n} \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{\partial h_1}{\partial x_1} & \cdots & \frac{\partial h_1}{\partial x_n} \end{bmatrix} \qquad D = \begin{bmatrix} \frac{\partial h}{\partial u} \end{bmatrix}$$

It's important to note that certain simplifying assumptions are made during linearization, which don't always reflect real-world complexities. However, these assumptions aid in managing complexity and serve as a starting point for analysis and prediction of rocket behaviour.

2.2.2. PID (Proportional-Integral-Derivative) Controller

The PID Controller, widely applied in control systems, is a feedback control method that maintains a process close to a setpoint value by making real-time adjustments to its output. It finds broad utility in industrial automation, robotics, motor control, and various other domains.
The PID controller relies on three fundamental components:

- **Proportional (P):** Responds to the current error (setpoint-measured value) by generating a correction signal directly proportional to the error's magnitude.

- **Integral (I):** Accumulates error over time and continually adds a correction signal, particularly beneficial in addressing persistent, small errors and enhancing system stability.
- **Derivative (D):** Considers the rate of error change and makes timely corrections to prevent abrupt responses to rapidly changing errors.

The PID controller combines these components using the transfer function:

$$C(s) = K_p + \frac{K_i}{s} + K_d$$

Here, C(s) represents the PID controller's transfer function, and the coefficients K_p, K_i, and K_d are adjustable parameters, fine-tuned to optimize control system performance.

In summary, PID control is a versatile and effective approach for maintaining processes near desired values. By configuring the Proportional, Integral, and Derivative components, as shown in Figure 2, precise parameter tuning ensures favourable results across various applications.

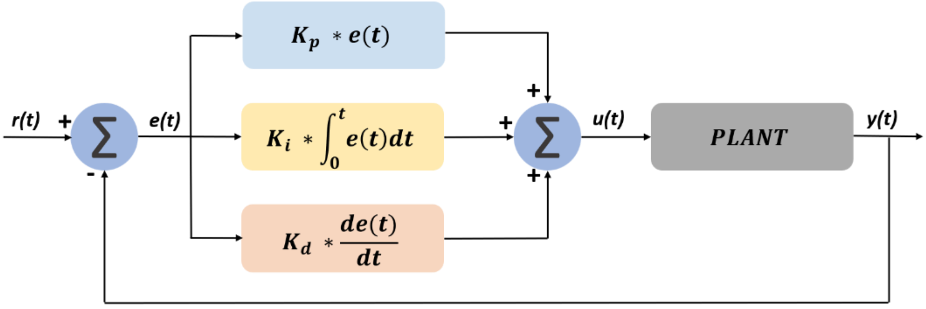

Figure 2. PID Controller Overview

The PID controller is designed to take control of the rocket's descent. It utilizes feedback from the rocket's angular rates and angular positions to optimize the vertical descent. The PID controller offers a simple yet powerful control mechanism, adjusting the control signals based on the error between the desired and actual angular positions and rates.

The results of this study demonstrate the efficacy of the PID controller in significantly improving the vertical descent performance of the rocket. This approach provides a robust and widely applicable control strategy that can be employed to enhance the success of space exploration missions.

2.2.3. MPC (Model Predictive Control) Controller

Model Predictive Control (MPC) is an advanced control strategy tailored for managing complex systems with dynamic and variable conditions. MPC excels in simultaneous control and optimization of multiple input and output variables, as shown in Figure 3, making it especially relevant in continuous time systems and advanced applications.

MPC's fundamental principle involves predicting control variables (inputs) and output variables within the system while constantly monitoring system behaviour [14]. The method employs a predictive approach, simulating the system's future behaviour over a predefined time interval within a control loop. Subsequently, optimal control signals are calculated based on these simulations and promptly implemented. This iterative process continually updates the control strategy to optimize system behaviour in alignment with defined objectives and constraints.

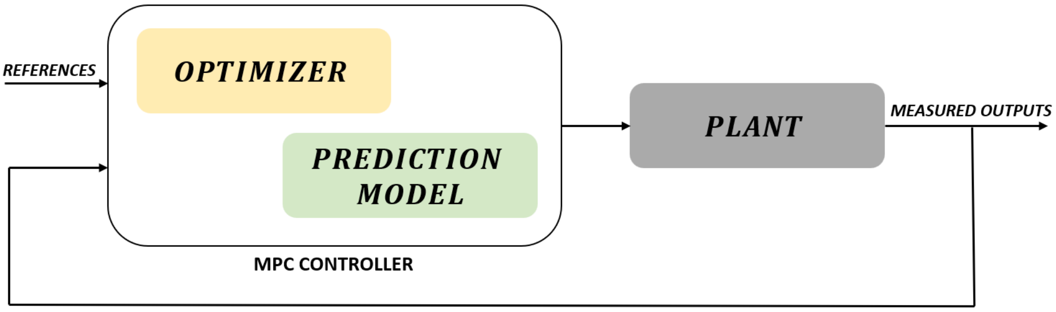

Figure 3. MPC Controller Overview

The key steps in the MPC process include [15]:

1. Mathematical Model: MPC relies on a precise mathematical model of the system, often expressed as dynamic differential equations.
2. Goal Function and Constraints: A goal function is formulated to optimize system behaviour within set constraints.
3. Predictions: MPC predicts future system behaviour based on the current state and past decisions.
4. Optimization: The predictions guide the selection of optimal control actions, refining future decisions.
5. Implementation: The optimized actions are applied to the real-time process.
6. Update: MPC continuously adapts control decisions based on real-time variables and differences between actual and predicted states, ensuring optimal process management.

MPC's iterative approach results in the constant adaptation of control decisions, ultimately aligning the process with defined objectives and constraints. This methodology proves highly effective in achieving control and optimization in complex systems with dynamic and variable conditions.

In this study, a Model Predictive Control (MPC) approach is applied to the modelling and control of vertical landing rockets. The primary objective of this study is to optimize the vertical descent of rockets by integrating various control mechanisms, such as grid fins, cold gas thrusters, and a gimballed engine. To achieve this goal, angle and angular velocity control are implemented using feedback from angular rates and angular positions of the rocket.

The MPC controller is designed to take charge of the rocket's control. This controller is tailored to optimize the rocket's vertical descent based on its angular velocities and angular positions. Different control mechanisms, including grid fins, cold gas thrusters, and a gimballed engine, are coordinated by the MPC controller. This enables the rocket to automatically determine the most suitable control strategies to cope with wind disturbances and other external factors during the descent.

The results of the study indicate that the MPC controller can significantly enhance the vertical descent performance of the rocket. This approach can improve the success of space exploration missions by enabling rockets to perform precise and safe vertical landings.

3. EVALUATION AND DISCUSSION

In this section, an analysis of the research results is presented, with a focus on the evaluation of PID and MPC controllers regarding their efficiency and effectiveness in the realm of rocket modelling and control. The results, depicted through graphs and analyses, provide insights into the capabilities of each controller concerning the stabilization and steering of the rocket. Additionally, this section offers an in-depth exploration of the strengths, limitations, and overall effectiveness of PID and MPC controllers by comparing the achieved outcomes.

The primary focus of this research lies in the comparison of PID and MPC controllers during the pitch angle control process, particularly in the rocket's separation phase. This phase entails a significant adjustment in the pitch angle, transitioning from 55 degrees to 130 degrees within a brief span of 169 seconds. This transition occurs after a 167-second separation event taking place at an average altitude of 70 kilometres. During this pivotal stage, the main objective is the maintenance of yaw and roll values at 0 degrees.

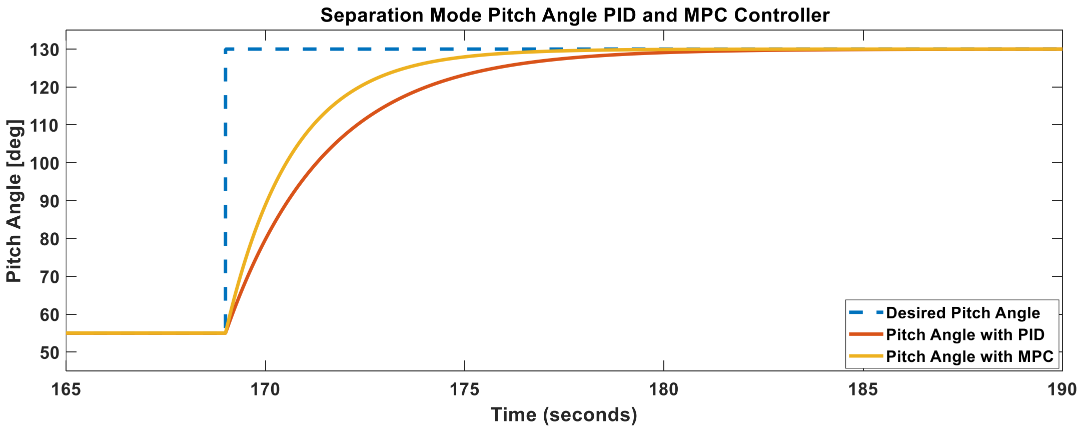

Figure 4. Separation Mode Pitch Angle PID and MPC Controller

The outcome of the study becomes evident when assessing the performance of MPC and PID controllers through data analysis and graphical representations. Notably, these results highlight a noticeable disparity in the performance between the two controllers, as shown in Figure 4. Specifically, the data illustrates that MPC exhibits a quicker response in executing commands compared to the PID controller, and the pitch angle converges towards the desired value at an accelerated pace.

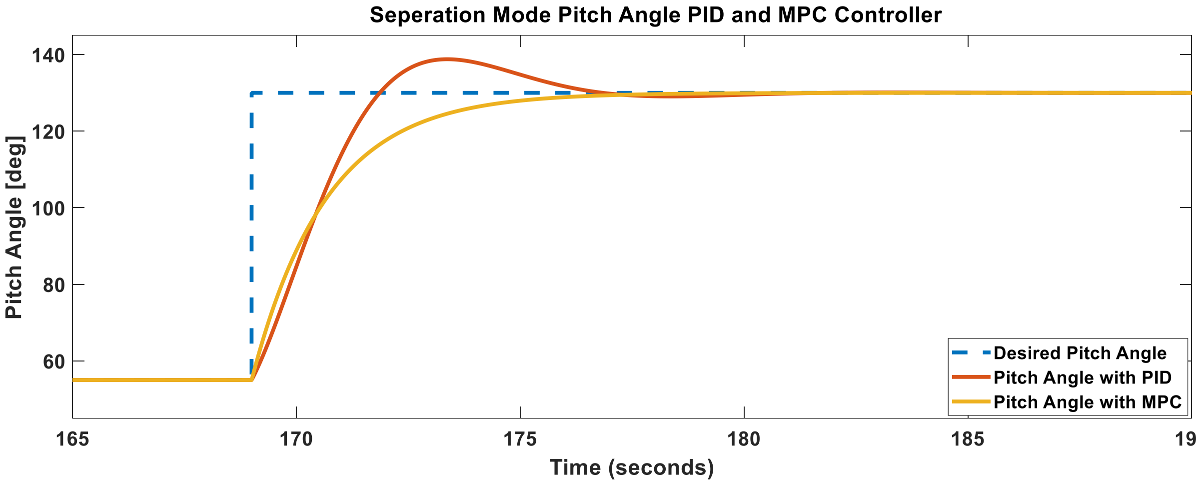

Figure 5. Separation Mode Pitch Angle PID and MPC Controller

To enhance the PID controller's performance, it underwent re-tuning and speed improvements, enabling it to match the MPC's command response speed. However, during this acceleration process, an intriguing observation was made. The accelerated PID controller occasionally exhibited temporary overshoots beyond the target pitch angle, emphasizing that overshoot behavior becomes more pronounced when the PID controller is accelerated, as shown in Figure 5, potentially affecting rocket control performance. These findings highlight that the MPC controller offers quicker and more precise control during rocket separation, benefitting from its predictive capabilities and complex control strategies. MPC addresses control as a predictive and optimization process, with its performance influenced by the horizon time interval. A longer horizon predicts future system behavior better but comes with increased computational demands.

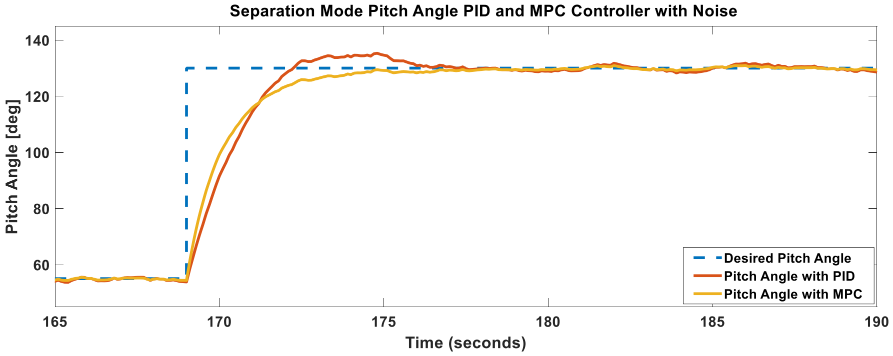

Figure 6. Separation Mode Pitch Angle PID and MPC Controller with Noise

In terms of managing external disturbances in control systems, this study introduced disturbances into rocket control. The MPC's predictive capabilities enable it to compensate for disturbances effectively and return to desired targets rapidly, as demonstrated in the graph. This predictive ability provides robust protection against disturbances, particularly in the dynamic separation mode of rocket control, as shown in Figure 6. In contrast, the simpler structure of the PID controller lacks predictive capabilities and evaluates only the current state, rendering it vulnerable to momentary changes and rapid disturbances.

When comparing responses to disturbances, the MPC controller demonstrated a swifter and more efficient approach to reaching the target, thanks to its predictive capabilities. This advantage is particularly pronounced in situations involving abrupt and rapid changes, as encountered during the separation mode. Conversely, the PID controller's simpler structure was found to be more sensitive to certain types of disturbances, potentially rendering it less adept at handling rapid changes.

4. CONCLUSION

This study delves into the modeling and control of vertical landing rockets in response to the rapidly evolving aerospace industry. These steps are pivotal for comprehending the rocket's behavior and enhancing control algorithms.

Subsequently, PID and MPC controllers are evaluated, with MPC outperforming PID in tests and analyses. The MPC controller exhibits superior response, stability, and adaptability, making it a preferred choice for future vertical landing rocket projects.

It's worth noting that the performance of the MPC is significantly influenced by the chosen prediction horizon. The horizon dictates the number of predictions steps the controller takes to anticipate future system behavior. A longer prediction horizon enables a more accurate forecast of the system's long-term behavior but requires additional computational resources.

In conclusion, this study recommends employing MPC controllers to improve rocket landings, providing valuable insights for aerospace researchers. Future work should expand on these findings and address more complex scenarios, aiming to optimize results in real-world applications.

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