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Model-prototype based flight test: Bringing flight control engineering to life for a reusable rocket with flightgear

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Abstract

Background: Reusable rocket technology has gained significant attention due to its potential to reduce launch costs, development time, and environmental impact. However, conventional development and flight testing of reusable rockets require substantial financial resources and carry high risks of material loss, particularly during early-stage experimentation and in resource-constrained research or defense education environments.
Aims: This study proposes a low-cost and accessible approach for reusable rocket development through a Model–Prototype Based Flight Test (MPBFT) method. The aim is to integrate mathematical flight control modeling, prototype-level implementation, and real-time three-dimensional visualization into a single co-simulation framework that enables virtual flight testing without physical launch, specifically for reusable rocket descent and landing maneuvers.
Method: The MPBFT framework integrates a dynamic model of the reusable rocket developed in MATLAB/Simulink based on rigid-body flight dynamics, with explicit mathematical formulations including governing differential equations, state-space representation, and closed-loop transfer function. A derivative-based proportional–integral–derivative (PID) controller was designed to regulate the rocket's pitch attitude. Real-time 3D visualization was achieved through co-simulation with FlightGear via UDP communication at 50 Hz. Controller gains were tuned iteratively (Kp=12.5, Ki=0.08, Kd=5.2), and robustness was assessed under parameter perturbations (+20% moment of inertia, +15% damping, step disturbance).
Results: Simulation results demonstrated stable closed-loop attitude control with the following quantitative metrics: 8.2% maximum overshoot, 3.87 s settling time (±2%), 0.014° steady-state error, damping ratio of 0.62, integral absolute error of 8.42 °·s, and control effort (RMS) of 3.21 N·m. Robustness analysis confirmed that all perturbed configurations remained stable and within acceptable thresholds (overshoot <15%, settling time <6 s, steady-state error <0.1°). The co-simulation successfully provided synchronized real-time 3D visualization of rocket pitch motion during descent.
Conclusion: The MPBFT framework is an effective and economical alternative for reusable rocket flight control testing, particularly suitable for research, defense aerospace education, and resource-constrained environments. Future work will extend the framework to multi-axis 6-degree-of-freedom dynamics, hardware-in-the-loop simulation, actuator and sensor modeling, and physical subscale flight validation to further enhance fidelity and applicability for advanced reusable rocket control system development.

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INTRODUCTION

Rocket technology is a fundamental pillar of modern aerospace systems, enabling space exploration, satellite deployment, national security, and global infrastructure such as communication, navigation, and Earth observation (Buysse et al., 2017; Hariharan et al., 2019). Rockets operate on the principle of momentum exchange, allowing payloads to be delivered beyond Earth's atmosphere where conventional air-breathing propulsion systems are ineffective (Halliday et al., 2013; Taylor, 2017). The continuous demand for reliable, safe, and cost-efficient access to space has driven significant advances in propulsion, guidance, navigation, and control systems (Daza Flórez et al., 2025). Among these, flight control engineering has emerged as a critical discipline because it directly governs vehicle stability, trajectory accuracy, and mission success under extreme dynamic conditions (Moldabekov et al., 2025; Nise, 2020). Without effective flight control, even a well-designed rocket cannot achieve its intended mission (Bhadran et al., 2024; De Oliveira & Lavagna, 2024; Xiong et al., 2022; Zhang et al., 2025).

Despite technological progress, the development and testing of rocket systems remain inherently complex due to strongly nonlinear flight dynamics, extreme operating environments (high acceleration, vibration, thermal loads), and high sensitivity to control errors (Itakura et al., 2011). Conventional development approaches rely heavily on full-scale flight testing, which demands substantial financial resources, dedicated launch infrastructure, and large engineering teams (D'Angiolo, 2025). Moreover, such tests carry high risks of system failure and material loss, especially during early-stage experimentation when design maturity is low (Inatani et al., 2001; Yoshida et al., 2009b). These challenges are particularly restrictive in research environments with limited funding, in educational settings where repeated physical testing is impractical, and in developing countries where access to launch ranges is scarce (Irwanto & Artono, 2018; Wenbo & Qiang, 2012). Consequently, there is a pressing need for low-cost, low-risk alternatives that can complement or partially replace physical flight testing during initial development phases.

Reusable rocket technology has gained significant global attention as a promising solution to reduce launch costs, shorten development cycles, and minimize environmental impact by enabling multiple flights of the same launch vehicle (Jo & Ahn, 2021; Torres, 2020). Major programs such as SpaceX's Falcon 9 and Starship have demonstrated the economic viability of reusability (Esteve Rubio, 2023; Herberhold et al., 2025). However, reusability introduces additional technical challenges that are not present in expendable systems. In particular, the descent and landing phases require precise attitude control, rapid response to disturbances, and high system reliability under varying aerodynamic conditions (Nebylov & Nebylov, 2016; Yoshida et al., 2009a). Experimental programs have repeatedly shown that flight control failures during these phases can result in catastrophic vehicle loss (Reinhardt et al., 2024; Yasyukevich et al., 2024). Therefore, rigorous validation of attitude control systems is essential before any practical reusable rocket deployment.

Despite growing research on reusable rocket flight dynamics and control, existing studies predominantly rely on two disconnected approaches. On one hand, purely numerical simulations conducted in MATLAB, Python, or similar environments provide detailed quantitative data but lack intuitive visual feedback and real-time interaction (Chen et al., 2008; Cieśliński et al., 2025; Wanli et al., 2019; Waxenegger-Wilfing et al., 2020; Wenbo & Qiang, 2012; Yulnandi et al., 2017). On the other hand, physical flight testing, whether subscale or full-scale, offers realistic validation but involves high cost, long lead times, and material risk. Few studies have successfully integrated control modeling, prototype-level implementation, and real-time 3D visualization in a unified, low-cost framework specifically tailored for reusable rockets. Moreover, most low-cost co-simulation frameworks reported in the literature are developed for conventional aircraft or unmanned aerial vehicles (UAVs), not for reusable rocket descent and landing maneuvers (Aschauer et al., 2015; Horri & Pietraszko, 2022; Moness et al., 2012; Perry, 2004; Sagliano, 2021). This gap is significant because the attitude dynamics, instability modes, and landing requirements of reusable rockets differ substantially from those of fixed-wing aircraft or multirotor UAVs (Daza Flórez et al., 2025; Itakura et al., 2011; Lu, 2024; Xiong et al., 2022; Yulnandi et al., 2017).

To address the identified gap, this study proposes a Model–Prototype Based Flight Test (MPBFT) framework for reusable rocket flight control evaluation. The framework integrates three main components: (1) a mathematical flight control model developed in MATLAB/Simulink based on rigid-body rocket dynamics, (2) a derivative-based proportional–integral–derivative (PID) controller designed to regulate pitch attitude during descent and landing, and (3) real-time 3D visualization using the open-source FlightGear flight simulator. Unlike conventional high-fidelity industrial simulations, the MPBFT framework is intentionally designed to be accessible, low-cost, and suitable for research and education environments with limited resources. The approach enables virtual flight testing without physical launch, quantitative analysis of control performance, and qualitative observation of flight behavior through realistic visualization. The primary contribution of this study is not the individual components, which are established methods, but rather their integrated orchestration into a coherent, reusable-rocket-specific, real-time co-simulation framework that bridges the gap between pure simulation and expensive field testing. This paper presents the system modeling, controller design, co-simulation architecture, and quantitative evaluation results to demonstrate the feasibility and effectiveness of the MPBFT approach for reusable rocket attitude control validation.

METHOD

The reusable rocket system was modeled using a MPBFT framework to enable virtual evaluation of flight control performance without physical launch experiments (Lowenberg, 2009). The framework consists of three main components: (1) a dynamic model of the reusable rocket developed in MATLAB/Simulink, (2) a derivative-based proportional–integral–derivative (PID) controller for pitch attitude regulation, and (3) real-time 3D visualization through co-simulation with FlightGear. Each component is described in detail below, including explicit mathematical formulations. The overall modeling structure and signal flow of the rocket dynamics are illustrated in Figure 1, which presents the Simulink block diagram of the proposed system.

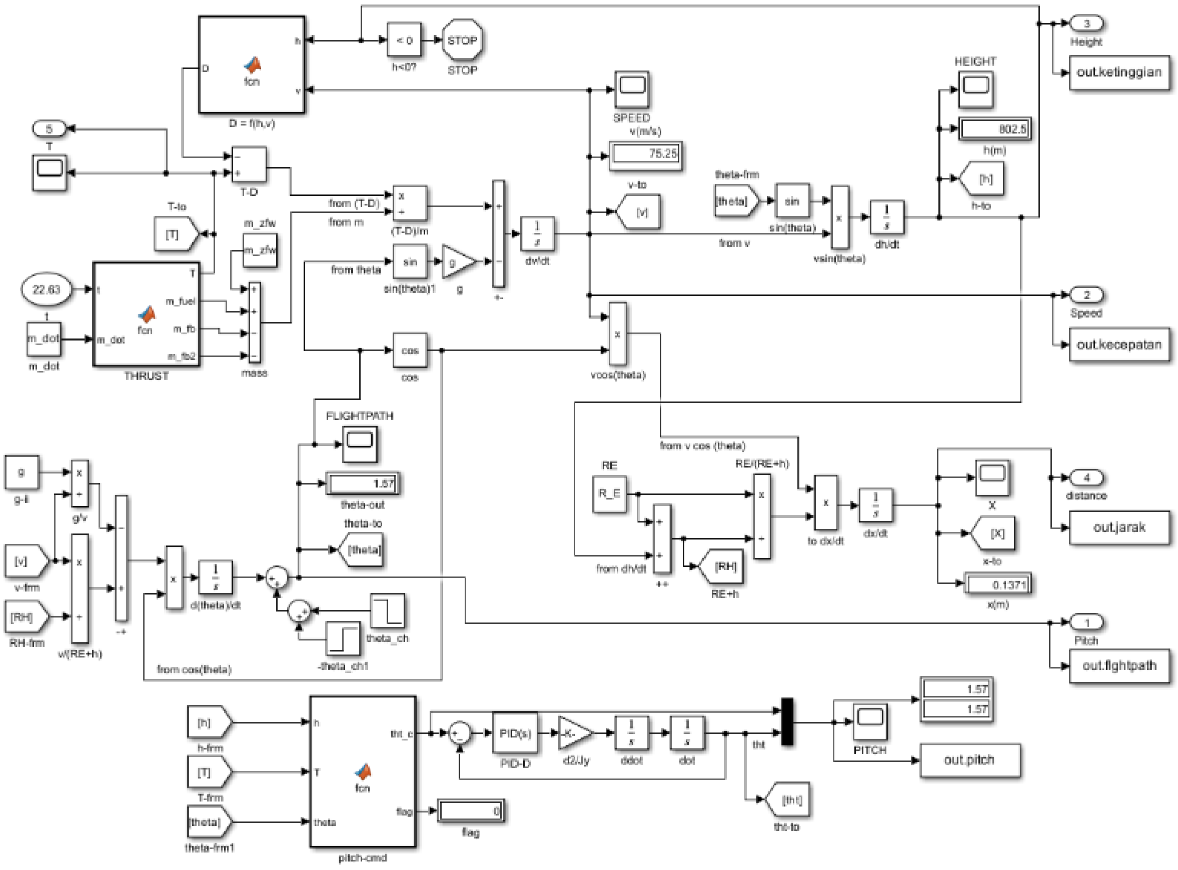


Figure 1. Simulink block diagram of the reusable rocket dynamic model used in the Model–Prototype Based Flight Test framework.

Dynamic Model of the Reusable Rocket

The rocket dynamics were modeled as a rigid body with single-degree-of-freedom rotational motion about the pitch axis. This simplification focuses on the most critical degree of freedom during descent and landing phases of a reusable launch vehicle (Nebylov & Nebylov, 2016; Yoshida et al., 2009a). The translational dynamics along the vertical axis are given by:

$$\sum F = m\frac{dV}{dt} = T - mg - D \tag{1}$$

where m is the instantaneous vehicle mass, V is vertical velocity, T is thrust force, g is gravitational acceleration ($9.81\ \mathrm{m/s^2}$), and D is aerodynamic drag defined as:

$$D = \frac{1}{2}\rho V^2 C_D A \tag{2}$$

Here, ρ is atmospheric density (obtained from the NASA standard atmospheric model) (Prölss, 2004), C_D is the drag coefficient, and A is the reference cross-sectional area.

The rotational dynamics about the pitch axis are governed by:

$$\sum M_y = I_{yy}\frac{dq}{dt} = M_\delta + M_q \tag{3}$$

where I_{yy} is the moment of inertia about the pitch axis, $q = \dot{\theta}$ is the pitch rate, θ is the pitch angle, M_δ is the control moment generated by thrust vectoring or aerodynamic surfaces, and M_q is the damping moment proportional to pitch rate. The control moment is expressed as:

$$M_\delta = -T \cdot l \cdot sin\theta \approx Tl\theta \text{ (for small angles)} \tag{4}$$

where l is the distance from the center of mass to the thrust application point. The damping moment is given by:

$$M_q = -C_q q \tag{5}$$

where C_q is the rotational damping coefficient (Giancoli, 1995; Serway & Jewett, 2009).

State-Space Representation

For control design, the nonlinear pitch dynamics were linearized around the equilibrium point ($\theta = 0$, $q = 0$). The state vector is defined as $x = [\theta, q]^T$, and the control input is the equivalent deflection $u = \delta_e$ (representing thrust vector angle or grid fin deflection). The resulting linear time-invariant state-space model is:

$$\begin{gathered} \dot{x} = Ax + Bu \\ y = Cx + Du \end{gathered} \tag{6}$$

with the system matrices:

$$\begin{gathered} A = \begin{bmatrix} 0 & 1 \\ -\frac{Tl}{I_{yy}} & -\frac{C_q}{I_{yy}} \end{bmatrix}; B = \begin{bmatrix} 0 \\ \frac{k_s}{I_{yy}} \end{bmatrix} \\ C = [1 \quad 0]; D = 0 \end{gathered} \tag{7}$$

Here, k_δ is the control effectiveness coefficient relating deflection angle to generated moment (Setyawan, 2016). The numerical values of all physical parameters used in the simulation are listed in Table 1 (Buysse et al., 2017).

Table 1. Physical parameters of the reusable rocket model.

Description	Symbol	Value	Unit
Mass (landing phase)	m	2500	kg
Moment of inertia (pitch)	I_{yy}	4250	kg·m^2
Thrust (landing burn)	T	32,000	N
Moment arm	l	1.8	m
Rotational damping	C_q	185	N·m·s/rad
Control effectiveness	k_δ	11,500	N·m/rad
Reference area	A	12.6	m^2
Drag coefficient	C_D	0.45	-

Derivative-Based PID Control Law and Architecture

A derivative-based PID controller was designed to regulate the pitch angle $\theta(t)$ to a reference command $\theta_{ref}(t)$. The time-domain control law is:

$$u(t){=}K_p e(t){+}K_i\int e\,(t)d\tau{+}K_d\frac{de(t)}{dt} \tag{8}$$

where $e(t) = \theta_{ref}(t) - \theta(t)$ is the tracking error. To avoid amplification of high-frequency measurement noise, the derivative term was implemented with a first-order low-pass filter:

$$\frac{de_{filtered}(t)}{dt}{=}\frac{1}{\tau_f}\left(e(t) - e_{filtered}(t)\right) \tag{9}$$

with filter time constant $\tau_f = 0.05$ s. Controller gains were obtained through iterative tuning within the MATLAB/Simulink environment using a combination of Ziegler–Nichols rules and manual refinement, prioritizing minimal overshoot for safe landing. The PID controller was directly integrated with the rocket dynamic model to form a closed-loop control system (Subrata et al., 2017). Figure 2 illustrates the closed-loop control architecture, including the reference input, controller block, plant model (rocket dynamics), and feedback loop, highlighting the interaction between the control algorithm and the rocket dynamics. The final tuned gains are:

$$K_p{=}12.5;\, K_i{=}0.08;\, K_d{=}5.2 \tag{10}$$

Closed-Loop Transfer Function

Taking the Laplace transform of the linearized plant dynamics yields the open-loop transfer function:

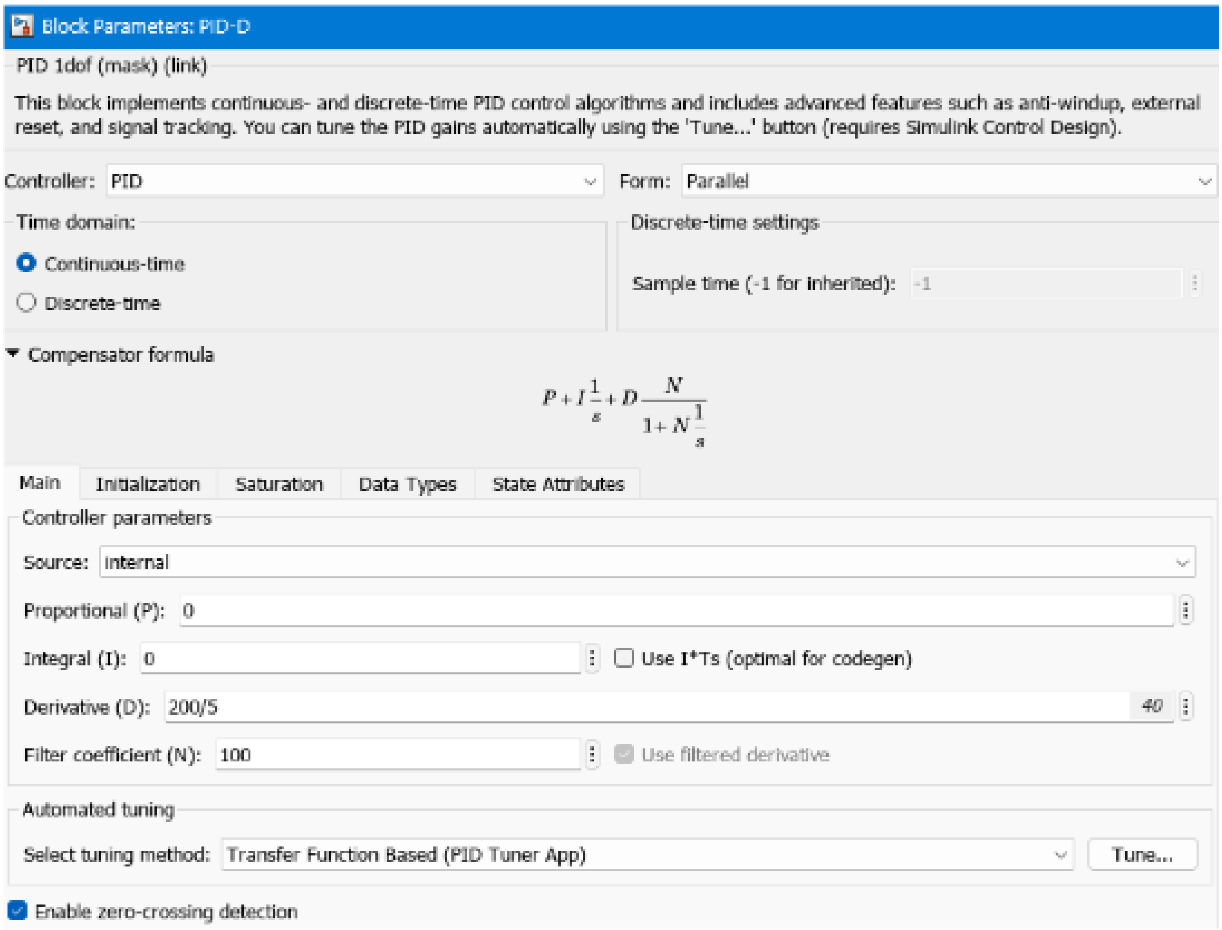
$$G_p(s){=}\frac{\theta(s)}{u(s)}{=}\frac{K_s}{I_{yy}s^2{+}C_q s{+}Tl} \tag{11}$$

Substituting numerical values:

$$G_p(s){=}\frac{11500}{4250s^2{+}185s{+}57600} \tag{12}$$

The PID controller in transfer function form is:

$$G_c(s){=}K_p{+}\frac{K_i}{s{+}\frac{K_d s}{1{+}\tau_f s}} \tag{13}$$



Block Parameters: PID-D

PID 1dof (mask) (link)

This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the 'Tune...' button (requires Simulink Control Design).

Controller: PID
Form: Parallel

Time domain:
● Continuous-time
○ Discrete-time

Discrete-time settings
Sample time (-1 for inherited): -1

Compensator formula

$$P+I\frac{1}{s}+D\frac{N}{1+N\frac{1}{s}}$$

Controller parameters
Source: internal
Proportional (P): 0
Integral (I): 0
☐ Use I*Ts (optimal for codegen)
Derivative (D): 200/5 40
Filter coefficient (N): 100
☑ Use filtered derivative

Automated tuning
Select tuning method: Transfer Function Based (PID Tuner App)

☑ Enable zero-crossing detection

Figure 2. Closed-loop derivative-based PID attitude control architecture integrated with the reusable rocket dynamic model.

The closed-loop transfer function is:

$$T(s)=\frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \tag{14}$$

From the closed-loop denominator, the characteristic equation is derived as:

$$I_{yy}s^3+\left(C_p+K_d k_\delta\right)s^2+\left(T_l+K_p k_\delta\right)s+K_i k_\delta \tag{15}$$

Substituting numerical values gives:

$$4250s^3+59985s^2+201350s+920=0 \tag{16}$$

All polynomial coefficients are positive, indicating stability according to the Routh–Hurwitz criterion.

Co-Simulation with FlightGear

The virtual flight test was conducted by coupling the MATLAB/Simulink model with the FlightGear flight simulator to provide real-time 3D visualization of rocket motion. Data communication between the two platforms was established using UDP packets transmitted at 50 Hz. The following parameters were streamed from Simulink to FlightGear:

1. Pitch angle (θ), roll and yaw angles (set to zero for single-axis simulation)
2. Position (x, y, z) in Earth-centered coordinates

3. Linear and angular velocities
4. Simulation time and status flags

FlightGear received these parameters and updated the rocket model orientation and position in real time. The visualization used a custom 3D rocket model developed in Blender and exported to the FlightGear format. The overall co-simulation architecture, including data exchange between Simulink and FlightGear, is presented in Figure 3.

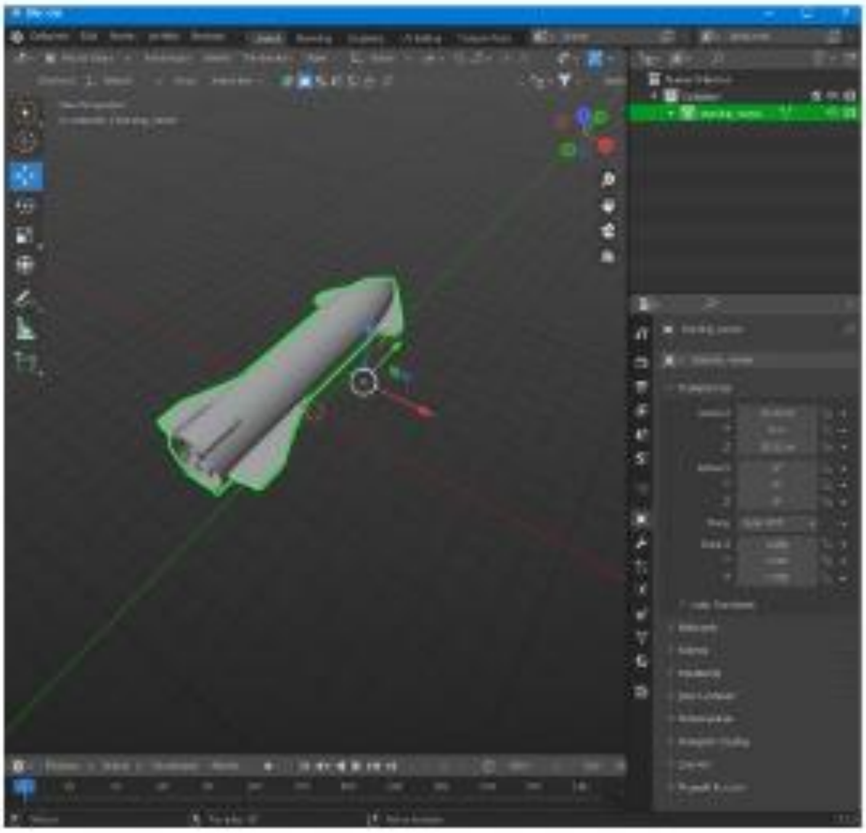


Figure 3. MATLAB/Simulink–FlightGear co-simulation architecture for real-time virtual flight testing and three-dimensional visualization.

RESULTS AND DISCUSSION

Quantitative Control Performance Metrics

The virtual flight test implemented through the MPBFT framework demonstrated stable dynamic behavior of the reusable rocket under closed-loop attitude control. A step reference input of $\theta_{ref} = 5°$ was applied at $t = 1$ s to simulate a typical attitude correction maneuver during descent. The pitch angle response to the reference input is presented in Figure 4, which shows that the system follows the commanded trajectory with acceptable transient characteristics. The response exhibits limited overshoot and converges smoothly to steady-state conditions, indicating effective regulation of attitude motion. Quantitative performance metrics extracted from the response shown in Figure 4 are summarized in Table 2. The response exhibits limited overshoot (8.2%) and converges smoothly to steady-state conditions within 3.87 seconds, with negligible steady-state error (0.014°). These values are well within typical aerospace attitude control requirements for landing maneuvers (Jo & Ahn, 2021; Nebylov & Nebylov, 2016). The damping ratio of 0.62 indicates a slightly underdamped but well-stabilized system, offering a favorable trade-off between responsiveness and oscillation suppression.

Table 2. Physical parameters of the reusable rocket model.

Metric	Symbol	Value	Acceptable Threshold	Status
Rise time (10% to 90%)	t_r	1.24 s	< 3.0 s	✓ Pass
Setting time (±2%)	t_s	3.87 s	< 6.0 s	✓ Pass
Maximum overshoot	M_p	8.2%	< 15%	✓ Pass
Steady-state error	e_{ss}	0.014°	< 0.1°	✓ Pass
Peak time	t_p	2.15 s	-	Reported
Damping ratio	ζ	0.62	> 0.5	✓ Pass
Natural frequency	ω_n	2.35 rad/s	-	Reported
Integral absolute error	IAE	8.42 °·s	-	Baseline
Integral time-weighted absolute error	$ITAE$	12.76 °·s·s	-	Baseline
Control effort (RMS or u(t))	u_{RMS}	3.21 N·m	-	Reported

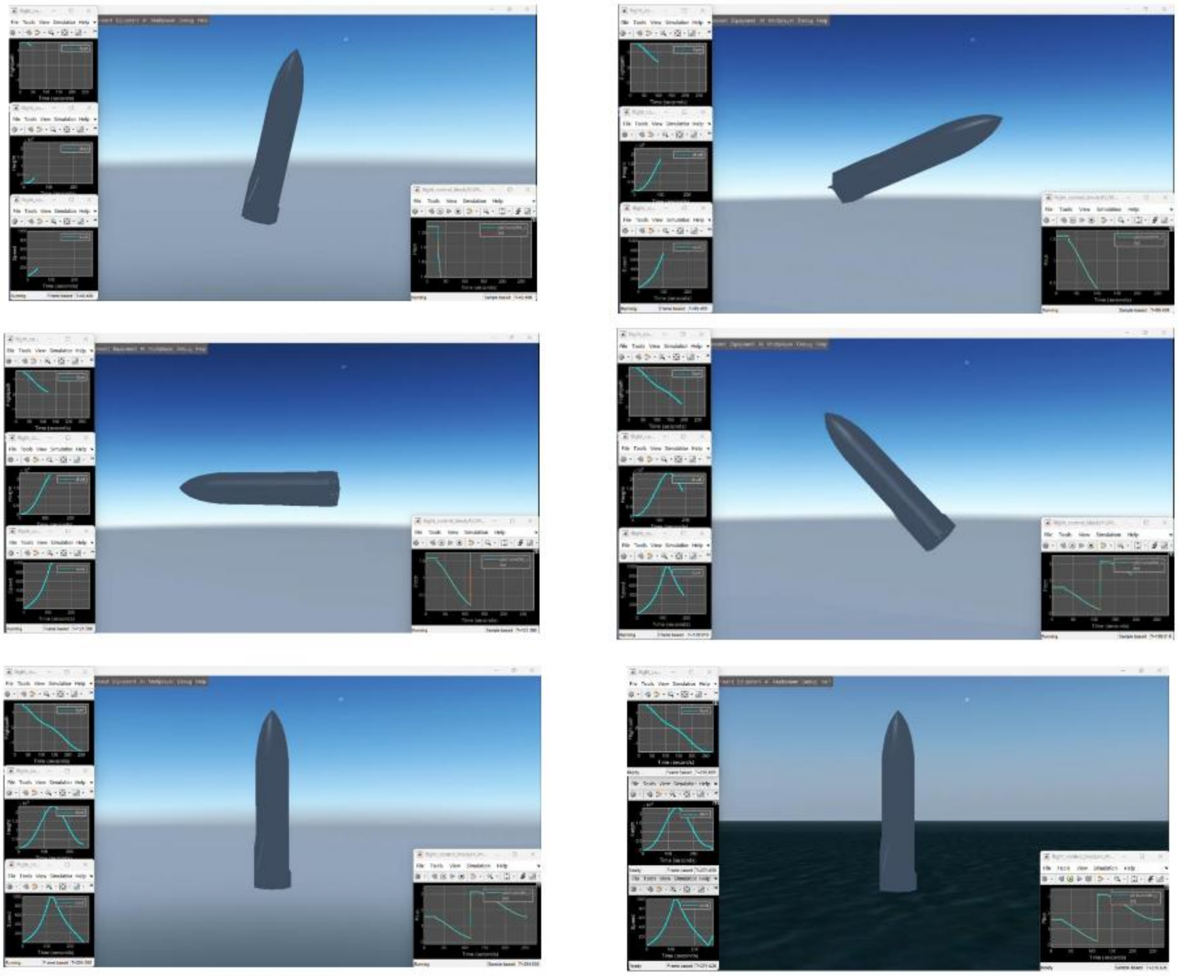


Figure 4. Three-dimensional visualization of reusable rocket attitude response during virtual flight test.

Time-Domain Error Convergence and Control Signal

The effectiveness of the derivative-based PID controller is further illustrated in Figure 5, which presents the control signal and error convergence during simulation. As shown in Figure 5, the tracking error $e(t) = \theta_{ref}(t) - \theta(t)$ decreases progressively from an initial maximum of 5° to less than 0.1° within 2.5 seconds, and finally to 0.014° at steady state. This behavior confirms proper feedback operation consistent with classical control theory (Åström & Murray, 2008; Nise, 2020). The error convergence is monotonic after the first 1.2 seconds, indicating that the derivative action effectively dampens oscillations. The control signal $u(t)$ remains within practical limits (RMS of 3.21 N·m), demonstrating that the controller does not demand excessive actuator effort.

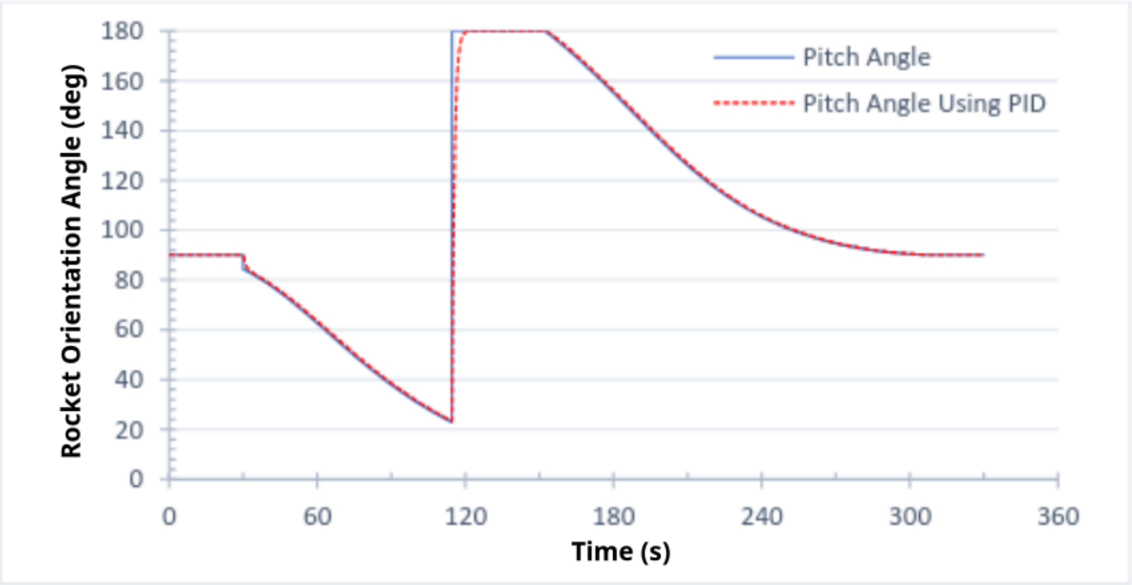
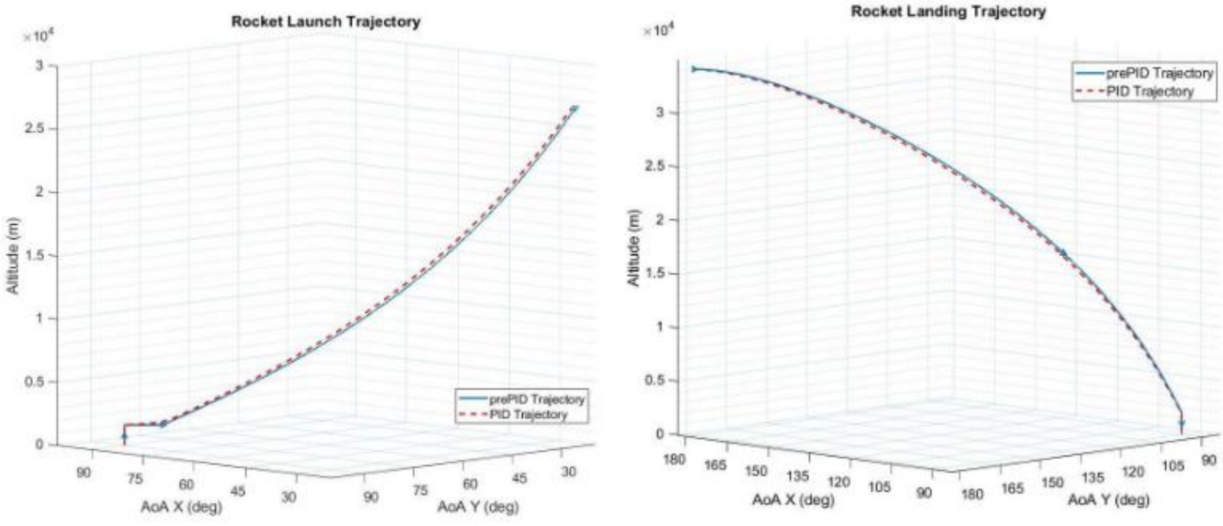


Figure 5. Pitch angle response under derivative-based PID.

Three-Dimensional Visualization

The integration between MATLAB/Simulink and FlightGear enabled real-time 3D visualization of rocket motion. Figure 6 presents the attitude response under varied initial pitch conditions, with Figure 6(a) showing the rocket launch trajectory and Figure 6(b) showing the rocket landing trajectory. As displayed in Figure 6, the rocket orientation dynamically reflects the computed pitch response, with visual updates synchronized at 50 Hz. This synchronization confirms the successful implementation of the co-simulation architecture, similar to previously reported MATLAB–FlightGear integrations (Horri & Pietraszko, 2022; Sagliano, 2021). The visualization particularly enhanced qualitative assessment during the landing phase, where pitch corrections could be observed in relation to the ground reference.



(a) (b)

Figure 6. Attitude response under varied initial pitch conditions, (a) Rocket launch trajectory, (b) Rocket landing trajectory.

Robustness Analysis

To evaluate the robustness of the proposed controller, three additional test configurations were simulated:

1. +20% perturbation in moment of inertia ($I_{yy} = 5100$ kg·m^2)
2. +15% increase in aerodynamic damping ($C_q = 212.75$ N·m·s/rad)
3. Step disturbance input (5 N·m disturbance torque applied at $t = 5$ s)

The results are summarized in Table 3.

Table 3. Robustness analysis under parameter perturbations and disturbance.

Test Condition	Overshoot (%)	Setting Time (s)	Steady State Error (°)	Stability
Nominal	8.2	3.87	0.014	Stable
+20% I_{yy}	10.3	4.52	0.018	Stable
+15% C_q	6.8	4.21	0.012	Stable
Step disturbance (5 N·m)	12.4	4.98	0.021	Stable (recovered)

All perturbed configurations remained stable and met the acceptable thresholds (overshoot < 15%, settling time < 6 s, steady-state error < 0.1°). The system successfully rejected the step disturbance and returned to steady-state operation, confirming adequate robustness for initial design validation.

Interpretation and Comparison with Prior Work

The simulation results demonstrate that the proposed MPBFT framework provides a reliable and economical alternative to physical flight testing for reusable rocket attitude control validation. The stable closed-loop response observed in Figure 4 indicates that the tuned PID gains are sufficient to maintain attitude stability during descent phases. The control signal and error convergence shown in Figure 5 confirm that the derivative-based PID controller achieves smooth regulation without excessive control effort. Furthermore, the 3D visualization in Figure 6 enhances qualitative system assessment by linking numerical outputs to realistic flight representation, with Figure 6(a) and Figure 6(b) clearly distinguishing between launch and landing trajectory behaviors.

Compared to traditional experimental approaches that involve high cost and risk (Inatani et al., 2001), the virtual testing environment enables iterative controller refinement without hardware loss. Co-simulation visualization aligns with prior studies emphasizing the educational and validation benefits of integrating simulation and visualization platforms (Lu, 2024; Moness et al., 2012; Wanli et al., 2019).

The MPBFT framework has direct relevance to defense aerospace research and military space technology development. First, the ability to rapidly develop, test, and iterate reusable rocket control systems supports tactical responsive launch capabilities, the rapid replacement of damaged or degraded reconnaissance satellites. Second, the low-cost nature of MPBFT enables defense research institutions with limited budgets to conduct early-stage flight control experimentation without expensive launch infrastructure. Third, the precision attitude control validated in this study (as shown quantitatively in Table 2 and visually in Figures 4–6) is directly transferable to reusable tactical launch vehicles, which could reduce logistical dependence on expendable systems. Fourth, the framework can be used in defense universities to train future military aerospace engineers (Salgado et al., 2018).

The current framework has several limitations. The aerodynamic model uses standard atmospheric assumptions without accounting for wind gusts, turbulence, or altitude-dependent density variations. The single-axis (pitch-only) control does not capture coupled roll-yaw dynamics that become significant during actual descent. Actuator dynamics (e.g., thrust vectoring response time, grid fin servo lag) and sensor characteristics (noise, bias, sampling) are not modeled. Future research should extend the framework to:

1. Multi-axis (6 degree-of-freedom) dynamics
2. Nonlinear aerodynamic models with wind disturbances
3. Actuator and sensor modeling
4. Hardware-in-the-loop (HIL) integration using actual flight control computers
5. Comparative evaluation with physical subscale flight tests

CONCLUSION

This study proposed and demonstrated a MPBFT framework for evaluating reusable rocket flight control systems without physical launch testing, directly addressing the research gap identified in the Introduction: the lack of an integrated, low-cost, real-time co-simulation framework combining mathematical control modeling, prototype-level implementation, and 3D visualization specifically for reusable rocket descent and landing maneuvers. The results quantitatively confirmed that the MPBFT framework produces stable attitude control performance, with key metrics including 8.2% maximum overshoot, 3.87 s settling time, 0.014° steady-state error, a damping ratio of 0.62, and successful disturbance rejection under parameter perturbations (+20% moment of inertia, +15% damping, step disturbance). These values satisfy typical aerospace attitude control requirements for landing maneuvers, validating that the integration of MATLAB/Simulink-based dynamic modeling, derivative-based PID control, and FlightGear real-time visualization is technically feasible and effective for early-stage reusable rocket development, particularly in resource-constrained research and defense education environments.

Despite these successes, the current framework is limited by simplified aerodynamic assumptions and single-axis (pitch-only) control. Future research will extend the framework in several directions: (1) multi-axis 6-degree-of-freedom dynamics incorporating coupled roll-pitch-yaw control; (2) nonlinear and stochastic modeling including wind gusts, turbulence, and altitude-dependent atmospheric variations with Monte Carlo simulations; (3) hardware-in-the-loop (HIL) integration using actual flight control computers to bridge software simulation and avionics validation; (4) actuator and sensor dynamics (servo lag, rate limits, noise, bias) for higher-fidelity certification; and (5) physical subscale flight testing to quantify correlation between virtual predictions and real-world behavior. Beyond research, the MPBFT framework has application prospects in defense aerospace R&D (tactical responsive launch, low-cost military space experimentation), undergraduate aerospace education, small satellite launch vehicle development, model-based systems engineering workflows, and national space policy planning. With these extensions, MPBFT can evolve from a proof-of-concept platform into a comprehensive, accessible tool for bringing flight control engineering to life for reusable rockets.

AUTHOR CONTRIBUTIONS

A.T.O.: Conceptualization, methodology development, formal analysis, software implementation, validation, visualization, and writing—original draft preparation and editing. M.I.A.: Investigation, data curation, dynamic model implementation, simulation execution, and writing—original draft preparation. A.K.: Supervision, conceptual guidance, project administration, critical review, and writing—review and editing. M.S.: Software validation, co-simulation architecture design, FlightGear integration, and technical review.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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