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REVOLUTIONIZING SPACE LAUNCH RELIABILITY: A MULTI-MODE LAUNCH VEHICLE FAILURE SIMULATION

Abstract

The advancement of space exploration demands a robust space launch services program capable of reliably propelling payloads into orbit. Despite rigorous testing and quality assurance, launch failures still occur, leading to significant financial losses and jeopardizing mission objectives. Traditional failure prediction methods often lack the sophistication to account for multi-mode failure scenarios, as well as the predictive capability in complex dynamic systems. Traditional approaches also rely on expert judgment, leading to variability in risk prioritization and mitigation strategies. Hence, there is a pressing need for robust approaches that enhance launch vehicle reliability from lift-off until it reaches its parking orbit through comprehensive simulation techniques.

In this study, the developed model proposes a multi-mode launch vehicle simulation framework for predicting failure scenarios when incorporating new technologies, such as new propulsion systems or advanced staging separation mechanisms in the launch system. To this end, the model combined a 6-DOF system dynamics with comprehensive data analysis to simulate multiple failure modes impacting launch performance. The simulator utilizes high-fidelity physics-based simulations to capture the complex interactions between different subsystems and environmental conditions. In the second phase of the simulator, Machine learning algorithms will be employed to analyze historical launch data and identify patterns indicative of potential failure modes.

Preliminary results indicate that the multi-mode simulation framework can accurately predict the failure cascade profile for different failure scenarios. By incorporating various failure modes such as propulsion system anomalies, coupled fluid-structural instabilities, namely Pogo instabilities, and environmental disturbances, the simulation demonstrates its ability to simulate realistic launch conditions. The model is validated against Relativity's Terran 1, accurately predicting the mission trajectory in the case of 2nd stage ignition failure in 2023.

This study shows a significant and promising potential to revolutionize the space launch program's reliability assessment and mitigate the risks associated with space missions. By accurately predicting failure scenarios before launch, space agencies and commercial entities can implement proactive measures to safeguard mission success and protect valuable payloads. Moreover, the insights gained from our multi-mode simulation approach can inform future design iterations, leading to the development of more robust and resilient launch vehicle systems. Ultimately, this research contributes to the advancement of space exploration by enhancing the reliability and safety of launch operations. In sum, the development of a multi-mode launch vehicle simulator represents a significant step forward in failure prediction methodologies, offering a promising avenue for improving launch services reliability and mission success rates.