Throttling Control Techniques for Hybrid Rocket Controlled Ascent Proposal

AeroMavs Internal Document

***Abstract*—In 1975, NASA successfully implemented ascent throttling on its Space Shuttles to survive Max Q (maximum dynamic pressure), providing a lighter and safer solution than overbuilding the structure like the Saturn V. These days Aero Mavs faces a similar issue: as we pursue higher altitudes, the uncontrollable acceleration of solid rocket motors have, to suffer extremely large dynamic pressures at low altitudes. To help solve this problem, we propose the development of a throttle system, taking advantage of a hybrid motor utilizing a mix of valve controls and electromagnetic pintles to maximize throttle control and mitigate the chance of flameout.**

I. Project Description

A. Why is this study relevant?

Within the past fifty years, the goal of having a throttleable engine for a rocket has been necessary to minimize the maximum high aerodynamic loading caused by high dynamic pressure q_{max}.

$$q = \frac{1}{2}\rho v^2 \tag{1}$$

High q_{max} can cause rapid unplanned disassemblies (RUD), such as structural buckling and disintegration. Some famous examples include the Delta II GPS IIR-1 in January 1997, the Mercury Atlas 1 in 1960, the North Korean Unha-3, and even Rocket Lab's "Pics or it didn't happen" Mission in 2020. Compared to liquid rocket engines, Hybrid rocket engines are, in principle, much easier to throttle. By simply reducing the oxidizer mass flux, the diffusion flame will shrink into the oxidizer plume, resulting in less heat transfer to the fuel grain and resulting in decreased combustion and thrust.

B. What is the goal?

The goal of this project is to develop a system capable of throttling the hybrid rocket engine down to 20 percent thrust without extinguishing the combustion process before engine shutdown. This target was chosen because it corresponds to the minimum thrust-to-weight ratio (TWR) required for flight under the Tripoli Unified Safety (TUS) code, which mandates an initial TWR of 5. Lower thrust is desirable because it not only reduces structural loads and the risk of RUD, during tropospheric flight, excessive thrust is less efficient due to higher drag losses compared to a slower ascent.

Achieving this level of throttling will allow the AeroMavs 2026 rocket to carry a payload to apogee while safely surviving passage through Max Q.

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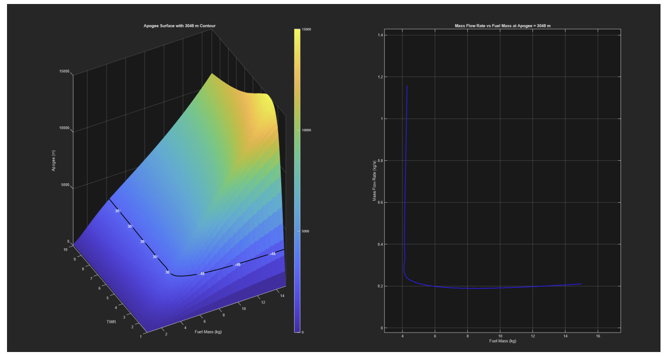

Fig. 1. 1-D flight simulation of IREC Vehicle

C. Understanding the Physics

A rocket engine produces thrust primarily by accelerating the propellants to high velocities using a rocket nozzle.

$$F = (\dot{m}_{ox} + \dot{m}_f)v_e \tag{2}$$

Our throttling authority fundamentally stems from our ability to regulate the oxidizer mass flow rate ($\dot{m}_{ox}$) in a hybrid rocket engine. If oxidizer flow is cut off, then combustion ceases. As can be seen in Equation 2 above, increasing the oxidizer flow rate would increase thrust level if all other variables were equal. However, there are various secondary effects when changing the oxidizer flow rate: with less oxidizer present, the diffusion flame shifts to a new equilibrium, resulting in a change to the fuel mass flow rate.

$$\dot{m}_f = \rho_{fuel} a \left(\frac{\dot{m}_{ox}}{A_p}\right)^n P_c^m S_b \tag{3}$$

The mass flow rate in a hybrid is highly dynamic. It relies on the physical fuel grain characteristics (a, m, and n, geometric parameters like the bore area A_p and the port surface area S_b, as well as oxidizer flow rate. Decreasing $\dot{m}_{ox}$ in this equation directly results to a cut in $\dot{m}_f$ which would contribute to a reduction in thrust via the previous equation.

Due to the nonlinear nature of the fuel grain regression, this throttling does come with one final side effect. When $n \neq 1$ (almost always the case), the fuel-to-oxidizer ratio shifts from its nominal value, resulting in typically reduced heat generation through combustion, reducing available enthalpy. This would reduce the pressure in the equation above, as well as reduce the enthalpy of the combustion products. In an isentropic nozzle - which assumes ideal, lossless expansion - this would result in reduced exhaust velocity and hence further reduce thrust.

$$v_e = v_c + \sqrt{2(h_c - h_e} \tag{4}$$

This, however, will only go so far. The O/F ratio must remain within bounds; too lean or rich mixtures risk flameout.

In short, throttling is not as simple as reducing oxidizer flow; it is a balancing act between lowering thrust to survive Max Q and maintaining stable combustion. These competing requirements define the core challenge of hybrid rocket throttling and motivate a range of solutions that have been explored.

D. The Differing Solutions

There are multiple solutions to provide throttling based on varying levels of complexity and technological advancements. The earliest forms of throttling include valves and deep-throttles on rocket engines. With valves, the control system is simpler but is limited to a 4:1 thrust ratio [1].

$$\dot{m}_{ox} = A_{in} C_d \sqrt{2\rho_{ox}\Delta P} \tag{5}$$

Throttling via an upstream valve reduces the pressure drop across the injector ΔP , making it more susceptible to combustion instabilities backpropagating into the feed lines, leading to a flameout.

In a Utah State lecture [2], Stephen Whitmore provides examples of deep-throttle engines by Northrup Grumman, where it introduces propellants into the combustion chamber with a "single element coaxial pintle injector". Rather than reduce the pressure upstream of the injector, a movable sleeve directly reduces the orifice area, resulting in decreased oxidizer flow. This is what allows a pintle to reach a throttling ratio as low as 10:1 - the engine is capable of outputting one-tenth of its maximum rated thrust while maintaining stable combustion

We look to Dr. Frederick Jr's study on throttling history with NASA, where he discusses the applications of both shallow throttling and deep throttling and the respective capabilities. Dr. Frederick Jr presents the context of a liquid fuel engine and states that a 4:1 thrust ratio - ratio of max thrust to minimum controlled thrust - is considered shallow throttling [1], and anything more falls under the category of deep-throttling.

We can also look to Austin's paper on military applications for their Hybrid motor solutions [3] and Dongfeng Yan's paper on thrust control for solid motors [4]. Austin's paper includes a variable position valve to control oxidizer flow- enabling thrust variation and energy management. Austin uses a Habonim ball-type control valve, where they achieved a 10:1 throttling ratio in lab tests, though scale-up presents challenges. Meanwhile, Dongfeng Yan suggests a unique method: a hybrid combination of a mechanically controlled pintle and fluidic throat control, and achieved a thrust modulation capability of 1.8 to 1 - limited to 55% throttle. While these systems were applied to a solid motor, they can be extrapolated to hybrid engines. The system is designed to control oxidizers with valves; meanwhile the fluidic pintle can control the throat, complementing the oxidizer and at the same time stabilizing combustion (by managing back-pressure and flow separation) and reducing thermal loads (especially with paraffin-based hybrids).

This extrapolation is supported by a study from Alessandro Ruffin and EUCASS. The paper emphasizes that oxidizer flow control is the primary method for throttling, but pintles allow a precise modulation of oxidizer[5]. This approach also simplifies control architecture compared to liquid systems [5]. Several pintle geometries illustrated in Fig.2 have been applied to both liquid and hybrid engines. These designs highlight the adaptability of pintle injectors as a means of extending both throttle range beyond what values alone can provide.

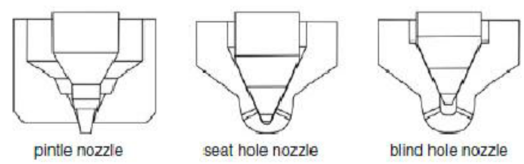

Fig. 2. Different types of Pintles, Yan

E. Our Solution: Valve and Electromagnetic Sleeve Pintle

The project goal is to provide efficient throttling - eventually being able to throttle down to 20 percent of nominal thrust without flaming out. Hence, the best solution is a mix of systems utilizing Suheom Kim's solution [6] (leaning towards deep-throttling) with both valve controls and electromagnetic sleeve pintles - giving us both coarse and fine control over $\dot{m}_{ox}$ - as shown in Fig 3 that shows a sleeve pintle in a liquid fuel engine. It is important to recognize that the research will involve testing out multiple different features to reach the desired thrust profile; however, the goal will be to build complexity with the desired system. We plan to start with a simple valve system and test to see the limits first, then get complex.

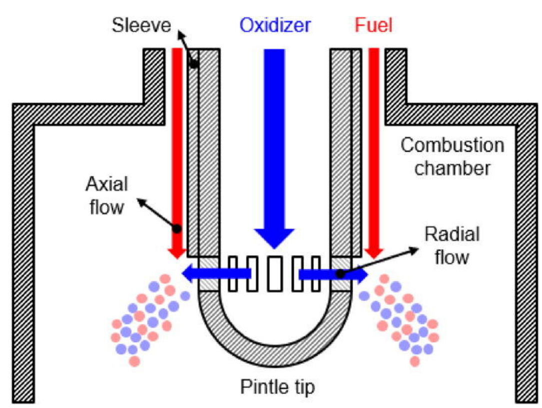

Fig. 3. This sleeve design is applied in a liquid rocket engine.

F. Student Involvement

The project is being conducted by the AeroMavs Hybrid Division, offering students direct, hands-on experience in design, testing, and analysis. Students contribute through simulation and modeling, experimental setups, and control system development, working to design, build, and test oxidizer flows, fuel regression rates, and combustion stability. These activities not only drive innovation for the team but also deepen students' understanding of hybrid rocket propulsion.

G. Principal Investigator Involvement

The Principal Investigators for this project are Dr. Hongru Chen and Dr. Animesh Chakravarthy. Utilizing their experiences, Dr. Chakravarthy will guide the development of the closed-loop control architecture for stable deep-throttling, while Dr. Chen will provide expertise in flight dynamics and trajectory-thrust coupling, ensuring the hybrid engine's throttle system meets structural and performance requirements during Max Q ascent.

II. Expected Outcomes

A. Visual Architecture

The diagrams in Figure 4 and 5 illustrate the proposed system architecture for controllable throttling. Figure 3 shows the visual architecture of the prototype control system, highlighting how valve and pintle mechanisms can work to regulate oxidizer flow. Figure 4 presents the control logic framework, where valve and pintle positions are adjusted through a closed-loop PID system in response to trajectory demands. Together these diagrams demonstrate how our approach links the underlying physics of oxidizer flow with an active feedback system to maintain stable combustion while reducing thrust.

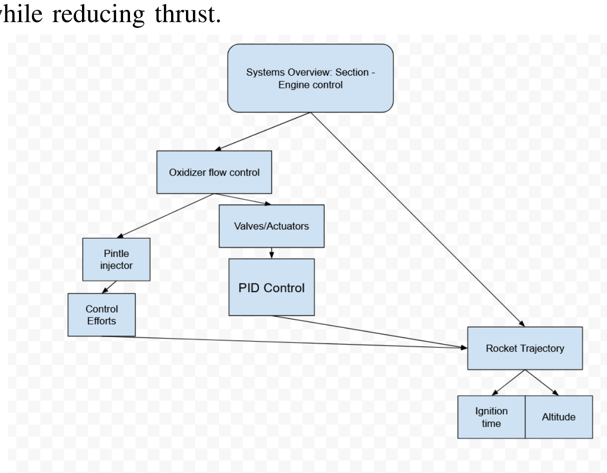

Fig. 4. Visual architecture of the prototype control system showing valve and pintle components for oxidizer flow regulation

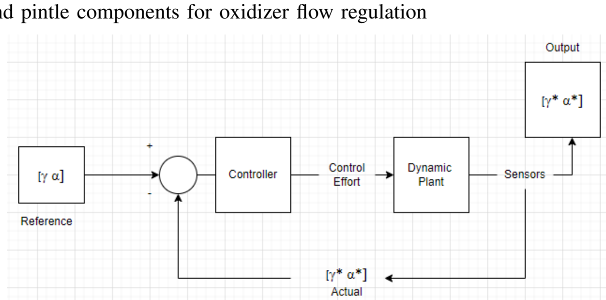

Fig. 5. Controls logic in pintle system

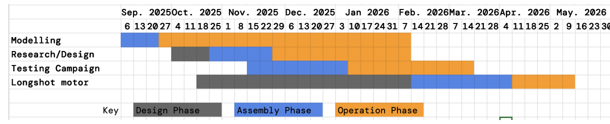

Fig. 6. This figure is the suggested timeline for the project length.

B. Timeline

The expected length of the project is a full academic year split into two major portions. The first stage takes place in the fall of 2025. After the development of a base hybrid engine (one that has no upgrades) students will design and build the throttle controls system. The second stage, starts after the design and construction of the throttle system then continues through January of 2026. The research will require the engine and the controls systems to undergo multiple rounds of rigorous testing. Once testing has proven that the engine controls system is nominal, it can be applied to the upcoming 2026 AeroMavs full-scale rocket.

C. Budget

TABLE I
Throttling Control Budget

Item	Unit Cost ($)	Qty	Total ($)
Hybrid Motor Test Apparatus	1025.00	1.00	1025.00
Moving Pintle Injector Design	75.00	1.00	75.00
PID controllers	100.00	3.00	300.00
SRAD Tank Cylinder	200.00	1.00	200.00
Machined Sleeve	29.00	1.00	29.00
Misc.	297.00	1.00	297.00
Subtotal			1926.00
Total W/Tax			2000.00

With this proposal we are trying to raise $2000 from UTA REU in order to cover the consumables from testing and a potential full scale implementation of the technology. The first category includes injector designs, sleeve designs, PID controllers, and miscellaneous stuff that assist in the development. The second will help finance the improvements to the test stand including but not limited to improvements to run tank, instrumentation, and purge system in order to facilitate higher test cadence to make this possible. And the third involves demonstrating this technology in a M-Class hybrid rocket motor.

III. Intellectual Merit

This project advances the scientific understanding of hybrid rocket propulsion by experimentally exploring the limits of deep-throttling - a capability that remains largely uncharacterized compared to liquid engines. By introducing and validating a duel control architecture, the work indirectly addresses the central challenge of maintaining flame stability during aggressive throttle transients. The campaign will generate new datasets on regression law coefficients, blowout thresholds, and mixture-ratio dynamics throttling conditions. Meanwhile, the accompanying simulations will yield operating maps that connect injector geometry, oxidizer mass flux, and thrust stability. Together these contributions fill a critical gap in propulsion literature, providing both fundamental insights and practical design tools for future research and designs.

IV. Broader Impacts

By demonstrating reliable, precise, and deep throttling, this project expands the applications of hybrid propulsion to reusable launch vehicles, planetary landers, and responsive space access for small satellites. These advances directly support national interests for safer, low-cost, and flexible space flight.

Beyond the technology itself, the project provides significant impact in education and workforce development. Undergraduate students gain hands-on experience in propulsion design, testing, and modeling—skills that directly prepare them for careers in aerospace, energy, and advanced manufacturing. The work also enhances the training environment at UTA, fostering a culture of student-led research in high-impact areas. In this way, the project not only contributes to national aerospace capability but also helps cultivate the next generation of engineers and innovators.

References

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[6] S. Heo, I. Kim, Y. Yoon, and B. J. Lee, "Spray structure of a multi-slit type throttleable gas–liquid pintle injector," *Physics of Fluids*, vol. 37, 08 2025.