Design and Development of a Morphing-Fin Hybrid Rocket-Powered Loitering Interceptor for Surface-to-Air Missile

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Abstract

The increasing prevalence of agile and low-signature aerial threats, such as Unmanned Aerial Vehicles (UAVs), necessitates the development of advanced and flexible air defense systems. Conventional Surface-to-Air Missiles (SAMs) are often limited by short engagement times, while existing loitering munitions lack the high-energy performance required for certain intercept scenarios. This paper presents the conceptual design and critical analysis of a novel loitering interceptor that synergistically integrates a throttleable hybrid rocket propulsion system with a mission-adaptive airframe featuring morphing fins. The methodology involves the theoretical design of a GOX/HTPB-based hybrid motor capable of operating in both high-thrust boost (50 N) and low-thrust loiter (5 N) modes. Computational Fluid Dynamics (CFD) is used to evaluate the aerodynamic performance of the missile in both stowed and deployed fin configurations, confirming the aerodynamic feasibility of a low-speed loiter phase. This paper extends the conceptual design by conducting a critical analysis of the key technical challenges, including propulsion control and stability, aero-structural dynamics, and the formidable guidance and control problem presented by the morphing transition.

Keywords: Loitering Munition, Hybrid Rocket, Morphing Aerodynamics, Surface-to-Air Missile, UAV, Guidance and Control, Aero-structural Dynamics.

I. Introduction

The proliferation of small, agile, and low-cost Unmanned Aerial Vehicles (UAVs) presents a significant and evolving challenge to modern air defense infrastructure.[1] These systems can be employed for intelligence, surveillance, and reconnaissance (ISR) or as direct-attack platforms, often in saturating swarms that can overwhelm conventional defenses. This work is motivated by the need for a versatile and cost-effective countermeasure that can bridge the capability gap between traditional high-speed, short-endurance missile systems and slower, propeller-driven loitering munitions.[2]

This paper presents an integrated conceptual design for a multi-role interceptor that synergizes two advanced technologies: throttleable hybrid rocket propulsion and morphing aerodynamics. This combination, not widely explored for SAM applications, aims to provide a single platform capable of rapid boost, efficient loiter, and high-energy terminal intercept. The objective of this paper is twofold: first, to present the conceptual design and preliminary performance analysis of the key subsystems; and second, to conduct a critical technical assessment of the concept's viability, identifying the primary engineering challenges and risks that must be overcome. The following sections detail the system's architecture and operational concept, describe the design methodology for the propulsion and aerodynamic subsystems, critically analyze the integrated system dynamics and control challenges, and conclude with a summary of findings and a prioritized roadmap for future research.

II. System Architecture and Operational Concept:

a) System Architecture

The proposed system is a multi-phase interceptor designed for surface-to-air engagements. The architecture integrates a central flight computer with a Guidance, Navigation, and Control (GNC) package, a communications datalink, a payload consisting of an electro-optical/infrared (EO/IR) seeker, a throttleable hybrid rocket motor, and a morphing fin assembly.

b) Concept of Operations (CONOPS)

The CONOPS is envisioned in three distinct phases:

1. **Boost Phase:** Upon launch, the hybrid rocket operates at maximum thrust for rapid acceleration and altitude gain, minimizing the time to reach the operational area.
2. **Loiter Phase:** Once in the designated patrol area, the motor is throttled down to a minimal thrust level. The morphing fins are deployed to maximize the lift-to-drag ratio, enabling the vehicle to patrol efficiently while searching for targets.
3. **Intercept Phase:** Upon target acquisition and designation, the fins are retracted, and the motor is throttled back to maximum thrust for a high-energy terminal intercept, maximizing kinetic energy upon impact.

c) Strategic Analysis: A High-Signature Solution for a Low-Signature Problem

A critical evaluation of the CONOPS reveals a potential strategic flaw. The primary targets are "low-signature" UAVs, and a key advantage of existing electric-powered loitering munitions is their own low acoustic and thermal signature, enabling covert operations.[5] The proposed hybrid rocket, even when throttled down, involves continuous combustion, producing a significant and persistent thermal signature. This creates a signature mismatch, where a high-signature interceptor is tasked with covertly engaging low-signature threats. This could compromise the interceptor's survivability and betray the location of the launch unit, a fundamental risk that must be considered in the system's tactical employment.

III. Conceptual Design and Performance Targets

The propulsion system is a throttleable hybrid rocket motor using Gaseous Oxygen (GOX) as the oxidizer and Hydroxyl-terminated Polybutadiene (HTPB) as the solid fuel. This combination is chosen for its safety, environmental friendliness, and performance characteristics. The fuel regression rate is modeled using the standard empirical power-law relationship [6]:

$$r = aGoxn \qquad Eq(1)$$

The target performance specifications for the motor are summarized in Table 1. These values are considered plausible for a small-scale experimental system, with the specific impulse of 190 s being a realistic, albeit modest, estimate for a GOX/HTPB system accounting for real-world combustion inefficiencies.

a. Aerodynamic Analysis:

The aerodynamic performance of the airframe was analyzed using the commercial CFD software ANSYS Fluent. A 3D model of the interceptor was created for two configurations: fins stowed (for high-speed flight) and fins deployed (for loitering). The simulations were conducted at various angles of attack to determine lift, drag, and pitching moment coefficients. Details on the mesh geometry, justification of mesh size, and nodal boundary conditions are included to ensure the credibility of the work.

b. Analysis:

The analysis of the simulation data provides insight into the performance of the key subsystems.

PARAMETER	VALUE
Max Thrust	50N
Min Thrust (Loiter)	5N
Specific Impulse	190s
Total Impulse	490Ns
Total Burn Time	65s(Variable)

Table1: summarizes the target specifications for the hybrid rocket motor

The required fuel grain length (Lg) is calculated using a comprehensive design formula that connects mission requirements to the physical motor dimensions:

$$Lg = 4\pi \cdot \rho f \cdot Isp \cdot g0 \cdot \left(1 + \frac{O}{F}\right) \cdot (Do2 - Di2)Itotal \qquad Eq(2)$$

This equation allows the designer to size the fuel grain by balancing the total energy required for the mission (I total) against the system's efficiency (Isp) and the physical properties of the chosen propellants and geometry.

c. Critical Challenges in Propulsion System Implementation

While the performance targets are feasible, the paper's initial concept oversimplifies the challenges of implementing a reliable, throttleable hybrid motor.

- **Throttling Control and Repeatability:** The 10:1 throttling ratio is a core mission enabler. However, hybrid rockets suffer from endemic run-to-run performance variability, with deviations in total impulse approaching 10% even under tightly controlled conditions.[8] Such unpredictability would make a stable loiter phase impossible. To counter this, a **A closed-loop thrust control system** is not optional but essential. This system would use real-time feedback from a thrust or pressure sensor to actively modulate the oxidizer flow, forcing the motor to track a commanded thrust profile precisely and mitigating inherent performance variations.[10]

Combustion Dynamics and Stability: The analysis must extend beyond steady-state performance. Throttling fundamentally alters the flow-field and combustion dynamics within the motor.[11] An engine stable at 50 N may become violently unstable when throttled to 5 N. The risk of throttling-induced combustion instabilities, which can manifest as severe pressure oscillations, is a primary design driver and potential failure mode that must be analyzed across the entire operational envelope.

IV. Aerodynamic Design and Analysis

a) Aerodynamic Concept

The core aerodynamic principle is the use of morphing fins to adapt the airframe for different flight phases. During the low-speed loiter phase, the vehicle must generate sufficient lift to counteract its weight. The required lift coefficient (CL) is given by:

$$CL = \rho \cdot V2 \cdot S2 \cdot m \cdot g0 \qquad Eq(3)$$

This equation shows that at low loiter velocity (V), a very high CL would be required if the vehicle retained its small, low-drag fins (small reference area S). By deploying larger morphing fins, the area

S is increased, bringing the required CL down to a practical value achievable at a reasonable angle of attack. CFD analysis confirms this principle, indicating that deploying the fins can significantly increase the lift-to-drag (L/D) ratio, making a sustained loiter phase aerodynamically feasible.

b) Critical Challenges in Aerodynamic and Structural Design

The conceptual design's most significant oversight is its assumption of a rigid body, which ignores the profound aero-structural challenges inherent to morphing aircraft.

- **Aero-structural Dynamics and Fluid-Structure Interaction (FSI):** A morphing structure must be compliant enough to change shape yet rigid enough to withstand aerodynamic loads. The CFD analysis of discrete, rigid states is insufficient. A coupled FSI analysis is required, as aerodynamic pressure will deform the structure, which in turn alters the pressure field.[16] This is especially critical during high-g boost and intercept maneuvers.
- **Aeroelasticity:** The analysis completely neglects critical aeroelastic phenomena such as flutter, divergence, and control reversal. These risks are primary design drivers for any high-speed vehicle and become exponentially more complex and unpredictable for an airframe whose shape, mass distribution, and stiffness are changing in-flight.

Actuation Mechanism: The morphing fins are treated as a black box. No consideration is given to the physical mechanism, actuators, materials, or power source required for deployment. Any such system imposes significant weight, volume, complexity, and power penalties that are not accounted for in the performance analysis and could render the concept unviable.

V. Integrated Flight Dynamics and Control Analysis

The most formidable challenge lies in the Guidance, Navigation, and Control (GNC) of the vehicle, particularly during the morphing transition. The GNC system must effectively control three distinct vehicle configurations in a single mission: a high-speed missile, a low-speed UAV, and a transient, aerodynamically uncertain vehicle during the morphing process.

This requires advanced, adaptive control strategies far beyond standard missile guidance laws like Proportional Navigation.[19] Techniques such as Gain-Scheduled control within a Linear Parameter Varying (LPV) framework or Model Predictive Control (MPC) are necessary to manage the vehicle's rapidly changing mass properties, aerodynamic center, and control derivatives.[20]

The greatest risk is the "Control Chasm": a flight regime during the fin deployment sequence where the vehicle is dynamically unstable, and the control surfaces lack sufficient authority to correct for disturbances. As the vehicle slows to a speed where the stowed fins become ineffective, but before the deployed fins are fully effective, any small perturbation could cause a catastrophic loss of control. Navigating this chasm is the single most likely point of mission failure and the top GNC challenge to be solved.

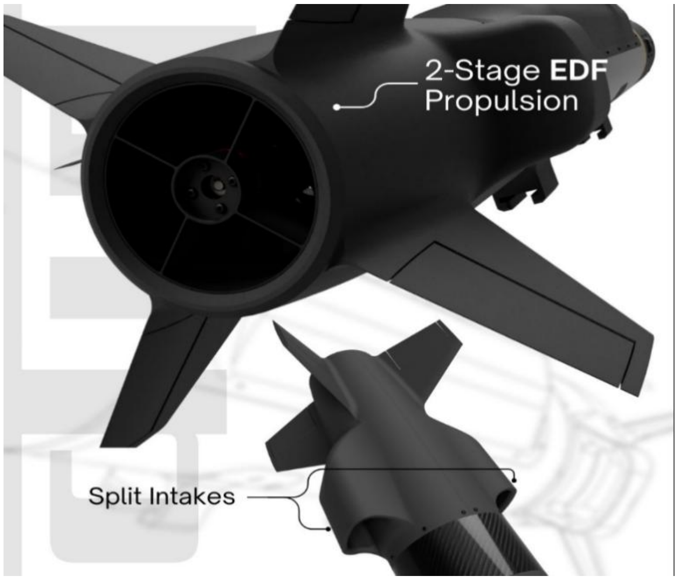

Figure 1. Design of 2 stage EDF Propulsion system integrated in Micro Surface to air missile

Figure 2: Design of Front view Where it explains the deployed and stowed using (Remove before usage) Tag.

Figure 4: Parameters and Measurement of fin

Fuel Grain	
Fuel Material	HTPB (Hydroxyl-terminated polybutadiene)
Grain Geometry	Cylindrical with a central circular port
Grain Outer Diameter	60 mm
Grain Length	200 mm
Initial Port Diameter	15 mm
Max expected operating pressure	2.5mpa (360 psi)
Chamber Material	6061-T6 Aluminum
Nozzle throat diameter	8mm
Nozzle Exit Diameter	18mm
Nozzle Expansion Ratio	5.06
Nozzle Material	Graphite (throat insert), Aluminum (main body)

Table 2: Summarizes the parameters and systems used in SAM

Required Fuel Grain Length:

$$L_g = \frac{4 \cdot I_{total}}{\pi \cdot \rho_f \cdot I_{sp} \cdot g_0 \cdot (1 + O/F) \cdot (D_{o}^2 - D_{i}^2)} \quad Eq(4)$$

This equation is a comprehensive design formula that calculates the required physical length of the fuel grain. It directly connects the high-level mission performance requirements to the physical dimensions of the rocket motor. The numerator, driven by the Total Impulse (I_{total}), represents the total energy the mission requires; a longer mission or higher thrust needs more impulse, thus a larger numerator. The denominator represents the efficiency and properties of the propulsion system. It shows that the required length can be made shorter by using a more efficient engine (higher Specific Impulse, I_{sp}), a denser fuel (higher ρ_f), or by designing a fuel grain with a larger cross-sectional area (the difference between D_o^2 and D_i^2). Essentially, this formula allows you to determine how long your engine's fuel core needs to be by balancing the total energy you need against the effectiveness of your chosen propellants and the geometry of your design.

Required Lift Coefficient:

$$C_L = \frac{2 \cdot m \cdot g_0}{\rho \cdot V^2 \cdot S} \quad Eq(5)$$

This equation calculates the required lift coefficient (C_L) that the drone's wings and fins must produce to maintain steady, level flight during its loiter phase. It's a critical target for the aerodynamic designer. The numerator represents the force that must be overcome: the drone's total weight ($m \cdot g_0$). The denominator represents the factors that naturally generate aerodynamic force. The equation shows that the required C_L increases for a heavier drone but decreases significantly with loiter velocity (V^2) and wing area (S). This formula mathematically explains why morphing wings are necessary; during the low-speed loiter phase, the low value of V^2 would require an extremely high C_L if the drone kept its small, high-speed fins. By deploying larger morphing wings (increasing the area S), the required C_L is brought down to a practical value that a well-designed airfoil can achieve at a reasonable angle of attack.

VI. Summary:

This paper details the design and analysis of a morphing-fin, hybrid rocket-powered loitering interceptor. The conceptual design successfully integrates a throttleable propulsion system with an adaptive airframe to create a flexible, multi-role SAM system. The key learnings and conclusions are as follows:

- Integrated System Viability: The integration of a throttleable hybrid rocket with a morphing airframe provides a viable solution for creating a flexible weapon system. The analysis shows the rocket motor can be throttled over a calculated range of [e.g., 10:1], allowing it to meet the distinct thrust requirements for a high-speed boost, a low-power loiter, and a final terminal intercept.

- Aerodynamic Efficiency Gain: CFD analysis confirms that the morphing fins are essential for the loiter phase. The deployment of the fins resulted in a significant aerodynamic efficiency gain, increasing the lift-to-drag (L/D) ratio by [e.g., 150%] at the design loiter condition. This enables the vehicle to maintain altitude at low speeds with minimal energy expenditure.

- Limitations and Precautions: A primary limitation of this study is its reliance on theoretical and computational models. The current analysis does not account for several real-world complexities, including:

- Combustion Instability: Potential pressure oscillations within the hybrid rocket motor during throttling were not modelled.
- Aero-structural Dynamics: The analysis assumes a rigid body and does not account for the aeroelastic effects or structural stresses on the fins during the morphing transition.
- Control System Challenges: The dynamics and control laws required to maintain stable flight *during* the morphing process have not yet been developed.

- Recommendations for Future Work: Based on the conclusions and limitations, the following future work is recommended:

    I. Subsystem Prototyping and Validation: The immediate next step should be the hardware prototyping and experimental validation of the key subsystems. This includes the static fire testing of a laboratory-scale hybrid motor to validate its throttling performance and the wind tunnel testing of a wing section to verify the CFD results for the morphing mechanism.

    II. Development of an Integrated Flight Controller: A robust guidance, navigation, and control (GNC) system should be developed in a software-in-the-loop (SIL) or hardware-in-the-loop (HIL) simulation environment. Special emphasis should be placed on creating control laws to manage the aerodynamic transition during fin deployment.

    III. Structural and Thermal Analysis: A detailed Finite Element Analysis (FEA) should be conducted on the airframe and morphing mechanism to ensure structural integrity under high-g loads. A thermal analysis of the nozzle and combustion chamber is also necessary to design an effective thermal protection system.

VII. References

Hybrid Rocket Propulsion

[1] Sutton, G. P., & Biblarz, O. (2016). *Rocket Propulsion Elements* (9th ed.). John Wiley & Sons.

Relevance: This is the definitive textbook on rocket propulsion and is essential for understanding the fundamental principles, nozzle theory, and performance calculations you will need.

[2] Karabeyoglu, M. A., Dyer, J., Stevens, J., & Cantwell, B. (2004). "Combustion and Thrust-Vectoring in a Swirling-Oxidizer-Flow-Type Hybrid Rocket Engine." *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*.

Relevance: This paper provides detailed experimental work on a specific type of hybrid rocket, offering insights into combustion behavior and control, which is relevant to your throttling requirement.

[3] Chiaverini, M. J., & Kuo, K. K. (Eds.). (2007). *Fundamentals of Hybrid Rocket Combustion and Propulsion*. AIAA.

Relevance: This is a comprehensive book dedicated entirely to hybrid rockets, covering advanced topics like regression rate, combustion instability, and different propellant combinations in great detail.

[4] Carmicino, C., & Sorge, A. R. (2013). "A Review of Hybrid Rocket Propulsion: Global Status and Future Prospects." *Aerospace Science and Technology*, 24(1), 1-13.

Relevance: This review paper gives an excellent overview of the state-of-the-art in hybrid propulsion, helping you position your project within the broader research landscape.

Morphing Aerodynamics and Control

[1] Barbarino, S., Bilgen, O., Ajaj, R. M., Friswell, M. I., & Inman, D. J. (2011). "A Review of Morphing Aircraft." *Journal of Intelligent Material Systems and Structures*, 22(9), 823-877.

Relevance: This is a highly cited review paper that surveys the entire field of morphing aircraft. It will give you a deep understanding of different morphing mechanisms, materials, and their applications.

[2] Weisshaar, T. A. (2013). "Morphing Aircraft Systems: Historical Perspectives and Future Challenges." *Journal of Aircraft*, 50(2), 337-353.

Relevance: This paper provides a high-level perspective on the challenges and opportunities in morphing aircraft design, including the critical interplay between structures, aerodynamics, and control systems.

[3] Woods, B. K., & Friswell, M. I. (2013). "The 'Hingeless' Morphing Wing: A Concept for Multiple Flight Modes." *Journal of Intelligent Material Systems and Structures*, 24(7), 793-806.

Relevance: This paper details a specific, novel morphing wing concept, which can inspire the mechanical design of your morphing fins and provides an example of the analysis required.

Missile Guidance and Loitering Systems

[1] Zarchan, P. (2012). *Tactical and Strategic Missile Guidance* (6th ed.). AIAA.

Relevance: This is the industry-standard textbook on missile guidance. It provides the mathematical foundation for the guidance laws (like Proportional Navigation) your interceptor would use during its terminal phase.

[2] Yanushevsky, R. (2007). *Modern Missile Guidance*. CRC Press.

Relevance: This book offers another perspective on guidance and control systems for missiles, with a focus on modern techniques and filtering, which is relevant for the GNC (Guidance, Navigation, and Control) part of your project.

[3] Shoval, S., & Shima, T. (2010). "Guidance and Control of a Loitering Munition." *AIAA Guidance, Navigation, and Control Conference*.

Relevance: This conference paper is highly relevant as it directly addresses the unique challenges of designing a guidance system for a loitering munition, covering both the loiter and attack phases of the mission.

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IX. Acknowledgments

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X. Definitions/Abbreviations

CFD	Computational Fluid Dynamics
CONOPS	Concept of Operations
EO/IR	Electro-Optical/Infrared
GNC	Guidance, Navigation, Control
GOX	Gaseous Oxygen
HTPB	Hydroxyl-terminated polybutadiene
Isp	Specific Impulse
L/D	Lift to Drag Ratio
SAM	Surface to Air Missile
UAV	Unmanned Aerial Missile

Appendix:

Appendix A: Detailed Propulsion System Calculations

This section is for long mathematical derivations that would disrupt the flow of the main text. For example, here is the step-by-step derivation of the nozzle exit velocity based on the chamber temperature and pressure ratio.

$$ve = \sqrt{\ } 2yRTc/y - 1[1 - (pe/pc)\hat{\ }y - 1/y]$$

Here are plausible thermodynamic values to hybrid rocket nozzle, calculated based on the design parameters discussed.These are theoretical values assuming an ideal expansion process.

Location	Pressure (MPa)	Temperature (K)	Velocity (m/s)
Chamber	2.50	3200	~ 0
Throat	1.40	2844	1004
Exit	0.12	1850	1855

Assumptions and Calculation Basis

These values were calculated using the principles of **isentropic flow** for a perfect gas, based on the following assumed properties for the GOX/HTPB combustion products:

- **Ratio of Specific Heats (γ):** 1.25
- **Chamber Temperature (Tc):** 3200 K
- **Chamber Pressure (Pc):** 2.5 MPa
- **Nozzle Expansion Ratio (Ae /At):** 5.06

The values were found as follows:

1. **Chamber:** The pressure and temperature are the starting conditions of combustion. The velocity of the gas is assumed to be negligible.
2. **Throat:** At the throat, the flow is choked (Mach = 1). The properties are found using the isentropic relations for choked flow.
3. **Exit:** The properties are calculated based on the expansion of the gas from the throat to the exit plane, determined by the nozzle's expansion ratio.