Design and Trade Study Evaluation of a Modular Fixed-Wing UAS for Wildfire Detection and Post-Fire Recovery

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As wildfire frequency and severity increase, there is growing demand for aerial systems capable of supporting both early detection and post-fire ecological recovery across large, remote regions. Fixed-wing unmanned aerial systems (UAS) offer advantages in endurance and area coverage, yet most existing platforms are optimized for single mission roles. This work presents the design, trade study evaluation, and prototype development of a modular fixed-wing UAS intended to support both wildfire detection and post-fire reseeding within a unified airframe architecture. The system incorporates interchangeable wing configurations to enable mission-specific aerodynamic optimization, trading loiter endurance for cruise speed and coverage, and supports modular payload integration for both infrared wildfire sensing and aerial seed deployment. Trade studies were conducted to evaluate wing placement, propulsion configuration, tail geometry, and landing gear arrangement while accounting for payload integration, center-of-gravity management, and operational robustness. A full-scale prototype has been developed to assess structural feasibility, aerodynamic performance, and mission adaptability. The results demonstrate the viability of a single modular fixed-wing UAS capable of supporting multiple phases of wildfire response through combined payload and aerodynamic reconfiguration.

I. Nomenclature

AR	=	aspect ratio
CD	=	drag coefficient
CL	=	lift coefficient
CLmax	=	maximum lift coefficient
Cm	=	pitching moment coefficient
Cmq	=	pitch damping coefficient
Cn	=	yawing moment coefficient
Clp	=	roll damping coefficient
D	=	drag force
E	=	battery energy capacity
L	=	lift force
P	=	power
*R*e	=	Reynolds number
S	=	wing planform area
SM	=	static margin
T	=	thrust
V	=	velocity
Vstall	=	stall velocity
W	=	weight

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α = angle of attack
η = propulsion efficiency
ρ = air density
n = propeller rotational speed (rev/s)

II. Introduction

As wildfire frequency and burn severity increase due to changing climatic conditions, the demand for technologically driven response and recovery tools continues to grow. Over the past several decades, total annual burned acreage in the United States has more than doubled, with a marked increase in the frequency of high-severity fire events [1]. These trends place significant strain on land management agencies such as the U.S. Forest Service and the National Interagency Fire Center, which are tasked not only with fire suppression but also long-term ecological restoration.

While there has been substantial research on UAV-based wildfire detection, active fire monitoring, and perimeter mapping, the body of work addressing post-fire ecological recovery is comparatively smaller; even comprehensive surveys of AI-enabled unmanned aerial systems emphasize advances in pre-fire and active-fire tasks, with only limited discussion of post-fire management roles such as damage assessment and ecosystem recovery in the broader wildfire management workflow [2]. Following severe burns, affected regions frequently experience soil destabilization, nutrient loss, and erosion due to the absence of vegetative ground cover [3]. Rapid reseeding of native grasses and early successional species plays a critical role in stabilizing soil, mitigating erosion, and accelerating ecological regeneration [4]. Ground-based stabilization and reseeding efforts are often constrained by limited site accessibility, narrow treatment windows, and the logistical difficulty of treating large burned landscapes [5].

Existing UAV platforms are typically optimized for single-mission roles such as surveillance or mapping. This specialization limits their operational flexibility across the full wildfire response lifecycle. Although UAV-based wildfire monitoring and aerial reseeding have been explored independently, the integration of these capabilities within a modular fixed-wing UAS architecture developed through formal aerodynamic and structural trade studies has received limited treatment in the aerospace systems design literature. A mission-adaptable system capable of transitioning between sensing and ecological recovery roles offers significant logistical and economic advantages for agencies operating under constrained budgets and limited field infrastructure. Modular integration strategies can enhance system scalability and facilitate mission-driven reconfiguration while reducing the need for complete airframe redevelopment [6].

This paper presents the design and development of a 20 lb-class, hand-launched fixed-wing UAV incorporating both payload modularity and aerodynamic reconfiguration. The platform enables rapid integration of an infrared sensing payload for wildfire detection and a modular seed deployment system for post-fire restoration. Interchangeable high and low aspect ratio wings allow mission-driven aerodynamic optimization, trading loiter endurance for cruise speed and area coverage.

Formal trade studies were conducted to determine the baseline configuration of the aircraft. Structural trade studies evaluated fuselage architecture, wing spar configuration, and landing gear layout to balance strength, manufacturability, cost, and durability. Aerodynamic trade studies assessed wing planform geometry, airfoil selection, and dihedral configuration to optimize lift generation, stall predictability, and flight stability. Payload trade studies compared camera configurations and seed dispersion mechanisms to ensure reliable sensing performance and consistent aerial distribution. These analyses were integrated with general sizing simulations and structural validation to converge on a modular baseline design.

The primary technical contribution of this work is the integration of aerodynamic reconfiguration and payload modularity within a single fixed-wing UAS architecture validated through systematic trade studies and prototype development. Fabrication is currently underway, with flight validation scheduled for early 2026. The objective of this work is to demonstrate the feasibility of a scalable, endurance-optimized unmanned platform capable of supporting multiple phases of wildfire response through combined payload and aerodynamic modularity, enabling scalable aerial monitoring and post-fire recovery operations.

III. Mission Requirements and Operational Constraints

The aircraft configuration was defined by operational requirements associated with two primary mission phases: wildfire detection and post-fire reseeding. These missions impose differing performance demands, requiring both extended endurance for surveillance operations and increased cruise speed for efficient area coverage during seed dispersal. The resulting requirements establish the performance envelope within which the aircraft must operate.

A. Endurance and Cruise Performance Requirements

A minimum sustained flight time of 20 minutes was established as a baseline operational requirement to ensure safe sortie completion and return margin under conservative conditions. In addition to this minimum threshold, a target loiter endurance of 60 minutes was defined for wildfire surveillance missions requiring persistent monitoring of burn zones.

Two cruise performance targets were defined to support mission-specific operations. The endurance configuration, utilizing a high aspect ratio wing, is required to sustain steady cruise at approximately 35 knots to support efficient loiter operations. The dispersal configuration, utilizing a lower aspect ratio wing, is required to sustain cruise at approximately 45 knots to increase coverage rate during seed deployment missions. These performance requirements establish the aerodynamic and propulsion constraints for the system.

B. Weight and Deployment Constraints

To preserve field deployability and enable operation in remote terrain, the maximum takeoff weight was limited to 18 lb. The aircraft must be capable of hand launch without auxiliary equipment. Recovery operations must be achievable on maintained dirt roads or similarly semi-prepared surfaces.
These deployment constraints influence structural design, propulsion sizing, and landing gear configuration.

C. Modularity and Payload Requirements

The aircraft must support interchangeable payload configurations corresponding to wildfire detection and post-fire reseeding missions. Payload exchange must be achievable without major structural modification and without compromising flight stability or controllability.

Payload integration must preserve acceptable center-of-gravity limits across configurations. The modular architecture must also allow interchangeable wing assemblies to enable mission-driven aerodynamic reconfiguration while maintaining compatibility with a common fuselage and propulsion system.

D. Operational Envelope

Flight operations are limited to a maximum altitude of 400 ft above ground level and are restricted to fair-weather conditions without precipitation. These constraints align with typical small UAS wildfire monitoring operations and define the intended operating environment of the system.

IV. Aerodynamic Configuration and Stability Validation

A. Airfoil Selection and Reynolds number analysis

Airfoil selection was driven by the expected Reynolds number range of the aircraft during cruise flight. Based on the 35–45 kt cruise envelope and representative chord lengths, the wing operates primarily within Reynolds numbers between approximately 5×10^4 and 2×10^5. Three candidate airfoils were evaluated: NACA 0015, NACA 2412, and NACA 2415.

Two-dimensional analyses were conducted in XFLR5 across Reynolds numbers of 50,000, 100,000, and 200,000. Lift curves and drag polars were compared to assess lift capability, stall behavior, and lift-to-drag performance. Both cambered airfoils (NACA 2412 and 2415) generated sufficient lift within the target cruise angle of attack range. However, the NACA 2415 consistently demonstrated a slightly improved lift-to-drag ratio across the operational Reynolds range. The increased camber also provided higher lift coefficients at moderate angles of attack, improving low-speed performance and stall margin. Based on these results, the NACA 2415 was selected for the main wing. A symmetric NACA 0012 airfoil was selected for the horizontal tail to ensure predictable control response and linear pitching moment characteristics.

B. Wing Configurations and Lift Capability

Two interchangeable rectangular wing configurations were developed: a 7 ft span, low aspect ratio configuration for seed dispersal missions, and a 10 ft span, high aspect ratio configuration for endurance and sensing missions. Both wings share a common root interface and structural architecture.

Three-dimensional aerodynamic simulations were performed using XFLR5 to evaluate lift capability, stall speed, and trimmed angle of attack for both configurations. The analysis assumed a maximum takeoff weight of 20 lb for conservative evaluation.

At a cruise angle of attack of approximately 3.5°, both configurations generated lift exceeding the maximum takeoff weight. Calculated stall speeds were 26.9 knots for the 7 ft wing, and 22.5 knots for the 10 ft wing.

These values provide adequate margin relative to cruise speeds of 45 knots and 35 knots respectively. The high aspect ratio wing achieves lower stall speed due to increased wing area and reduced induced drag, supporting extended loiter operations.

The modular wing system therefore enables mission-dependent aerodynamic optimization while preserving sufficient lift and stall margin in both configurations.

C. Induced Drag and Mission-Driven Aspect Ratio Trade

The primary aerodynamic distinction between the two wings lies in induced drag scaling with aspect ratio. Induced drag is inversely proportional to aspect ratio, making the 10 ft wing more efficient at lower cruise speeds and extended endurance operation.

The 7 ft wing reduces span and structural mass, improving roll responsiveness and enabling higher cruise velocity during seed dispersal missions. Although induced drag increases, the higher cruise speed reduces total mission time for coverage-focused sorties.

This architecture allows a single fuselage and propulsion system to support both endurance-optimized surveillance missions and higher-speed dispersal missions without aerodynamic redesign.

D. Structural Feasibility of Modular Wings

The wing structure consists of a carbon fiber skin, dual carbon spars, and an XPS foam core. Finite element analysis was performed in ANSYS under both 1g and 3g loading conditions, modeling each wing as a cantilever beam under distributed loading.

Maximum von Mises stress occurred at the wing root in all cases. The lowest factor of safety was 11.9 under 3g loading for the 10 ft wing configuration. Maximum tip deflection under 3g loading remained below 3% of semispan. These results indicate that both wing configurations are structurally robust under expected operational loading, with sufficient margin to tolerate adverse maneuvers.

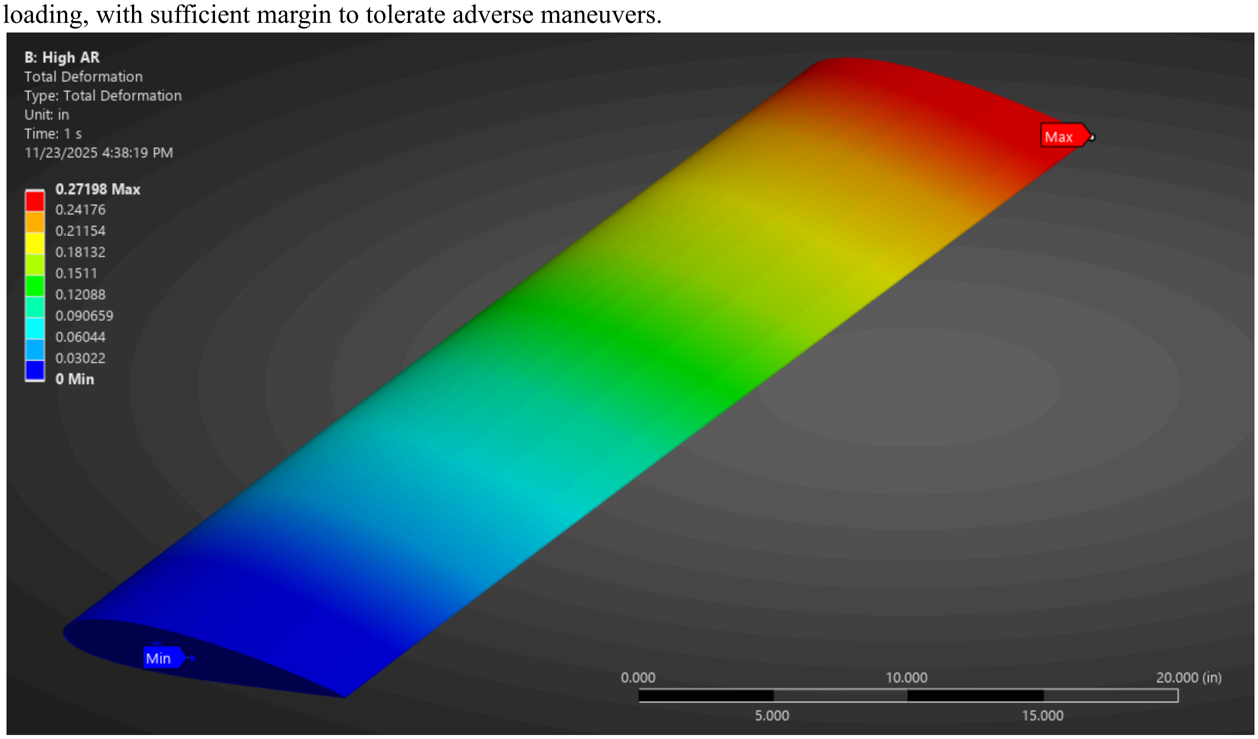

Fig. 1 Von Mises Stress concentration in 3G loading.

E. Static Stability Across Modular Configurations

Static stability was evaluated using Athena Vortex Lattice (AVL) for both wing configurations. Only lifting surfaces were modeled, consistent with standard preliminary design practice. The computed static margins were, 8.9% for the 10 ft wing and 9.8% for the 7 ft wing.

In both configurations, longitudinal stability derivatives exhibited the correct sign and magnitude. The pitching moment derivative with respect to angle of attack was negative, confirming static pitch stability. Pitch damping coefficients were strongly negative, indicating favorable dynamic damping behavior.

Lateral-directional derivatives also satisfied classical stability criteria. Yawing moment due to sideslip was positive, and roll damping derivatives were negative, confirming stable response to perturbations.

The preservation of static margin and derivative sign consistency across both wing configurations confirms that aerodynamic modularity does not compromise stability characteristics.

V. Propulsion and Performance Validation

A. Thrust and Power Availability

The propulsion system consists of a 245 kV brushless motor, 22 × 14 in two-blade propeller, 6S 16,000 mAh LiPo battery, and 135A ESC.

Theoretical no-load rotational speed at 22.2 V is approximately 6174 RPM. Accounting for power availability limitations and assumed 85% system efficiency, the achievable maximum RPM is approximately 4517 RPM. Overall propulsion efficiency was conservatively estimated between 80–85% to account for motor losses, ESC inefficiencies, propeller aerodynamic losses, and real-world operating conditions. These values are consistent with reported efficiencies for electric fixed-wing UAV propulsion systems operating in the low subsonic regime.

At this operating point, static thrust is approximately 67.97 N (15.28 lbf), yielding a thrust-to-weight ratio of approximately 0.85 for an 18 lb aircraft. This provides adequate thrust margin for climb and maneuvering.

B. Cruise Power and Endurance

Cruise power requirements were computed from drag force and cruise velocity: 358.65 W at 35 knots (10 ft wing), 763.02 W at 45 knots (7 ft wing)

The 6S 16,000 mAh battery provides approximately 355 Wh of nominal energy. Theoretical aircraft endurance is approximately 59 minutes at 35 knots and 27 minutes at 45 knots.

Under conservative 80% propulsion efficiency assumptions, endurance at 45 knots remains approximately 22 minutes, exceeding the 20-minute minimum requirement.

The high aspect ratio configuration satisfies the 60-minute loiter objective, while the low aspect ratio configuration supports rapid coverage missions within acceptable endurance limits.

VI. Modular System Architecture and Payload Integration

A. Modular Architecture Philosophy

The core objective of the proposed platform is to enable dual wildfire mission capability within a single fixed-wing airframe. Rather than designing two independent aircraft optimized for sensing and reseeding respectively, a modular systems architecture was developed to allow rapid mission reconfiguration without structural redesign. The architecture consists of three primary modular elements: Interchangeable wing assemblies, a modular payload bay, and a common fuselage and propulsion core

The fuselage, propulsion system, avionics, and tail assembly remain constant across configurations. Mission-specific optimization is achieved by replacing the wing assembly and payload module while preserving aerodynamic stability and structural integrity.

B. Interchangeable Wing Interface

Both the 7 ft and 10 ft rectangular wings share a common root interface and spar alignment geometry. The primary carbon spar remains consistent between configurations, while the outer panels and secondary spar extensions differ in span. This configuration enables rapid field-level wing interchange, consistent center-of-gravity envelope preservation, preservation of tail volume coefficient, and minimal modification to control system tuning.

Structural analysis confirmed that both wing assemblies exceed required safety margins under 3g loading. Stability analysis further demonstrated that static margin remains positive for both configurations, validating that aerodynamic reconfiguration does not destabilize the aircraft.

By maintaining a fixed fuselage and tail geometry, modularity is achieved without requiring rebalancing of the entire aircraft.

C. Payload Integration Strategy

The aircraft incorporates a centralized modular payload bay located near the nominal center of gravity. This placement minimizes trim shifts when switching between mission configurations. Two payload configurations were defined as an Infrared sensing payload for wildfire detection, and a Modular seed dispersion system for ecological recovery

The infrared payload consists of a lightweight camera approximately the size of a playing card, minimizing aerodynamic and mass impact. The seed dispersion module replaces the sensing payload while maintaining similar mounting geometry to preserve center-of-gravity location.

No fixed seed mass requirement was imposed during early design phases. Instead, the fuselage was sized to accommodate a modular dispersal mechanism within the overall 18 lb maximum takeoff weight constraint. This approach provides flexibility for future payload scaling while maintaining structural feasibility.

D. Propulsion Architecture Selection

The final propulsion trade study evaluated the placement and configuration of the propeller system. Three electric propulsion architectures were considered: a single tractor configuration with a nose-mounted propeller, a dual tractor configuration with propellers mounted on wing nacelles, and a single pusher configuration with a rear-mounted propeller. All configurations utilized brushless electric motors and electronic speed controllers.

The dual tractor and single pusher configurations were primarily considered to preserve unobstructed access to the aircraft nose, which houses mission-critical sensing payloads and avionics. The single tractor configuration was included due to its mechanical simplicity and widespread implementation in small unmanned aircraft.

The trade study metrics included reliability, implementation complexity, nose access, cost, and manufacturability. Nose access was assigned the highest weighting due to the integration of infrared sensing payloads and flight control electronics within the forward fuselage. Ease of sensor installation and maintenance was considered critical to mission adaptability. Complexity and cost were assigned moderate weightings, as minimizing subsystem duplication and hardware requirements reduces failure points and preserves system-level efficiency. Reliability and manufacturability were included as evaluation criteria, although all three configurations were deemed structurally feasible and compatible with available manufacturing resources.

The dual tractor configuration scored highly in reliability due to propulsion redundancy. However, it introduced increased structural and electrical complexity, additional wiring, and higher integration overhead. The single tractor configuration offered mechanical simplicity and ease of maintenance but limited usable nose volume for sensor integration. The single pusher configuration achieved the highest score in nose accessibility, preserving a fully unobstructed forward fuselage while maintaining a single-motor propulsion system.

Although cost differences between configurations were modest, the dual tractor configuration required duplicated propulsion components and additional structural reinforcement, increasing integration complexity. Both single-motor configurations demonstrated favorable manufacturability relative to the dual-motor alternative.

Based on weighted scoring, the single pusher configuration was selected. This architecture provides optimal forward fuselage accessibility for payload integration while preserving mechanical simplicity, acceptable reliability, and efficient structural integration. The selected configuration supports both modular wing assemblies without requiring propulsion system modification.

Metric	Weight	Single Tractor	Double Tractor	Single Pusher
Reliability	0.1	2	4	2
Complexity	0.2	4	2	4
Nose Access	0.4	1	3	5

Cost	0.2	3	4	3
Manufacturability	0.1	4	3	4
Totals		**2.4**	**3.1**	**4**
Rankings		3	2	1

Fig. 2 Propulsion configuration trade study.

Evaluation criteria included propulsive efficiency at low airspeeds, center-of-gravity impact, structural integration complexity, maintenance accessibility, and aerodynamic interference with tail surfaces. The pusher configuration with a two-blade propeller was selected due to simplified structural integration, reduced complexity compared to twin-propulsion systems and superior efficiency relative to ducted fan alternatives at low subsonic speeds. This configuration supports both wing configurations without requiring propulsion system modification.

E. System-Level Feasibility

The integrated architecture demonstrates that both wing configurations generate sufficient lift and maintain acceptable stall margins, static stability is preserved across configurations, and the thrust-to-weight ratio remains adequate for climb and maneuvering. Endurance targets are satisfied for both mission types.

The modular strategy enables mission adaptability while preserving aerodynamic efficiency and structural robustness. This systems-level integration confirms the feasibility of supporting wildfire detection and post-fire reseeding within a single airframe.

VII. Prototype Status and Validation Plan

A. Fabrication Status

A full-scale prototype of the modular UAS platform is currently under fabrication. The airframe structure, including carbon fiber wing skins, primary spars, and fuselage components, is being manufactured in accordance with the baseline configuration defined through the structural and aerodynamic trade studies. Both wing configurations share a common root interface and will be produced to enable validation of the modular architecture.

The propulsion system components have been selected and bench integration of the motor, ESC, and battery system is planned prior to flight testing. Avionics integration will utilize ArduPilot-based control hardware to enable trim tuning and data logging during initial flight validation.

B. Ground Validation Testing

Prior to flight operations, a series of ground-based validation tests will be conducted.

Structural validation will include static load testing of the wing assembly to verify deflection behavior under representative loading. The wing will be loaded incrementally up to the equivalent of 3g flight conditions to confirm agreement with FEA predictions.

Propulsion validation will include static thrust testing of the 22 × 14 in propeller configuration to confirm thrust output and power draw at representative throttle settings. Measured thrust-to-weight ratio will be compared against analytical predictions. Battery discharge testing will be conducted to verify usable energy capacity and validate endurance calculations under expected cruise loads.

C. Flight Test Plan

Initial flight testing will focus on trim characterization and stability verification for both wing configurations. Key metrics to be evaluated include trimmed cruise angle of attack, measured stall speed, climb performance, cruise power consumption, and endurance under steady-state flight.

Static margin and control authority will be qualitatively assessed through controlled pitch and roll perturbation testing. Particular attention will be given to confirming stable behavior across both wing configurations without requiring major retuning of control parameters.

Following validation of baseline flight performance, mission-representative testing will be conducted to assess operational feasibility for both wildfire sensing and seed dispersal configurations.

VIII. Conclusion

This work presented the design and feasibility validation of a modular fixed-wing unmanned aerial system intended to support both wildfire detection and post-fire reseeding within a unified airframe architecture. The central objective was to demonstrate that aerodynamic reconfiguration and payload modularity could be integrated into a single platform without compromising lift capability, endurance, structural integrity, or static stability.

Two interchangeable rectangular wing configurations were developed to enable mission-specific optimization. The 10 ft high aspect ratio wing supports endurance-focused sensing operations, while the 7 ft configuration enables higher cruise speeds for seed dispersal missions. Aerodynamic analysis confirmed sufficient lift generation and acceptable stall margins for both configurations. Static stability derivatives computed using AVL demonstrated positive static margin and stable longitudinal and lateral-directional behavior across both wing geometries, confirming that modular wing exchange does not degrade stability characteristics.

Structural feasibility was validated through finite element analysis under 1g and 3g loading conditions. Both wing configurations exhibited low deformation and large factors of safety, indicating robustness under anticipated operational loads. Propulsion sizing demonstrated adequate thrust-to-weight ratio and endurance capability, with the high aspect ratio configuration achieving near one-hour loiter performance and the low aspect ratio configuration exceeding minimum endurance requirements.

The integrated results confirm that a single fixed-wing UAS architecture can be configured to support multiple phases of wildfire response through aerodynamic and payload modularity. Rather than relying on separate dedicated platforms, the proposed system enables scalable mission adaptability while maintaining consistent structural and stability performance.

A full-scale prototype is currently under fabrication, and planned validation testing will further assess flight performance, endurance, and mission-specific capability. Future work will focus on flight test verification, refinement of the seed dispersal mechanism, and evaluation of operational deployment procedures in representative environments.

The demonstrated feasibility of this modular architecture supports its potential as a flexible and cost-effective tool for integrated wildfire monitoring and ecological restoration operations.

Acknowledgments

The author acknowledges the contributions of the senior design team members whose collaborative efforts supported the development of the baseline aircraft configuration and trade study analyses that form the foundation of this work. Their participation in concept generation, subsystem evaluation, and preliminary design activities contributed significantly to the development of the modular UAS architecture.

The author also thanks the faculty advisors and laboratory staff for their technical guidance, access to facilities, and continued support throughout the senior design process.

Portions of the manuscript drafting and structural refinement were assisted using generative artificial intelligence tools for language editing and organizational clarity. All technical content, analyses, and engineering conclusions were developed and verified by the author.

References

[1] [1] Cunningham, C. X., Williamson, G. J., and Bowman, D. M. J. S., "Increasing Frequency and Intensity of the Most Extreme Wildfires on Earth," *Nature Ecology & Evolution*, Vol. 8, 2024, pp. 1420–1425.
doi: 10.1038/s41559-024-02452-2

[2] S. P. H. Boroujeni, A. Razi, S. Khoshdel, F. Afghah, J. L. Coen, L. O'Neill, P. Z. Fule, A. Watts, N. M. T. Kokolakis, and K. G. Vamvoudakis, "A comprehensive survey of research towards AI-enabled unmanned aerial systems in pre-, active-, and post-wildfire management," *Information Fusion*, vol. 108, Art. no. 102369, 2024. https://doi.org/10.1016/j.inffus.2024.102369

[3] Robichaud, P. R., Lewis, S. A., and Ashmun, L. E., "Post-Fire Soil Erosion and Mitigation Effectiveness," Earth Surface Processes and Landforms, Vol. 41, No. 1, 2016, pp. 1–16.
doi: 10.1002/esp.3788

[4] Beyers, J. L., "Postfire Seeding for Erosion Control: Effectiveness and Impacts on Native Plant Communities," Conservation Biology, Vol. 18, No. 4, 2004, pp. 947–956.
doi: 10.1111/j.1523-1739.2004.00523.x

[5] Miller, M. E., and Robichaud, P. R., "Effectiveness of Post-Fire Stabilization Treatments in Reducing Erosion and Improving Recovery: A Review," International Journal of Wildland Fire, Vol. 22, No. 2, 2013, pp. 173–193. doi: 10.1071/WF11129

[6] Stone, R. B., and Wood, K. L., "A Heuristic Method for Product Architecture Design," *Design Studies*, Vol. 21, No. 1, 2000, pp. 5–31. https://doi.org/10.1016/S0142-694X(99)00003-4