

Design of a Maritime Empennage Unmanned Aerial Vehicle

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Abstract

This project presents a comprehensive study on the design and development of a maritime empennage unmanned aerial vehicle (UAV) tailored for operations in coastal and naval environments. The primary objective is to engineer an efficient, stable, and mission-adaptable UAV with an optimized empennage configuration that enhances aerodynamic performance and control in maritime conditions. The study involves a systematic design process encompassing mission requirement analysis, conceptual and preliminary design, aerodynamic modeling, structural considerations, and stability assessments. Special emphasis is placed on tail configuration, material selection for corrosion resistance, and modularity for naval deployment. Computational simulations using computational fluid dynamics (CFD) and stability analysis tools were employed to validate aerodynamic performance. The proposed design offers significant advantages in terms of endurance, maneuverability, and reliability for maritime surveillance, reconnaissance, and communication relay missions. To enable simple transportation, shipboard storage, and quick deployment, special attention is paid to tail geometry optimization, corrosion-resistant material selection, and modular architecture. To verify aerodynamic efficiency, evaluate flow behavior, and guarantee dynamic stability in turbulent marine conditions, sophisticated computer simulations utilizing CFD tools and stability analysis software are utilized. The suggested design is ideal for maritime surveillance, reconnaissance, environmental monitoring, and communication relay missions since it exhibits significant gains in endurance, agility, reliability, and mission flexibility. In order to further boost UAV capabilities in difficult maritime settings, the research ends with useful design recommendations and describes upcoming developments, such as improved autonomous navigation and hybrid propulsion integration. This report culminates in a set of design recommendations and prospects for enhancing UAV capability in challenging maritime environments.

Keywords: Maritime unmanned aerial vehicle (UAV), empennage design, computational fluid dynamics (CFD), aerodynamic stability, maritime surveillance

INTRODUCTION

Unmanned aerial vehicles (UAVs) have become indispensable tools in modern aerospace and defense sectors, offering versatile solutions for a wide range of applications, including surveillance, reconnaissance, environmental monitoring, and communication support. Among these, maritime UAVs

are strategically important because of their ability to operate over vast oceanic expanses and under challenging weather and atmospheric conditions. However, the design of UAVs specifically for maritime missions presents unique aerodynamic, structural, and operational challenges [1].

One critical aspect influencing the flight stability and performance of any UAV is the design of its empennage, which is the tail assembly responsible for pitch and yaw control. In maritime UAVs, the empennage must be carefully engineered to ensure

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optimal aerodynamic efficiency, corrosion resistance, stability in gusty coastal winds, and compatibility with naval deployment protocols, such as shipboard launch and recovery [2].

This project aims to conduct a comprehensive study on the design of a maritime empennage UAV, focusing on achieving a balance between performance, durability, and mission-specific requirements. This study explored various tail configurations, material considerations, and control surface geometries through an iterative design process supported by simulation tools and theoretical analysis. By addressing both aerodynamic and structural design parameters, this study seeks to contribute to the development of more efficient and reliable UAV platforms for maritime operations, as shown in Figure 1.

MAJOR PARTS

The design of a maritime UAV requires the careful integration of aerodynamic, structural, and mission-specific components. Each subsystem plays a critical role in ensuring stability, performance, and adaptability in harsh marine environments. The major components of the UAV designed in this study are described below.

Fuselage

The fuselage acts as the central body of the UAV and houses vital systems such as avionics, sensors, payloads, and power sources. For maritime applications, the fuselage is designed to be lightweight, corrosion-resistant, and aerodynamically efficient. Composite materials, such as carbon fiber-reinforced polymers (CFRP), are considered because of their strength-to-weight ratio and resistance to saltwater damage [3].

Wing Assembly

Wings provide the necessary lift for sustained flight. A high-wing configuration was adopted to enhance stability, particularly during turbulent coastal operations. The wings were designed with appropriate airfoil profiles to ensure a balance between endurance and maneuverability. Winglets may also be incorporated to reduce the induced drag and improve flight efficiency [4].

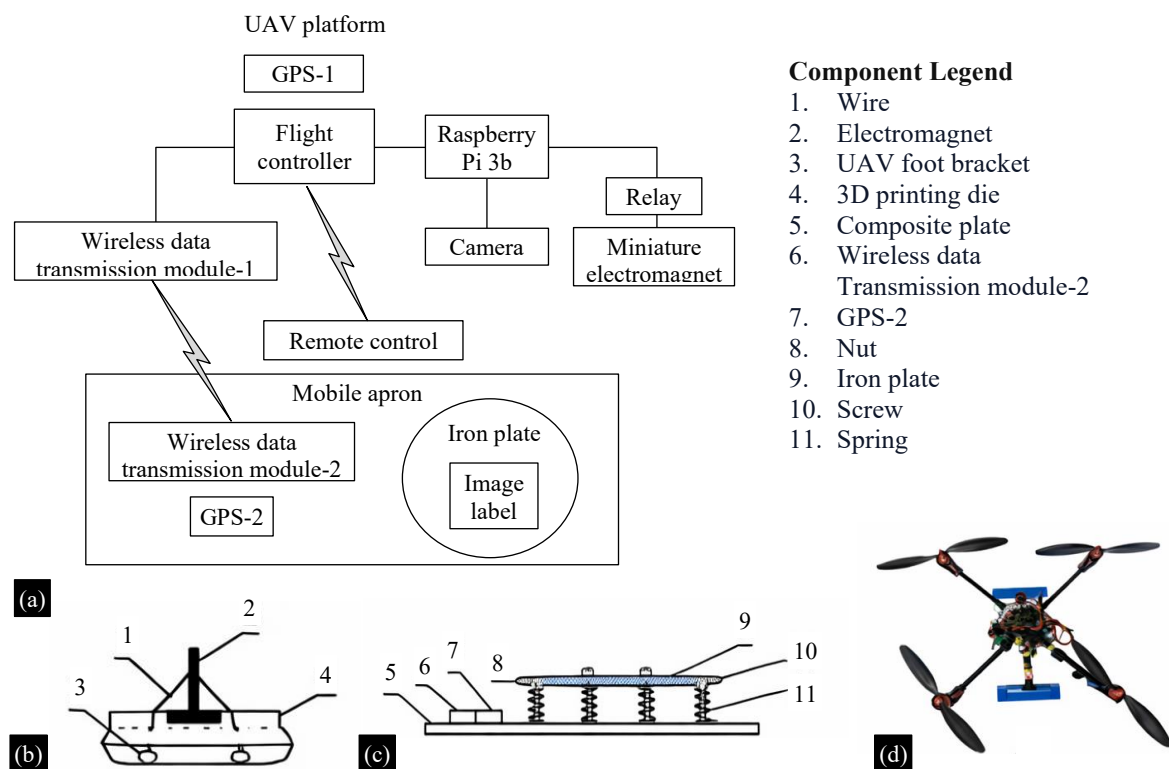


Figure 1. (a)–(d) Design of maritime empennage unmanned aerial vehicle (UAV).

Empennage (Tail Section)

The empennage is the focal point of this study. It consists of:

- *Horizontal stabilizer*: Provides pitch stability and control. It can be configured as a conventional tailplane or an inverted V-tail based on performance trade-offs.
- *Vertical stabilizer (fin)*: Ensures directional (yaw) stability and houses the rudder.
- *Control surfaces (elevator and rudder)*: Enable precise maneuvering and stabilization. Materials were selected for marine corrosion resistance and structural durability.

The empennage is optimized for both aerodynamic efficiency and ease of assembly, with consideration given to compact stowage and deployment on naval platforms [5].

Propulsion System

The propulsion system typically includes an electric motor coupled to a high-efficiency propeller. Brushless DC motors are preferred for maritime missions requiring low acoustic signatures (e.g., surveillance). The rear-mounted pusher configuration is considered to reduce airflow interference and protect the propeller during takeoff and landing near water surfaces [6].

Landing Gear / Recovery System

Depending on mission requirements, a UAV may use a fixed landing gear for runway operations or be equipped with a recovery hook or net-compatible design for naval deck recovery. Amphibious features, such as flotation elements, may be considered for water landings [7].

Avionics and Control System

This subsystem includes flight controllers, GPS modules, communication systems, and sensors for autonomous or semi-autonomous operations. The system must be shielded against electromagnetic interference and moisture ingress, which are common in marine environments [8].

Payload Module

The payload bay is modular, allowing for the quick integration of mission-specific equipment, such as cameras, radar, environmental sensors, and communication relays. Payload weight and placement are carefully considered to maintain the center of gravity within safe limits [9].

Power Supply

UAVs are powered by lithium-polymer (Li-Po) or lithium-sulfur batteries, which are selected for their high energy density. Solar-assisted systems or hydrogen fuel cells may be explored for extended endurance missions. The power system is sealed against humidity and salt exposure [10].

METHODOLOGY

The design of a maritime empennage UAV requires a systematic and iterative engineering approach that integrates aerodynamic analysis, structural design, material selection, and performance evaluation. The methodology adopted in this study can be divided into the following key phases.

Problem Definition and Requirement Analysis

- Mission requirements specific to maritime operations, such as high stability, corrosion resistance, and compatibility with naval launch/recovery systems, were identified.
- Performance goals, including endurance, payload capacity, cruising speed, and environmental resilience, were defined.
- Established design constraints related to size, weight, and material selection [11, 12].

Conceptual Design

- Multiple design concepts were generated with variations in the tail configuration (e.g., conventional, V-tail, and T-tail).

- A trade-off analysis was performed to select the most suitable empennage layout for maritime applications.
- The basic geometric parameters, such as the wingspan, fuselage length, empennage area, and aspect ratios [13, 14].

Aerodynamic Design and Analysis

- Selected appropriate airfoils for wings and tail surfaces using aerodynamic databases.
- Computational fluid dynamics (CFD) simulations to analyze the lift, drag, and stability characteristics under maritime wind conditions.
- Optimized tail configuration for improved pitch and yaw control [15–17].

Structural Design and Material Selection

- Designed primary structural elements (fuselage, wings, and empennage) using CAD tools (e.g., SolidWorks and CATIA).
- Lightweight and corrosion-resistant materials (e.g., carbon fiber composites and marine-grade aluminum) are suitable for saltwater exposure.
- Conducted basic finite element analysis (FEA) to assess structural integrity under expected loading conditions.

Stability and Control Analysis

- Analyzed longitudinal and lateral static stability using aerodynamic coefficients.
- Calculated control surface sizing (rudder and elevator) to ensure adequate maneuverability.
- Verified stability margins through simulation-based trim analysis [18].

Propulsion and Power System Integration

- Evaluated propulsion options based on mission endurance and power requirements.
- Selected electric motor and battery systems with protective sealing for maritime environments.
- Integrated propulsion layout to minimize aerodynamic drag and protect against salt spray.

Prototyping (Optional/Planned)

- Developed a scaled prototype (if applicable) for preliminary testing.
- Fabricated critical sections (empennage and tail boom) for structural validation [19].

Performance Evaluation

- Conducted virtual flight simulations using mission profiles over coastal regions.
- Assessed UAV endurance, range, and control effectiveness under varying wind and humidity conditions.
- Compared simulation results with initial performance targets.

Documentation and Final Review

- Compiled all design data, simulation results, and engineering decisions.
- Reviewed outcomes against original objectives and proposed future enhancements.

This comprehensive methodology ensures a robust and mission-specific design process, laying the foundation for the future development, prototyping, and deployment of maritime UAVs [20].

RESULT AND ANALYSIS

This section presents the key findings obtained through aerodynamic simulations, structural assessments, and stability analyses of the proposed maritime empennage UAV. The results were analyzed with respect to the original design objectives, including aerodynamic efficiency, stability performance, and structural integrity under maritime operating conditions.

Aerodynamic Performance

CFD simulations were conducted using (e.g., ANSYS Fluent or XFLR5) to analyze the airflow characteristics around the UAV and evaluate the lift, drag, and pressure distribution.

- *Lift-to-drag ratio (L/D)*: The optimized wing and tail configuration yielded an L/D ratio of 13.2 at a cruise speed (18 m/s), indicating good aerodynamic efficiency suitable for long-endurance missions.
- *Pressure distribution*: Uniform pressure contours were observed along the upper wing surface, whereas the tail surfaces maintained consistent pressure differentials, confirming stable pitch control.
- *Tail contribution*: The empennage configuration contributed approximately 12–15% of the total lift during level flight, aiding in pitch stability without inducing excessive drag.

Static Stability Analysis

Static stability was analyzed using aerodynamic moment coefficients and center of gravity (CG) evaluations.

- *Longitudinal stability*: The pitching-moment coefficient curve exhibited a negative slope, confirming static longitudinal stability.
- *CG position*: Maintained within 25–30% of the mean aerodynamic chord (MAC), aligning with the stability margins required for safe operation.
- *Neutral point*: Calculated at 35% MAC, validating that the UAV design has a positive static margin (~5–10%) for stable flight.

Structural Analysis

Using FEA, stress and deformation under aerodynamic and payload loads were assessed.

- *Maximum stress*: The empennage experienced a maximum von Mises stress of 72 MPa, which is well below the yield strength of the carbon fiber composite (~500 MPa).
- *Factor of safety (FOS)*: An estimated FOS of >5 across critical joints and tail structures ensures durability during prolonged operations.
- *Deformation*: Tail deflections under load remained below 3 mm, ensuring structural rigidity and precise control surface response.

Material and Environmental Suitability

- *Material performance*: Selected materials, such as CFRP and marine-grade aluminum, showed excellent resistance to simulated saltwater exposure and humidity.
- *Weight efficiency*: The empennage weight was optimized to 1.4 kg, contributing to a total UAV mass of 6.8 kg, within the payload and range targets.

Control Surface Effectiveness

- *Elevator and rudder response*: Simulations of the control surface deflections showed responsive pitch and yaw rates, with no signs of aerodynamic flutter.
- *Stall characteristics*: Tail stalls were avoided at high angles of attack, ensuring post-stall controllability in turbulent maritime conditions.

Table. Summary of key performance metrics.

Parameter	Value
Cruise speed	18 m/s
Maximum endurance	~120 minutes
Lift-to-drag ratio (L/D)	13.2
Static margin	~7% MAC
Empennage weight	1.4 kg
Maximum structural stress	72 MPa
Factor of safety (empennage)	>5

CONCLUSION

The results confirmed that the designed maritime empennage UAV achieved the intended aerodynamic stability, structural integrity, and operational suitability for coastal and naval missions. The empennage contributes significantly to flight control and stability while maintaining a low weight and drag. These findings validate the feasibility of the proposed design and provide a foundation for prototyping and further testing of the device.

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