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Designing A Framework for A Bio-Inspired Amphibious UAV Control System for Multi-Medium Operations

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Abstract- Unmanned Aerial Vehicles (UAVs) have become an important tool for modern surveillance and reconnaissance systems. However, existing UAVs are used in a single medium, either aerial or aquatic regions, which imposes a limitation for maritime and coastal operations that need a multi-medium capability. Inspired by the flying fish, this paper proposes a state-based control framework with rule-based transition logic to maintain transitions between air and water for a cyclic operation, and a control mechanism for a stability during medium transitions. The proposed study focuses on supporting the development of a future framework design for UAV modelling, energy analysis during transition, and stability maintenance. However, the study provides an overview of the foundations for the development of intelligent amphibious UAV systems for defence surveillance and coastal monitoring applications.

Keywords: Bio-Inspired Robotics, Cyclic Operation, Energy Efficiency, Future Framework, Unmanned Aerial Vehicle, UAV Model.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have become an important technology for modern defence, inspection, and monitoring activities. Their capacity to conduct surveillance without endangering human life has made them extremely helpful in dangerous and complex environments, such as mountains and areas that are difficult for humans to access. Unfortunately, the majority of current UAV systems are only able to operate in the air and are unable to operate effectively in underwater environments or on water surfaces. The existing security challenges in maritime and coastal areas require platforms that can operate across multiple environments.

Flying fish are our inspiration through nature, which can effectively make a transition from water to air. In recent years, biological intelligence has turned into engineering systems that have become popular in the field of robotics and autonomous systems. The development of simulation and control algorithms helps to study vehicle behaviors virtually before the use of actual hardware. By using the simulation framework approach, researchers can construct an intelligent decision-making system for medium transition, stability, and energy optimization. The proposed framework focuses on state-based transition logic, control mechanisms, and simulation architecture for the future system evaluation and development. The remainder of this paper is structured as follows. Section 2 describes the problem statement related to multi-medium UAV operations. Section 3 presents the existing literature on amphibious UAV systems and control mechanisms. Section 4 explains the objectives of the proposed research. Section 5 provides the methodology and system architecture. Section 6 discusses the expected outcomes, and Section 7 concludes the paper.

Contribution of this work:

- A bio-inspired control system based on flying fish locomotion for amphibious UAV operation.
- A state-based transition mechanism is used to manage a cyclic process.
- A system architecture will help in the upcoming hardware implementation and simulation.
- Including control stabilization in a framework.

II. PROBLEM STATEMENT

Existing UAVs are limited to certain environments where they need to be submerged for camouflage and aerial observation, because drones are manufactured mainly focusing on aerial operations. But the lack of focus on the simulation framework design to handle the transition between water and air, which helps to analyze the stability and energy analysis across multi-medium operations, even though several studies addressed flight stability and autonomous navigation. The absence of a simulation framework design that focuses on analyzing within the software, helps in a low cost, and testing before hardware implementation, which enables safe and efficient multi-medium UAV operations.

III. LITERATURE OVERVIEW

3.1 Mathematical modelling and control of a submersible multi-medium UAV

This study proposes a mathematical model and control systems to analyze UAV transition between air and water environments, and control algorithms are evaluated based on system modeling for their stability and performance during medium switching [1]. However, the study focuses on system design and hardware implementation, not on simulation-based transition intelligence.

3.2 The Design and Implementation of a Multi-mode Control System for Air-Sea Amphibious UAV

In this study, the regular checking methods in the field of offshore wind power need manual labor or a single medium drone. The authors introduce a tiltable coaxial propulsion structure and a separable underwater chain-type tethered optical communication relay module (extended range of high-speed optical wireless communication without losing connection even when the line of sight is blocked) to enable cross-medium operation and stable communications. In level three sea conditions, based on the results, UAV operations are stable [2]. However, the study focuses on implementing hardware and a strong communication connection rather than energy consumption awareness, stable control using a simulation framework design.

3.3 The Controller Design of the Water-Aerial Vehicle Based on Variable Gain PID (Proportional-Integral-Derivative)

This study proposes that water-aerial vehicles operating across the air-water environment are facing difficulty maintaining stability during the transition stage. To solve this, the authors developed a mathematical model for different operation stages, and a stability controller was designed based on a variable-gain PID approach. Simulation results show clearly that the proposed control method is feasible and meets the stability requirements during medium switching [3]. Furthermore, the study focuses on designing a controller and adaptation within a simulation-based control environment, with a limited attention to the energy consumption analysis and a framework design for state-based transition to manage repeated multi-mode operation.

3.4 Quadrotor UAV Kinematics and Dynamics: A Comprehensive Model with Suggested Control Techniques

This study presents the development of a mathematical model for a quadrotor UAV, focusing on both kinematics, which contains position, velocity, and acceleration, without considering forces and dynamics, which contains forces, torque analysis, and causing motion using the Newton-Euler method of six degrees of freedom [4]. The paper provides a framework for multiple flight modes and helps in stability and control. The authors recommended relevant control mechanisms such as Active Disturbance Rejection Control (ADRC) and adaptive techniques to improve system performance. While the study involves a reference for an aerial UAV dynamic modeling, it does not address multi-medium transition, state-based control for the amphibious operations, or energy-consumption analysis within a simulation-driven transition framework.

3.5 Simulation Tools, Environments, and Frameworks for UAV Systems Performance Analysis

This study presents a overview of existing UAV simulation tools, virtual environments, and ground control stations framework for the analysis of the performance before the hardware implementation. The authors compare various flight simulators, such as FlightGear, Gazebo, AirSim, J-MavSim, and UE4Sim, along with different GCS platforms

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scenarios, highlighting their requirements, goals, strengths, and limitations [5]. The work highlights the importance of Software-In-The-Loop (SITL) and Hardware-In-The-Loop to reduce the implementation cost and improve safety before testing. However, the study guides us to the selection of suitable simulation environments, but it's not focused on structured state-based mechanisms, control framework, multi-medium modelling for amphibious UAV operations.

3.6 Literature Summary and Research Gap

- Lack of a unified Simulation-driven framework for amphibious UAV operations.
- State-based transition logic for controlling cyclic mode switching is partially integrated.
- Limited focus on multi-medium modeling is used for aerial and aquatic at the same time.
- Lack of energy consumption analysis during mode switching between water and air.

IV. OBJECTIVES

- To design a multi-medium unmanned aerial vehicle using a simulation-based control framework before implementation.
- To create algorithms that provide a secure transition between air and aquatic environments.
- To create a framework that can assess energy analysis and dependability in amphibious UAV operations.
- To demonstrate that it is relevant to the Defence Surveillance situation.

V. PROPOSED METHODOLOGY

5.1 SYSTEM MODELING:

The proposed paper modeled the UAV separately for air and water, due to the variation of forces being different. In the air, thrust, gravity, and aerodynamic drag become heavy. In aquatic regions, buoyancy and hydrodynamic drag play an important role during the transition phase sudden drag may create instability.

5.2 STATE-BASED TRANSITION LOGIC

The research presents a rule-based mechanism that is used as a system's decision-making unit in three primary states: water mode, transition mode, and air mode. The decision-making happens based on the collection of the environmental data, such as depth, altitude, thrust thresholds, and water surface tension, in different operational modes.

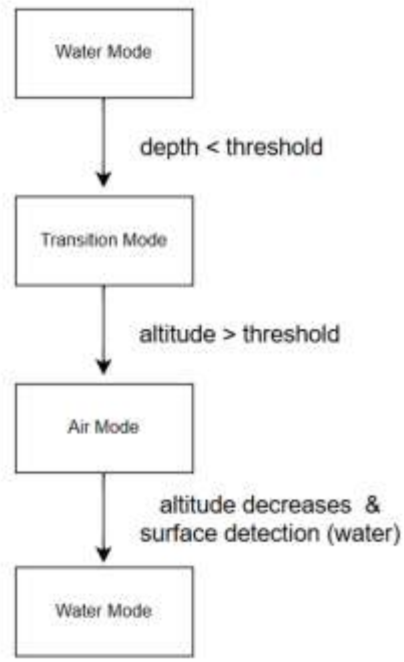

Figure 1: State-based transition diagram for Amphibious UAV Operation.

Transition condition:

$$S = \begin{cases} Water, & depth > d_{th} \\ Transition, & depth \leq d_{th} \wedge thrust > T_{th} \\ Air, & altitude > h_{th} \end{cases}$$

d_th depth threshold
T_th thrust threshold
h_th altitude threshold

5.3 CONTROL STRATEGY

The proposed system makes a decision based on stability to decide when to switch using a state mechanism, and the control mechanism stabilizes the UAV during transition mode, when taking off or landing on a water surface, buoyancy effects and hydrodynamic drag using PID-based thrust regulation.

5.4 ENERGY USAGE ANALYSIS

A system design framework is used to examine the energy consumption in different operational modes.

5.5 SIMULATION FRAMEWORK

The proposed research framework is designed to be implemented in Python using numerical simulation.

5.6 SYSTEM ARCHITECTURE

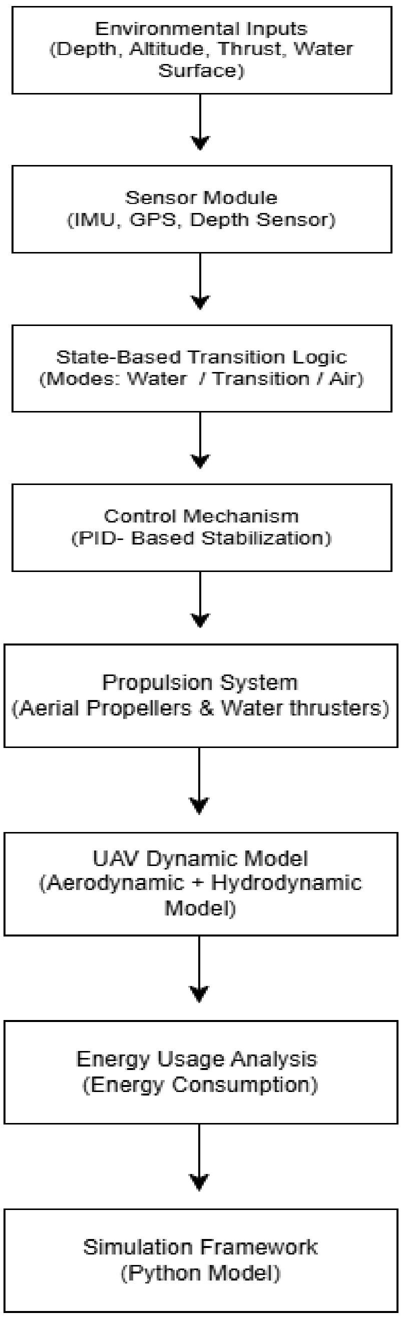

Figure 2: The Proposed architecture of the bio-inspired amphibious UAV control framework.

Figure 2 illustrates the overall architecture of the proposed bio-inspired amphibious UAV framework. The system gets an input such as depth, altitude, thrust, and water surface conditions based on the environment, which are collected through onboard sensors including IMU, GPS, and depth sensor. The acquired data is processed by the state-based transition logic that decides the operational state of the UAV, namely Water Mode, Transition Mode, or Air Mode.

A PID-based control mechanisms is integrated to maintain stability and regulate thrust during medium transitions. Based on the control decisions, the propulsion system consisting of Aerial Propellers and Water thrusters generates the required motion for the both aerial and aquatic operation. The UAV dynamic model combines aerodynamic and hydrodynamic behaviors to represent system movements across multiple environments. The framework continues with the energy usage analysis module to evaluate energy consumption during operation and transition phases. Finally, the overall architecture is intended to support future implementation within a Python-based simulation framework for performance evaluation and system analysis.

5.7 FUTURE SIMULATION WORK

Analyzing the UAV dynamics, thrust variation, and energy consumption during the cyclic process will be included in future work by involving a Python-based modeling environment.

VI. EXPECTED OUTCOMES

- Development of a structured simulation-driven framework for cyclic water-air-water UAV operation.
- A rule-based state-based system implemented with a control-based approach to maintain stability for smooth transition in different modes.
- The precision control of the thrust and dynamic model balance during transition mode
- The energy consumption analysis is compared throughout the aquatic, aerial, and transition modes for the system efficiency.

CONCLUSION

This paper presents a study of the design of an amphibious UAV control framework inspired by the natural locomotion of flying fish, which can perform repeated water-air operations. And the system uses separate modeling for air and water, a decision made by a rule-based state mechanism for switching modes, and a control mechanism to maintain a stability during transition. Our future research is focused on simulation and hardware implementation.

REFERENCES

[1] S. Panigrahi, V. Ashok, V. K. Pediredla, T. Ranganathan, and A. Thondiyath, "Mathematical modelling and control of a submersible multi-medium UAV," OCEANS Conference, Chennai, 2022.

[2] Z. Cai, Y. Wu, R. Zheng, L. Wu, B. Zhang, J. Ding, and T. Chen, "The Design and Implementation of a Multi-mode Control System for Air-Sea Amphibious Unmanned Aerial Vehicle," Neuro-Inspired Computational Elements Conference (NICE), 2025.

[3] H. Liu, Z. Meng, X. Yang, and S. Ding, "The Controller Design of the Water-Aerial Vehicle Based on Variable Gain PID," Chinese Control and Decision Conference (CCDC), 2020.

[4] A. R. A. Majid, "Quadrotor UAV Kinematics and Dynamics: A Comprehensive Model with Suggested Control Techniques," International Conference on Modeling, Simulation & Intelligent Computing (MoSICom), 2024.

[5] A. I. Hentati, L. Krichen, M. Fourati, and L. C. Fourati, "Simulation Tools, Environments and Frameworks for UAV Systems Performance Analysis (1495-1500)", 2018.