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Autonomous Drone-Based System for Multi-Sensor Aircraft Surface Inspection and Defect Detection

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Abstract

Manual visual inspections are the standard for traditional aircraft maintenance; however, this method is time-consuming, hazardous to personnel, and prone to human error. This paper outlines the design and development of an autonomous robotic system to address these limitations. The proposed solution is a drone equipped with a multi-sensor inspection payload, including a high-resolution AI camera for visual inspection, a LiDAR sensor for 3D mapping of structural damage, and a thermal camera to detect anomalies such as ice or degraded materials. The physical design was created using CAD software, and aerodynamic performance was validated through flow simulations. Using a novel observable sensor fusion technique, a custom AI model was developed to fuse and analyze payload data, yielding greater analytical depth than single-sensor methods. The objective is to achieve a defect detection accuracy of at least 95% and reduce inspection time by 50%. While currently in the simulation phase, this work represents a significant step toward improving the safety, efficiency, and accuracy of aircraft maintenance.

Keywords: autonomous drone, aircraft maintenance, flight safety

Introduction

Conducting manual aircraft inspections presents a major logistical challenge in the aviation industry. Inspectors must visually assess defects while utilizing ladders and scaffolding, a process that is both dangerous and inefficient. Manual inspections typically require 6 to 12 hours per aircraft, causing operational delays and increasing maintenance costs (Pérez et al., 2025). Furthermore, human error remains a critical risk; inspectors may overlook detrimental defects such as dents, surface contamination, or ice (Silva et al., 2023). This project addresses these disadvantages by developing an intelligent drone and sensor system designed to be consistent and reliable, thereby introducing a safer and more efficient maintenance process.

Proposed Solution

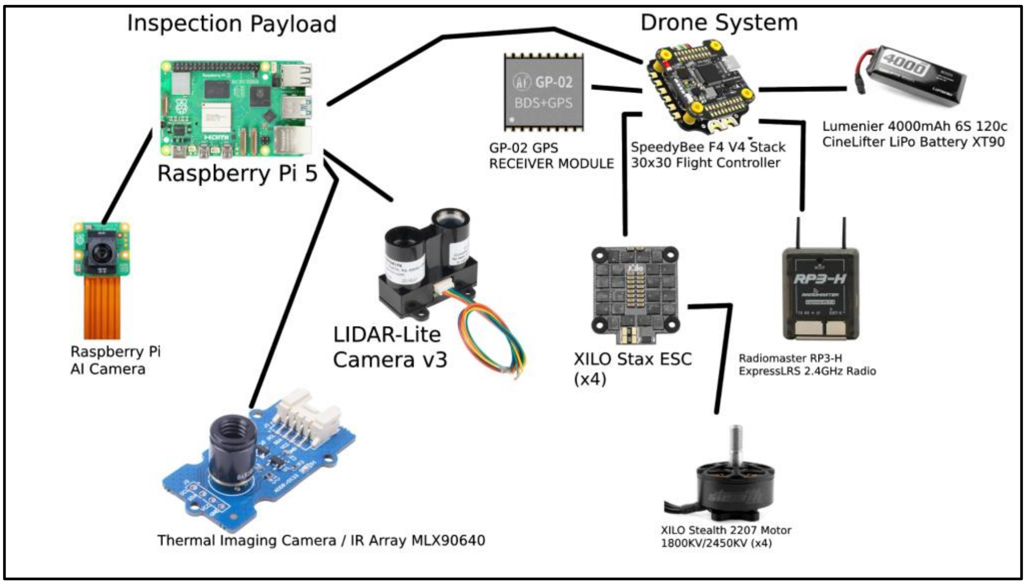
The proposed system is an autonomous drone designed for pre-flight and planned maintenance inspections. It is capable of detecting a wide variety of defects, including structural damage (dents and cracks), surface contamination (dirt and ice), and surface degradation (damage to paint and sealants).

Hardware and System Architecture

The Inspection Payload is constructed on top of a Raspberry Pi 5, which processes information from a comprehensive suite of sensors purposefully selected for thorough inspection. A Raspberry Pi AI Camera provides high-resolution imagery and serves as the primary tool for defect identification. To detect and measure structural deformations such as dents that are invisible in 2D images, a LiDAR-Lite Camera v3 is utilized for 3D mapping. Additionally, an MLX90640 Thermal Imaging Camera allows for the detection of ice and thermal anomalies indicating subsurface issues (Rao et al., 2016). A multispectral camera is included to identify minute damages that other sensors might miss, and a flashlight ensures high-quality image capture in low-light environments (Pérez et al., 2025).

Figure 1

Electronics Schematic and System Integration



Note. The schematic details the connections between the Raspberry Pi 5 inspection payload and the SpeedyBee F4 flight controller system.

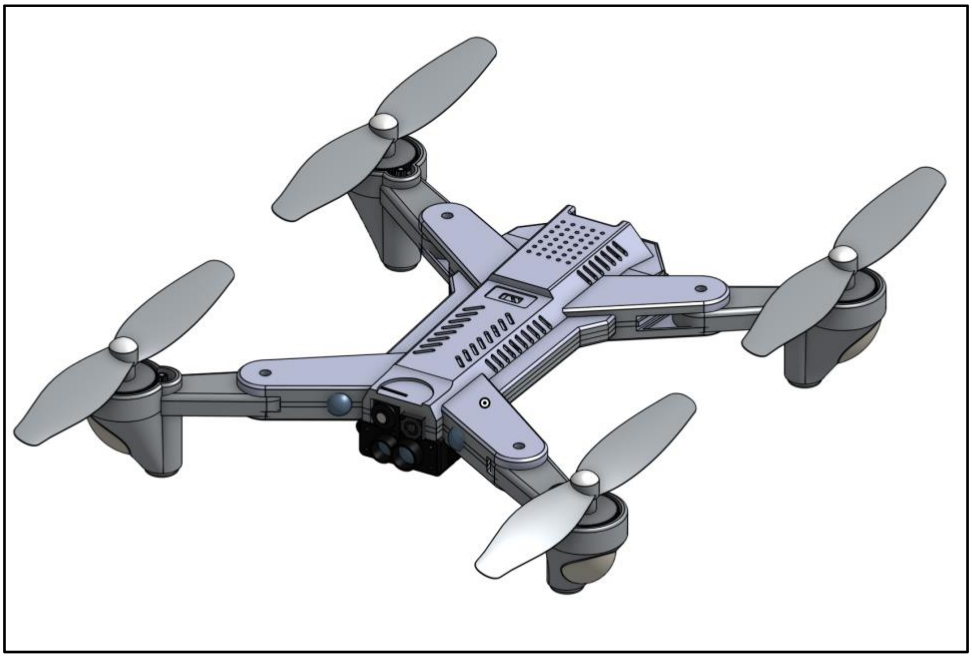
The Drone System is controlled by a SpeedyBee F4 V4 Stack Flight Controller and powered by a Lumenier 4000mAh LiPo Battery. Propulsion is achieved using XILO Stealth 2207 Motors paired with XILO Stax ESCs.

Optimum Location of Sensors

Sensor placement is critical for accurate data collection. The primary inspection payload, consisting of the AI and multispectral cameras, is mounted underneath the front of the airframe. The LiDAR sensor is positioned at the front and angled slightly forward, ensuring it scans the aircraft's surface to generate a high-detail 3D point cloud. A notable design update places the thermal camera on top of the drone rather than the side; this orientation angles the camera downward toward the inspection surface while shielding it from direct sunlight. Lighting is placed uniformly to prevent shadowing, ensuring consistent data quality regardless of environmental conditions.

Figure 2

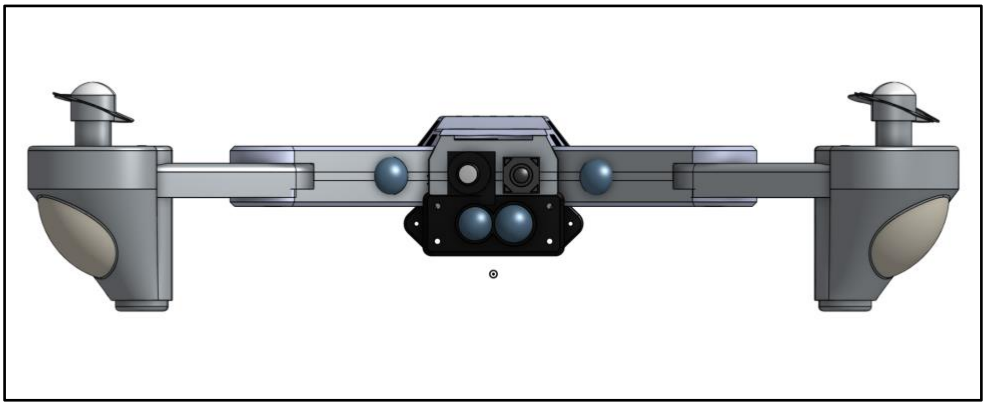
Isometric View Final Drone Model



Note. The 3D CAD rendering depicts the structural housing for the sensors, showing the downward-angled orientation of the thermal camera and the forward-facing LiDAR-Lite v3.

Figure 3

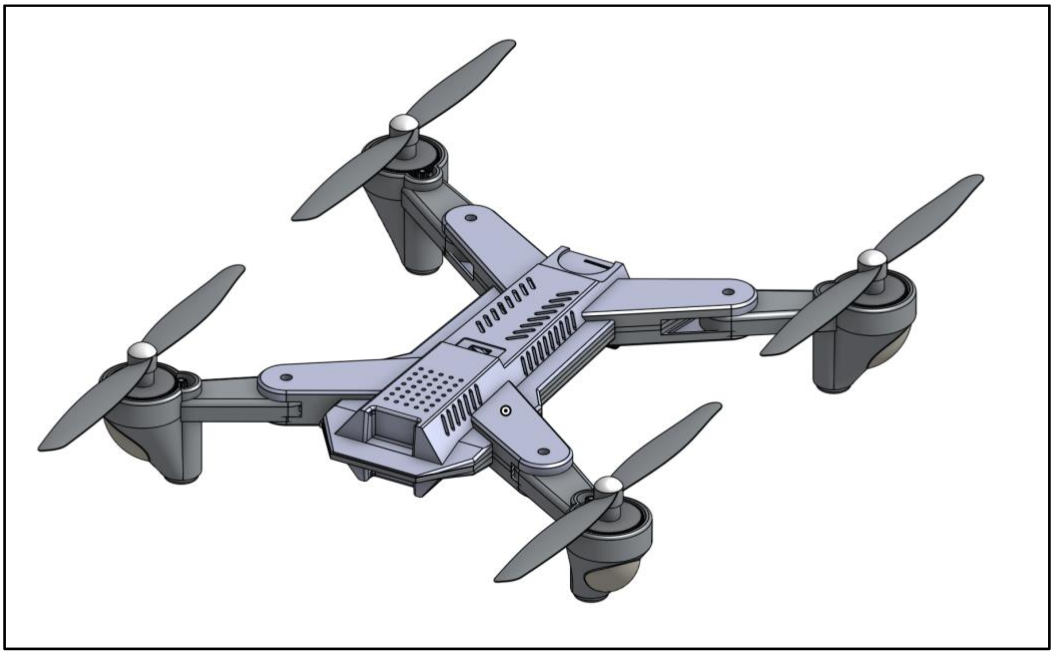
Front View Final Drone Model



Note. The 3D CAD rendering depicts the structural housing for the sensors, showing the downward-angled orientation of the thermal camera and the forward-facing LiDAR-Lite v3.

Figure 4

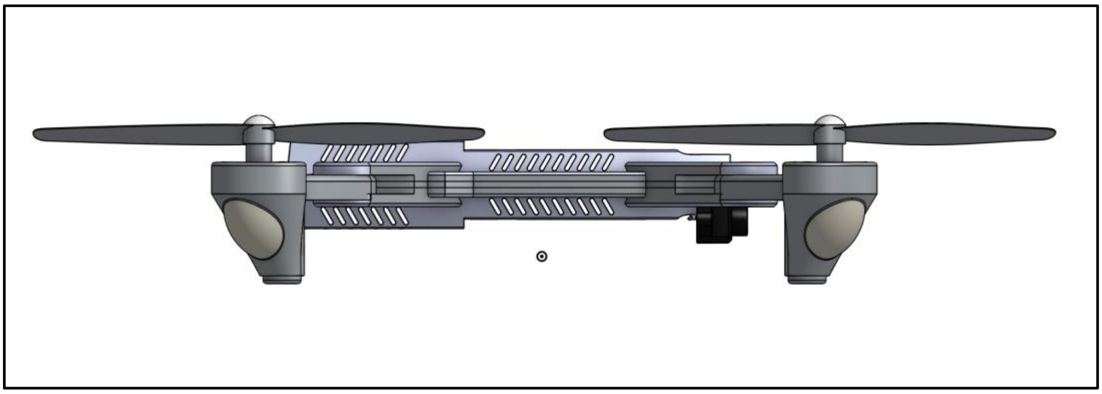
Isometric View Final Drone Model



Note. The 3D CAD rendering depicts the structural housing for the sensors, showing the downward-angled orientation of the thermal camera and the forward-facing LiDAR-Lite v3.

Figure 5

Right View Final Drone Model



Note. The 3D CAD rendering depicts the structural housing for the sensors, showing the downward-angled orientation of the thermal camera and the forward-facing LiDAR-Lite v3.

Drone Physics and Performance Analysis

Flight performance relies on the balance between thrust and weight. Thrust (*T*) produced by a single propeller is proportional to the square of its rotational speed (ω), expressed in Equation 1:

$$T = k * w^2$$

where *k* is a constant dependent on propeller shape and air density (Khorram, 2025). To achieve liftoff, the total thrust must exceed the drone's total weight (*W*), represented as $T_{total} > W$ (Shukla et al., 2020). Solidworks Flow Simulation verified that the design produces a positive thrust-to-weight ratio, confirming its capability to operate with the sensor payload.

Analysis of the Model

Sensor Integration Analysis

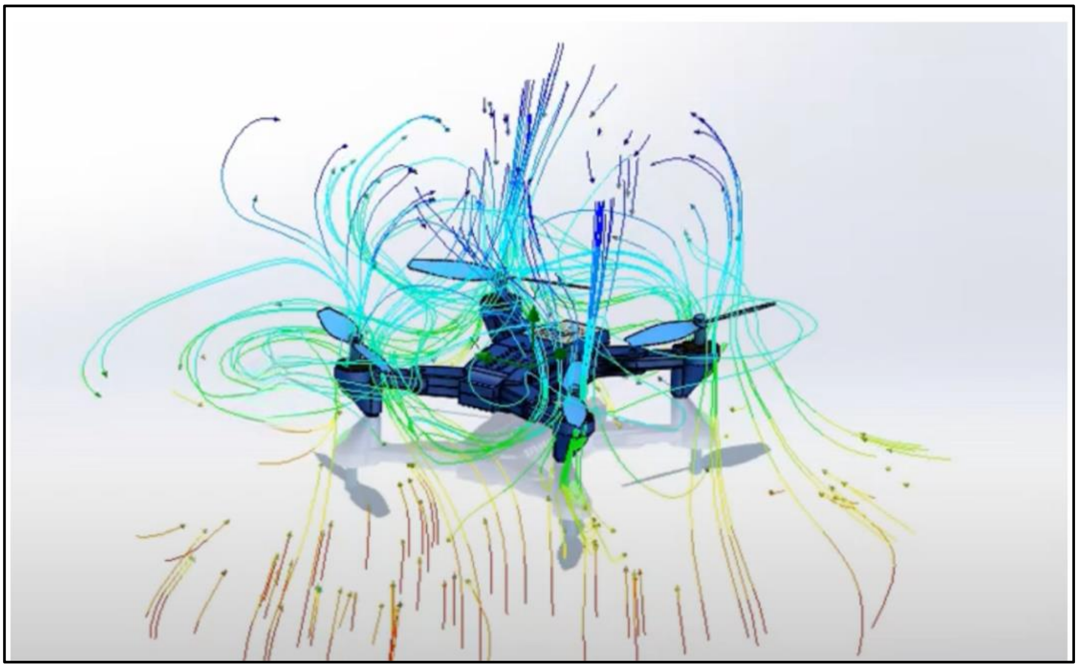
The arrangement of sensors was analyzed to ensure optimal performance. The LiDAR sensor's location at the bottom front is ideal for collecting 3D data of the surface beneath the drone, allowing for the identification of small structural defects. The AI camera, located on the right of the payload, provides a forward-facing view for defect detection and visual inspection. Complementing this, the thermal camera is positioned on the left, enabling the detection of heat signatures such as water intrusion or overheating components. Placing these cameras adjacent to one another facilitates the comparison of visual and thermal data for a more robust analysis.

Aerodynamic Analysis

Solidworks Flow Simulation was utilized to evaluate the drone's aerodynamics at 150 RPM. The simulation results, visualized in Figure 6 and Figure 7, illustrate the interaction of air with the structure. High-pressure regions (red and yellow) at the leading edges and upper propeller surfaces generate lift, while low-pressure regions (blue and green) on the underside contribute to the upward pull. Turbulence behind the motors indicates drag, and the downwash pattern confirms the stability required for hovering.

Figure 6

Solidworks Flow Simulation Test Results



Note. High-pressure regions (red) on the propeller surfaces indicate lift generation.

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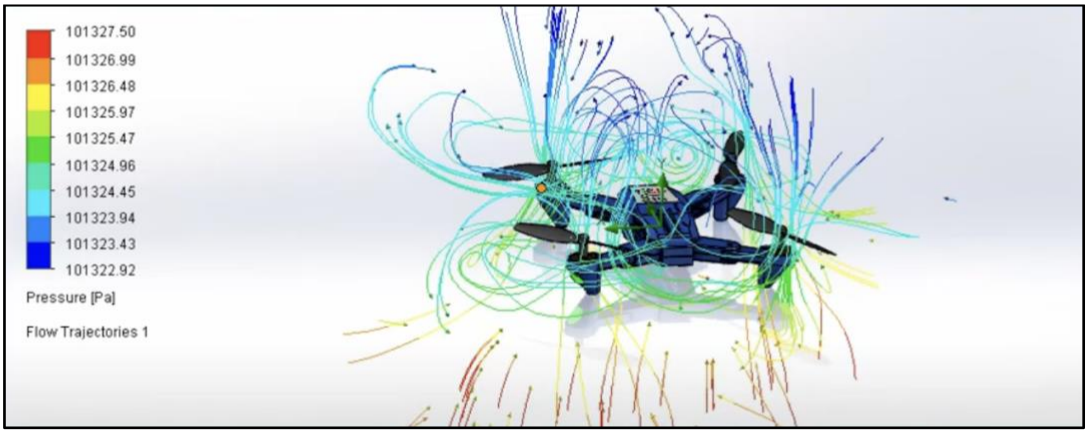
Figure 7

Solidworks Flow Simulation Test Results



Note. The velocity streamlines demonstrate the downwash effect and confirm that air turbulence around the sensor housing is minimized to maintain flight stability.

Methodology

The project methodology involves physical assembly, software integration, and rigorous testing in a controlled environment. The drone frame is assembled by 3D printing components based on the final CAD model, followed by the mounting and soldering of electronics. Software integration focuses on the flight controller firmware (e.g., Betaflight or ArduPilot) and communication protocols such as MAVLink.

Central to the system's novelty is a customized AI model trained on a database of structural damage. Unlike earlier versions relying on off-the-shelf sensors, this system utilizes a novel sensor fusion approach, combining thermal, LiDAR, and visual data to provide superior inspection detail (Preciado et al., 2024).

Testing follows a phased strategy. Individual components are tested independently, followed by controlled flights in open spaces to establish stability. Finally, a mock-up of an aircraft fuselage is used to validate the autonomous inspection capability. The system is evaluated against the project goals: achieving 95% defect detection accuracy and a 50% reduction in inspection time.

Conclusion and Future Work

This study presents a viable solution for autonomous aircraft maintenance, addressing safety hazards and inefficiencies in current practices. While the theoretical modeling and simulations confirm the system's potential, the next phase focuses on physical construction and experimental validation. Future work will include 3D printing the final prototype, integrating the Raspberry Pi with OpenCV for defect detection, and conducting bench tests followed by live inspection trials on a fuselage mock-up. Once verified, this multi-sensor system will serve as a step toward safer and more reliable air travel.

Acknowledgments

I would like to thank Dr. Nafiz Chowdhury of the University of Cambridge for his guidance on aerodynamic simulations and sensor integration. I also acknowledge the use of the GrabCAD community for open-source structural components (Jalalzad, 2025). No external funding was received for this research.

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