

Modeling and Simulation of a Border Surveillance UAV with a Low- Signature Quadcopter

A R Rumahis Yackoob Sharief¹, B H Sanchit², Chinna V³, Asst Professor R Ram Babu⁴

^{1,2,3}*Department of Electronics and Communication Engineering Atria Institute of Technology, Bengaluru, India.*

⁴*Asst Professor, Department of Electronics and Communication Engineering Atria Institute of Technology, Bengaluru, India.*

Abstract—This study presents the modeling and simulation of a low-signature unmanned aerial vehicle (UAV) designed for aerial surveillance applications. The work focuses on evaluating the vehicle's radar cross-section (RCS), flight stability, propulsion efficiency, and sensor integration through simulation-based analysis. The proposed design aims to investigate the relationship between UAV configuration and its detectability while maintaining stable flight characteristics and efficient operation. Modeling and simulation techniques are used to analyze the system's performance under defined operating conditions. The results are intended to provide insights into the design trade-offs associated with low-signature UAV development and to identify potential improvements in aerodynamic configuration, propulsion, and surveillance capability.

Index Terms—Unmanned Aerial Vehicle (UAV), Radar Cross-Section (RCS), Low-Signature Design, Aerial Surveillance, Modeling and Simulation, Flight Stability, Propulsion Efficiency.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are widely used in aerial surveillance due to their maneuverability, compact structure, and ability to carry imaging sensors. This project focuses on the modeling and simulation of a low-signature UAV, with emphasis on structural design, flight stability, propulsion efficiency, camera integration, and radar cross-section (RCS) analysis.

The UAV design incorporates a lightweight reinforced-plastic frame, appropriately selected motors and propellers, and a flight controller with sensor feedback to support stable flight. A LiPo

battery supplies power to the propulsion system and onboard electronics. The upper cover provides an enclosure for selected components, while the integrated camera supports image and video acquisition for human and object detection.

RCS analysis is used to evaluate the electromagnetic scattering characteristics of the UAV under specified frequencies and observation angles. The simulation results are intended to assess the relationship between the vehicle's configuration and radar signature, alongside its operational performance. The overall objective is to evaluate the design trade-offs between surveillance capability, flight efficiency, and radar signature.

II. PROBLEM STATEMENT

Conventional UAV designs may involve trade-offs between structural weight, flight stability, propulsion efficiency, surveillance capability, and radar detectability. This project addresses the need to model and simulate a UAV configuration that balances these factors through lightweight structural design, efficient propulsion, stable flight control, and camera integration. Radar cross-section (RCS) analysis is used to evaluate the UAV's radar-scattering characteristics under specified simulation conditions, while performance analysis helps identify potential design improvements.

III. LITERATURE REVIEW

- Guay et al. [1]: Studied the dynamic radar cross-section (RCS) of UAVs, highlighting the influence of observation angle and propeller motion on radar scattering.

- Pieraccini et al. [2]: Investigated RCS measurements and radar images of small UAVs to characterize their electromagnetic scattering behavior.
- Rosamilia et al. [5]: Analyzed measured UAV RCS data across different radar frequencies and azimuth angles to evaluate radar detection performance.
- Propulsion research [3]: Examined motor, propeller, and battery selection to understand their effects on thrust, power consumption, and flight endurance.
- Dutta [4]: Investigated multirotor UAV design considerations, focusing on robust performance under varying operating conditions.
- Research gap: These studies provide a foundation for UAV RCS characterization and multirotor performance analysis. The present project combines RCS simulation with UAV configuration and operational performance evaluation to study their relationship under specified conditions.

IV. AIM AND OBJECTIVES

Aim

To design and evaluate a surveillance UAV with a lightweight structure, integrated camera-based human and object detection, and simulated radar cross-section (RCS) analysis to study its flight-related design considerations and radar-scattering characteristics.

Objectives

- To develop a lightweight UAV structure with a suitable frame and protective upper enclosure using Blender for 3D modeling.
- To consider structural weight, propulsion efficiency, flight stability, and component placement in the overall drone design.
- To integrate a camera system for capturing images and videos for aerial surveillance.
- To implement YOLOv10 using Python for visual human and object detection from the camera feed.
- To model the drone enclosure in Blender and evaluate its radar cross-section using open EMS under defined simulation conditions.
- To analyze RCS variations with observation angle and assess the relationship between the UAV's

physical configuration and electromagnetic scattering.

- To evaluate the combined surveillance and simulation workflow and identify potential improvements to the UAV design.

V. METHODOLOGY

The proposed UAV development methodology consists of drone assembly, camera integration, visual object detection, three-dimensional modeling, and radar cross-section (RCS) simulation.

- A. UAV Design and Assembly: The UAV is constructed using a lightweight frame with motors, electronic speed controllers (ESCs), a flight controller, a LiPo battery, and a camera system. The components are integrated to support stable flight and aerial surveillance.
- B. Three-Dimensional Modeling: Blender is used to create the three-dimensional model of the drone enclosure. The model represents the external geometry required for visualization and subsequent electromagnetic analysis.
- C. Camera Integration and Object Detection: A camera provides the visual input for human and object detection. YOLOv10 is implemented using Python to process the camera feed and identify detectable objects in the captured images or video.
- D. RCS Simulation: The drone enclosure model is prepared for electromagnetic analysis using openEMS. The simulation evaluates the radar cross-section under specified radar frequencies, material properties, and observation angles to characterize the electromagnetic scattering response.
- E. Performance Analysis: The results from object detection and RCS simulation are analyzed separately. Detection performance is assessed using camera-based outputs, while RCS plots are examined to understand variations in radar scattering with observation angle. These results are used to identify potential improvements in the UAV configuration.

VI. RESULT AND DISCUSSION

The radar cross-section (RCS) of the UAV was analyzed using openEMS based on the three-dimensional model developed in Blender. The

simulation was performed at a frequency of 10 GHz, corresponding to the X-band radar range, using a Perfect Electric Conductor (PEC) material assumption.

The preliminary simulation produced an RCS value of -27.72 dBsm, equivalent to approximately 0.001692 m². The azimuth and elevation analyses were configured to investigate angular variations in radar scattering, while a frequency sweep from 9 to 11 GHz was used to study the frequency-dependent response of the UAV model.

The obtained result represents the simulated radar-scattering response under the selected conditions. However, the result should be considered preliminary because the imported STL geometry contained open boundaries and invalid polyhedron faces. Therefore, mesh correction, convergence testing, and further validation are required before the simulated RCS can be considered reliable format for importing into the openEMS simulation environment

A. UAV Modeling

The three-dimensional model of the UAV was developed using Blender. The model was prepared for electromagnetic analysis and exported in STL

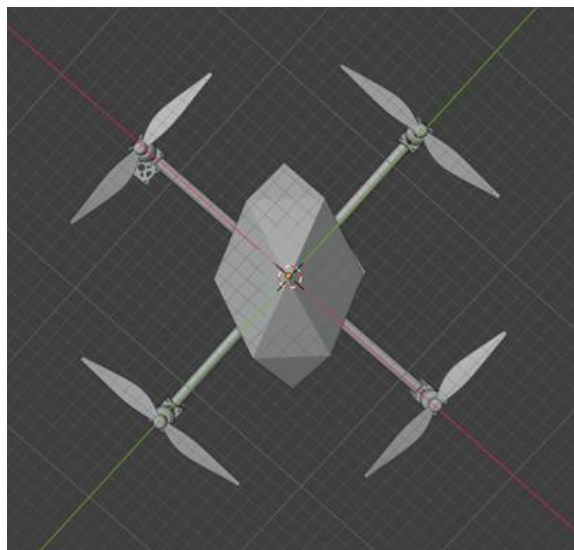


Fig. 1: Three-Dimensional Model of the UAV

B. Camera-Based Object Detection

A camera-based object detection system was developed using Python and YOLOv10 to identify objects from live camera footage. The system processes video frames and provides visual object detection for UAV surveillance applications.



Fig. 2: Camera-Based Object Detection Using YOLOv10

C. Radar Cross-Section Simulation

The UAV model was analyzed in openEMS using the FDTD method, with 10 GHz plane-wave excitation, PEC material assumptions, and NF2FF processing to estimate RCS. Azimuth and elevation variations were evaluated, along with frequency-dependent scattering across the 9–11 GHz range.



Figure 3.1 — UAV geometry

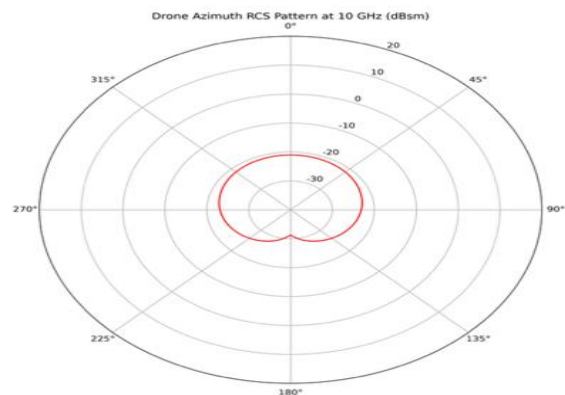


Figure 3.2 — Azimuth RCS

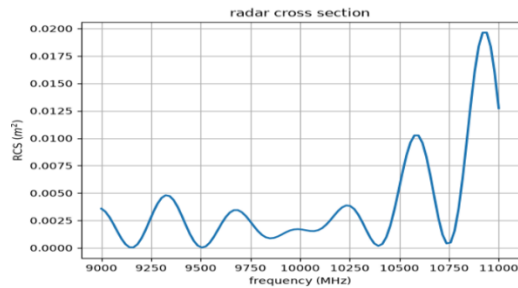


Fig. 3.3 — RCS versus frequency

VII. APPLICATIONS

- Border surveillance and security monitoring.
- Autonomous monitoring of remote and inaccessible regions.
- AI-based human and object detection.
- Aerial observation and real-time situational awareness.
- Radar cross-section analysis of UAV structures.
- Search and rescue operations.
- Environmental and disaster monitoring.
- Military and tactical surveillance.
- Infrastructure inspection and perimeter security.
- Remote sensing using unmanned aerial vehicles.

VIII. ADVANTAGES

- Compact and lightweight UAV construction.
- AI-based object detection using YOLOv10.
- Cost-effective modeling and simulation tools.
- Easy modification of the three-dimensional UAV model.
- Preliminary radar cross-section analysis at 10 GHz.
- Evaluation of RCS variations with angle and frequency.

X. CONCLUSION

The project presents the modeling and simulation of a UAV for surveillance applications, integrating YOLOv10-based object detection with radar cross-section (RCS) analysis using openEMS. The preliminary simulated RCS value was -27.72 dBsm at 10 GHz. Further work is required to correct the STL mesh, validate the simulation results, and improve the UAV design for reliable surveillance performance.

X. FUTURE SCOPE

- Developing lightweight UAV structures for improved flight performance.
- Optimizing UAV aerodynamic design for enhanced stability and maneuverability.
- Increasing UAV flight endurance through efficient propulsion and battery systems.
- Implementing autonomous take-off, landing, and navigation.
- Developing AI-enabled UAVs for autonomous aerial monitoring.
- Optimizing UAV structural design to reduce radar cross-section (RCS).

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