Development Of A Drone-Based Surveillance System For Monitoring Vessels Plying In Port Areas And Encroachment

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***Abstract*—**Our team has developed a drone-based surveillance system for vessels plying in port areas. The surveillance system will have a 24x7 bird's eye view for absolute situational awareness, vessel tracking & traffic monitoring, encroachment monitoring, maritime recon & surveillance, data collection, disaster management, and similar applications. Most ports have sprawling water and land areas where licenses are issued by the port authorities to marine vessels for plying within port limits. A cost-effective solution is required to track and report harbour crafts such as boats, barges and dinghies that ply in the port water limits and monitor encroachments in port limits. To achieve this, our solution involves two drones, 'Garuda' and 'Shikara', each defining a different tier, that work hand in hand to give us the optimum solution for the problem of monitoring such a large area round the clock with complete situational awareness. Each tier has dedicated functions like surveillance and first response. This paper describes the entire process of recognizing pain points, ideation for solution, designing the system and each subsystem, realizing the product, and testing along with results and analyses in utmost detail. Serving as a guide and documentation for future solutions, this paper aims to describe our developed system in a manner such that it will aid in the development of better solutions for this critical application.

***Keywords*—**aircraft, ardupilot, autonomous, autopilot, drone, maritime, pixhawk, port, reconnaissance, security, surveillance, UAS, UAV, VTOL

I. Introduction

Cochin Port, spanning across 2177 acres of land and water bodies, faces challenges in monitoring maritime activities within its limits. With licenses issued for vessels navigating within the port, an urgent need arises for a cost-effective solution. The primary concerns include tracking and reporting harbour crafts such as boats and barges, constant vigilance against encroachments within the port limits, and the implementation of a Management Information System to manage violators and encroachments. In response to these challenges, our innovative team has developed a cutting-edge drone-based surveillance system tailored for the Cochin Port. Named "Garuda" and "Shikara," these two drones work collaboratively to provide a 24x7 bird's eye view, ensuring absolute situational awareness. This comprehensive solution addresses issues ranging from vessel tracking and traffic monitoring to encroachment surveillance, maritime reconnaissance, data collection, and disaster management. Garuda" functions as the ultimate surveillance drone, while "Shikara" serves as the Rapid Action First Responder. Together, these drones are poised to empower the Cochin Port, effectively tackling the problems of encroachment and unmarked vessel tracking.

II. Literature Review

This research introduces a resilient drone-based surveillance system designed for maritime security in challenging port environments, specifically addressing adverse weather conditions. The study assesses the system's efficacy in ensuring uninterrupted surveillance during extreme weather events. By focusing on the system's ability to withstand and operate effectively in harsh weather, the research aims to provide insights into its reliability and performance, crucial factors in maintaining continuous monitoring and security in dynamic port settings [1].

This paper delves into the ethical dimensions of drone-based surveillance in port areas, with a particular focus on addressing privacy concerns. Investigating the delicate balance between surveillance efficacy and individual privacy, the study proposes and evaluates mechanisms dedicated to preserving privacy. The research aims to establish a framework that ensures effective monitoring of vessel activities while respecting and safeguarding the privacy rights of individuals within the surveilled port environment [2].

This research employs machine learning techniques to propose an anomaly detection system for early identification of potential encroachments within port limits. The system's effectiveness is evaluated through an assessment of accuracy and efficiency, aiming to provide timely detection, and reporting of encroachments. By leveraging advanced machine learning algorithms, the paper contributes to enhancing the overall security and surveillance capabilities of port environments, ensuring a proactive approach to addressing potential threats and maintaining the integrity of port boundaries [3].

This paper proposes an energy-efficient drone deployment strategy tailored for extensive port facilities, aiming to extend surveillance duration. The study systematically assesses the effectiveness of energy-saving measures incorporated into the drone system. By analysing the impact on overall efficiency, the research aims to provide insights into the optimization of surveillance capabilities while minimizing energy consumption. The findings contribute to the development of sustainable and enduring drone-based surveillance solutions for large-scale port environments [4].

This research centres on human-in-the-loop systems, introducing a decision support system that seamlessly integrates human intelligence with drone-based surveillance. The study evaluates the collaborative effectiveness achieved by combining the insights and decision-making capabilities of human operators with the efficiency and automation of surveillance technologies. This integration aims to enhance overall system performance, situational awareness, and response capabilities, providing a comprehensive assessment of the symbiotic relationship between human and automated elements in the context of port surveillance [5].

This study introduces a dynamic geofencing approach to enhance drone surveillance adaptability in port environments. It assesses the system's capability to dynamically adjust surveillance parameters in response to changing port dynamics. The proposed geofencing strategy aims to optimize coverage by intelligently adapting to evolving conditions, ensuring effective monitoring and response capabilities. The research explores the potential benefits of this dynamic approach in maintaining situational awareness and addressing the challenges posed by the ever-changing dynamics within port areas [6].

This research centres on cybersecurity, conducting thorough vulnerability assessment of drone-based port surveillance systems. The study is dedicated to proposing effective mitigation strategies with the overarching goal of fortifying the resilience of surveillance networks against potential cyber threats. By identifying vulnerabilities and implementing targeted countermeasures, the research aims to ensure the robustness and security of drone-based port surveillance, contributing to the safeguarding of critical maritime infrastructure against evolving cyber risks and unauthorized access [7].

This paper explores the application of drone swarming techniques for scalable surveillance in high-traffic port areas. The study delves into the advantages of employing coordinated drone swarms to efficiently monitor vessel activities. By leveraging the collective capabilities of multiple drones, the research aims to assess the effectiveness of this approach in enhancing surveillance coverage and response capabilities within bustling port environments [8].

This research introduces a pioneering solution to data security concerns in drone-based port surveillance by proposing a blockchain-enabled secure data storage system. The paper systematically evaluates the effectiveness of blockchain technology in safeguarding the integrity and confidentiality of surveillance data. By leveraging the decentralized and tamper-resistant nature of blockchain, the system aims to establish a robust foundation for storing sensitive information, ensuring that surveillance data remains secure and unaltered, thereby enhancing the overall reliability of port surveillance operations [9].

This study introduces augmented reality (AR) interfaces to enhance operator-centric drone surveillance in port environments. By overlaying digital information onto the real-world view, AR aims to boost operator efficiency and situational awareness. The research systematically evaluates the impact of AR integration, assessing its effectiveness in providing operators with real-time data, enhancing decision-making, and improving overall responsiveness in dynamic port scenarios. The findings contribute valuable insights into the practical applications of augmented reality for optimizing drone-based surveillance in maritime settings [10].

This paper delves into cutting-edge technology by introducing quantum-inspired computing for advanced analysis of surveillance data in port security. It meticulously assesses the potential advantages that quantum-inspired algorithms bring to the table, particularly in efficiently processing large volumes of surveillance data. By leveraging the unique properties of quantum-inspired computing, the study aims to revolutionize the analytical capabilities applied to port security, paving the way for more effective and expedient data processing in the context of surveillance and threat detection [11].

This research delves into the multifaceted application of drones beyond security, specifically focusing on environmental monitoring within port operations. The study critically assesses the pivotal role of drone-based surveillance in advancing sustainable practices and mitigating the environmental impact associated with port activities. By providing real-time data and insights, drones emerge as instrumental tools for enhancing the overall ecological footprint of ports, offering a proactive approach to balance industrial operations with environmental stewardship [12].

III. Ideation

A. *Inferring Design Objectives and Defining Solution*

The very first step was to understand the motivation behind the problem identified and the pain points that need to be addressed. Upon initial brainstorming, the crude requirements from the solution were listed to be the following:

1. Real-time tracking of vessels which have no form of electronic identification or tracking system onboard
2. Classification (ship / boat based on size)
3. Covering large areas with high cycle frequency
4. Need for control room setup
5. Environmental considerations
6. Cost efficiency
7. Defining geo-fences of restricted areas and changing detection algorithm accordingly
8. Land surveying solution

An exhaustive discussion between our team and various stakeholders yielded crucial understanding guiding the development of our solution. Let us discuss in brief the crust of the matter.

Firstly, it is important to be noted that the vessels to be tracked are smaller harbour vessels which typically do not have any form of electronic identification systems such as the Automatic Identification System (AIS) fitted on larger ships. This means that detection and tracking of vessels needs to be done visually or by scanning the surface. The most optimum solution for this scale and specification is using Computer Vision techniques. The same applies for encroachment monitoring. Encroachment can be monitored by visually scanning the Port area once and extracting geotagged features. Upon collection of sufficient features, encroachment can be detected by comparing features of every subsequent scan with the original features for that particular geotag and detecting features that have been added which were not there before.

The second point which was considered is the scale of operation and environmental conditions. To cover an area of 2177 acres and a sprawl of more than 5 km x 5 km, the developed system needs multiple long-range drones which can cover a large area fast and with high endurance. Along with this, the weather at the shore is rough, with high gusty winds and saline air necessitating excellent aircraft design and the use of composite materials and ingress protected components and outer shell. Moreover, operations should not stop due to nightfall or rain and thus we included a thermal imaging payload.

Lastly, for convenience and minimizing cost of operation, the drones are capable of Vertical Take-Off & Landing (VTOL) but shift to fixed wing operation later to offer high flight times of at least 3 hrs.

Thus, from the above discussion, we can now list properly defined objectives:

1. Computer Vision based detection and tracking
2. High endurance

3. Long-range operation
4. Selectable levels of autonomy
5. Weather-resistant
6. Resistant to turbulence
7. Cost optimized

Finally, with this backdrop, our team's solution involves 2 tiers of drones, called *Garuda* and *Shikara*. The first tier (Garuda) will fly higher and surveil the area, while the second tier (Shikara) will be dispatched only when any vessel or area detected by Garuda needs to be investigated closely. Both tiers have a switchable level of autonomy as per the mission's requirements.

Garuda, a quadplane configuration hybrid VTOL classifying as a DGCA small class UAV, flies at 400 feet above ground level and classifies any vessel that it detects as either a 'target vessel' or not depending on the vessel's size.

It then extracts and sends the data of all detected target vessels like location (coordinates), speed and direction of movement, timestamp, no. of passengers detected, and its images (zoomed, wide-angle and thermal) to the IMS hosted on the Ministry's secure server.

Next, if a target vessel needs to be inspected closely, then Shikara, a quadcopter classifying as a DGCA micro class UAV, flies to the location and follows the target from a very close range. Equipped with target tracking algorithms and obstacle avoidance systems it is more robust in capabilities with a time on target of approximately 20 minutes.

The flight path of Garud along with other operation settings are dynamic depending upon the time of the year, time of the day, security alert status, location of Vital Areas / Vital Points (VA/VPs) etc. for example, Garuda's operation modes include:

1. Manual control (Full manual)
2. Autonomous path planning with manual payload control
3. Waypoint path planning with manual payload control
4. Preprogrammed path and payload functioning
5. Fully autonomous – Individual drone level
6. Fully autonomous – swarm level:
    a. Scan only (no flagging, only tracking)
    b. Low threat (For use in low traffic / downtime periods)
    c. Routine operation (For regular periods)
    d. High threat (For use in security threat situations)
    e. Red alert (For use in extreme emergency situations)
    f. Lockdown (For use in complete lockdown situations)

These modes alter parameters such as:

1. Number of drones deployed at once
2. Operation times
3. Path planning
4. Payload functioning
5. Flagging style
6. Ground Control Station (GCS) functions
7. Access to System
8. Interaction with Shikara
9. Intercept types
10. Scanning types
11. Geofencing
12. No-go zones

Having defined the solution, the next step is to design the required system accordingly.

IV. Methodology

A. System Design

The capabilities of the system to be developed were defined. The designed system is described using the system architecture diagram in Fig. 1.

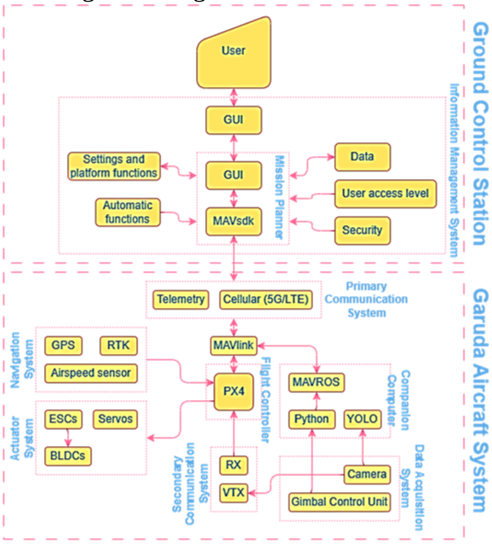

Fig. 1. System architecture

B. Aircraft Design

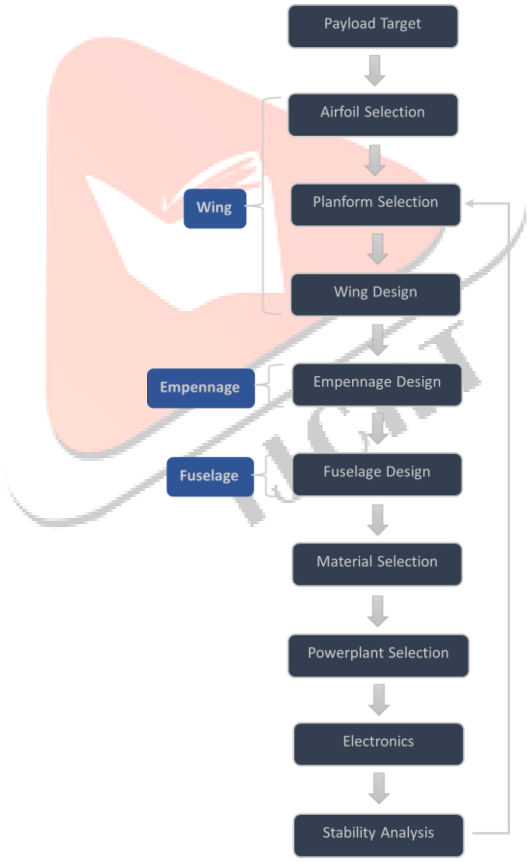

Fig. 2. Design flow

1) Airfoil Selection: Airfoil selection is a critical aspect of aircraft design as it directly affects the aerodynamic performance and efficiency of the aircraft. The choice of airfoil must consider a range of factors including the desired flight characteristics, speed range, lift and drag coefficients, and structural requirements. The designer must balance the trade-offs between performance and other factors such as stability and controllability to achieve an optimal solution. For the performance envelope required for our application, four high lifting airfoils were considered: Selig 1223 with Richard T. LaSalle modification (S1223RTL), Selig 1223 (S1223), NACA 2412 and the EPPLER 817 (e817).

Extensive computational and experimental analysis was conducted to evaluate the performance of different airfoil designs under various flight conditions, and the final selection is based on a combination of analysis results, experience, and engineering judgement. Following these principles, the airfoil with high lift, low speed and appropriate Reynolds numbers was chosen: the S1223-il.

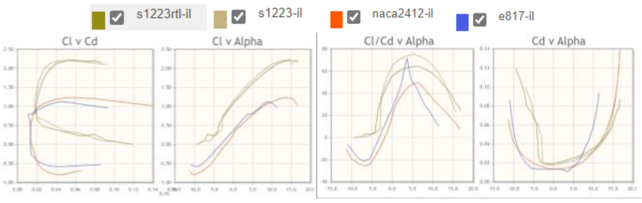

Fig. 3. Airfoil analysis

2) Wing Dimensioning: Before developing the wing, various factors like maximum lift, stability, and maximum lift to drag ratio were considered. These variables contribute to lowering drag, maximising lift, and thus enabling the plane to take heavy loads. Other aspects of the plane, including the aerodynamic centre, pitching moment, and stability, are significantly influenced by the size and orientation of the wing.

The dimensioning process started by defining a payload target, and the subsequent lift requirement. The lift of various wing forms is obtained using the formula:

$$F = \frac{1}{2}\rho A v^2 C_L$$

The minimum necessary lift force should be 60 N because the aircraft's targeted weight is 6 kg. According to the aerofoil charts, the S1223's C_L value is 1.75. Hence, after entering the necessary values, the wing area necessary is 0.65 m^2 according to calculations.

3) Planform Selection: The team investigated several planform designs including the rectangular, tapered, semi-tapered, Schumann and hybrid planforms to incorporate in the aircraft. Few of them were shortlisted and analysed based on lift, drag, efficiency, control, and overall ease of manufacturing. The requirements of the aircraft's flight envelope are dictated by the aerodynamic conditions to which it is subjected. This necessitates a robustness to high Reynolds numbers and turbulent airflows in gusty wind conditions. An aircraft with these qualities needs to have a planform which maintains stability and control even in near-stall conditions and avoids flow separation in critical positions on the wing. The planform was selected prioritising this condition and the primary objective of maximising lift (high C_L/C_D).

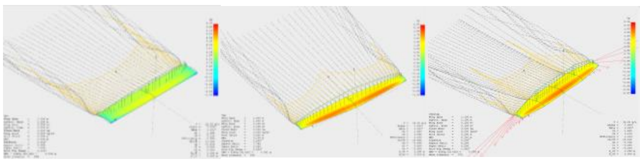

Fig. 4. Planform analysis

TABLE I. PLANFORM ANALYSIS

Planform		Rectangular	Semi-tapered	Tapered
Area		0.220 m^2	0.193 m^2	0.186 m^2
C_L/C_D	3°	15.159	16.952	19.807
	5°	13.541	15.028	17.576
	7°	12.252	13.518	15.824
Lift	3°	21.71 N	20.12 N	20.29 N
	5°	24.42 N	22.69 N	22.91 N
	7°	27.08 N	25.19 N	25.47 N

The semi-tapered and tapered planforms have a better C_L/C_D ratio but produce lesser lift. The changing chord also causes them to suffer from lower stability and unforgiving stall characteristics.

The rectangular wing stalls outward from the root, giving adequate stall warning, and maintains manageable aileron effectiveness. This makes it very stable despite the penalty of relatively high induced drag. Along with ideal stall characteristics, uniform pressure distribution improves the overall stability of the rectangular wing due to a near-neutral pitching behaviour. It is also the simplest to manufacture, which makes it least susceptible to manufacturing errors that otherwise increase the difference between predicted and actual performances.

Hence, the rectangular planform emerged to be the most suited for our design. Upon scaling the wing area to the value required for desired lift, the wing was finalised.

4) Wing design: The final design is a rectangular wing with polyhedral to improve roll stability. Ailerons are the only control surfaces present on the wing. Wingtip devices were explored but not incorporated due to the insignificant performance improvements obtained.

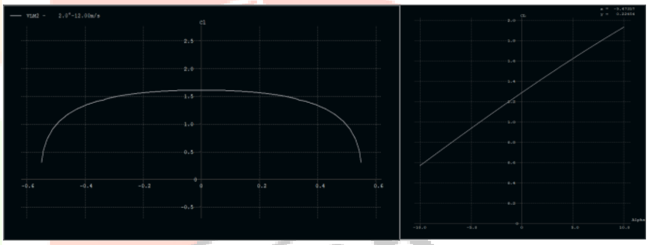

Fig. 5. Spanwise lift distribution & Cl vs. alpha plots

5) CFD Analysis: The 3D model of the wing was designed in SolidWorks and exported for analysis. After some finite set of iterations, the value of lift converged to 63 N and the value of drag to 2.5 N for the designed wing.

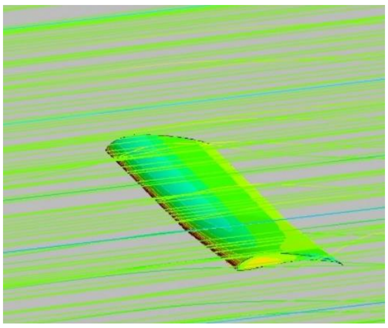

Fig. 6. CFD analysis of wing

6) Structure & Construction: The wings are structured with two main pultruded carbon fibre spars supporting expanded polypropylene (EPP) wing panel which was manufactured using CNC hot wire cutting technique. These panels were then coated with a clear layer of resin for structural benefits and superior surface quality.

Fig. 7. Wing structure

7) Empennage: The empennage provides longitudinal stability, directional control, and trim. The higher the value of tail volume, the more influence the empennage has on the behaviour of the aircraft. A very large tail volume can cause the aircraft to be extremely responsive and nimble, making it difficult to control, while a very small tail volume can result in a sluggish aircraft.

The team analysed various empennage configurations. The conventional tail was found to offer the best performance, but the team noticed that in the event of an actuator failure, the conventional tail offers no redundancy because the horizontal and vertical stabilizers have no component in each other's directions. This means that the rudder cannot influence the pitch of the aircraft in any way and the elevator cannot influence the yaw in any way.

In contrast, a V-tail offers two identical and symmetric control surfaces which each have components in pitch as well as yaw axes. Thus, in the case of failure of one, it is possible to maintain some control of both axes leading to a safe recovery.

Hence a V-tail configuration was selected. Upon analysing for stability, it was discovered that the V-tail did not offer sufficient surface area to provide longitudinal stability but was enough for manipulating the pitch axis. Thus, an innovative and novel solution was implemented. Two small stabilizers were attached to the empennage which did not have control surfaces and had no component in the vertical direction. The final Tail Volume was designed to be 0.61.

This novel solution was experimentally verified to work better than expected.

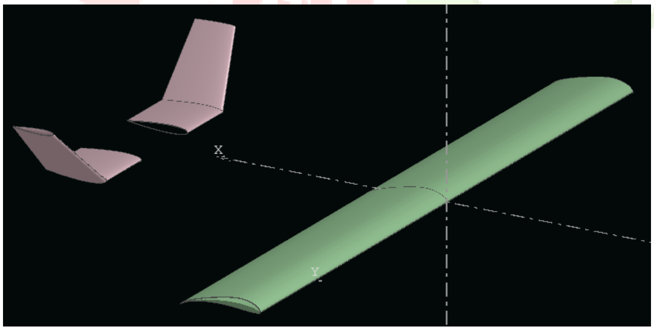

Fig. 8. Model in XFLR5 software

8) Fuselage: The fuselage has been constructed from Depron Foam coated with a layer of carbon fibre for strength. The fuselage has been developed according to the requirements of payload volume and placement. It is important for the fuselage to be as lightweight as possible while respecting aerodynamic preferences. This principle lies at the core of our fuselage design.

9) Drag Analysis: Drag analysis is an important part of understanding whether the aircraft is at its maximum efficiency. Using OpenVSP, we have calculated our total drag as 3.59 N, out of which induced drag accounts for 2.32 N and parasitic drag accounts for 1.27 N. OpenVSP was also used to calculate the parasitic drag produced by each component.

Fig. 9. Drag analysis in OpenVSP

10) Forward-Flight Powerplant: Being a VTOL, a lower thrust is required for flight since it does not have any specific launch thrust requirements. Thus, calculation of parameters yielded a thrust requirement of 40 N. To achieve this, we have chosen a KDE4012XF 400 kV BLDC motor from a reputed manufacturer due to its high power-to-weight ratio, efficiency, and reliability. Choosing a motor is one part, but propeller selection is the second half of the puzzle. A motor's full power can only be extracted from a suitable propeller. According to the manufacturer's documentation, a KDE Direct 15.5x5.3 Tri-blade propeller was chosen based on desirable performance characteristics. Both these together provide the thrust required for forward flight.

The chosen motor-propeller pair draws a maximum current of 30 A at full throttle. Thus, an electronic speed controller (ESC) of 120 A from a reputed manufacturer was selected based on research and experience.

11) Servo Motor Sizing: The size of the servo motor directly affects other servo system components, so accurate sizing of the motor is critical. Load, speed, and torque are the three factors to consider during this process. After rigorous analysis, the team selected the following specifications of servo motors based on the forces required to control the moments in the three axes.

TABLE II. SERVO SIZING

Sr. No.	Parameters	Ailerons	Rudder	Elevator
1.	Chord length of control surface (c)	0.07 m	0.045 m	0.05 m
2.	Length of control surface (l)	0.22 m	0.115 m	0.40 m
3.	Surface Angle (S)	30°	30°	30°
4.	Servo Angle (S')	25°	20°	20°
5.	Required Servo Torque (T)	0.19 Kg cm	0.04 Kg cm	0.09 Kg cm

12) VTOL Powerplant: Finding the thrust requirements for vertical take-off is an iterative and recursive process. Without previous experience, it is difficult to find an entry point into the design cycle. At the time of weight budgeting, a maximum weight of 1 kg was allocated to the VTOL subsystem based on experience. The all-up-weight (AUW) of the aircraft was budgeted to be 6 kg as described previously. Considering a thrust-to-weight ratio (T/W) of 1.5:1, which is a decent standard for VTOL hybrid aircrafts, we get a thrust requirement of 9 kg total i.e. 2.25 kg per motor (since we have 4 motors).

To achieve this, we selected 750 kV BLDC motors from a reputed manufacturer. Paired with 12x3.8SF multirotor propellers, the thrust target is met and surpassed marginally.

TABLE III. PROPELLER SELECTION

Sr. No.	Dimensions (inch)	Material	Current (A)	Thrust (Kg)	Power (W)
1.	13x6.5	APC	38	2.39	360
2.	12x6		42	2.54	
3.	12x3.8		30	2.32	
4.	13x8		32	2.08	

30 A optocoupled ESCs from a reputed manufacturer were selected for each motor based on experience to accommodate the current draw.

13) Mounts & Assembly Components: Parts were designed using CAD software for convenient and reliable assembly of the aircraft components. They were further validated for mechanical integrity under flight and operational loads using computational structural analyses. The parts were manufactured using additive manufacturing techniques for rapid prototyping. ABS was selected as the 3D printing filament material.

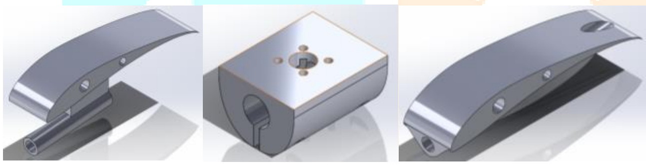
Fig. 10. Wing mount, VTOL motor mount, VTOL structure mount (L to R)

14) Stability analysis: To attain good longitudinal stability for an aircraft, a positive stability margin must be maintained. For this, the centre of gravity (CG) should be positioned ahead of the neutral point (NP). The location of the CG can be estimated by considering the weight of the components and their placement from a reference datum. After pluging in values and calculating, the CG was found to be at 0.267 m from the reference datum.

a) Aerodynamic Center: The aerodynamic centre (AC) is the point where the pitching moment does not vary with the Angle of Attack (AoA). The AC lies at about one-fourth of the root chord of the wing from the leading edge of the wing. It lies at 0.25 m from the reference datum.

b) Neutral Point: The neutral point of an aircraft is that point where the centre of gravity remains neutrally stable, and all pitching moments are constant. To achieve static stability the neutral point must be located aft of the centre of gravity. The neutral point location was determined using the below formula and verified by plotting the C_m vs. α curve for the location of the neutral point.

$$\frac{l_{np}}{\bar{c}} = \frac{C_m}{C_L}$$

Where, l_{np} is the distance of neutral point from CG, C_m is the moment coefficient of aircraft, and C_L is the lift coefficient of the wing.

Following calculations, the position of neutral point of this aircraft is at 0.297 m from the reference datum. Thus, it is confirmed that the aircraft is stable since the CG is placed forward of the NP.

c) Static Stability Margin: The static stability margin (SSM) is a good measure of the 'hands-off' stability of an aircraft. The greater the SSM, the more stable the aircraft, but it becomes equally difficult to manoeuvre due to additional robustness to external disturbances.

$$SSM = \frac{X_{NP} - X_{CG}}{MAC_{Wing}}$$

Hence based on research and experience, the team targeted an SSM of 15.6% to achieve desired flight characteristics. From the SSM value, we can determine the CG location to be 0.267 m from the reference datum.

d) Static Stability Analysis: The concept of static stability analyses situations where some momentary disturbance deflects the aircraft along some axis and defines the nature of the aircraft's response to this disturbance. The placement of points such as NP, CG and aerodynamic centre determine the longitudinal stability of an aircraft.

The ideal response of a stable aircraft upon deflection in its pitch is to generate a net moment which opposes the direction of disturbance. This means that the C_m should have positive values for negative AoAs and vice versa. Upon several iterations of the tail surfaces and placement of inertias, the team achieved an ideal C_m vs. α graph.

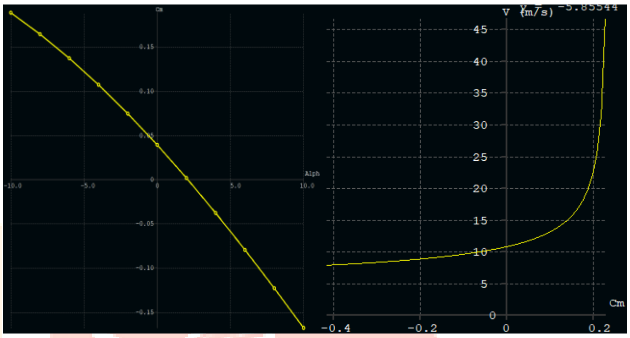
Fig. 11. Static stability analysis

e) Dynamic Stability Analysis: While the static stability analyses the nature of response to disturbances, the dynamic stability deals with the magnitude of response over time to these disturbances. This reveals whether the aircraft will return to level flight after a deflection and the amount of time required to stabilize.

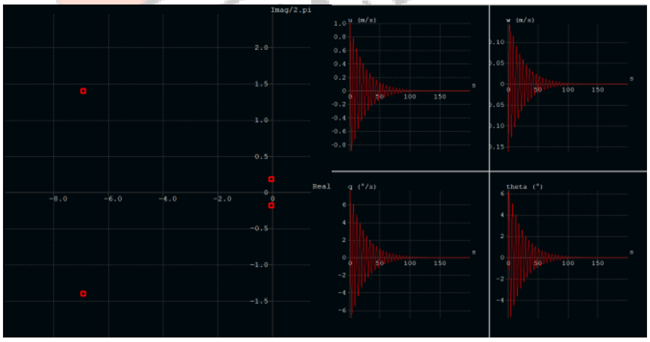
Fig. 12. Dynamic stability analysis

This is quantized using the concept of natural modes. Each mode is defined by an eigenvector, which describes the modal shape, and an eigenvalue, which describes the mode's frequency and damping.

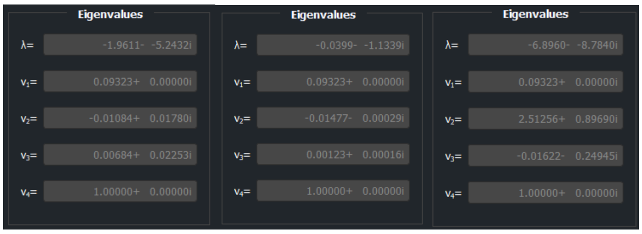

Fig. 13. Eigenvalues of different modes

As illustrated, the design achieved desired stability behaviours. This ensures superior flight characteristics leading to better control and ability to fly reliably in turbulent environments.

15) Flight Control System: The flight control system enables the VTOL functionality (quadcopter control), transitioning from VTOL to forward flight and vice versa, and the autonomous controlled flight in forward flight operation. It is the system responsible for receiving positional and attitude data from various sensors, calculating flight parameters, and controlling the actuators to maintain stable flight while performing the desired function of the mission. The flight control system implemented uses the Cube+ Orange flight controller with its ADS-B carrier board running ArduPlane firmware. This ecosystem uses the Here Pro GNSS+RTK positioning system for geolocation, an Optical Flow module consisting of a downward facing camera and wide-beam LiDAR for localising fine movements along with a digital differential airspeed sensor for forward flight dynamics. Flight control can also be shifted from autonomous to manual flight, in which case, an 868 MHz radio telemetry system is implemented from a reputed manufacturer which will relay control signals. The system provides connectivity in nearly a 10 to 15 km radius.

a) Flight Controller: Cube Orange+ ADS-B Standard Set used. Cube Orange+ runs Ardupilot open source software. Hardware is patented. Features STM32H757 with 2 MB flash and 1 MB RAM, ICM 20649 30G integrated accelerometer / gyro, MS5611 barometer, all connected via SPI. Details can be found in their official documentation at [13].

b) GPS (RTK): Here Pro Base & Rover modules used.

c) Optical Flow: A combination of LiDAR and a low resolution downward facing camera used.

C. Payload System Selection

The primary function of the designed aircraft is to collect data. The data is primarily in the form of video, audio, and pictures in visible as well as thermal spectrums, geotags of identified objects, textual data like distance from target, timestamps, and aircraft / zone identification of whatever kind needed.

This tells us that we need a high-resolution visible camera of variable field of views, a thermal camera of suitable temperature range, field of view, range of accuracy, and resolution, a laser rangefinder of appropriate sensing range, and a visible wide-angle camera with a decent resolution to be able to keep situational awareness. From this inference, the team chose two payloads:

1. Primary payload:
   a. 1x 4K 8MP 30X optical zoom visible spectrum camera
   b. 1x 88º FoV 4MP wide-angle visible spectrum camera
   c. 1x 8 to 14 um, -20 ºC to +550 ºC thermal imaging camera
   d. 1x 5 to 1200 m laser rangefinder
2. Secondary payload:
   a. Downward facing 88º FoV 4MP wide-angle visible spectrum camera

The primary payload is mounted on an aluminium CF composite frame gimbal with brushless motors in IP4X packaging while the secondary payload is mounted in the interior with a window in the belly of the aircraft.

The video is streamed in H.265 codec at 15 Mbps stored in a FAT32 file system in MP4 format while images are stored in JPG format. The camera interfaces with the companion computer via ethernet and the flight controller through UART.

The heavy video streams generated by the payloads dictate the video transmission to be done over cellular network using 5G. As a backup, the video stream from the primary wide-angle camera is also fed to a double redundant FPV radio link, one via analog 5.8 GHz, and another via digital 2.4 GHz.

D. Communication Systems & Telemmetry

There are 3 broad types of data being communicated to and from the aircraft to various points on the ground and each requires a dedicated communication system: aircraft control link, aircraft flight data telemetry, and data relay for the data collected by the payload and generated by the onboard companion computer. Each of these must be isolated from each other for very thoughtful reasons.

The aircraft control link is the very link that controls the fight of the aircraft and is the most crucial link of all in terms of safety. Arguably, it is not required in case of autonomous flight, but it is still good practice to always be ready to take manual control of the aircraft in case of a failure. This link must always be given priority with the most reliable connection. In our system, we have utilized 868 MHz and 2.4 GHz ELRS as our most reliable radio links for backup aircraft control.

The next most important link is the aircraft flight data telemetry link which relays data about the functioning of individual subsystems of the aircraft. This link is what controls the flight modes of the aircraft as well as relays direct data of the aircraft health parameters and raw sensor values. This link can keep the aircraft in the air until you safely land in case of a failure of the high bandwidth primary link. We have used open source mLRS over 868 MHz running in tandem with the control link for telemetry. In case of failure, the priority shifts to flight telemetry first since control can also be achieved over flight telemetry, but if that fails too, it shifts to ELRS.

Finally, the primary link over which the payload video stream as well as target detection data is communicated is the high bandwidth data link. This link is the primary communication link of the aircraft which supports the payload data as well as telemetry and control when operating properly (in any autopilot assisted flight mode). This is implemented via 5G network in our system.

E. Detection & Decision Algorithms

The objectives of the aircraft require autonomous detection of vessels, classification of vessels into target or non-target, extraction of required data from target vessels, and implementation of some logic for decision making based on predetermined parameters.

1) Vessel Detection: The YOLO models are great at detection of objects in chaotic environments without pretrained parameters. Due to this, we have used the YOLO v5 model to detect vessels with a trained data set of around 50,000 images.

2) Vessel Classification: The classification is done based on distance from the detected vessel and size estimation performed on the basis of real size estimated from percieved size (algorithm described ahead). If vessel is smaller than threshold, then it is flagged as target vessel.

3) Target Data Extraction: If vessel is classified as target type, then the first step performed is location estimation. Using the drone's GPS location and the orientation of the gimbal, we can estimate the facing of the camera. After this, using the bounding box drawn around the target vessel by the YOLO model, we can calculate the position of the centroid of the box inside the camera frame. On a properly calibrated camera, this information is sufficient to give us the angles of deviation along all 3 axes from the camera facing. Thus we now have the angles of deviation from the aircraft's heading and the direction of the vector from the aircraft to the vessel. Using simple geometry we can calculate the ground distance from the aircraft's GPS coordinates to the vessel, thus giving us the coordinates of the vessel. Now these coordinates along with the other required information like timestamps, thermal temperature, etc. are printed on the frame.

4) Decision-Making Logic: Depending on the current flight mode and functional settings, the data will either be accompanied by a slight alarm or relaying the data to Shikara tier drones for immediate dispatch along with sending the data to the information management system (IMS). The specific response logic is best customized as per requirements.

V. Results & Discussion

To test such a system requires deployment of at least one of each tier of drones and operating this system at some large enough water body. Naturally, this would be the last of a series of tests run after a system function test round, integration tests, simulations, and gradual escalation of stakes to match real life use case. For an unfunded student project like ours, this was highly impractical. As a result, we came up with our own methods and ideas for testing to the best extent possible.

Each subsystem was tested separately either in simulation or in a suitable testing environment. As much real-world testing was performed as possible giving it highest priority in aspects where interactions involving the unpredictability of the real-world determined effectiveness.

The aircraft was tested for flight worthiness on the ground before conducting aerial tests for performance parameters. The aircraft used for tests was a slightly scaled down version of the same design retaining all the important characteristics of the full-scale design and manufactured using more affordable materials keeping originality wherever possible. The only motivation behind this slight change was to reduce the prototyping cost to a more affordable range. Through these, the functioning of flight control system, flight telemetry links, navigation, sensor operations, VTOL stabilization, etc. were also tested.

Computer vision and image processing subsystem was tested without integration by running the algorithm on a Raspberry Pi connected to a PC and transferring a video stream of aerial footage of a port and giving predefined parameters like GPS coordinates and camera calibration parameters for calculating the coordinates of targets.

The data generated by the computer vision subsystem was streamed to a cloud server hosted on another PC via 5G dongle connected to both PCs. The server hosted a make-shift IMS with basic functionality like a database for storage of these data and parameters and a custom modification of the Mission Planner software as a web application for universal access. Although not practical, it served the purpose of testing and providing proof of concept satisfactorily.

The operation of the Shikara drone being unclear and customisable according to the end user, was not tested. The system which invokes the Shikara drone to arm and take off to automatically specified coordinated according to target detected was tested as part of the IMS operational logic.

From these tests, we can conclude that the aircraft flight characteristics and performance parameters were satisfactorily met as described in Table IV.

TABLE IV. Results Table

Stall speed	Cruise speed	Max speed
55 km/h	80 km/h	128 km/h
Max current	Max power	Tested climb capacity
78 A	1227.8 W	1500 m
Electric power	Mechanical power	Revolutions
1164 W	950 W	11024 rpm
Tested endurance	Calculated aircraft range	Tested link range
74 min	98 km in cruise	10 km

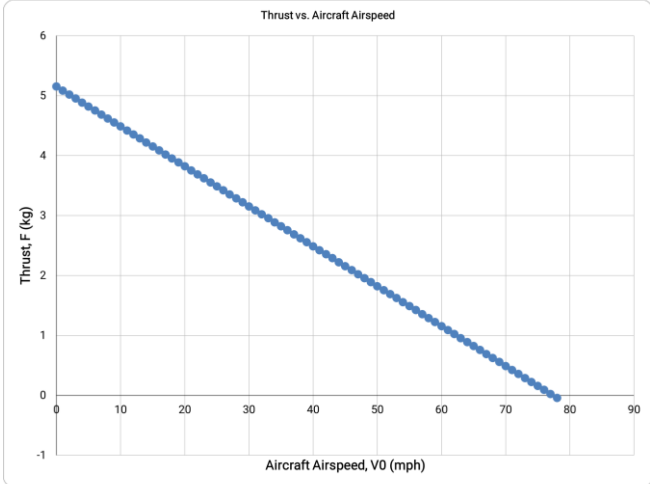

Fig. 14. Dynamic thrust

The computer vision subsystem was able to detect every vessel within one second of appearance inside frame. Classification of vessels gave perfect results as far as human verification was possible. Each vessel logged necessary data in the database and coordinates were printed inside bounding box. Accuracy of detected coordinates could not be verified due to simulated nature of tests.

Fig. 15. Detected vessel with bounding box and coordinates

The IMS database functioned perfectly with slight lags introduced by the 5G network. The logic for deployment of the Shikara drone was also tested by flagging some target vessels in the database tables and triggering a call to the Shikara deployer node on ROS.

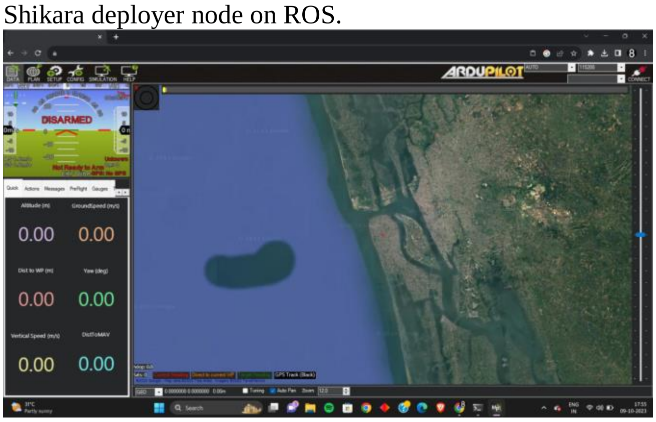

Fig. 16. GUI

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