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Development of a Cost-Effective UAV for Extended Duration Disaster Management Operations using Expanded Polystyrene

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ABSTRACT

Commercial UAVs specifically developed for disaster management purposes are frequently priced at an exorbitant level. Usually, unmanned aerial vehicles (UAVs) have a flight length of 15-30 minutes. However, crisis management operations often demand longer mission durations, occasionally in difficult weather circumstances. In order to tackle this problem, Expanded Polystyrene (EPS) was selected as the material for the body and wings of the UAV due to its cost-effectiveness in comparison to materials such as fiberglass, carbon fibre, epoxy, Kevlar, and wooden balsa. The EPS material utilized exhibits a tensile strength of 88 pounds per square inch (psi). For flight testing, a LiPo 3S battery with a voltage of 11.1 volts was used in the UAV. The virtual wind tunnel test was carried out with precise parameters, including an air density of 1.225 kg/m³ and a wind speed of 50 m/s. In order to improve the wing's structural integrity, a lightweight aluminium bar was incorporated. The initial design of the UAV wing showcased an elongated glider-like structure, enabling prolonged flight durations using a solitary propeller. The simulation findings showed that the UAV successfully controlled the drag coefficient with time, maintaining a traction force of 200N during testing. The UAV's capacity to endure gusts of up to 70 knots, achieve elevations of 5000 feet, and travel lengths of up to 90 km was demonstrated in practical trials, contingent upon the control systems employed. Ultimately, the newly designed UAV has the capability to sustain flight for a duration of 8 hours, thereby overcoming the constraints typically encountered with commercial UAVs employed in disaster management.

1. Introduction

Floods are a common natural disaster in Malaysia that occur practically annually during the monsoon season, which in the East Coast states runs from October to December and in the West Coast states from January to March. A flood disaster on December 17, 2014, forced 200,000 people to flee their homes in the states of Terengganu and Kelantan. Most businesses were impacted by the

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disruptions to train services and transportation infrastructure that occurred along the East Coast. Planning and preparedness are essential for disaster management and flood control to reduce damage. The two main tasks of disaster management are identifying possible disaster locations and giving victims the critical support that they require [1-3].

Helicopters play a key role in identifying disaster areas, assessing community damage, and suggesting emergency aid strategies. However, their flights carry risks for both pilots and the populations below. A pertinent example occurred on December 31, 2014, when a Royal Malaysia Police helicopter crashed in Kelantan during a flood-related patrol, resulting in injuries to four crew members [4]. Additionally, the operational costs of helicopter flights are notably high. The UAV has a low operating cost, much lower than crewed aircraft and can access the areas where helicopters cannot fly. There are many benefits to gain by replacing the pilot with an automated system.

In recent years, UAVs have been a proven tool for effective disaster management in many countries. Aerial survey by UAV can work as a tool in disaster management by taking aerial photographs or capturing a live video; whereby the extent of the disaster can be identified and digitized to high level of precision and accuracy. Flying over the disaster area of altitude between 20-2000 m, aerial survey by the UAV can be effectively employed for disaster control and management [5-7]. The UAV can be launched from anywhere, fast and is able to be operated in narrow weather windows. The use of narrow air space can be accessed from anywhere to assist in various operations [8-10].

Having prior information about the disaster before any rescue team departure helps reduce the risks, selecting appropriate equipment to carry out and determining the required members for security and rescue purposes. The UAV is a security unit that can be deployed when the alert is received. It travels to the coordinates of the problematic area and can provide live video feeds of the situation. This information helps the authority to make important decisions and allows for monitoring a rescue mission. With the UAV ready in a few locations near the disaster site, the rescue team can attain visual images of the disaster at the coordinates as close as possible to the area [11-13].

Live video feeds from disaster areas can be provided within minutes of emergency calls. In addition, if the location of the disaster cannot be established, the UAV autonomy can study the area and locate the victims [8]. Rescue teams can send significant assistance to them like dry food, water or a first aid kit. Even though monitoring can be conducted by a helicopter, it uses a significant amount of fuel which makes it rather expensive. In addition, the helicopter size is bigger than the UAV; thus, it cannot hover in narrow space. Furthermore, if any accident happens much more money is lost. In contrast, electric powered UAVs consumes deficient power, are inexpensive and can hover in tiny space as it is small. Therefore, it is more efficient, cost-effective, and environmentally friendly [12,14].

This research provides insights into the efficacy of Expanded Polystyrene, a groundbreaking material, in crafting an economical Unmanned Aerial Vehicle (UAV). Expanded Polystyrene's performance is meticulously evaluated against current UAV materials such as balsa, carbon fibre, aluminium, light fly, and Styrofoam. The study delves into various aspects like durability, weight, cost, and aerodynamic efficiency, offering a comprehensive comparison. It also considers the environmental impact and ease of manufacturing associated with each material. This comparison is crucial in determining the viability of Expanded Polystyrene as a superior alternative for UAV construction, potentially revolutionizing the UAV industry by balancing cost-efficiency with performance.

2. Methodology
2.1 UAV Definition and Design Options

A study was conducted using competitor data. Performance parameters, design options, and geometry were used to start design investigations [15,16]. A starting point for designing a UAV with established price and research features has been obtained. Three elements outlined in Table 1, encompassing performance parameters and design options, contribute to the execution of design studies [17].

Table 1
Feature price levels of feature for unmanned aircraft

FEATURE	USD 5000 (Basic Response)	USD 50,000 (Advanced Response)	USD 500,000 (Top Response)
Flight time	10 – 20 min	20 – 60 min	2 – 5 hr.
Flight distance	500 m	1 – 3 km	2 – 80 km
Flight speed	slow	slow – medium	medium
Take off	manual	manual	manual/system
Landing	belly	belly/system	system

2.2 Design and Manufacturing Phases

The concept design phase involves creating flexible designs that meet performance requirements. If successful, the initial design phase is initiated. The preliminary design phase involves structural, aerodynamic, and control system analysis, with wind tunnel testing. The design process is divided into three main parts: concept, development, and detailed design. The concept phase involves drawing the aircraft’s layout, shape, size, weight, and performance [18,19]. The development phase improves the aircraft's manufacturing, preservation, cost, and efficiency, resulting in a balanced design. The detailed design phase is completed when the aircraft is finalized. For the aerodynamic estimations, the SolidWorks CAD software was used. The software provides a reliable flow simulation, calculating rates and budgets for appropriate aircraft implementation. Key parameters include drag rate, lift rate, velocity and pressure on surfaces and flow trajectories. These parameters are measured under the worst conditions the aircraft should face, such as air velocity of 150 m/s, a Mach number of < 0.8, pressure of 101325 Pa, and density of 0.8575 kg/m3.

2.3 Fuselage Aerodynamic

The fuselage, a hollow tube, is designed to reduce weight and generate drag types such as profile drag, compressibility drags, and induced drag as shown in Figure 1. It contributes to induced drag primarily because its adverse effect on wings spans load distribution. Fuselage design involves careful consideration of various factors, including low aerodynamic drag, stability, passenger comfort, emergency safety, efficient cargo handling, structural support for wings and tails, weight-saving structural optimization, flight deck optimization for reduce pilot workload, convenience, noise minimization, climate control and accommodation of various sub-systems [18].

The primary purpose of the fuselage is to place the UAV system and payload, ensuring low drag. The final drag of the fuselage falls in the glider plane category, where all ways to reduce, drag are used to the maximum extent possible. The aerodynamic analysis method applied to a symmetrical fuselage can be applied to analyse the corresponding fuselage up to the zero-lift angle of attack.

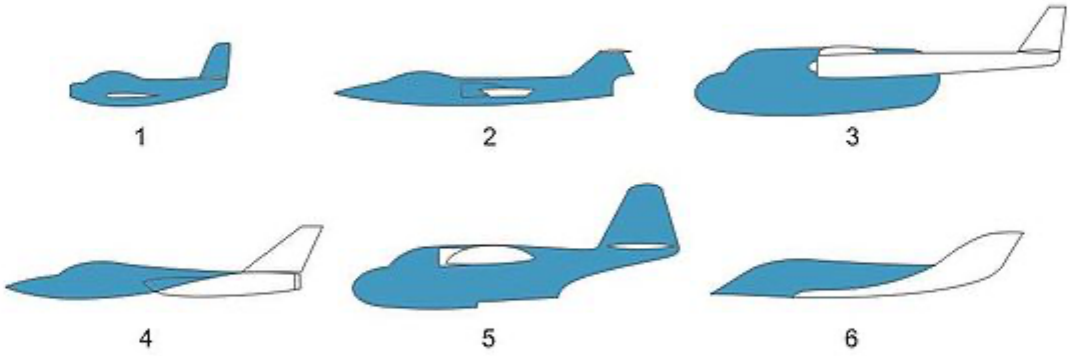

Fig. 1. Fuselage Shape [18]

The first design version of the fuselage can be seen in Figure 2. The shape of the fuselage was defined with charges in shape to be as smooth as possible. In the first concept sketch, the payload bay is embedded to the wing structure, to maximally the frontal area of the fuselage.

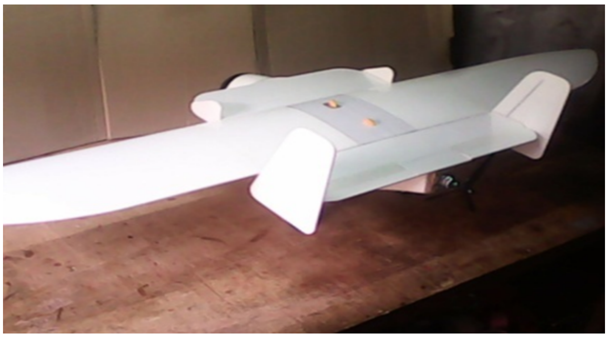

Fig. 2. Fuselage First Design

Due to the structural design difficulties of the wing to fuselage attachment node arising from the embedded payload bay, it was decided to simplify this construction node by moving the payload bay above the wing structure. The new fuselage concept can be viewed in Figure 3.

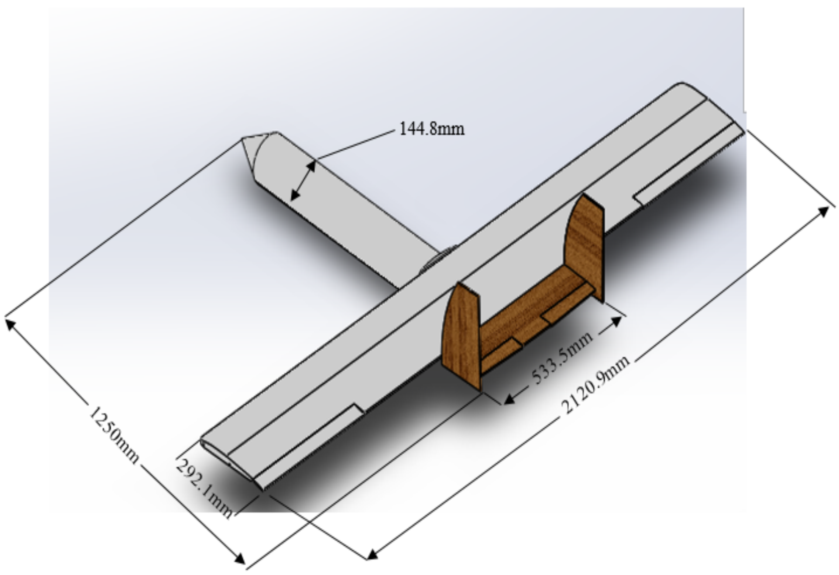

Fig. 3. New Fuselage Design using SolidWorks

Most aerodynamics design parameters are interrelated in the aircraft conceptual design process. It is not easy to find the best methodology for each type of aircraft. Considering the battery's energy density and weight of structural materials, the critical challenge in reducing production costs and achieving design goals is to optimize the efficient use of battery energy Re-evaluation of design model design and recalculation of parameters required to implement new UAVs design. The coefficient of drag zero lift aircraft and the drag-up factor is selected as the parameter for the custom design procedure to be implemented. New fuselage concept could be viewed in Figure 3.

The UAV shown in Figure 3 fulfils size and payload requirements. It has many advantages as fuselage:

i. First, the UAV has simple flying wings shape with few appendages to break or suffer damage in a crash.
ii. Second, it has soft leading edges, which absorb impact energy protecting the aircraft and payload.
iii. Third, it is exceptionally lightweight, weighing only 1 kg.
iv. Fourth, its flying wing design has plenty of room for avionics and antennas installations.

The UAV fuselage is a remote-controlled airplane whereby its radio receiver has been replaced by Ardupilot module. One of its advantages is the wingspan with 2120.9 mm (83 ½inches) length, 292.1 mm width and powerful electric motors (1 kW) which enables top speed of 80 km/h at a mass of 1.5 kg show in Figure 3. Its payload capability is around 2 kg which is sufficient to house electronics and sensor delivery systems including microsensors (which have negligible mass). The autopilot code was modified to enable more firm take-offs and landings (the airplane is not hand launched and must land on a road section).

2.4 Fixed Wing UAV

The deployable UAVs come in various wing styles, including rigid, inflatable, and membrane wings. Lifting mechanisms include fixed, rotary, and flapping wings. A rotary wing is preferred for higher flight speeds, while flapping is better for lower speeds. Fixed wing UAVs offer increased flight time and range. The Pegasus fixed wing UAV system is a durable system for remote sensing. Research focuses on applications using rotating and fixed-wing UAVs for natural resource management, crop map generation, vegetation monitoring, hyperspectral image classification, and agriculture accuracy.

2.5 Low-Cost System

Low-cost drones, like powerful paragliders, are fixed UAV alternatives for individual applications. The UAV frame is mounted on a paraglider, ensuring stable flight and high security in case of motor failure. The platform allows for sensor installation and remote image acquisition, determined by a low-cost GPS system [10,20]. The material analysis is essential before it is used to build unmanned aerial vehicles. Aluminium is an abundant low-cost material, with the characteristic of constructing UAVs. Figure 4 shows the material analysis to build unmanned aerial vehicles.

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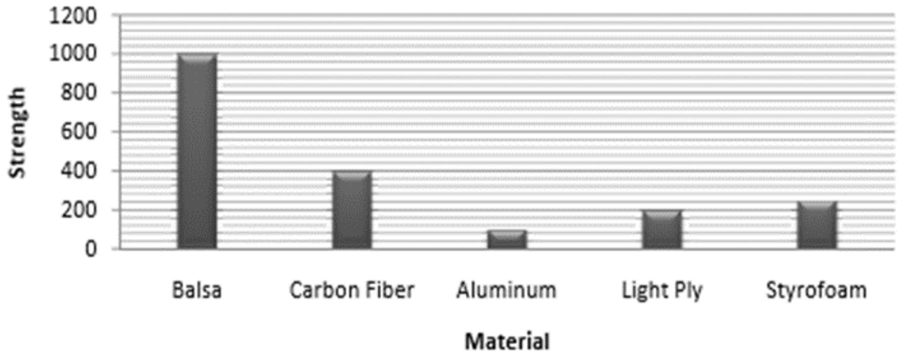


Fig. 4. Material Analysis

Expanded Polystyrene (EPS) foam is a versatile material with excellent mechanical and physical properties, making it ideal for construction applications. Its typical properties are shown in Figure 5, and it is the best material for UAVs due to its cost-effectiveness. The density of EPS is 3.0, making it the most cost-effective option.

Density (pcf)	Stress @ 10% Compression (psi)	Flexural Strength (psi)	Tensile Strength (psi)	Shear Strength (psi)
1.0	13	29	31	31
1.5	24	43	51	53
2.0	30	58	62	70
2.5	42	75	74	92
3.0	64	88	88	118
3.3	67	105	98	140
4.0	80	125	108	175

Fig. 5. Typical Properties of EPS Moulded Packaging (70 F Test Temperature) [21]

3. Results and Discussion

3.1 Mission Characteristics

The system aims to predict potential issues caused by malfunctions, accidents, and users to minimize harm. The system includes a take-off, climb, cruise, high speed, descent, and landing phases. Figure 6 illustrates the mission duration is 1 s, with an estimated time of 10 min to reach 1000m above the track. The cruise phase involves monitoring and data recording tasks, with an endurance of 8 hr. High speed is optional and may occur in some operations. Depending on the descent speed, the descent phase involves losing altitude and a duration of 29 min. The landing phase includes the final approach and touches down.

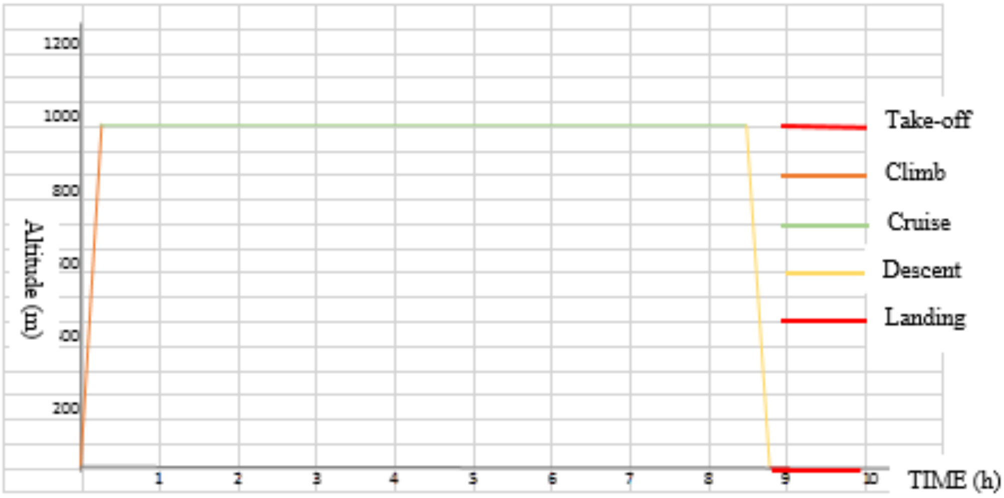


Fig. 6. Mission of UAV

3.2 Fuselage Design

The fuselage is a crucial and challenging design for aircrafts, ensuring sufficient weight, strong wind resistance, and reduced drag for durability and safety. It is designed for structure, payload distribution (CG consideration), and aerodynamics. The fuselage remains designed with materials not affected by radio waves so that the antenna can be installed and protected. Internal antenna configuration can make the surface smoother fuselage and thus reduce drag and damage to the antenna. The wing to the fuselage is vital because this is the part where the wings will be installed on the fuselage. The wings must withstand wing lift and take off, descent, and converts the power during flight missions. The load distribution in the fuselage affects the CG position along the fuselage and vertical axis, crucial for longitudinal stability. UAV has a longer distance between CG and AC points on the vertical axis due to its propulsion system location.

The fluid flow analysis of the UAV fuselage was simulated using inlet and outlet details in a stable environment. Results in Figure 7 showed pressure counter and velocity streamlines for inflow speed of 50m/s and air density of 1.225 kg/m3, as well as for the UAV fuselage. The presented results align with Bernoulli's principle, showcasing distinct characteristics. The velocity contours highlight a low-velocity region on the lower side of the fuselage and a higher-velocity acceleration region on the upper side. This distribution is crucial for understanding the aerodynamic behaviour of the UAV during flight. The observed low-velocity region on the lower side may indicate areas of potential drag or turbulence, influencing the overall efficiency and stability of the UAV. Conversely, the higher-velocity acceleration region on the upper side suggests effective aerodynamic lift, essential for optimal flight performance.

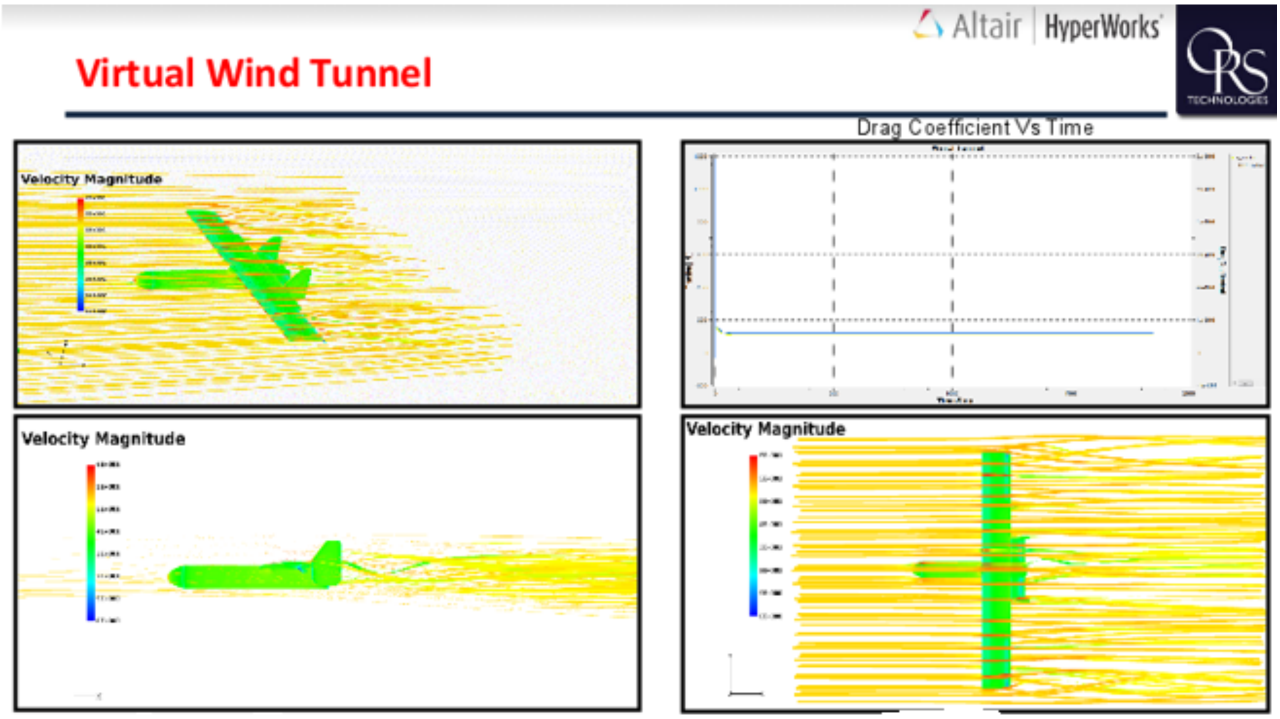


Fig. 7. Velocity and Drag Coefficient Analysis

3.3 Wing Design

The performance of the UAV in near space is significantly influenced by its aerodynamic characteristics, particularly due to the low operating pressure and Reynolds number, necessitating improvements in elevator design. The main wing design aims to simplify manufacturing without compromising aerodynamic benefits. It lacks flaps for aircraft flight conditions and mission. The wings boast standard configurations, featuring ailerons with a length of 40% of 2120.9 mm (83.5 inches) and a width of 25% of 292.1mm (11 ½ INCI), as illustrated in Figure 8. This design, carefully tailored to the UAV's operational requirements, reflects a balance between structural integrity, aerodynamic performance, and manufacturing feasibility.

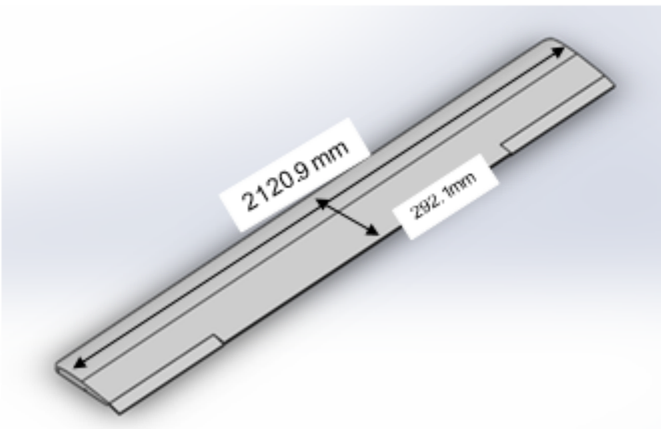
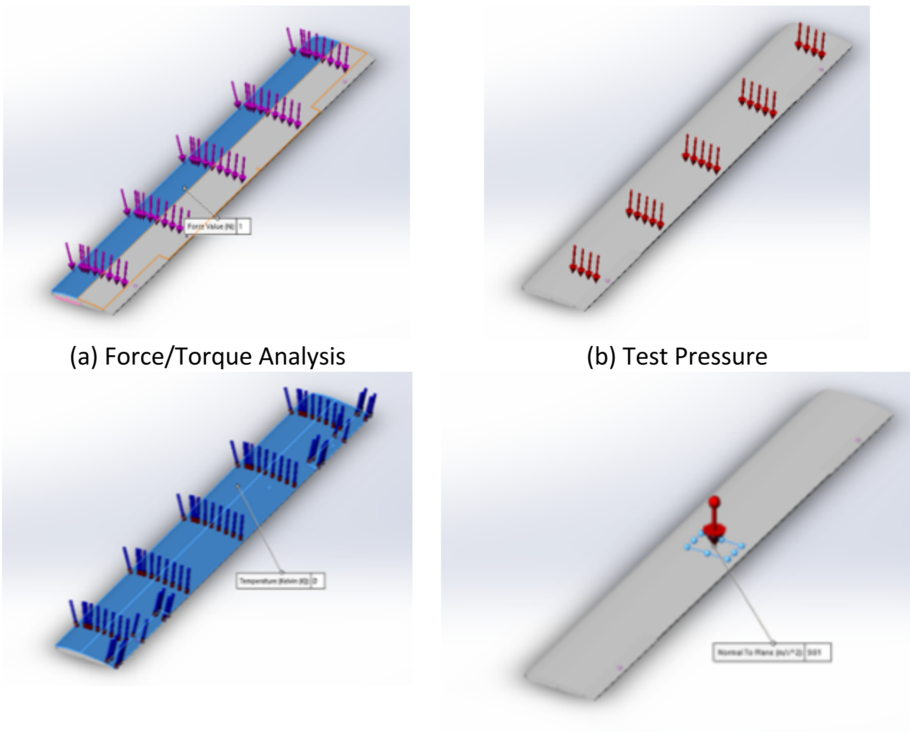


Fig. 8. Elliptical Wing Platform Shape Comparison

The UAV model's wing information, including material properties and mesh control, was analysed using SolidWorks Simulation. The Selig S1223 air foil was found to perform exceptionally well during flight. The procedure for designing and analysing the wing was presented, and the wing information of force/torque, pressure, and temperature was also calculated using SolidWorks software. The centre of gravity (CG) location for the wing was crucial for stability and control. The wing was very stable in given loading regimes due to highly high critical stresses, as shown in ORS Technologies and Solid Works analysis. The wing's design and analysis procedures are presented in Figure 9, emphasizing the importance of the wing's centre of gravity location for stability and control.

The wing information of the UAV model, encompassing material properties and mesh control, underwent thorough analysis using SolidWorks Simulation. The Selig S1223 air foil showcased exceptional performance during the flight. The comprehensive design and analysis procedures for the wing were presented, involving force/torque analysis, test pressure, temperature test, and test gravity, all conducted using SolidWorks software. The force/torque analysis provided insights into the aerodynamic forces and torques acting on the wing, crucial for understanding its behaviour during different flight conditions. Test pressure and temperature analyses were instrumental in evaluating the wing's response to the challenging near-space environment. These analyses accounted for the unique needs the wing would encounter, ensuring that it meets performance expectations under various pressures and temperatures. Moreover, the test gravity analysis significantly assessed structural integrity and stability.

The wing demonstrated remarkable stability in given loading regimes, attributed to its ability to withstand highly critical stresses. This stability was corroborated by analyses conducted by both ORS Technologies and SolidWorks. The wing's identified centre of gravity (CG) location emerged as a critical parameter for stability and control. The meticulous design and analysis procedures, as highlighted in Figure 9, underscore the importance of considering these factors in the overall UAV model. This integrated approach ensures that the wing performs well aerodynamically and maintains stability and control, crucial aspects for successful operations in near-space environments.

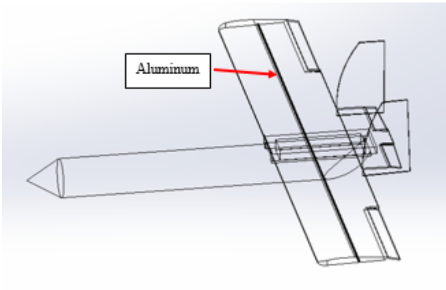


(a) Force/Torque Analysis (b) Test Pressure

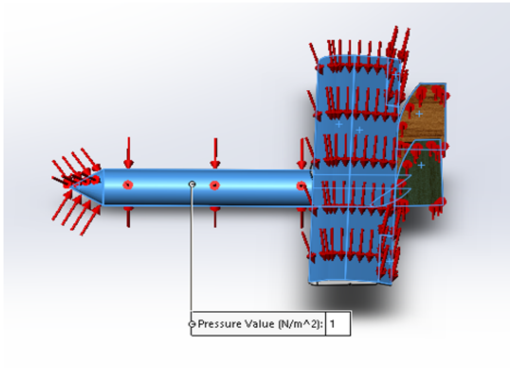
(c) Temperature Test (d) Test Gravity

Fig. 9. The wing's design and analysis procedures are based on (a) force/torque analysis, (b) test pressure, (c) temperature test, and (d) test gravity

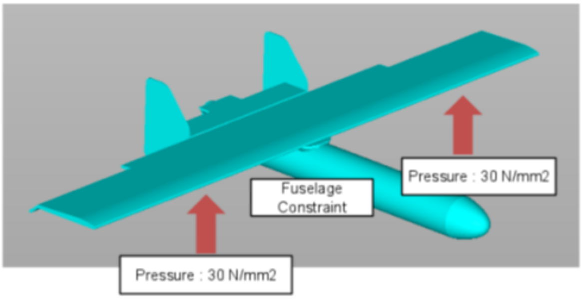
The design incorporates aluminium reinforcement for a safety factor, allowing for bending and torsional loads to be moved. The aircraft's wing, constructed from polystyrene with central aluminium reinforcement, is designed for straight and level flight, with a flat-bottom design for easy aerofoil manufacturing. UAV is the best design for wings due to its ability to protect against high stress, as determined by ORS Technologies' structural analysis, which includes a pressure of 30 N/mm2 in Figure 10.



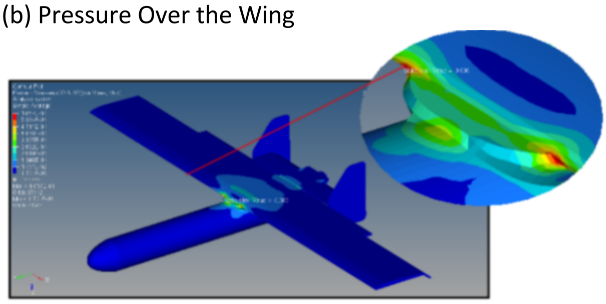
(a) Wing Design with Aluminium Reinforcement



(b) Pressure Over the Wing



(c) UAV Airframe

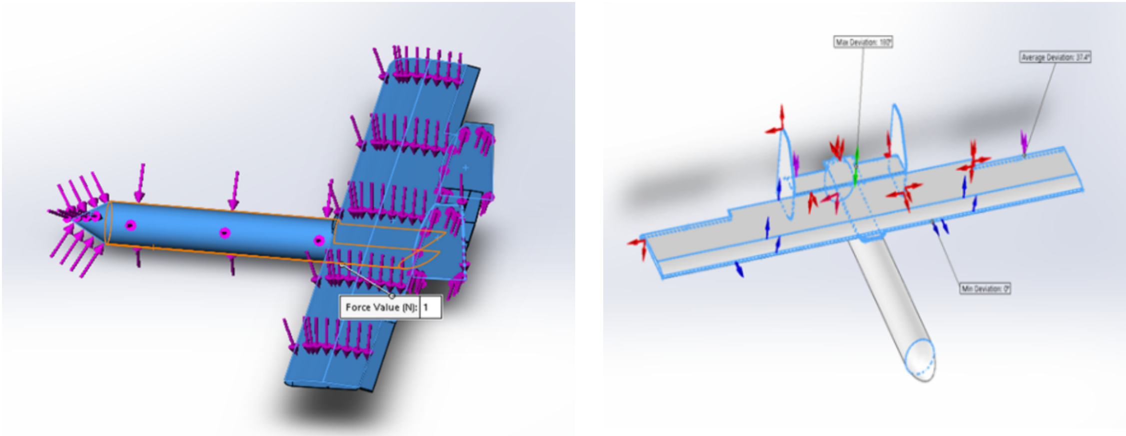


(d) Structural Analysis Contours

Fig. 10. Structural Analysis Contours

Figure 11(a) and 11(b) illustrate the results of force analysis and deviation analysis, respectively. The force analysis was conducted to simulate airflow over the area and quantify the interaction between airflow and surface area. The mesh properties and control were found to be well-suited, and the effect of bulk temperature on the relationship between applied force and approach was observed to be minimal. The lower-pressure region above the front dome of the fuselage indicates a lift, suggesting an effective design. The UAV, encompassing wings, stabilizers, and fuselage, proved to be sufficient for gaining and maintaining flight, especially when paired with the air foils.

The critical consideration of the centre of gravity (CG) location emerged as essential for aircraft stability and control. Additionally, the deviation analysis tool was employed to calculate interface angles based on selected sample points along the edge. By calculating interface angles based on selected sample points along the edge, this analysis ensures that the physical structure closely matches the intended design. Minimal deviations indicate well-manufactured and aligned components, enhancing structural integrity, reliability, and overall performance.



(a) Force Analysis (b) Deviation Analysis

Fig. 11. The force and deviation analysis

3.5 Testing Performance

After completing the aircraft design, tests were conducted to optimize the configurations for each mission. The aircraft exhibited stability, was secure to control, and perform well during flight. After manufacturing, flight tests were carried out to compare results with the initial analysis Before the final flight test, unsuccessful prototypes were built to check representative flight profiles for cruises and gliders. The test flight highlighted areas for improvement, but a detailed analysis of cost-benefits was necessary to ensure cost-effectiveness. Safety guidelines were established to safeguard the well-being of staff and bystanders. These included pre-flight check procedures, definitions of danger and safety zones, as well as the provision of safety equipment [22,23]. The inaugural test flight focused on flying the UAV using radio control, allowing for an evaluation of its structural integrity and performance, as depicted in Figure 12.

Fig. 12. Check Structure and Performance

In November 2017, the flight test was conducted at Sultan Zainal Abidin University Campus and Kampung Gong Kubur to tune and test the autopilot as depicted in Figures 13 and 14. After two successful tests, the model lifted off the ground, flew, and landed, indicating that the success of the mission relies on optimizing different parameters.

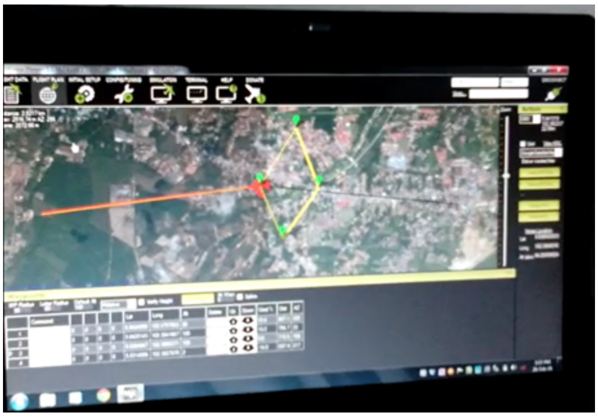


Fig. 13. Procerus Virtual Cockpit

Fig. 14. Image Capture from UAV

3.6 Images Result

During the disaster phase, the emphasis shifts to gathering real-time reports, including critical information about the movement of affected people and rescue teams. This data is invaluable for orchestrating swift and targeted response efforts, optimizing resource allocation, and enhancing overall disaster management strategies. The UAVs, equipped with advanced camera systems, play a pivotal role in this information-gathering process. The UAVs capture scenes from vantage points that might be inaccessible or hazardous to human responders. The aerial image data obtained through UAV surveillance provides a comprehensive and detailed overview of the disaster-affected areas, aiding decision-making and resource prioritization. To ensure the effectiveness of UAV operations in disaster response, thorough flight tests are conducted. These tests assess the UAVs' performance and the quality and extent of photogrammetric coverage they can provide. Photogrammetry, as illustrated in Figure 15, involves precisely measuring objects through aerial imagery. This method enhances the accuracy of data collected by UAVs, facilitating more informed decision-making in disaster management.

Fig. 15. Screenshots from the Flight Area Flood in Kemaman

Apart from that, more than 15 flight tests have been conducted to evaluate the performance of the UAV and identify the necessary improvements in planning, as illustrated in the attached Figure 16 from various locations in Malaysia.

(a) (b) (c) (d)

Fig. 16. Flight test from various Malaysian locations (a) Kg. Bechah Semak, Pasir Mas, Kelantan on June 2016 (b) Paser Putih, Kelantan on June 2016 (c) Besut, Terengganuon May 2017 (d) Pulau Perhentian, Terengganu on September 2017

4. Conclusions

The primary objective of this study is to investigate the performance of a reconnaissance Unmanned Aerial Vehicle (UAV) designed for disaster management in Malaysia, with a focus on the utilization of a new material, EPS foam. Positioned as the most cost-effective option among available UAVs, the design process involved intricate engineering considerations, system selection, and meticulous comparisons with competitor aircraft. The UAV, built with EPS foam, demonstrates a forward-looking approach to disaster management, offering local applications in reconnaissance missions.

The study explores various parameters affecting UAV performance, including velocity, take-off capability, flight performance, and landing distance. The UAV's design, based on mature software, has successfully met its objectives, allowing for innovative approaches such as remote-control using scale electric servos and an autopilot designed for RC aircraft. These design choices not only ensure the UAV's immediate readiness for flight tests but also contribute to the development of empirical methodologies for future conceptual UAV designs.

The research emphasizes the significance of the UAV's readiness for flight tests and subsequent design improvements, marking a substantial stride in advancing UAV technology for efficient and cost-effective disaster response in Malaysia and beyond.

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