© Universiti Tun Hussein Onn Malaysia Publisher's Office

PAAT

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/paat
e-ISSN : 2821-2924

Progress in Aerospace and Aviation Technology

The Structural Design and Aerodynamics Analysis for a Hybrid VTOL Fixed-Wing Drone for Parcel Delivery Applications

Seyhrvin Kumar Chakraverty[1] , Mohd Fadhli Zulkafli[1*], Mohammad Fahmi Pairan[1], Mohamad Nadjmi Mohd Shakir See[1], Izzat Khair Mahmud[1]

[1]Research Center for Unmanned Vehicle, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, 86400, MALAYSIA

*Corresponding Author

DOI: https://doi.org/10.30880/paat.2022.02.01.006
Received 23 February 2022; Accepted 21 August 2022; Available online 28 August 2022

Abstract: A number of companies are experimenting with multicopter drones to deliver items to clients. Because electric planes have a restricted range, their flight range is usually limited. However, if propelled by gasoline, electric multicopter drones can only travel a short distance because of high power consumption and noise difficulties. Despite their lower aerodynamic efficiency than fixed-wing aircraft, multicopters' ability to perform vertical take-off and landing (VTOL) makes them an ideal delivery vehicles. A hybrid fixed-wing VTOL system with a tilting system that alters the flight mode could be an upgrade to the current design of hybrid fixed wing VTOL. The goal is to effectively manufacture a fixed-wing drone with an appropriate structural design and a functional tilting mechanism that can take off vertically. SolidWorks and SIMNET aero were the two approaches used throughout the design software. The drone's aerodynamic qualities were investigated in order to better understand its behaviour, such as range of flight at a given altitude, stall speed, and maximum lift created, in order to determine the maximum parcel weight the drone can carry. The drone was built using SolidWorks 3D-Solid modelling and SIMNET aero design software. The tilting mechanism is 3D printed with Polylactic Acid (PLA) material since it is both light and strong. The structural strength can also be altered by changing the in-fill. After the drone was manufactured, numerous test flights were made to examine the drone's actual behaviour and enhance its functionality. The drone's theoretical stall speed was determined to be 12.74 m/s with a maximum payload of 500g and 11.43 m/s at no load. The maximum glide distance was estimated to be 1.2 kilometres. The drone yaws to the left during test flights at a rate of 63.43 degrees per second and 4.879 degrees per second at 50% throttle. It slanted to the front, nose down, with a weight of 516 g while support was given at the tip of the left wing. The pitch rate was 2.5 degrees per second without a payload and 3.12 degrees per second with the 516g payload. With further design and calibration advancements, experimental findings that are comparable to theoretical outcomes might be possible.

Keywords: VTOL, drone, aerodynamic, structure, design, SIMNET, test flight, tilting mechanism

1. Introduction

The two primary ways through which aircraft produce lift, vertical take-off and landing (VTOL) and horizontal take-off and landing (HTOL), are often utilised in helicopters and aeroplanes, respectively [1]. Hybrid VTOL UAVs combine VTOL functionality with a fixed-wing UAV's regular forward propulsion. In many hybrid VTOL UAVs, rotary lift propellers are frequently built into the aircraft's wings, which then convert for forward flight. There are various advantages to VTOL and multirotor drones over fixed-wing unmanned aircraft. They take up significantly less space to launch and land because they don't need a runway. They're ideal for inspection and monitoring missions that require the

*Corresponding author: fadhli@uthm.edu.my

aircraft to remain in one place for a lengthy period of time. They can change the relative speed of each rotor, so changing the power and torque produced, making them more manoeuvrable than fixed-wing aircraft [2].

1.1 Delivery Drones

A number of technologies designed to transport drone cargo have made significant advancements. Some are completely controlled by a human operator from a distance, while others are fully or largely self-contained. Drones can weigh as little as a few kilogrammes or as much as a container ship. If delivery drones are successfully deployed on a large scale, the industry could be severely disrupted. Drones are employed in the delivery of goods and couriers such as UPS delivery courier drone (Fig. 1), food and humanitarian relief (see Fig. 2), and passengers [3].

Fig. 1 - UPS delivery courier drone [4]

Fig. 2 - NHS England's drone for humanitarian aid [5]

1.2 Aerodynamic Properties of Drone

All aircraft in flight are affected by thrust, drag, lift, and weight. Understanding how these forces work and how to regulate them using power and flight controls is critical to flying [6]. Thrust, drag, lift, and weight are the four forces operating on an aeroplane in straight-and-level, unaccelerated flight, according to Newton's third rule of motion, which states that every reaction has an equal but opposing reaction. The following are their definitions:

- Thrust is the thrust of the motor, propeller, or forward rotor. The drag force is reduced or eliminated. In most cases, it operates in a straight line parallel to the longitudinal axis [7]
- Drag is a rearward, retarding force caused by the disturbance of airflow caused by the wing, rotor, fuselage, and other projecting components. Drag acts in a rearward direction parallel to the relative airflow and opposes push [8]. The formula to drag coeeficient is:

$$C_d = C_d O + k C_l^2 \tag{1}$$

- The dynamic effect of air on the aerofoil provides a force acting perpendicular to the flight path through the centre of pressure and perpendicular to the aircraft's lateral axis. In flight, lift counteracts weight's downward pull [9]. Formula for lift coeeficient:

$$C_L = \frac{2L}{\rho u^2 S} \tag{2}$$

- The aircraft's entire weight, including the crew, fuel, and cargo or baggage. Weight is a force that pulls the aeroplanes downward due to gravity. It works against lift by acting vertically downward through the aircraft's centre of gravity [10].

2. Methodology

The methodology to complete the project includes several softwares such as SolidWorks and SIMNET. SolidWorks is for designing purposes and SIMNET was utilized to study the aerodynamic properties for the chosen design. In addition, SIMNET has extra features such as simulation and design warnings.

2.1 SolidWorks

To design the structure of the drone, all 3 modes of drawing was used. These modes include parts, assembly, and drawing.When creating a 3-dimensional model, it is best to utilise all modes. Part will be used to create a specific section of the model. It is important to divide the model intended to be created into its designated section to ease the visualisation of each part.When creating a solid modelling of an object with complex shape, it is best to divide it into parts. This way, more attention can be given towards the details of each section.

Assembly was used to combine all parts to create the finalised 3-Dimensional model of the object. During assembly, the parts can be fixed using ‘Mate’, a toolbar which ‘glue’ the parts together. When mating, the menu offers several modes of mating, which includes coincident, parallel, perpendicular, tangent, concentric and lock. Different selection of mating offers different accuracy. Lock has the lowest accuracy as when zoomed, faces placed together can be seen might not be parallel to each other.

Drawing was used to create a sketched view of the 3-Dimensional model. The views include side, top and front view. It is a standardised sketch which also consist of the dimensions of parts for each view. Drawing can be selected at the start menu of the software.

2.2 SIMNET

SIMNET is a web-based environment for exploring and simulating next-generation drone designing. SIMNET combines modern technical approaches to create a range of capabilities that is unrivalled. SIMNET has a number of capabilities that enable users to evaluate their proposed drone's design and flight performance. In a single software, interdisciplinary analysis aids in the examination of multiple design features. Its real-time analysis produces speedy findings, allowing you to quickly explore the design space with a low learning curve and a flexible yet simple interface.

The design of the drone's fuselage in SIMNET is shown in the Fig. 3. Because the design is made up of segments, the user must collect precise measurements before starting. The segments are established by the software's measurements of the thing being built. The fuselage of the drone was designed in up to eight parts. The 'Roundness' feature is an important characteristic that must be used. The number '0' denotes a spherical design, while the number '1' denotes a flat-surfaced pattern. It is also possible to specify the design of the drone's components. The specification for one of the motors may be seen in the Fig. 4. A propeller and a speed controller are also pre-installed on the motor. The database can be used to select components.

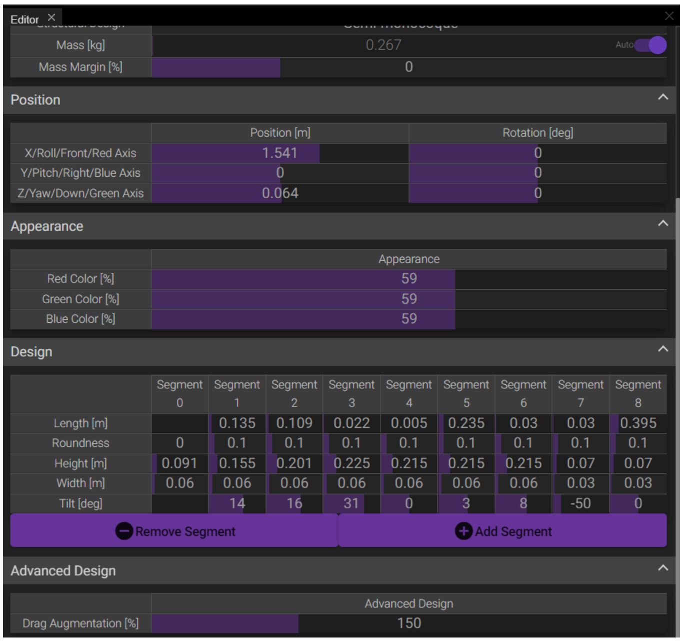

Fig. 3 - Designing drone in editor pane

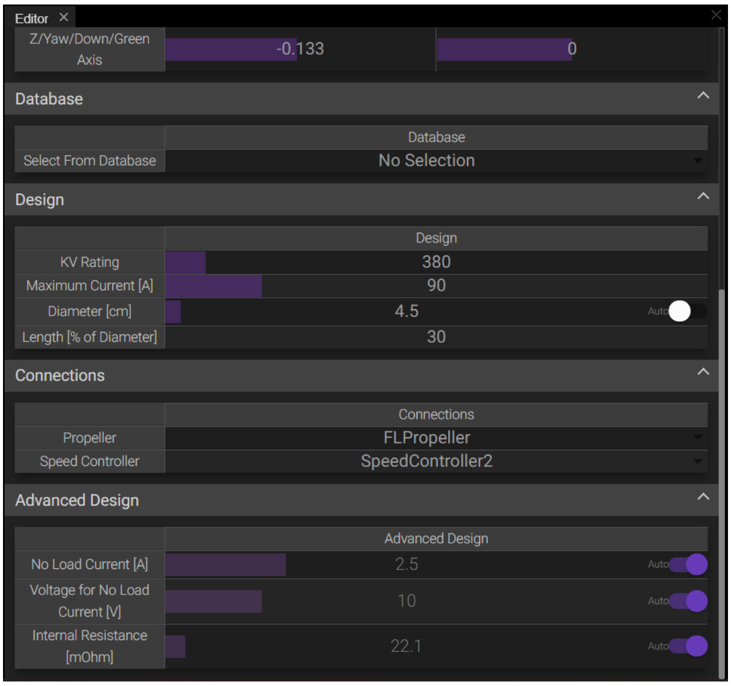

Fig. 4 - Editor pane component

A new pane was chosen from the 'Layouts' menu as shown in Fig. 5 to analyse the drone's aerodynamic qualities. Under 'Analyse,' you can get information about aerodynamic qualities and performance. The report will be automatically generated. Lift to drag vs angle of attack, lift coefficient vs angle of attack, drag coefficient vs angle of attack, and moment coefficient vs angle of attack are the four graphs that were produced as a result of the investigation.

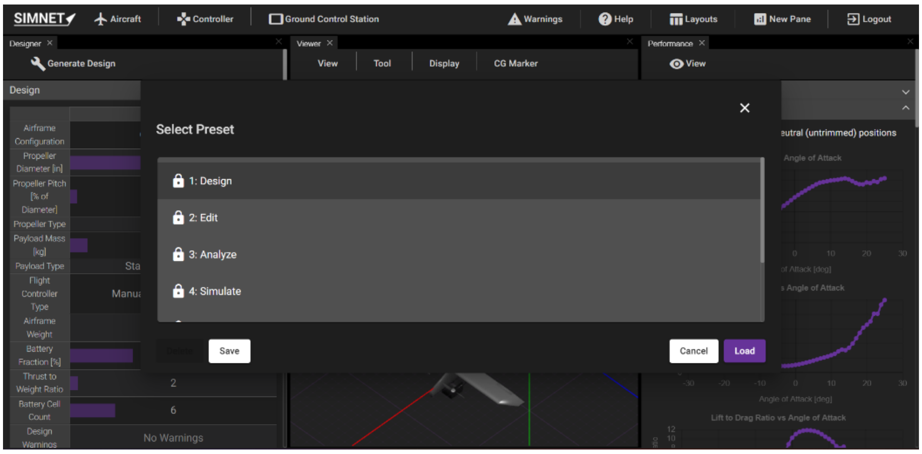

Fig. 5 - Options in 'Layout'

3. Results

Once the 3D solid modeling, design and aerodynamic analysis study have been completed, the fabrication process to realise the drone was done. The fabrication process inclused the assembly of the drone, 3D printing and fabricate the tilting mechanism and test flight once the fabrication process was complete.

3.1 Results from SolidWorks

The solid modelling also included the landing skids which was designed together with a parcel box compartment. The centre of mass was highlited and used as reference to attach the landing skids to the fuselage of the drone. Electronic components such as the micro servo was also designed to give the drone a realistic look.

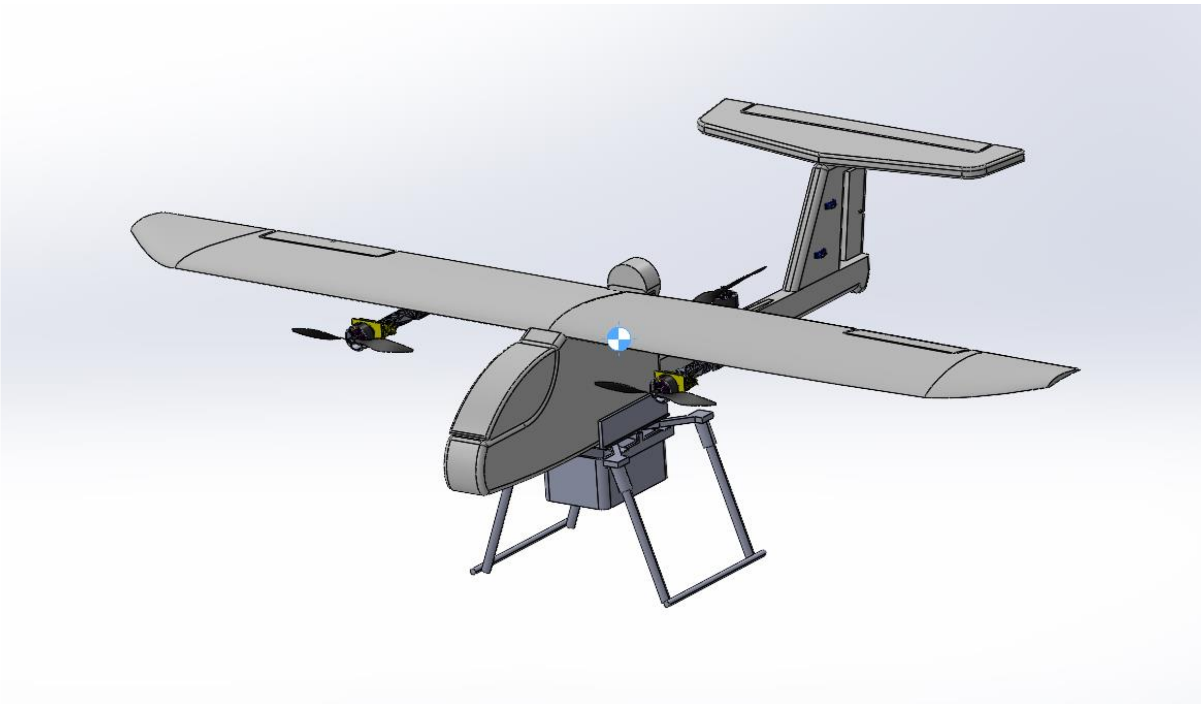

Fig. 6 - Complete 3D solid modelling of Hybrid VTOL Fixed-Wing Drone

3.2 Results from SIMNET

Several information was extracted which was used to study the behaviour of the drone in theory. From Fig. 7, the C_{Lmax} = 0.6 at angle of attack α = 14°. Since the mass of the drone is 2.1 kg and the wingspan is 0.429 m, the stall speed can be calculated.

$$V_s = \sqrt{\frac{2W}{\rho C_L max}} \quad (3)$$

$$V_s = \sqrt{\frac{2(20.601)}{1 \cdot 225(0.6)(0.429)}}$$

$$V_s = 11.43m / s$$

When carrying the 500 g payload, the stall speed becomes;

$$V_s = \sqrt{\frac{2(20.601)}{1 \cdot 225(0.6)(0.429)}}$$

$$V_s = 12.72\ m / s$$

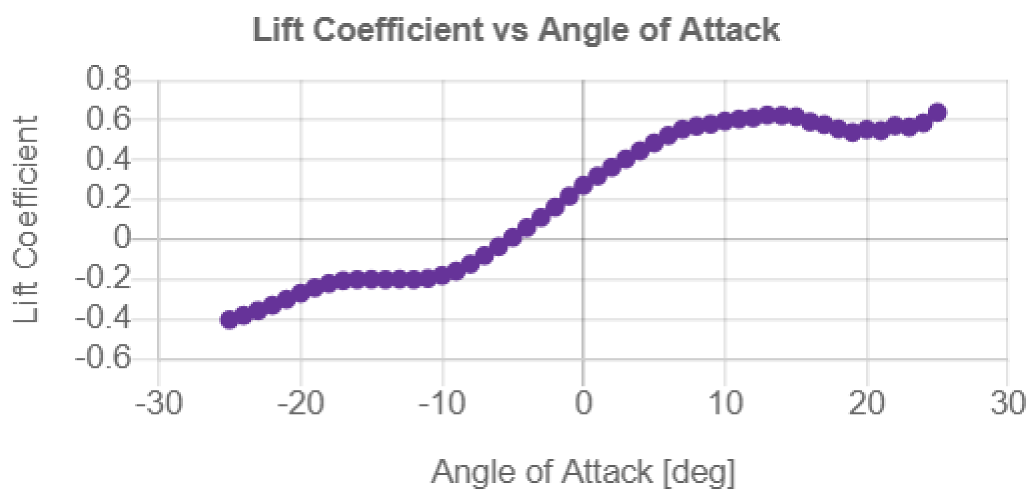

Fig. 7 - Lift coefficient vs angle of attack

Fig. 8 shows the drag coefficient associated with the angle of attack. From when the angle of attack is zero, the drag increases as the angle of attack increases. At some point, lift begins to decline while drag increases sharply. The critical angle of attack is the designation for this point. When the angle of attack exceeds the critical angle of attack, all lift is eventually lost while the drag continues to increase. It stalls at points above the angle of attack of 15 °.

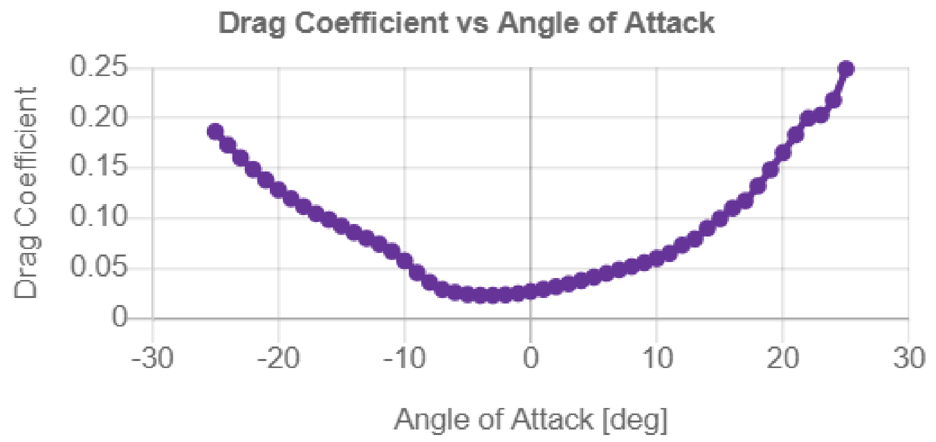

Fig. 8 - Drag coefficient vs angle of attack

Referring to Fig. 9, which is the graph of the lift to drag ratio compared to the angle of attack of the proposed drone, there are several critical points which explains the drone`s lift and cruise according SIMNET. At 0° angle of attack the lift to drag ratio is above 10 and rising. The optimum angle of attack is between 0° to 5° where the lift to drag ratio is close to 12. From the information above, the maximum glide can be obtained

$$R = H\left(\frac{L}{D}max\right) \tag{4}$$

Assume that the drone is at an altitude of 100 m;

$$R = (100)(12)$$

$$R = 1200m$$

$$R = 1.2\ km$$

Hence, the drone can be found in a 1.2 km radius if gliding from 100 m altitude at maximum lift-to-drag ratio or at optimum angle of attack.

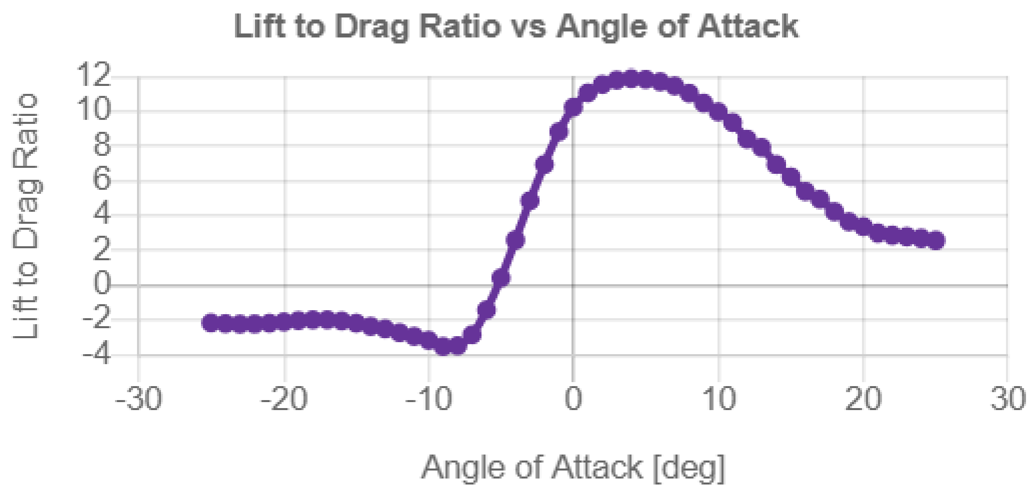

Fig. 9 - Lift to drag ratio vs angle of attack

3.3 Tilting Mechanism

The tilting mechanism shown in Fig. 10 allows the drone to hover vertically before being rotated horizontally to cruise once it has passed the take-off stage. The tilting mechanism was created using an Ender 3D-Pro printer and PLA material. Each build took exactly 8 hours and 54 minutes, with the exception of the carbon fibre mounter. M3 screws, nuts, and a hot glue gun are used to attach the pieces. Because a screw would damage the surface of the wing and cause faults, as well as chunks of polystyrene to come off, the arm is attached to the wing with a hot glue gun. The hot glue gun has no effect on the wing, but it is permanently bonded to the drone. The tilter is unaffected by the weight of the motor.

Fig. 10 - Upper part of tilting mechanism connected to wing

3.4 Test Flights

Four test flight session took place and each test flight is meant to improve the functionality of the Hybrid VTOL Fixed-Wing Drone (Fig. 11) to achieve certain objectives. The first test flight is resulted in learning that the tilter could not support the torque produced by propeller when the servo is engaged. The second test flight is done by intalling supporter at the tilter. This meant two modes of test flight will be done which is when the tilter is set at 90° and another one at 0°.

Fig. 11 - Fully assembled Hybrid VTOL Fixed-Wing Drone

Test flight three was done to study the drone behaviour. The rate of yaw was calculated after observing the drone yawing to the left during the first two test flights. The fouth test flight was done to prove the drone can carry a weight of 500g.

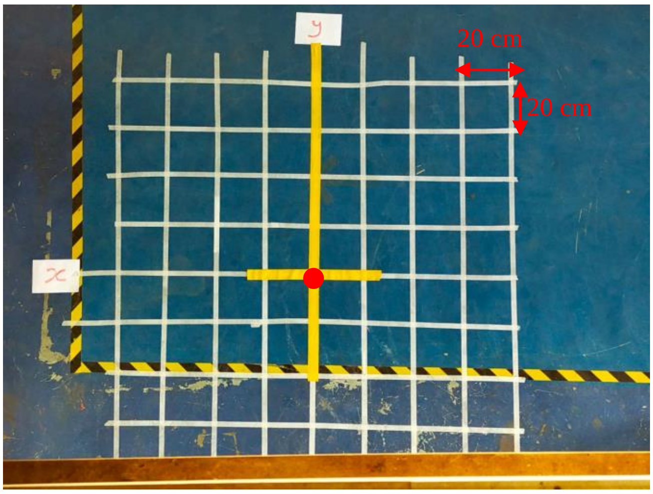

Fig. 12 - Grid with axis labelled

The grid was made out of tapes as shown in Fig. 12 and sized at 20 cm × 20cm which is optimal to avoid excessive use of tape. An 'x' and 'y' axis was made to evaluate the angle of yaw to futher be used in yaw rate calculation.

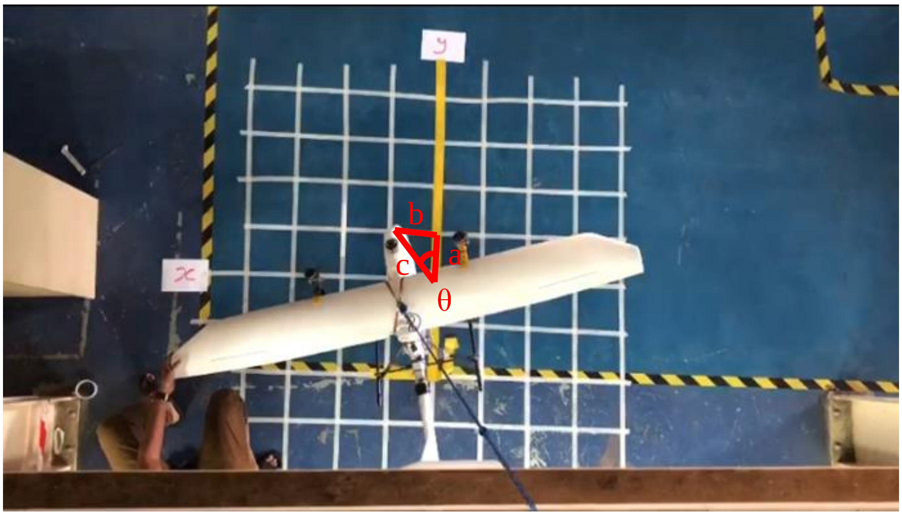

Fig. 13 - Drone yaw at 30% throttle

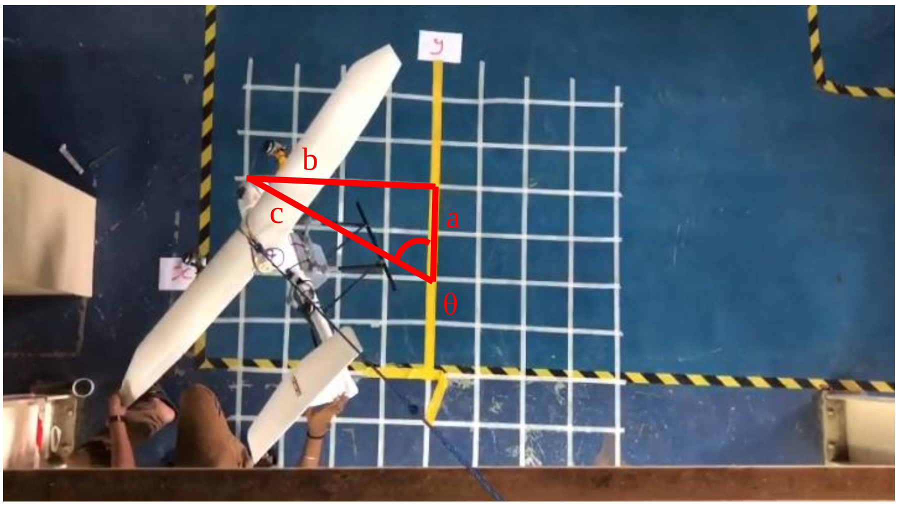

Fig. 14 - Drone yaw at 50% throttle

Yaw angle is calculated using tangent rule. The formula for tangent rule is given by equation (5).

$$\tan\theta = \frac{b}{a} \tag{5}$$

From the calculation of the yaw angle, the yaw rate can be evaluated. The yaw rate formula is defined by equation (6).

$$Yaw\ rate = \frac{Yaw\ angle}{Yaw\ time} \tag{6}$$

Based on Fig. 13 and Fig. 14, the drone yaws at an angle of 45° at 30% of throttle and of 63.43° at 50% throttle. The measured time to yaw from the start is 1 sec at 30% of throttle and 13 sec at 50% throttle. Thus, the yaw rate for 30% and 50% throttle is estimated to be $45°/sec$ and $4.879°/sec$, respectively. The detail calculation is given in Table 1.

Table 1 - Calculation for yaw angle and yaw rate at 30% and 50% throttle

30% throttle	50% throttle
$\tan\theta = \frac{20\ cm}{20\ cm}$	$\tan\theta = \frac{80\ cm}{40\ cm}$
$\theta = \tan^{-1}\left(\frac{20\ cm}{20\ cm}\right) = 45°$	$\theta = \tan^{-1}\left(\frac{80\ cm}{40\ cm}\right) = 63.43°$
$Yaw\ rate = 45°/sec$	$Yaw\ rate = 4.879°/sec$

In order to hover, which is at 50% throttle, the drone made a 63.43° yaw at the speed of 4.879°/sec to the left without activating the rudder. This was caused by a design flaw and several flaws in tuning the components. When the tip of the left wing was supported, the drone had the tendency to tilt to the front, nose down, before taking-off.

The final test flight was conducted to test the capability of the drone to carry more than 500g payload. In this test, 516g payload was used to test this capability. The weighs were placed in the parcel box to test its capability to withstand them without falling from the parcel box. In order to measure the pitch rate, the 9 mm × 9 mm in size grid box as shown in Fig. 16 is used. The reference line (blue) is stretched from the nose (reference point) to the rudder. Pitch rate is the rate at which an aircraft's orientation changes in relation to an inertial frame.

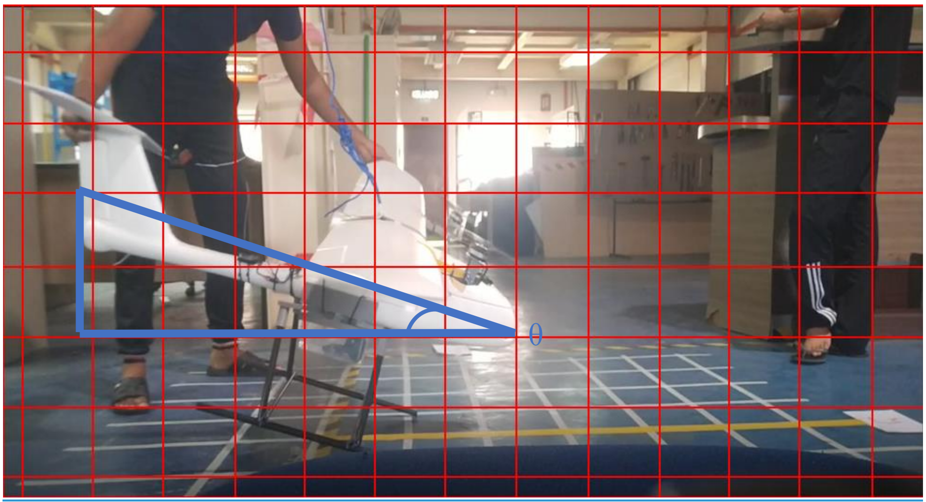

Fig. 16 - Pitch rate test at 60% throttle

The pitch angle is also calculated with the tangent rule and the pitch rate can be calculated as follows.

$$Pitch\ rate = \frac{Pitch\ angle}{Pitch\ time} \tag{7}$$

Table 2 - Calculation for pitch angle and pitch rate at 30% and 50% throttle

60% throttle without payload	60% throttle with 516g payload
$\tan\theta = \frac{16\ cm}{56\ cm}$	$tan\theta = \frac{19\ cm}{56\ cm}$
$\theta = \tan^{-1}\left(\frac{16\ cm}{56\ cm}\right)$	$\theta = \tan^{-1}\left(\frac{19\ cm}{56\ cm}\right)$
$\theta = 14.995°$ $Pitch\ rate = 2.5°/sec$	$\theta = 18.74°$ $Pitch\ rate = 3.12°/sec$

The initial anticipated result was for the drone to take-off without any pitching. However, factors such as the drone's design, the size of the propeller at the aft, and the propeller's speed all contributed to the drone's pitching (nose down) behaviour during take-off (Fig. 16). When compared to the pitch rate of the drone with and without payload, as shown in Table 2, the drone without payload has a 19.87 percent lower pitch rate. At this speed, the drone would reach its maximum stall angle of 12.4° in 5 seconds without payload and 4 seconds with payload, according to SIMNET.

4. Conclusions

The design of the drone resulted it to produce a maximum lift to drag ratio of 12. This means the drone is able to glide in horizontal distance 12 times farther than its height at optimal angle of attack. During the flight test, some design as well as calibration flaws did not produce the anticipated result. The drone has been proven to be able to take-off with a payload of 516 g but has the tendency to pitching down and yawing to the left wing. Further improvement in the design and calibration is deemed to produce results similar to the analysis done. The usage of SIMNET aero which aid in the aerodynamic analysis done helped to produce several calculations to better understand the behaviour of the aircraft. Most importantly, several numerations such as the stall speed, range for maximum glide and yaw rate and pitch rate can be used as reference to further improve the drone until the experimental results are similar to the theoretical result.

When it comes to designing, the materials that have been chosen for the drone are lightweight, except for the components such as motors and batteries. It is also advised to be more aware and study the parts received for manufacturers might include indicators to ease customers. The wing of the drone was included with circles arranged along the leading edge that should have been used when placing the arm of the tilting mechanism. This is due to the two propellers in the front throttling at the same speed as the one at the tail. Several design modifications are required to stabilise the drone. The throttle and size of the propeller should be increased to produce greater lift at the aft of the quadriplegia to allow it to hover. The motor at the aft of the drone should be located at the same height as the two motors at the front to balance the lift of the aircraft.

Finally, when 3D-printing, check the level, temperature, and determine the speed to print at prior to printing. These checks will determine a smooth print without defects on the product. A proper filament is crucial to ensure printed products have smooth surfaces, edges, and minimal or close to no defects. Filaments by Polymaker PolyMax™ PLA would produce quality 3D printed products with minimal defects and clogs. A quality filament can withstand being exposed to the environment for a longer time before becoming brittle. To ensure the quality of the filament is maintained, it can be kept in a 3D printer filament drying box.

Acknowledgement

The authors wish to express sincere gratitude and gratefully acknowledge the financial support received from Ministry of Higher Education under the Fundamental Research Grant Scheme (FRGS), reference code: FRGS/1/2020/TK02/UTHM/02/3 and the Faculty of Mechanical and Manufacturing Engineering, UTHM.

References

[1] A. CHA, "VTOL and HTOL drones," *OutDoor Robotics*. https://outdoorrobotics.com/what-is-a-vtol-drone/#:~:text=Vertical Take Off and Landing,in helicopters and airplanes respectively. (accessed Oct. 08, 2020).

[2] "VTOL UAV & Multirotor Manufacturers," *Unmaned System Technology*.

https://www.unmannedsystemstechnology.com/expo/vtol-uav/#:~:text=Multirotor UAVs (Unmanned Aerial Vehicles,incorporates four or more propellers.
[3] E. Frachtenberg and R. College, "Practical Drone Delivery," pp. 53–57, doi: 10.1109/MC.2019.2942290.
[4] Miriam McNabb, "UPS Will Purchase BETA Technologies VTOL Aircraft: the Future of Drone Delivery." https://dronelife.com/2021/04/13/ups-will-purchase-beta-technologies-vtol-aircraft-the-future-of-drone-delivery/ (accessed Apr. 13, 2021).
[5] L. M. and L. Postelnicu, "NHS test drones for blood and medical test delivery between London hospitals," *HIMSS21*, 2018. https://www.healthcareitnews.com/news/nhs-test-drones-blood-and-medical-test-delivery-between-london-hospitals (accessed Jul. 26, 2018).
[6] Federal Aviation Administration, "Pilot's handbook of Aeronautical Knowledge: Aerodynamics of Flight," no. Cl, 2016.
[7] NASA, "What is Thrust?" https://www.grc.nasa.gov/www/k-12/airplane/thrust1.html#:~:text=Thrust is the force which,the weight of a rocket.&text=Thrust is a mechanical force,working fluid to produce thrust. (accessed May 13, 2021).
[8] NASA, "What is Drag?," 2021. https://www.grc.nasa.gov/www/k-12/airplane/drag1.html (accessed May 13, 2021).
[9] NASA, "What is Lift?," 2021. https://www.grc.nasa.gov/www/k-12/airplane/lift1.html (accessed May 13, 2021).
[10] NASA, "What is Weight?," 2021. https://www.grc.nasa.gov/www/k-12/airplane/weight1.html (accessed May 13, 2021).