INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 17 No. 4 (2025) 137-152
https://publisher.uthm.edu.my/ojs/index.php/ijie

IJIE

Flight Performance of a VTOL Version of a Transport Blended Wing-Body UAV

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DOI: https://doi.org/10.30880/ijie.2025.17.04.012

Article Info

Received: 8 March 2025
Accepted: 29 August 2025
Available online: 19 September 2025

Keywords

Blended wing-body, VTOL, UAV, flight performance

Abstract

The blended wing-body (BWB) UAV, featuring vertical take-off and landing (VTOL) capabilities, has garnered attention in aviation due to its advancements and advantages, including noise reduction and enhanced safety features. This study analyses BWB UAV VTOL flight performance and mission capabilities. The evaluation involves conceptual design, theoretical calculations, and data analysis to assess parameters such as range, endurance, weight, manoeuvrability, and more. Furthermore, mission profile analysis is used for surveillance scenarios and offers insights into the UAV's performance in these operational environments. Microsoft Excel is the main tool used in this research for calculations, simulations, and data analysis. Using a spreadsheet, this method computes critical performance metrics according to the mission requirements, operational parameters, and design specifications of the UAV. The study's findings provide important insight into the BWB UAV VTOL prototype's flight characteristics and mission capabilities. These results point to the aircraft's ideal operating conditions and assist in identifying any potential drawbacks or performance limitations that may vary as further study proceeds. Microsoft Excel provides a useful and approachable way to evaluate UAV VTOL performance. It enables fast updates and modifications to meet changing mission requirements and design iterations. Other than that, a thorough examination of the flight characteristics and mission profile of the BWB UAV VTOL prototype brings this study to a close. It offers insightful information that can be used to improve design, schedule operations, and predict performance in the field of aerial transportation and other pertinent applications.

1. Introduction

The performance and aerodynamics of an aircraft are crucial for its effectiveness. The Blended Wing Body (BWB) design integrates the wings and fuselage seamlessly, resulting in a streamlined structure [1]. This design reduces drag and makes the aircraft lighter, improving its efficiency [2]. They have an advantage over manned aircraft due to their tiny size, minimal visual and acoustic profiles, and exceptional manoeuvrability [3]. Among the most demanding UAV operations are vertical take-off and landing, hovering, and long-distance flying. However, the criteria for VTOL and long-distance cruises are incompatible since VTOL is primarily propelled, but long-distance flights need fixed-wing aerodynamic efficiency. Although designing aircraft capable of transitioning to vertical take-off and landing (VTOL) is one of the major challenges in aviation [4–5].

The performance of the aircraft is the main target of this study, which is to discover the aircraft's capabilities and limitations. The previous analysis of the Fixed Wing UAV requires a distance during take-off and landing for it to transition to the next phase. This study on the BWB UAV with VTOL examines how its performance can be affected by performance challenges related to blended wing operations, including climb rate, stability, range, and endurance. Adding VTOL requires additional rotors and a battery for it to perform, thus increasing the weight of the BWB. Therefore, this study is to analyse the flight performance of the UAV VTOL prototype to achieve the standard operations and mission profile. Thus, to fill the existing gap, the performance data from past studies and research on the Fixed Wing BWB UAV need to be analysed and compared. The objective of this research is, firstly, to comprehend the mission profile and conceptual design of the project's aircraft. After that, to evaluate the flight performance of the blended wing-body (BWB) unmanned aerial vehicle (UAV) vertical take-off and landing (VTOL) as the weight of the aircraft increases.

A comparison study will be conducted in terms of flight performance between a Fixed Wing BWB UAV with the VTOL BWB UAV. This study focuses on the performance of the blended wing-body (BWB) unmanned aerial vehicle (UAV) vertical take-off and landing (VTOL) while examining the mission profile and conceptual design of the aircraft. In-depth analysis of various aspects that include the aerodynamic parameters, mission profile, and operational capabilities, with the goal of understanding the unique features and limitations of the aircraft.

This research acts as an approach towards development in aerospace advancement technology and Unmanned Aerial Vehicle (UAV) capabilities to offer insights that can lead to improvements in design, materials, and engineering principles. Furthermore, the study focuses on key challenges and harnessing advantages unique to the BWB VTOL configuration compared to the BWB Fixed Wing, as this study provides a deeper understanding of the trade-offs between the two aircraft. The goal of this study is to contribute valuable understandings into the aircraft's flight performance and mission capabilities by exploring critical parameters such as thrust, power, airspeeds, climb rate, and endurance. Additionally, the study's findings can influence future design decisions, operational strategies, and applications in fields such as surveillance, transportation, and beyond.

2. Literature Review

The Blended Wing Body (BWB) configuration excels in surveillance and intruder inspections due to its even weight distribution, lower radar signal strength compared to the alternative configurations, and minimal delay with movement [6]. Considering key design factors such as vertical take-off and landing, aerodynamic drag, and basic wing stability, an optimal BWB planform is crafted specifically for surveillance purposes. This specialized design ensures that the BWB configuration is particularly well-suited for tasks requiring discreet and efficient monitoring [7].

Nevertheless, the performance of the aircraft emphasizes the aircraft's ability to perform flight operations that are efficient and safe. By doing so, the limitations and advancements of the aircraft could be studied and evaluated based on the mission profile. The flight conditions vary with the altitude of the aircraft as the air becomes less dense; thus, it may reduce power, thrust, and lift. It is found that the weight, altitude, and configuration changes have a direct impact on both excess thrust and power, thus influencing the climb performance. The ability to generate excess thrust or power plays a crucial role in determining climb performance [8].

An upsurge in weight, a rise in altitude, or the act of lowering the landing gear or flaps leads to a reduction in both excess thrust and excess power across all aircraft types [9]. Other than that, Snorri et al. state that the conceptual weight of the aircraft also plays a pivotal role. The weight properties of the aircraft include the operational empty weight, payload, and maximum take-off weight [10].

The impact of weight on aircraft performance is highly noticeable. The weight affects the stall speed, take-off and landing distance, and manoeuvring speed. When additional weight is introduced to an aircraft, it necessitates flying at a steeper angle of attack to sustain a specific altitude and speed. In a study regarding the angle of attack, Daidzic et al. [11] researched and found that this elevation in the angle of attack results in heightened induced drag on the wings, along with an increase in the parasite drag of the aircraft. The extended drag demands extra thrust to reduce it, subsequently reducing the surplus thrust available for climbing.

Finger et al. researched that the actual endurance computation is a step-by-step procedure based on the amount of fuel used during each stage of flight. The aerodynamic model calculates the drag of the airplane during hovering flight for any given weight [5]. The study states that VTOL aircraft require a thrust-to-weight ratio larger than unity for the vertical portion of their mission to maintain stable flight. This is supported as there is a study by Parisa Footohi that also states that to achieve VTOL and hover, the propulsion system must produce thrust equal to or greater than the aircraft's weight [3]. Furthermore, the benefits of the Blended Wing-Body (BWB) concept include generating lift across the entire airframe and minimizing form drag at the wing-body junction. A set of four propellers is fully housed within the fuselage, playing a significant role in producing a substantial portion of the thrust force during the Vertical Takeoff and Landing, VTOL, phase of the flight [12].

However, using the Blended Wing Body (BWB) design for VTOL UAVs is beneficial because it allows for a distributed propulsion system. By housing the propulsion system inside the body, induced drag is reduced. Ducted propellers or shrouded rotors are often utilized to maximize performance and efficiency. A shrouded rotor can provide up to a 94% increase in thrust compared to an open rotor using the same power [13]. Other than that, the electrified system increases the overall reliability and decreases maintenance, production, and operation costs [14]. The electrified system lowers operating, production, and maintenance costs while improving overall reliability [15].

Bliamis et al. [16] also did research and found that the disadvantage of VTOL aircraft is that their motors use a lot of power, which shortens how long they can fly and how much weight they can carry. On the other hand, fixed-wing designs need much less power because their main wing creates lift and has less air resistance [16]. These benefits of more efficient aerodynamic design are attributed to increased payload capability, endurance, and cruise speed. Also, fixed-wing aircraft can glide naturally, and they have fewer moving parts exposed, so there's less risk of things breaking compared to multirotor designs. Ehab Sayed et al., as the aircraft weight decreases and fuel efficiency increases, which reduces pollutant fuel consumption and emissions. The electrified system increases overall reliability and decreases maintenance, production, and operation costs [14].

Özgür Dündar et al. evaluated the performance analysis of a fixed-wing VTOL that had a mounted system having four motors regarding its endurance, range, and the energy consumption when take-off, climb, hover, and landing [17]. The VTOL-FW UAV takes 1.5 minutes to reach a height of 300 meters, 30 seconds to rise, and 50 seconds to land. The study indicates that the most difficult aspect of operating a battery-powered VTOL-FW UAV is predicting the power needed for takeoff, particularly the change from hover to cruise flight [17]. A distributed electric propulsion of a BWB provides several benefits, including enhanced mobility, a reduction in the control surfaces, the capacity to inhale boundary layers, and more [18].

The hybrid wing VTOL UAV has two separate propulsion systems: one horizontal and one vertical. During takeoff, the UAV employs four lifting rotors oriented vertically to generate lifting power [19]. An aircraft's performance is related to its capacity to perform activities that are necessary for achieving particular goals. Climb rate, ceiling, payload, range, speed, manoeuvrability, and VTOL capabilities are all important performance-influencing elements. However, due to variations in design decisions and mission constraints, a newly constructed aircraft faces challenges in reaching its peak performance. As a result, the goal of this inquiry is to assess the UAV design prototype's flying performance to match it with mission profiles. To close current gaps in knowledge, performance data from earlier studies and research must be compared and analyzed.

3. Methodology

This project begins with analyzing the specifications of the aircraft with the addition of VTOL parameters included on a Fixed Wing BWB UAV. Then, the mission profile of the BWB UAV VTOL will help to predict the aircraft's performance, especially with the conceptual design made. Next, the data of the performance is collected of the UAV parameters of aerodynamic parameters, VTOL batteries, and electric ducted fan parameters, motor specification during flight, and design parameters. The data is also calculated by using relevant formulas and equations that have been obtained. Lastly, the result will be evaluated and documented.

3.1 Conceptual Design

A Blended Wing Body (BWB) Unmanned Aerial Vehicle (UAV) with Vertical Takeoff and Landing (VTOL) capabilities requires the evaluation and integration of several design considerations [20]. The center of gravity plays an important part in keeping the aircraft hovering vertically at a 90-degree angle for take-off and landing stably. The Blended Wing-Body (BWB) design exhibits significant instability in movement due to the absence of a tail section [21]. Hence, maintaining a critical center of gravity location is essential for stability. Thus, the placement of VTOL specifications such as batteries and motors must be monitored to achieve stability throughout the airframe. The conceptual design of the aircraft is from a previous study, only with an additional VTOL for performing take-off and landing. Similar functions as a traditional fixed-wing UAV while cruising and transitioning into a quadcopter configuration during take-off and landing [22]. Although with a similar conceptual design, the MTOW for the VTOL UAV is heavier than the previous study of the fixed-wing due to the additional power that is included. Therefore, the weight of each item would contribute to the distribution of weight at a stable center of gravity. The design of the UAV BWB in the OpenVSP software was given by the supervisor to analyze and convert the design into a vertical take-off and landing. With additional VTOL, the parameters of weight and center of gravity would be affected from the previous design. Since the weight of the aircraft directly affects flight performance, estimating the weight of the aircraft is an important step in the conceptual design process, particularly for the BWB configuration as a new concept design.

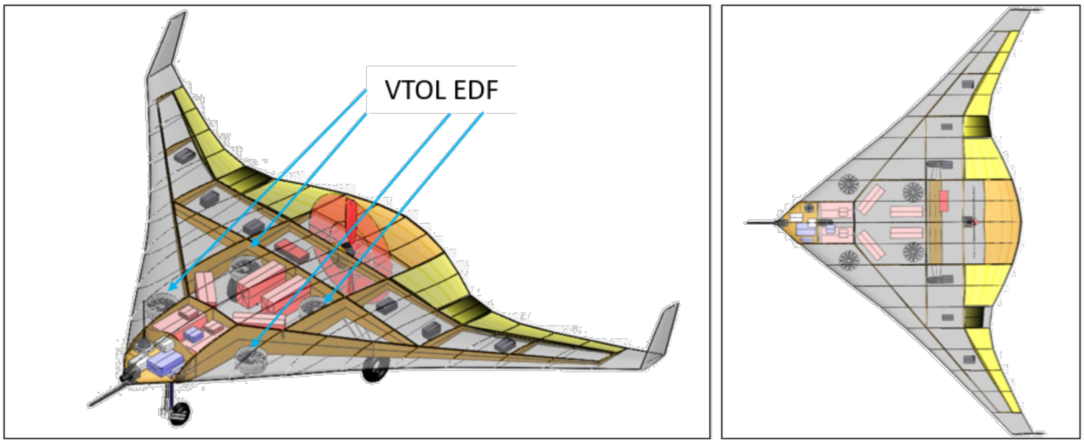


Fig. 1 *Conceptual design of the prototype with four VTOL EDF*

3.2 Flight Performance Analysis

The mission profile is used as an overview and prediction of the aircraft's performance capabilities of vertical take-off, cruising, and performing its objective of surveillance and landing vertically. The aim of the mission profile for this study is also to distinguish the differences in flight transition between fixed-wing and VTOL. The mission specification for the vertical take-off, as tabulated in Table 1, shows that the aircraft's maximum take-off weight will be 13.69 kilograms and should be able to take off and land vertically in approximately 4 minutes. Other than that, the aircraft should be able to cruise at sea level, covering its distance of 100 kilometers and 1 hour of endurance to perform its mission. These data provide valuable information to evaluate an aircraft's performance and the UAV's flight profile.

Table 1 *Specification of VTOL objective*

Parameters	Value
MTOW	13.69
VTOL duration (hr)	0.067
Range (km)	100
Cruising altitude	@ Sea level (<1000m)
Endurance (hr)	1

Firstly, the parameters of the aircraft should be achieved to calculate the performance using equations and formulas, and provide results to be analyzed and observed. Some of the data is available as this study is a continuous action of the previous study regarding the same type of aircraft, but with vertical take-off and landing. The data of aerodynamic parameters and design parameters are used to calculate the flight performance. The findings will be analyzed and discussed in more detail later.

Aerodynamics are crucial parameters of the aircraft as they affect the overall performance of the UAV. Any slight changes would produce a difference in the result. For this research, the aerodynamic parameters of Oswald efficiency (e), zero-lift drag ratio (CD0), and maximum lift coefficient are gathered from a previous study, as CD0 was collected from research conducted by one of the researchers from FTTC using simulation of computational CFD analysis. For standard light aircraft, the amount of Oswald efficiency is approximately 0.8. As for the induced drag factor, it is calculated by using Eq. (1). The aerodynamic parameters are summarized in Table 2.

$$k = \frac{1}{\pi e AR} \tag{1}$$

Table 2 *Aerodynamic parameters*

Parameters	Value
Oswald efficiency (e)	0.8
Zero-lift drag coefficient (CD_0)	0.01
Maximum lift coefficient (CL_{max})	0.8
Induced drag (k)	0.1

Important data, including the size, weight, and motor specifications of the aircraft such as wing area and wing aspect ratio (Eq. (2) & (3)), are gathered for this study from sources at the Flight Technology and Test Centre (FTTC) including the conceptual design with supervision regarding battery and motor VTOL specifications needed and placement in the conceptual design to support the aircraft thrust. Eq. (4) is a general equation to calculate the maximum take-off weight (MTOW). MTOW is a crucial parameter as it acts as a fundamental metric for the aircraft to guarantee safe and effective aviation operations. Table 3 shows the parameters and data collected.

$$\text{Wing Area, S } (\text{m}^2) = \text{b} * \text{c} \tag{2}$$

$$\text{Aspect Ratio (AR)} = \frac{\text{b}}{\text{c}} \tag{3}$$

$$\text{MTOW} = \text{OEW} + W_{\text{pay}} + W_{\text{batt}} \tag{4}$$

Table 3 *BWB UAV's design specification – VTOL version*

Parameters	Value
Wingspan, b (m)	2.0
Wing Area, S (m^2)	1.0
Length, L (m)	1.2
Width, W (m)	2.0
Height, h (m)	0.3
Mean chord, c (m)	0.5
Operational Empty Weight, OEW (kg)	6.4
Battery Weight, horizontal (kg)	2
Battery Weight, hover (kg) (each)	855
Maximum take-off weight (kg)	13.685
Propulsion, horizontal	1 x 13*6.5 inch, 600rpm/V, 22.2V, 45A, brushless motor rated at 960W
Electric ducted fan	QF3758,90 mm 12 Blades 8s 5kg
Max thrust, horizontal (N)	35.28
Max thrust, hover (N)	176.52
Thrust-to-weight ratio	1.32

This research primarily focuses on assessing the aircraft's performance. Hence, it is crucial to collect accurate data and employ appropriate equations to accomplish the study's objectives. The equations are systematically applied to ensure a smooth flow of data analysis. Initially, the calculation involves determining the drag coefficient using the zero-lift-to-drag ratio and induced drag with the maximum lift coefficient available.

As the data of aerodynamic parameters of CD0 and CL are known, Eq. (5) of the drag coefficient could be calculated. Eqs (6) and (7) can be employed to calculate airspeed and thrust required (TR) with the air density (ρ) at various altitudes. Afterwards, power available (PA) and power required (PR) are obtained by multiplying each thrust available and required by the airspeed (Eq. (7) and (8)) which can be computed in Eq. (9). Utilizing both PA and PR, the rates of climb (ROC) and sink (ROS) can be computed using Eq. (10).

$$C_D = C_{D0} + kCL^2 \tag{5}$$

$$\mathrm{D} = \mathrm{TR} = 0.5\rho \mathrm{SV}^2\mathrm{C_D} \tag{6}$$

$$\mathrm{PA} = \mathrm{TA}\cdot \mathrm{V} \tag{7}$$

$$\mathrm{PR} = \mathrm{TR}\cdot \mathrm{V} \tag{8}$$

$$\mathrm{V} = \sqrt{2\mathrm{W}/(\rho \mathrm{SC_L})} \tag{9}$$

$$\mathrm{RC} = (\mathrm{PA} - \mathrm{PR})/\mathrm{W} \tag{10}$$

3.3 Vertical Take-off and Landing Performance

Next, this study examines the ability of the aircraft to vertically take off and land, allowing the aircraft to ascend and descend vertically without the need for a traditional runway at the approximate time suitable and enough to perform its goals. The UAV utilizes specialized propulsion systems, such as vertical thrust engines or rotors, to lift off directly from the ground and achieve a stable hover. This research enhances operational adaptability, allowing the aircraft to access confined spaces or areas with limited infrastructure. Vertical Take-off and Landing (VTOL) is a widely used technique in diverse aerial vehicles, such as helicopters and drones, offering advantages in situations where Conventional Take-off and Landing (CTOL) approaches are unfeasible. The versatility of VTOL methodology extends its utility across military, civilian, and commercial domains, fostering advancements in aviation technology and broadening the capabilities of unmanned aerial vehicles [23].

For the aircraft to be lifted off the ground and perform vertically take-off and land is that the VTOL propulsion needs to produce enough thrust for it to be equal to or greater than the weight of the aircraft. The specification of the aircraft is in Table 4. After gathering the data on thrust-to-weight ratio between the thrust and weight, Eq. (11) is used to calculate the percentage extra that could be used to calculate the excess power of the battery that is available. Next, Eqs. (12) and (13) complete one another, as Eq. (13) needs the motor power to calculate the approximate time for vertical take-off and landing.

Table 4 *Specification of the BWB UAV VTOL's motor and battery*

Item	Parameters	Value
QF3758, electric ducted fan	Motor KV (rpm)	1200
	Max. Motor Power, Pmax	2800
	Blade (W)	12 blades
	Max. Rated Current, Imax	100
	Motor Voltage, Vmotor (V)	29.9
	Rotor Diameter (mm)	90 mm
	Weight (each) (kg)	430
	Thrust (kg/f)	4.5
	Rotor	12 blades
	no of propeller	4
	Total weight for motor (kg)	1720
Maxamps Lithium-Ion Polymer (Lipo) Battery	Voltage,V	29.6
	Capacity, C	5200 mAh
	Total Battery	4
	Weight (g)	855
	Amp hours (Ah)	234
	ESC (A)	120 A

$$\Delta\,\% = (T/W - [T/W]_{hover})/[T/W]_{hover} \tag{11}$$

$$\mathrm{P}_{motor}\ (\text{watts}) = \mathrm{I}_{motor}\ (\mathrm{A})\ \mathrm{V}_{batt}\ (\mathrm{V}) \tag{12}$$

$$\mathrm{t}_{hover}\ (\mathrm{s}) = \mathrm{C}_{batt}(\mathrm{mAh})\mathrm{V}_{batt}\ \mathrm{P}_{motor} \tag{13}$$

3.4 Range and Endurance

The range and endurance are crucial to identify the aircraft's capability to withstand a certain distance required within the time to achieve its mission objective.

$$\mathrm{I}_{motor} = \mathrm{PR}/\mathrm{V}_{batt} \tag{14}$$

$$E\ (\mathrm{hr}) = \mathrm{C}_{batt}/\mathrm{I}_{motor} \tag{15}$$

$$\mathrm{R\ (km)} = \mathrm{Ev(km/h)} \tag{16}$$

4. Results and Discussions

4.1 Thrust and Power Analysis

The evaluation of thrust and power against airspeed examines how an aircraft's conditions for thrust and power change across varying speeds. Analyzing thrust against airspeed helps identify the optimal speed range where motor thrust equals drag. On the other hand, analyzing power against airspeed aids in understanding the energy needed to overcome aerodynamic drag at different speeds, facilitating the identification of the most efficient airspeed for various flight phases. This analysis is crucial for optimizing aircraft performance and battery efficiency, ensuring the safety of flight operations by understanding the interplay between thrust, power, and airspeed. Eq. (6), (7), and (8) are used to calculate the thrust required, thrust available, power required, and power available.

The thrust available for the VTOL and fixed wing is the same as the maximum thrust of the motor for horizontal flight, given in the specifications, which is 35.28 N. After gathering the data from the equation mentioned, the data of the thrusts and powers, both against airspeed, is then plotted for the VTOL and fixed wing for altitude at Sea Level, 1000m, 2000m, 3000m, and 9900m, respectively. From the graphs shown in Fig. 2(a) to Fig. 2(d), the values of minimum speed, maximum speed, and optimal speed could be determined. The data that is collected is gathered and tabulated in Table 5 for VTOL UAV and fixed wing UAV.

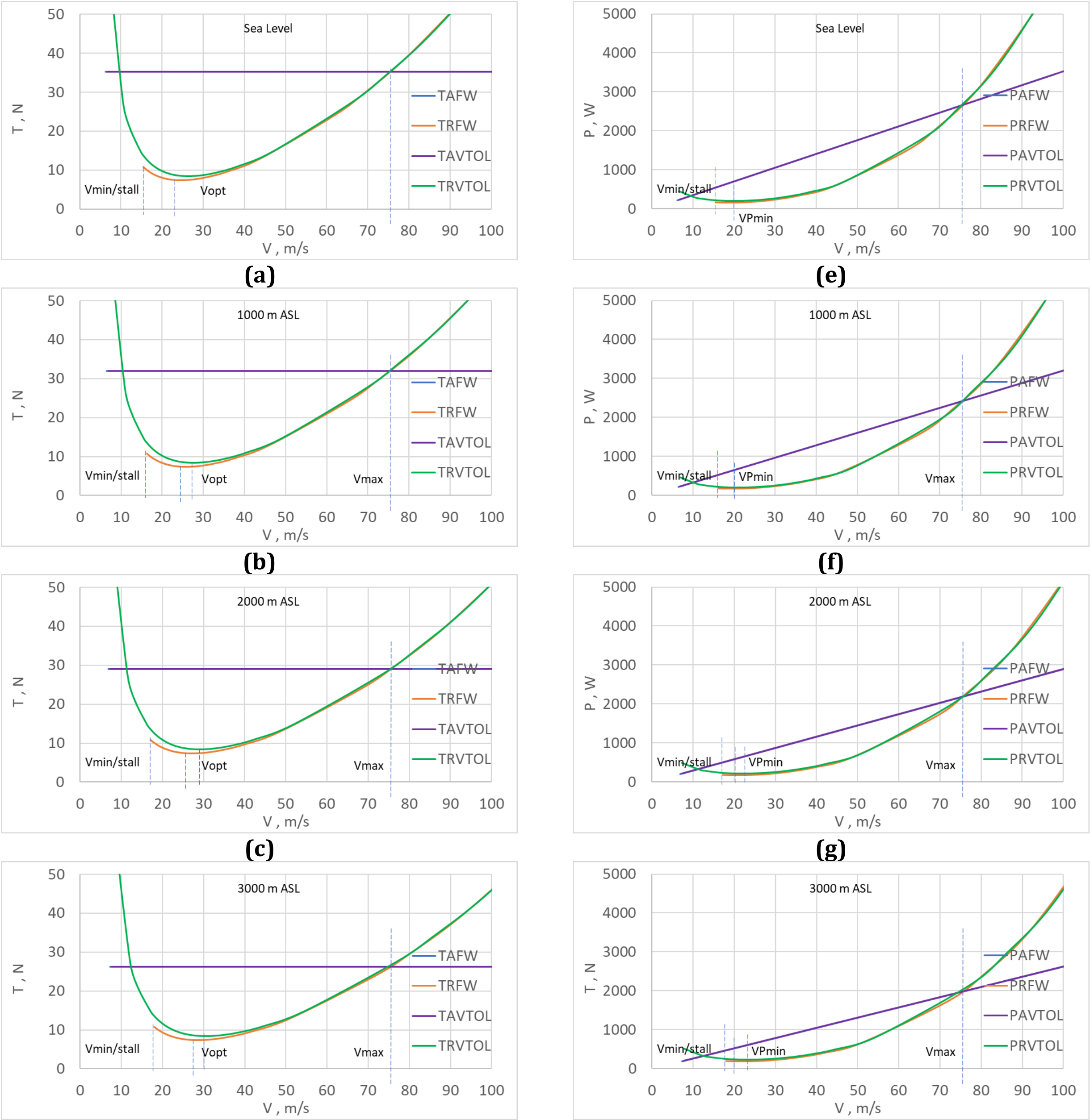
Table 5 *UAV's minimum, maximum, and optimal speed at various altitudes*

	Altitude, h (m)	0	1000	2000	3000
VTOL	Vmin, (m/s)	10	11	12	13
	Vmax, (m/s)	27.03	28.37	29.84	31.38
	Vopt, (m/s)	75.5	75.5	75.5	75.5
Fixed Wing	Vmin, (m/s)	8.5	9	10	11
	Vmax, (m/s)	25.31	26.57	27.94	29.38
	Vopt, (m/s)	75.5	75.5	75.5	75.5

The flight envelope of an aircraft is the abilities of a design, expressed in terms of airspeed and load factor or atmospheric density, which are frequently simplified to altitude. In other words, the flight envelope, depicted by a circular boundary, defines the space where the aircraft can safely operate, considering limitations related to stall conditions, propulsion, and the capabilities of control surfaces. As seen from the graphs, the intersections representing available thrust and required drag or thrust are the flight envelope [24].

The efficiency of an airplane is determined by the strength of the forces acting on it during a particular flight attitude. In steady and level flight, the drag equals the thrust, and the lift is balanced by the weight of the aircraft. The analysis underscores that the minimum speed is situated below the stall speed. However, if the minimum speed exceeds the stall speed, the stall speed is considered the minimum speed of the aircraft. Fig. 2 shows that both aircraft can function effectively when the required thrust is equal to or less than the available thrust and the aircraft is capped at the maximum speed. The optimum speed is reached at the point of minimum required thrust, corresponding to the maximum lift-to-drag ratio. Simultaneously, the limitations of this UAV are highlighted where the available thrust intersects with both maximum and minimum speeds, defining the operational parameters of the aircraft. Furthermore, it could also be seen from the graph that as the altitude increases, the minimum and optimal speeds increase as well. This is because when altitude increases, the density of air decreases, thus lighter atmospheric conditions occur.

Plotted graph of power against airspeed at various altitudes (Fig. 2(e) until (h)) for both aircraft, observing the comparison of the fixed wing and VTOL in terms of minimum, maximum, and optimal speeds in this study, the BWB UAV VTOL has a slight difference from the BWB UAV fixed wing. The maximum velocity could be seen higher in fixed-wing aircraft as the speed is influenced by the weight of the aircraft. Optimum speed tends to be higher at larger weights due to the lift-to-drag ratio being impacted by its weight can be seen that VTOL has a slightly higher result than compared to the fixed wing, as the more the weight of the aircraft, the more thrust is needed to overcome the gravitational forces during take-off, leading to higher power requirements.



(a) (e)

(b) (f)

(c) (g)

(d) (h)

Fig. 2 *Graph thrust versus airspeed at (a) sea level; (b) 1000m; (c) 2000m; (d) 3000 m, and graph power versus airspeed at (e) sea level; (f) 1000m; (g) 2000m; (h) 3000 m*

4.2 Stall Analysis

When an airplane's wing angle becomes too steep and the wing exceeds the critical angle of attack, leading to reduced lift and performance decline is the occurrence of stall of an aircraft. Any unstable due to flying at a low pace or when the angle of attack is high, airflow over the wings of the aircraft can significantly decrease lift and increase drag. Stall speed is a major contributor to flying safety, with a substantial number of fatal accidents [25].

The stall speed can be calculated using Eq. (9) by using the data from Table 3 and Table 2. Fig. 3 shows the data graphically after the stall speed for each altitude under consideration has been established for both fixed wing and VTOL UAVs. The graph illustrates that the stall speed of the UAV increases when the altitude increases, thus showing that the air density affects the stall speed. The weight of the aircraft affects the angle of attack, AOA. The heavier the aircraft, the closer it is to the critical AOA, causing the aircraft to stall at a faster airspeed [11].

Therefore, a lighter aircraft would serve the opposite of stalling at a lower airspeed. The comparison could be analysed from Fig. 3 and Table 6 below.

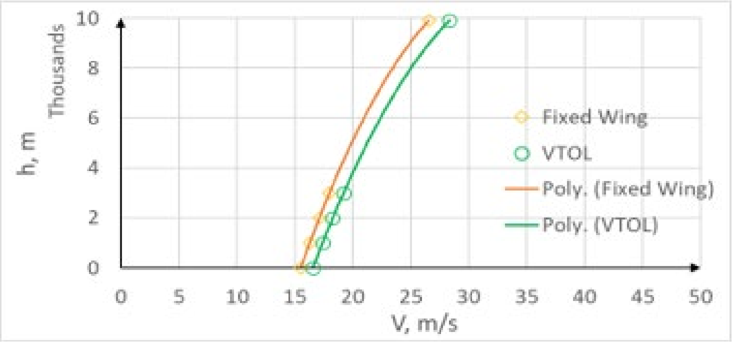


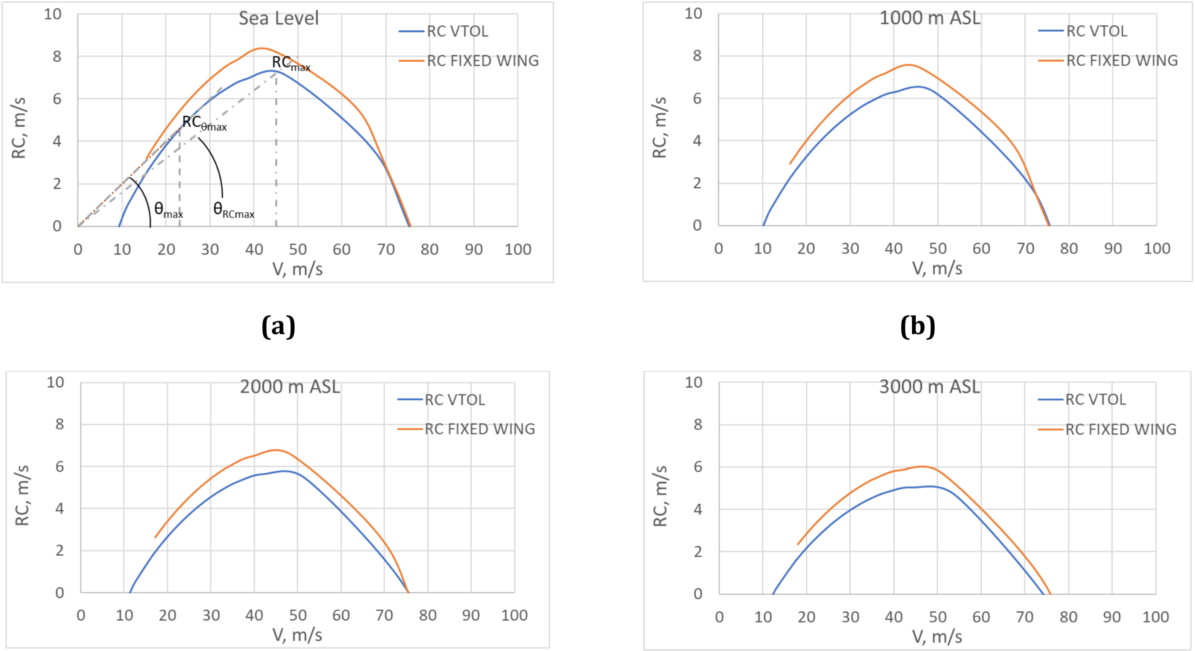
Fig. 3 *Stall speed against altitude graph of VTOL and fixed wing*

Table 6 *Stall speed at various altitudes of VTOL and fixed wing*

Altitude, h (m)	Stall speed of Fixed Wing, V_S (m/s)	Stall speed of VTOL, V_S (m/s)
0	15.5	16.55
1000	16.27	17.38
2000	17.11	18.27
3000	17.99	19.21
9000	26.54	28.34

4.3 Rate of Climb Analysis

The rate of climb is used to evaluate the UAV's speed to vertically climb to a certain height. It is a pivotal performance parameter that is affected by aerodynamic efficiency, weight considerations, and operational altitude requirements. The rate of climb of the fixed wing and VTOL UAV rate of climb is obtained by deriving Eq. (10), and Fig. 4 below shows the analyses depicted at various altitudes.



(a)

(b)

(c)

(d)

Fig. 4 *Rate of climb against airspeed at various altitudes for VTOL and fixed wing at (a) sea level; (b) 1000m; (c) 2000m; (d) 3000 m*

The data shown in the graph indicates a trend for the climb rate to decrease with increasing altitude for both UAVs. The chart illustrates that the UAV prototype design achieved its highest maximum rate of climb at sea level, recording 8.4 m/s for the fixed wing and 7.2 m/s for the VTOL. However, a more in-depth analysis of the climb rate at each specific altitude will be presented in the subsequent discussion.

Figure 4 shows the rate of climb at various altitudes of sea level, 1000m, 2000m, and 3000m. Data for both VTOL and fixed wing is present to analyse the comparison between them. The graph also provides the angles of the best rate of climb with the maximum value. To identify the optimum rate of climb and the overall efficiency without considering the climb angle, observe the airspeed at the maximum rate of climb, which also focuses on how quickly the UAV can climb. This analysis provides valuable insights into the aircraft's performance characteristics during ascent.

From Table 7 and the figures above, it indicates that to achieve the maximum and efficient rate of climb, the graphs and data analyzed above show the recommended rate of climb angle and the airspeed. The aircraft should operate at a maximum rate of climb speed, VRCmax, and maintain the speed with a climb angle at the maximum rate of climb angle, θRCmax, for all altitudes to achieve the optimum value for the aircraft to attain the best maximum rate of climb. On the other hand, to achieve the best rate of climb, the aircraft should operate at maximum steady climb speed, Vθmax in meters per second, and maximum steady climb rate, θmax angle degrees.

Table 7 *Rate of climb parameters at various altitudes*

	Alt., h (m)	RC_{max} (m/s)	V_{RCmax} (m/s)	$V_{\theta max}$ (m/s)	θ_{RCmax} (°)	θ_{max} (°)
VTOL	0	7.2	45	23.1	9.1	13.3
	1000	7.6	46	27.8	9.4	9.8
	2000	5.8	48	30.0	7.0	8.5
	3000	5.0	49	31.0	5.8	7.5
Fixed Wing	0	8.4	42	23.4	11.3	13.3
	1000	7.6	43	24.6	10.0	11.8
	2000	6.8	45	25.9	8.6	10.3
	3000	6.0	47	27.2	7.3	9.0

The data specified in the graphs indicates the optimal airspeed and climbing angles to attain the aircraft's maximum and optimal climb rates at various altitudes that should be taken into consideration when planning and conducting flight operations. Table 7 encapsulates the data derived from the previously constructed graph for easy reference and analysis of both VTOL and fixed-wing. It shows that the optimal rate of climb for the aircraft is affected by the value of the airspeed to be chosen and the climbing angle. The comparison between the two aircraft shows that the fixed wing contributes to a higher maximum rate of climb than VTOL, and this is because a larger weight means that the gravitational pull of the aircraft is higher.

4.4 Ceiling Analysis

Examining an aircraft's ceiling is crucial for understanding the highest operational altitude it can achieve. This analysis offers insights into the aircraft's performance constraints and capabilities in diverse mission scenarios. Elements like the aerodynamic efficiency of the BWB design and weight considerations play a role in determining the aircraft's capacity to reach elevated altitudes. A detailed analysis of the ceiling facilitates a comprehensive assessment to determine suitability for specific mission profiles.

Additionally, gaining insight into the ceiling analysis aids in optimizing the aircraft's performance, ensuring its functions and efficiencies within the altitudinal parameters. The absolute ceiling refers to the highest altitude at which an aircraft can climb before it is unable to produce enough thrust to overcome the forces of weight and drag. In this study, the climb rate for both aircraft is maintained at 100 feet per minute, equivalent to 0.508 meters per second in the metric system, to ensure the aircraft's flight operations are both safe and efficient, contributing to a stable and controlled ascent during its journey.

The graph in Fig. 5 is used to calculate both the absolute and service ceilings, while the corresponding values for these ceilings are then documented in Table 8. It could be derived that the absolute ceiling of the aircraft is determined to be 10500 meters, while the service ceiling is established at 9900 meters for fixed wing and 9845 meters absolute ceiling with 9100 meters of service ceilings for VTOL. This signifies the altitudes at which the aircraft can safely and effectively operate for both UAVs. However, the service and absolute ceilings seem to be lower as we analyze from the graph in Fig. 5, and this is because heavier weight can negatively affect an aircraft's ceiling (maximum altitude). As the weight increases, the ability to climb to higher altitudes is reduced due to the challenges to generate more lift to overcome its drag [26].

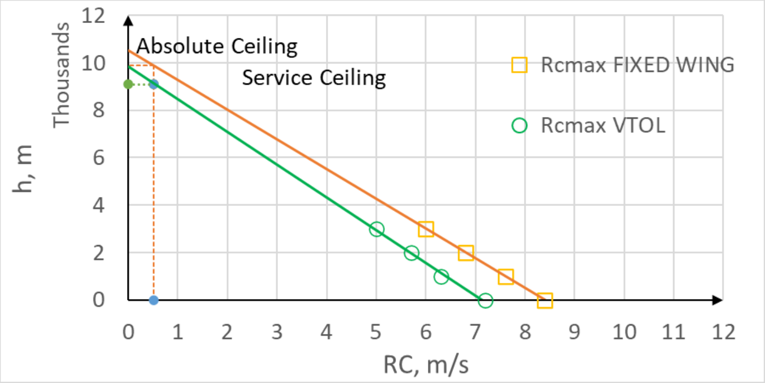


Fig. 5 *Altitude versus max. rate of climb of VTOL and fixed wing*

Table 8 *Absolute and service ceilings*

	Ceiling	Altitude, h	RCmax
VTOL	Absolute	9845 m	0 m/s
	Service	9100 m	0.508 m/s
Fixed Wing	Absolute	10500 m	0 m/s
	Service	9900 m	0.508 m/s

4.5 Endurance and Range

Analysing the endurance and range of an aircraft is crucial for understanding its operational capabilities, providing valuable insights into its ability to sustain flight over time and cover long distances. Endurance analysis evaluates how efficiently the aircraft utilizes its power, influencing its capacity for prolonged airborne missions. In contrast, range analysis explores the maximum distance the aircraft can cover in a single flight while considering fuel or energy limitations. This analysis is essential for optimizing the UAV's mission profile, ensuring the aircraft aligns with specific operational requirements, particularly in applications such as surveillance.

The endurance of the aircraft is evaluated using Eq. (14) and (15) and the continued in Eq. (16) for a range of translational flight (not VTOL). The endurance and range for each altitude are plotted in the graph, and the parameters for endurance are presented in Fig. 6 and Fig. 7, respectively.

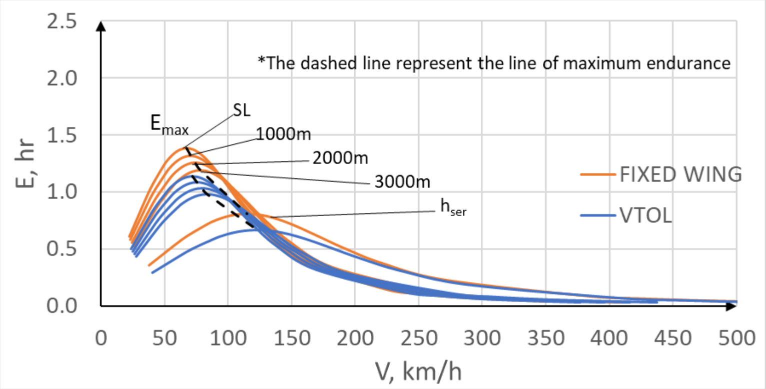


Fig. 6 *Endurance versus airspeed at various altitudes for VTOL and fixed wing*

Fig. 6 above shows the relationship between endurance and airspeed at different altitudes for both aircraft, revealing that the maximum endurance decreases as altitude rises. The graph illustrates that lower altitudes result in higher endurance but lower airspeed, while higher altitudes offer increased airspeed at the expense of endurance. The data gathered outlines specific endurance parameters, indicating the optimal airspeeds for achieving maximum endurance at various altitudes. The data indicates that, without factoring in airspeed, flying at sea level is recommended for maximizing endurance. Nevertheless, operators have the flexibility to adjust these parameters based on the unique requirements of their missions. Table 9 contains detailed information on the maximum endurance and range at sea level of the current study and the previous study's aircraft, as well as the best velocity to achieve it. When the UAV is at its maximum endurance, a lower weight may mean a longer endurance since it may use less energy during flight. Although at maximum range, a higher weight may mean a somewhat shorter endurance because the weight influences the power required for the aircraft. Heavier aircraft may need more powerful engines, and the efficiency of these engines at different weights can impact fuel consumption.

Table 9 *Endurance parameters at various altitudes*

	Altitude, h (m)	Optimal Speed, V_{opt} (m/s)	Endurance (hr)
VTOL	0	19.96	1.14
	1000	20.96	1.08
	2000	22.04	1.03
	3000	23.17	0.98
	9000	34.18	0.66
Fixed Wing	0	18.69	1.38
	1000	19.62	1.32
	2000	20.64	1.25
	3000	21.70	1.19
	9000	32.01	0.81

The range is associated with the ground speed rather than the airspeed. Therefore, in the presence of wind, it is necessary to reassess our range calculations to accommodate the influence of the wind.

Based on Fig. 7, the graph shows the relationship between the range and airspeed at different altitudes. Although there are noticeable changes for the optimal speed but only minimal changes in the range as the altitude increases. At high altitudes, the aircraft could obtain high maximum range as well as high optimal speed, but at low altitudes, the aircraft could obtain almost the same range but with low optimal speed. Table 10 outlines the data for the aircraft to achieve maximum range with its optimal airspeed at various altitudes for both aircraft.

From the data presented, the aircraft can operate at various altitudes. if it needs to operate within a 100-kilometer range, this is based on the previous study conducted. Although a higher altitude would provide a high airspeed for the aircraft, the weight influenced the range too, as at a maximum range, a heavier weight would provide a shorter range as the constant flight needs energy. Furthermore, the study has uncovered that the aircraft achieves its highest range by sustaining an optimal lift-to-drag ratio at various altitudes. This is accomplished by flying with the least necessary thrust, leading to the best efficiency and performance for both aircraft. The aircraft's weight can impact its capacity to achieve mission requirements, thereby influencing the overall distance it can travel and, consequently, the range differences in Fig. 7.

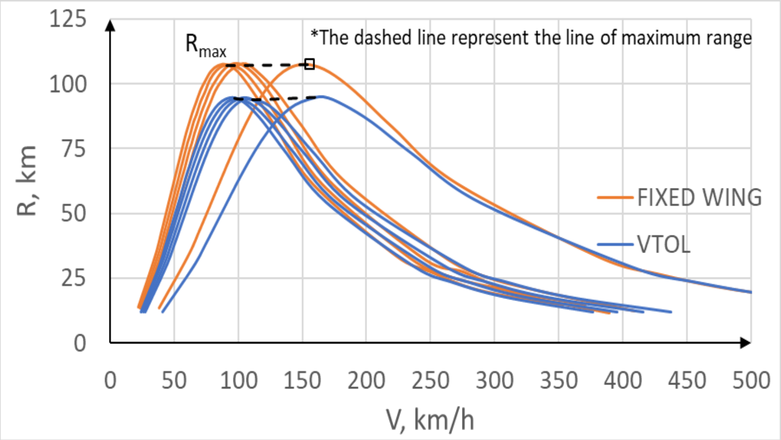


Fig. 7 *Range versus airspeed at various altitudes of VTOL and fixed wing*

Table 10 *Range parameters at various altitudes*

	Altitude, h (m)	Optimal Speed, V_{opt} (m/s)	Range (km)
VTOL	0	27.03	94.39
	1000	28.37	93.98
	2000	29.84	94.54
	3000	31.38	93.75
	9000	46.28	94.97
Fixed Wing	0	25.31	107.52
	1000	26.57	107.13
	2000	27.94	107.64
	3000	29.38	107.89
	9000	43.34	107.47

4.6 Vertical Take-off and Landing Analysis

The take-off distance is a crucial metric in flight performance as it specifies the minimum distance an aircraft needs to cover to lift off from a runway. Although for this study, take-off and landing are done vertically. The hovering performance of a vertically taking off and landing (VTOL) aircraft is determined by several factors, including the thrust-to-weight ratio, the battery capacity, and the motor power.

The thrust-to-weight ratio is the ratio of the aircraft's thrust to its weight. A higher thrust-to-weight ratio means that the aircraft has more power to lift itself off the ground. The thrust of the motor is divided by the maximum take-off weight of the aircraft to obtain the thrust-to-weight ratio. The thrust is 18 kg/f and MTOW is in Table 1. For hovering, a thrust-to-weight ratio of at least 1.0 is required about its own weight. This means that the aircraft's thrust must be equal to or greater than its weight. The thrust-to-weight ratio is calculated in 1.32, which results in 32% more thrust than it needs to hover for other purposes, such as accelerating or climbing.

The battery capacity is the amount of energy that the battery can store. A higher battery capacity means that the aircraft can hover for a longer period. The hovering time is limited by the amount of energy that the battery can store and the amount of power that the motor can draw from the battery. The motor power is the amount of power that the motor can produce. A higher motor power means the aircraft can hover with a heavier payload. The motor power must be sufficient to overcome the weight of the aircraft and the payload. Eq. (11), (12), and (13) are used to determine if the battery is sufficient to provide the duration of time needed for take-off and landing. At 70% to 60% throttle is used for each motor to provide a current of 70A and a voltage of 23V, with consideration of energy loss during flight.

The hovering time is estimated to be around 295.94 seconds, which is approximately 4 minutes. The motor power and battery capacity of the aircraft enable it to hover for a reasonable duration. However, the hovering performance could be improved by increasing the thrust-to-weight ratio. This could be achieved by reducing the weight of the aircraft or increasing the thrust of the motors.

4.7 Mission Profile Analysis

The mission profile, as shown in Fig. 8, studies the UAV's performance entirely, including its range, weight, and endurance to achieve its mission objectives. The BWB UAV VTOL initiates a vertical take-off and afterward, it seamlessly switches to horizontal flight after reaching the ideal altitude, maximizing aerodynamics for effective cruising. The UAV carries out the mission of surveillance throughout the cruise phase. The UAV may return to vertical flight for a precise descent or landing after completing mission operations. In-depth data and performance reviews are part of the post-mission analysis, which helps shape future mission planning and possible improvements to UAV operation or design. The performance data indicates that this is feasible because the aircraft can function within the designated mission parameters.

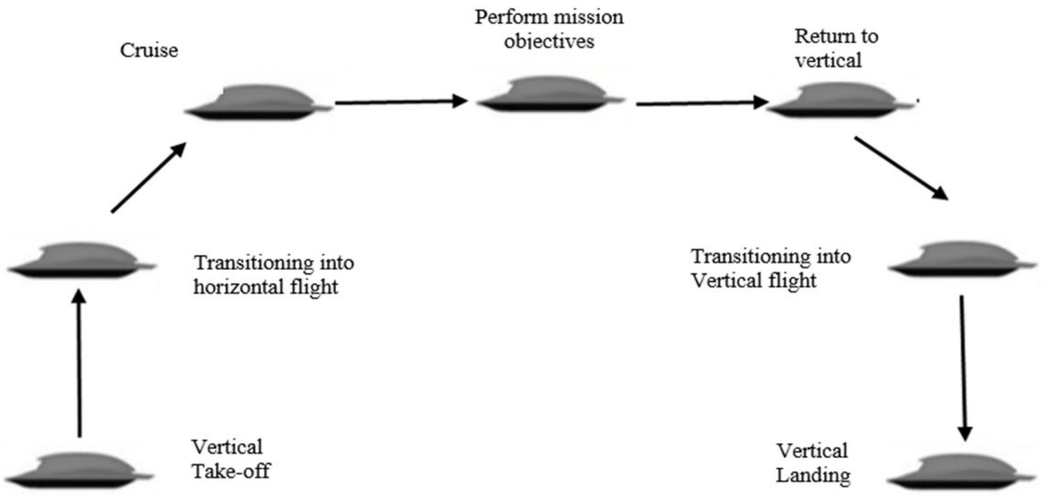


Fig. 8 *Mission profile of BWB UAV VTOL*

After examining the performance data summarized in Table 11, the unmanned aerial vehicle (UAV) demonstrates the capability to function according to the mission specifications, achieving its objectives. Moreover, the UAV provides an additional range of approximately seven kilometers, which could be beneficial in addressing unforeseen emergencies or disruptions during flight operations.

Table 11 *Performance operation at sea level condition*

Parameters	Value
Weight, m (kg)	13.69
Optimal Airspeed (m/s)	27.03
Optimal Airspeed (km/h)	97.31
Thrust (N)	8.48
Range, R (km)	94.39
Hovering Time (s)	295.94

5. Conclusion

The current study is an analysis of the performance of the blended wing-body (BWB) unmanned aerial vehicle vertical take-off and landing (VTOL). It evaluates the performance in terms of thrust, power, airspeed, rate of climb, rate of sink, absolute and service ceilings, maneuverability, endurance, and range that will be compared with the previous study of the BWB UAV fixed wing to evaluate the limitations and capabilities of the aircraft. Other than that, the mission profile of the VTOL UAV is emphasized to ensure that the goal of the performance is enhanced to fulfill and comply with the requirements of the mission profile. Therefore, the overall study provides a conclusion that could be used to expand the capabilities of the aircraft and improve flight performance.

In conclusion, this research has demonstrated the performance of the flight capabilities and mission profile of the blended-wing body (BWB) unmanned aerial vehicle (UAV) vertically take-off and landing (VTOL). Through a thorough examination of diverse performance metrics between the VTOL UAV compared with the previous study of the BWB UAV fixed wing and the mission profile with vertical take-off and landing, various understandings have been acquired, offering opportunities to elevate the UAV's efficiency and attain successful mission results. These discoveries hold the potential to be used in future improvements, making noteworthy contributions to the advancement of UAV technology, especially with the structure of a blended wing-body.

Some recommendations for future development regarding this research could be implemented to improve the study, such as the advancement of aerodynamic studies of the vertical take-off and landing, especially by using simulations, which should be undertaken to optimize lift and drag characteristics, enhancing overall efficiency and flight performance. By using simulations, real-life conditions could be tested, and this would widen the exploration of the aircraft's flight characteristics, which could be observed in-depth and provide a safe environment with benefits in cost as actual flight could be diminished. The simulation result could be compared with the theoretical approach to evaluate if there is an error in the flight parameters.

However, creating an actual prototype of this study could enhance the exploration of the combination of emerging technologies, such as the usage of lighter materials and advanced propulsion systems, which can significantly contribute to the UAV VTOL's capabilities. Modifying the performance characteristics to specific mission requirements is crucial, emphasizing the endurance, range, and weight of the aircraft. Nevertheless, some aircraft require different approaches depending on the objectives of the flight profile.

Another suggestion that could be implemented is that further research should focus on the development and enhancement of hovering systems, ensuring safer and more reliable operations in diverse environments. Instead of only performing hovering of vertical take-off and landing, the performance could be done by performing a hovering flight analysis of the UAV mission profile. By doing so, the performance could be compared when evaluating the performance through various circumstances with constraints, and advancement should be improved in further studies. To conclude, the recommendation mentioned above offers an opportunity to improve in various categories of performance, conceptual design prototypes, and the development of more trustworthy, effective, and efficient UAVs

Acknowledgement

The authors acknowledge the support for this study from the Ministry of Higher Education of Malaysia under the Prototype Research Grant Scheme (PRGS) with contract number PRGS/1/2022/TK08/UITM/02/1) and the Assistant Vice-Chancellor's Office, College of Engineering, Universiti Teknologi MARA. The authors also like to specially thank Dr. Ir. Wahyu Kuntjoro for his academic support in constructing and testing the UAV.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Rizal Effendy Mohd Nasir;* ***data collection:*** *Che Noureen Sabrina Saifuddin;* ***analysis and interpretation of results:*** Che Noureen Sabrina Saifuddin, *Atikah Basyirah Abdul Muta'ali,* Rizal Effendy Mohd Nasir*;* ***draft manuscript preparation:*** Che Noureen Sabrina Saifuddin, Rizal Effendy Mohd Nasir. *All authors reviewed the results and approved the final version of the manuscript.*

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