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Design of a Multi-Purpose Vertical Take-Off and Landing Unmanned Aerial Vehicle

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ABSTRACT

This study focuses on the conceptual and detailed design of a multi-purpose Vertical Take-Off and Landing (VTOL) Unmanned Aerial Vehicle (UAV) capable of operating in rugged terrains. Recent advancements in VTOL technology have significantly increased the demand for aircraft with reduced space requirements and versatile capabilities across sectors such as agriculture, logistics, and defense. VTOL aircraft, with their ability to efficiently alter operational payloads, are now used in various applications, including ammunition delivery, agricultural spraying, search and rescue, and firefighting. Thanks to their hybrid configurations, VTOL UAVs provide critical operational advantages, such as the ability to take off and land in confined spaces, hover during operations, and transition into horizontal flight mode. The UAV designed in this study has been optimized for challenging missions with a cruise speed of 20 m/s, a maximum altitude range of 100-500 meters, and a payload capacity of 0.5 kg. Configurable with various mission equipment, the UAV supports operations like data collection, cargo transport, and surveillance. The aerodynamic and structural features, including the NACA 4412 airfoil, inverted V-tail configuration, and modular components, were carefully selected to enhance performance. Analytical tools like XFLR5 and OpenVSP validated the aerodynamic parameters, while SolidWorks was used for modeling. The analyses confirmed that the UAV meets flight stability and performance requirements. This UAV provides a cost-effective, high-performance, and reliable solution for both defense and commercial applications. Its modular design allows easy adaptation to diverse mission scenarios. Ultimately, this study presents innovative approaches to enhance the operational potential of VTOL aircraft and offers practical solutions for various scenarios.

Çok Amaçlı Dikey Kalkış İniş Yapabilen Hava Aracının Tasarımı

Makale Bilgisi

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ÖZET

Bu çalışma, engebeli arazilerde çalışabilen çok amaçlı bir Dikey Kalkış ve İniş (VTOL) İnsansız Hava Aracının (İHA) kavramsal ve detaylı tasarımına odaklanmaktadır. Son yıllarda VTOL teknolojisindeki hızlı gelişmeler, tarım, lojistik ve savunma gibi sektörlerde geleneksel sistemlere kıyasla daha az alan gerektiren ve çok yönlü yeteneklere sahip hava araçlarına olan talebi artırmıştır. Operasyonel yükü rahat şekilde değiştirilen VTOL hava araçları günümüzde mühimmat bırakma, tarımsal ilaçlama, arama kurtarma, yangın söndürme gibi birçok sektörde kullanılabilmektedir. VTOL İHA'lar hibrit konseptleri sayesinde dar alanlarda kalkış ve iniş yapabilme, havada sabit kalabilme ve yatay uçuş moduna geçiş sağlayarak önemli operasyonel avantajlar sunmaktadır. Bu çalışmada tasarlanan İHA, 20 m/s seyir hızı, 100-500 metre arasında değişen maksimum irtifa aralığı ve 0,5 kg faydalı yük kapasitesiyle zorlu görevler için optimize edilmiştir. Hava aracı çeşitli görev aygıtları ile konfigüre edilerek veri toplama, yük taşıma ve gözlem gibi görev profillerini desteklemektedir, NACA 4412 kanat profili, ters V kuyruk konfigürasyonu ve modüler bileşenler gibi aerodinamik ve yapısal özellikler göz önünde bulundurularak geliştirilmiştir. Tasarım sürecinde XFLR5 ve OpenVSP gibi analiz araçları modelleme içinse Solidworks kullanılarak aerodinamik parametreler doğrulanmış, tasarımın uçuş stabilitesi ve performans gerekliliklerini karşıladığı onaylanmıştır. Bu İHA, hem savunma hem de ticari uygulamalar için maliyet etkin, yüksek performanslı ve güvenilir bir çözüm sunmaktadır. Ayrıca modüler yapısı sayesinde farklı görev senaryolarına kolayca uyum sağlayabilmektedir. Önerilen tasarım, günümüzün karmaşık operasyonel ihtiyaçlarını karşılamak ve İHA teknolojilerinde yenilikçi çözümler geliştirmek için önemli bir katkı sunmaktadır. Sonuç olarak, bu çalışma, VTOL hava araçlarının kullanım potansiyelini artırmaya yönelik yeni yaklaşımlar sunmakta ve çeşitli operasyonel senaryolar için çözümler önermektedir.

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INTRODUCTION

Today, unmanned aerial vehicles (UAVs) have become an important part of modern technology by being used in a wide variety of missions in different sectors. UAVs were first used for critical functions such as information gathering and target identification in military operations, but with the advancement of technological developments and autonomous systems, they have a wide range of applications in many fields such as logistics, agriculture, disaster management, infrastructure inspection and search and rescue (Çoban et al., 2022; Kurt & Ün, 2015). The main reason why UAVs have such a wide range of missions is their ability to offer customized solutions for mission profiles with different design concepts. Diversified design concepts such as fixed wing, vertical take-off and landing vehicles (VTOL), rotary wing and flapping wing have increased the operational flexibility and mission capability of UAVs, making them indispensable in both defence industry and commercial applications (Oktay & Özen, 2021; Uzun & Oktay, 2023).

One of the most important advantages of UAVs is their capacity to successfully accomplish many challenging missions without the need for human intervention. UAVs, especially in hard-to-access or hazardous areas, increase mission duration and efficiency by eliminating limitations such as G-force, fatigue and physical difficulties that humans may face. With the continuous development of autonomous systems, UAVs are becoming increasingly successful in performing high-precision missions by minimizing human errors and risks. For example, in the agricultural sector, UAVs have significantly reduced the need for manpower in functions such as monitoring the productivity of fields, analysing crop health, and planning fertilization and irrigation. These opportunities offered by UAVs contribute to sustainability and production efficiency in the agricultural sector, while at the same time reducing costs (Akkamış & Çalışkan, 2020).

In addition, in the infrastructure and energy sector, UAVs enable regular inspections of bridges, power lines and other infrastructure elements, thus facilitating maintenance and repair work. Offering a faster and more cost-effective solution compared to traditional methods, UAVs also increase occupational safety and reduce human-related risks. In the defence industry, UAVs, which are used in missions such as information gathering, reconnaissance and target identification, increase the security of operations and minimize the dangers for personnel in the field. UAV models designed for various operational needs are used in a wider range of missions every day, and in this direction, mission-specific designs of UAVs are of great importance (Mieloszyk et al., 2024; Wang et al., 2023).

In this study, the design of a multi-purpose VTOL class unmanned aerial vehicle (UAV) capable of operating in rugged terrain is discussed. Designed in accordance with the mission profile, this UAV will have the ability to take off vertically from the starting point, transition to cruise flight and land vertically again after the operation is completed. Thanks to its modular structure, this vehicle, which can easily adapt to various mission scenarios, has been optimized to perform different missions such as observation, data collection, and load carrying. During the design process, the UAV's wing profile, sizing, and dimensions were considered in detail, taking into account cost, time and production factors. These features aim to provide a user-friendly operation while increasing the mission effectiveness of the vehicle.

METHOD

The basic requirements for the designed aircraft to perform the task assigned by the operator are given with different mission scenarios. The designed aircraft is designed to drop 0.5 kg load in emergency situations or to carry equipment to observe anywhere. The aircraft has been designed to complete its mission in difficult terrain conditions. The design requirements of the aircraft designed in accordance with this mission profile are shown in Table 1.

Table 1

Aircraft design requirements

Requirement	Value
Cruise Speed	20 m/s
Stall Speed	15 m/s
Maximum Altitude	100-500 m
Climb Rate	2 m/s
Payload Capacity	0.500 kg

When the aircraft concept was selected, design requirements were taken into consideration, and when possible, mission scenarios were examined, it would be advantageous for the aircraft to have the ability to land and take off in all kinds of areas and to hover in the air. In this direction, the concept of the aircraft was determined as VTOL by evaluating parameters such as stability, maneuverability and take-off distance. This evaluation is given in Table 2.

Table 2

Aircraft concept decision matrix

Parameter	Importance [%]	Fixed Wing	Rotary Wing	VTOL
Stability	40	2	3	3
Manoeuvrability	20	3	1	2
Take-off Distance	40	1	3	3
Total	100	1.8	2.6	2.8

When selecting the wing concept of the aircraft, it is necessary to be very meticulous because the wing concept must be suitable for the mission profile and the aircraft concept. Considering the concept and mission profile of our aircraft, Delta Wing, Conventional Single Wing and Elliptical Wing were analysed in terms of manufacturability, drag force, stability and control parameters, and the Conventional Single Wing concept was decided (Uzun et al., 2022). The position of the selected wing concept is important in terms of avionics system layout, aerodynamic stability and vibration. For the wing position, a decision matrix was created by evaluating the stability, control and manufacturability parameters in Table 3, and as a result, a mid-wing structure was selected. Although this choice reduces the avionics system layout area, it will provide a more stable flight by reducing wing vibrations as it will be center supported.

Table 3

Wing Position Decision Matrix

Parameter	Importance [%]	Low wing	High wing	Mid wing
Stability	40	1	2	3
Control	30	2	2	2
Manufacturability	30	1	1	3
Total	100	1.3	1.7	2.7

The airfoil is the most important design parameter of an aircraft, it must meet the needs of the aircraft and be suitable for the mission profile and concept. If the important parameter for an aircraft is speed and maneuverability, thin airfoils with low camber ratio should be selected, while load-carrying aircraft need thick airfoils with high camber ratio. In this context, the aircraft designed in this study has speed and maneuverability due to its concept, so a thick airfoil is needed for load carrying (Erol et al., 2023).

Three different airfoils found in the literature were examined in the XFLR5 program. The speed, ceiling cruise altitude and Reynolds number given in equation 1 were used in this analysis.

$$Re = \frac{\rho V c}{\mu} \qquad (1)$$

ρ: Density of air (kg/m3)

V: Cruising Speed (m/s)

C: chord length of the wing (m)

μ: Dynamic viscosity of air ($kg/m.$ s)

As a result of the calculation, the Reynolds number was found to be 281,551.

The graph in Figure 1 illustrates the variation in lift coefficient with respect to the angle of attack for three different two-dimensional wing profiles. It is observed that, at an angle of attack of zero degrees, the NACA 4412 profile provides the highest lift coefficient.

Figure 1
Cl-Alpha graph

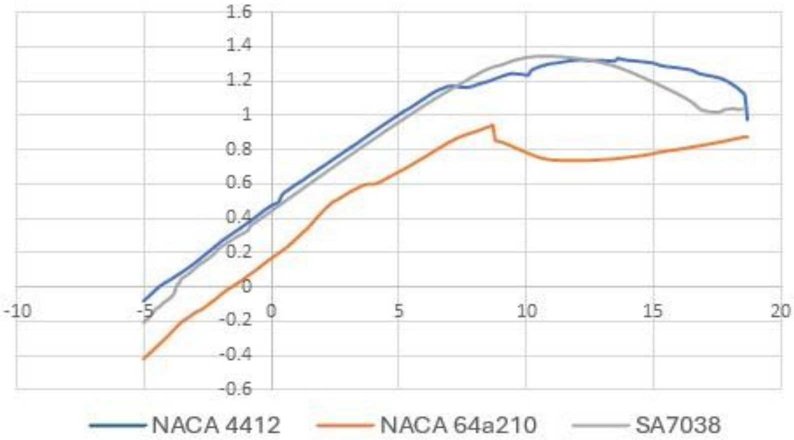


Figure 2 shows the drag coefficient of the three airfoils evaluated. Although there is not much difference between the airfoils at low angles of attack, as the angle of attack increases, the drag coefficient of the NACA 4412 profile is lower than the others.

Figure 2
Cd-Alpha graph

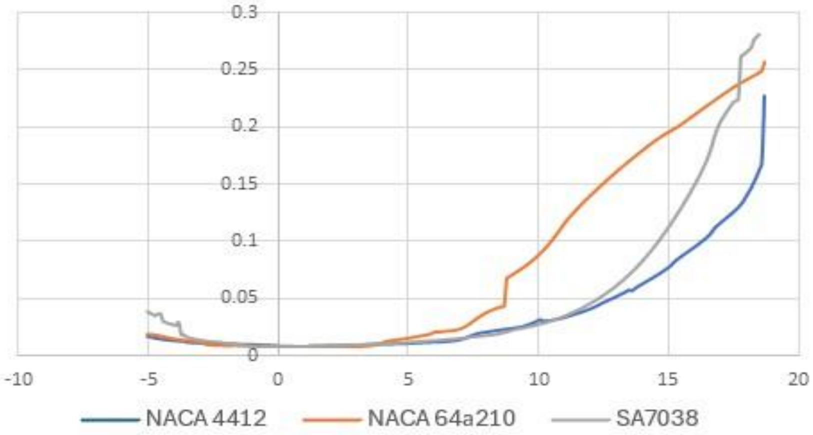


Figure 3 shows the variation of the moment coefficient according to the angle of attack. The most important parameter that ensures the longitudinal stability of the aircraft is the moment coefficient. During level flight, the aircraft will break its longitudinal stability and will tend to nose up, the aircraft must have a negative moment value in order to return to its stable position (Dağ et al., 2022). Thus, it will return to the equilibrium state without the use of control surfaces. When the results of the analysis in this context are analysed, it is seen that the most suitable airfoil is NACA 4412.

Figure 3

Cm-Alpha graph

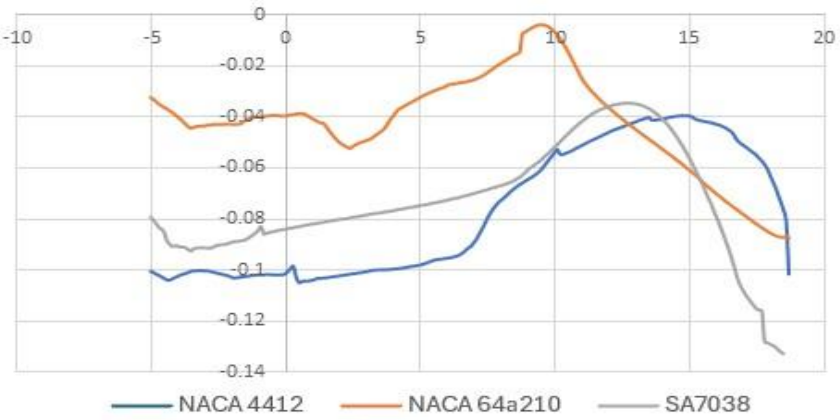


Table 4 shows the aerodynamic properties obtained as a result of the analysis performed on three different airfoils.

Table 4

Airfoils Aerodynamic Properties

Airfoils	C_{Lmax}	C_D	$(L/D)_{max}$	C_{m0}
NACA 4412	1.332	0.091	89.34	-0.102
NACA 64a210	1.346	0.073	87.44	-0.04
SA7038	0.947	0.083	69.82	-0.081

Considering the obtained numerical properties and analysis graphs, the airfoil decision matrix is given in Table 5

Table 5

Airfoil Decision Matrix

Parameter	Importance [%]	NACA 4412	NACA 64a210	SA708
$(C_L)_{max}$	20	2	3	1
$(C_D)_{min}$	25	1	3	2
$(CM)_0$	15	3	1	2
$(C_L/ C_D)_{max}$	25	3	2	2
Stall type	15	3	3	1
Total	100	2.55	2.45	1.65

As a result of the evaluation, it was decided that the NACA 4412 airfoil was suitable for the aircraft.

The tail configuration is a critical aspect to ensure optimal stability and control of the aircraft (Sertkaya, 2020). The tail assembly is the primary structure responsible for maintaining moment equilibrium during flight, thereby stabilizing the aircraft along its longitudinal axis. For effective stability, the tail configuration should have a low drag coefficient and minimal interference from the propulsion system's vortices. Within this context, T-tail, H-tail, Inverted V-tail, and Conventional tail configurations have been considered. Based on evaluations, which focused on stability, weight, and drag parameters, the Inverted V-tail configuration was selected for the aircraft. Table 6 presents a decision matrix of these parameters (Ünler, et al., 2022).

Advantages of the Inverted V-tail:

• By combining the functions of both vertical and horizontal stabilizers, the configuration minimizes wing surface area, thereby reducing parasitic drag.

• With fewer structural components compared to other configurations, the design is lighter.

• The reduced number of control surfaces simplifies manufacturing.

Disadvantages of the Inverted V-tail:

• Assembly is challenging.

• Control is more difficult due to the smaller wing surface area.

Table 6

Tail Assembly Concept Decision Matrix

Parameter	Importance [%]	H-tail	T-tail	Inverted V-tail	Conventional Tail
Stability	30	1	1	3	2
Drag	30	1	1	2	3
Structural Weight	30	1	1	3	2
Manufacturability	10	3	2	1	2
Total	100	1.60	1.30	2.30	2.10

It is critical for our aircraft to land at the end of the mission without breaking down. Our aircraft with VTOL configuration must be ready to land in case of any emergency. Considering these situations, it was decided that the landing gear configuration should be tricycle, considering the possibility of failure of the vertical engines.

The weight of the aircraft was determined as 4.300 kg by measuring the electronic and structural elements we will use. The maximum payload weight was determined as 0.500 kg. The total weight of the aircraft is determined as 4.300 kg by weighing each component separately. A sufficient lift force must be generated to support this weight during flight. In order to maintain a safe flight in cruise flight, it is essential that the carrying force to be generated by the geometric properties of the wing structure exceeds the weight of the vehicle. The cruise speed of the vehicle is determined as 20 m/s and the stall speed as 15 m/s. The required wing area is calculated according to the stall speed of the aircraft. Equation 2 expresses the balancing of the forces acting on the aircraft in the vertical axis during cruise flight.

$$W = L = \frac{1}{2} pV^2 SC_L \qquad (2)$$

Equation 3 can be used to calculate the wing surface area when considering stall conditions. This equation has been rearranged for this calculation, providing an expression for stall speed in terms of the vehicle's characteristic parameters.

$$V_{stall} = \sqrt{\frac{2W}{pSC_{L_{max}}}} \quad (3)$$

Using the expression in Equation 3, the minimum wing area requirement for the aircraft was calculated to be 0.24 m². However, as this value lies at the lower threshold, the risk of stalling increases under these conditions. Therefore, to enhance safety, a 25% safety factor was applied to the wing area. Following this adjustment, the wing area for the aircraft was determined to be 0.30 m².

The aspect ratio (AR), another characteristic feature of the wing element, has been set to 7.5. AR is a geometric parameter that directly influences the lift-to-drag ratio of the wing. The mathematical model is presented in Equation 4. Based on this model, typical aspect ratio ranges for various aircraft types have been established: 20–40 for gliders, 4–8 for mini-UAVs, 5–9 for passenger aircraft, 6–9 for low subsonic commercial aircraft, and 8–12 for high subsonic commercial aircraft (Raymer, 2012).

$$\mathrm{AR} = \frac{b^2}{S} \quad (4)$$

$$S = b * c \quad (5)$$

Using the equations in Equations 4 and 5, the wing span was determined as 1.5 meters and the chord length as 0.20 meters.

Following the completion of wing sizing, the sizing of the tail components was undertaken to effectively maintain the moment balance of the designed aircraft. To ensure complete aerodynamic stability, horizontal and vertical tail designs were carried out, leading to the selection of an Inverted V-tail configuration as the tail concept for the aircraft. This sizing approach is based on the principles of the conventional T-tail configuration. Accordingly, vertical and horizontal tail volume coefficients were determined, and the tail surface areas were calculated.

$$C_{HT} = \frac{s_{HT} L_{HT}}{S_W \, C_{MAC}} \quad (6)$$

$$C_{VT} = \frac{s_{VT} L_{VT}}{S_W \, b_w} \quad (7)$$

In Raymer's study, the vertical and horizontal tail volume ratios for composite mini-UAVs were determined as 0.50 and 0.04, respectively. The length of the moment arm was also decided to be 0.90 meters, assuming the vertical and horizontal moment arms to be equal. The design values obtained as a result of the detailed design of the aircraft are given in Table 7.

Table 7
Aircraft Properties

Parameter	Value
Wing span	1.5 m
Cord Length	0.20 m
Aspect ratio	7,5
Taper ratio	1
Wing Area	0.30 m2
Tail Cord Length	0.15 m
Moment arm length	0.90 m
Inverted V-tail angle	-30°

Based on the numerical data obtained from these calculations, the designs were created. SolidWorks and OpenVSP software were utilized during the design process. The resulting aircraft design is presented in Figures 4, 5, and 6.

Figure 4
The isometric view of the vehicle's SolidWorks design

Figure 5
The side view of the vehicle's SolidWorks design

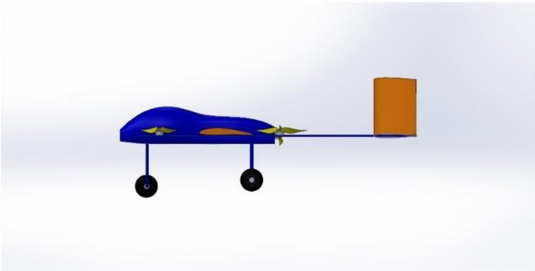
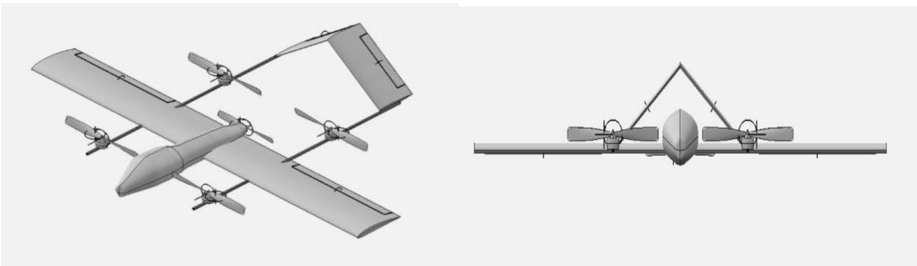


Figure 6
The view of the vehicle's OpenVsp design



RESULTS

Based on the design requirements and mission profile, the engineering model of the aircraft was created and modelled using various software tools. Subsequently, to validate the design, analyses were conducted using XFLR5 and OpenVSP software. The conditions and methods used in the analyses are presented in Table 8.

Table 8

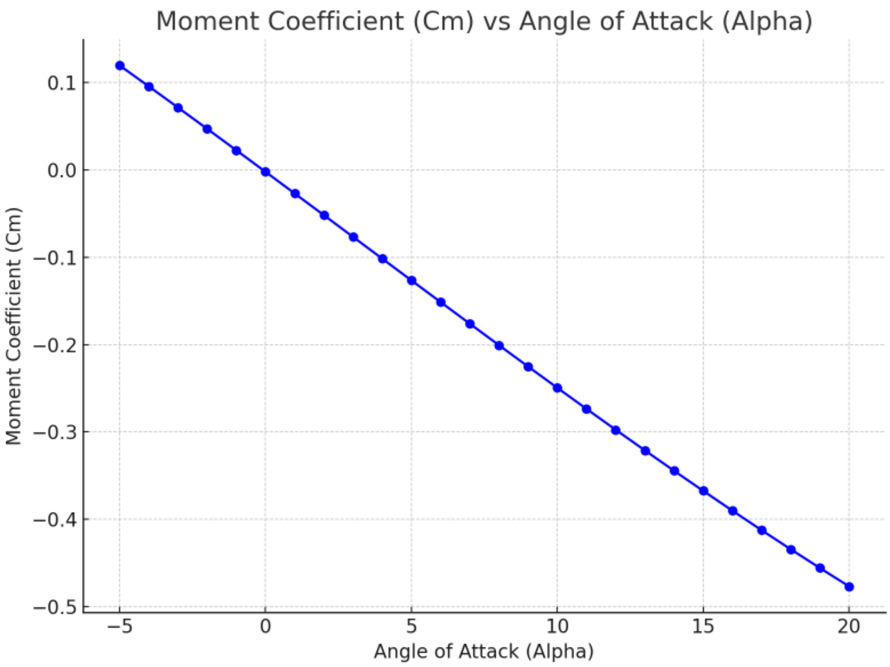
Analysis Conditions

Metot	Vortex Lattice
Reynolds Number	300,000
Mach	0.059
ρ	$1.225\ kg / m^3$
V∞	20 m/s

Under these conditions, an analysis was performed using XFLR5 software, and by examining the Cm graph Figure 7, it was observed that as the angle of attack increases, a negative moment is generated, while a positive moment is produced as the angle of attack decreases. This indicates that in the event of a disturbance that disrupts the aircraft's longitudinal stability, it will return to its equilibrium position, meaning it will remain stable in the longitudinal plane.

Figure 7

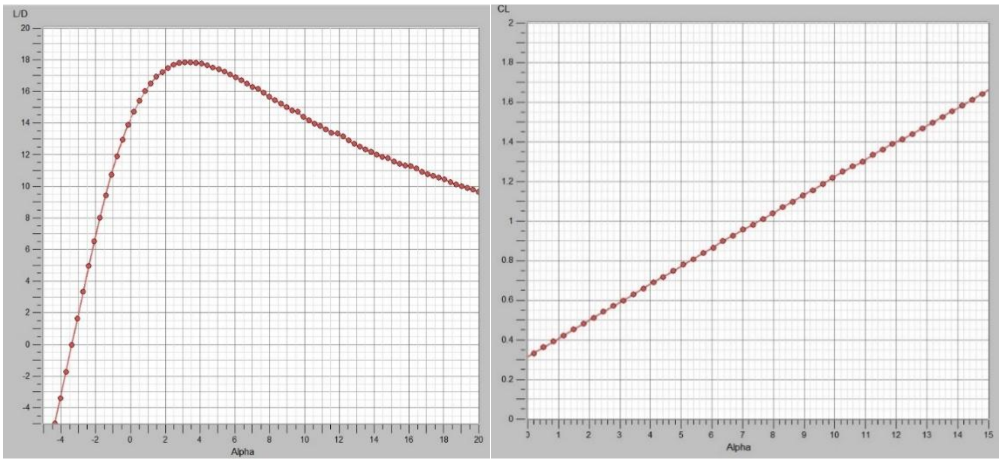
cm-alpha graph



The aerodynamic analysis of the aircraft was conducted using OpenVSP software, and it has been demonstrated that the required aerodynamic performance parameters for the mission profile are met.

Figure 8

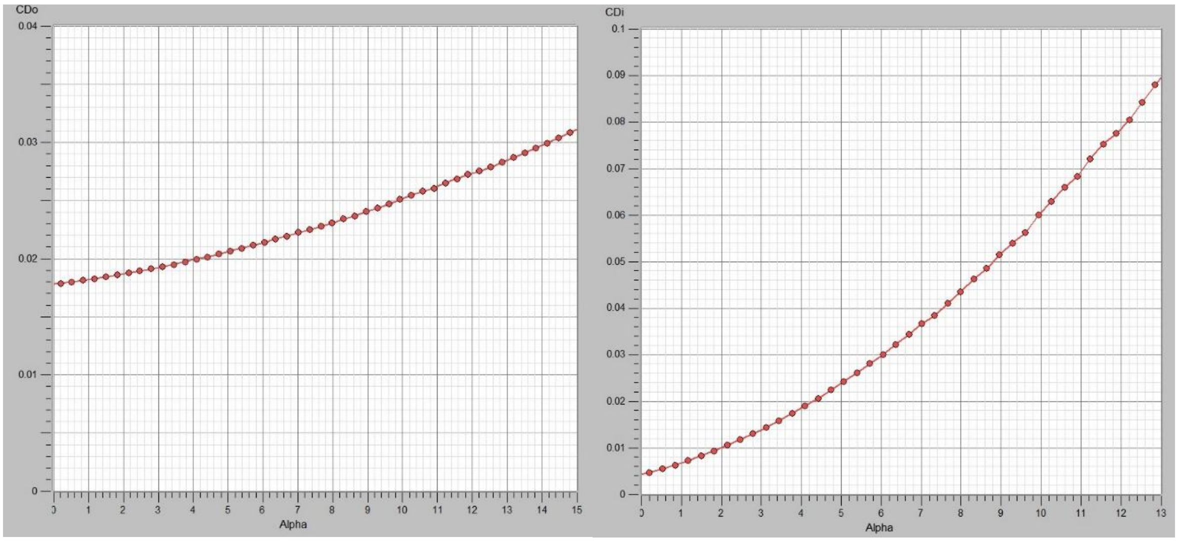
Cl-alpha and L/D Alpha graphs from OpenVSP



The aerodynamic analysis of the aircraft was conducted using OpenVSP software, and it has been proven that the necessary aerodynamic performance parameters for the mission profile are achieved. A critical factor for the aircraft's transition from multicopter mode to cruise mode is the selection of motors and propellers. To ensure these selections are suitable for the aircraft, the total drag must be calculated, and the minimum thrust value should be determined. In this context, the drag analysis of the aircraft was performed using OpenVSP software, categorized into induced drag and parasitic drag. The results of these analyses are presented in Figures 9.

Figure 9

CD-alpha and CD_i alpha graphs from OpenVSP



As a result of aerodynamic analysis with only wing and tail elements, the total drag coefficient of the aircraft was found to be 0.022. Then, the parasitic drag coefficient with the whole geometry of the aircraft was found to be 0.044. This obtained data is proved by equation 8.

$$C_D = c_d + \frac{C_L^2}{\pi e AR} \qquad (8)$$

Equation 9 was used to calculate the minimum thrust required by the aircraft for cruise flight. Taking a safety factor of 2, the required thrust is calculated as 2.115 N.

$$T = D = \frac{1}{2} \times q \times V^2 \times S \times C_D \qquad (9)$$

EMAX MT3515 brushless motor will be used as the horizontal propulsion motor of the vehicle. Considering the minimum thrust value obtained, APC 13x4 propeller was selected with the values given in Table 9.

Table 9

Cruise Motor Propeller Values

Voltage (v)	*Propeller Size (inch)*	*Amper* A	*Thrust* G	*Power* W	*Efficiency* G/W
22.2	12x3.8 CFRP Propeller	2	390	44.4	8.8
		4	650	88.8	7.3
		6	880	133.2	6.6
		8	1120	177.6	6.3
		10	1300	222	5.9
		12	1450	266.4	5.4
		14	1640	310.8	5.3
	APC 13x4	2	410	44.4	9.2
		4	700	88.8	7.9
		6	940	133.2	7.1
		8	1210	177.6	6.8
		10	1430	222	6.4
		12	1610	266.4	6
		14	1720	310.8	5.5

To meet the vertical take-off requirements, four Sunnysky X4108S KV480 brushless motors were chosen. After reviewing the motor's technical specifications, three propeller models with different sizes were examined for the best match. During the evaluation, key parameters such as the current drawn by the propellers from the power source, the maximum thrust provided, and the required power were considered. Table 10 contains the analysed parameters for these propellers. As a result, with a safety factor of approximately 2, the required minimum thrust was determined to be 8600 g. The APC 13x4 propeller, capable of achieving nearly twice the total weight's thrust capacity (7360 g), was selected as the most suitable option for the drive system. It was anticipated that the difference between the safety factor and the maximum values in the motor's technical data would be compensated for by the propeller material.

Table 10

Cruise Motor Propeller Values

Prop size (inch)	*Voltage(V)*	*Throttle*	*Current (A)*	*Thrust (g)*	*RPM (RPM/Min)*	*Güç (W)*
APC11x4.7	14.8	100%	7.8	950	5840	115.44
14x4.7		100%	13.6	1410	4825	201.28
APC11x4.7	18.5	100%	11.2	1350	6905	207.2
14x4.7		100%	18.3	1820	5450	338.55
APC13x4	22.2	100%	12.1	1840	8230	268.62
APC12x3.8		100%	18.6	1840	8230	412.92

DISCUSSION

The engineering model of the designed aircraft has been validated through analysis, meeting the required aerodynamic coefficients and forces. While the aircraft is capable of take-off and landing in various terrain conditions, its structural strength limits its mission profile. Surveillance, reconnaissance, and payload transport missions of up to 0.5 kg can be carried out with the current design; however, for different mission modules, the aircraft structure should be reinforced, and the propulsion system should be upgraded accordingly. To prevent the aircraft from experiencing structural failure during blind flight in challenging terrain conditions under the operator's control, a sensor-based control system is necessary.

During take-off, the four vertical motors will consume a high amount of power; however, during cruise flight, only one cruise motor will be used along with the aircraft's aerodynamic features, resulting in lower battery consumption. Therefore, to extend mission duration, a modular battery compartment could be designed, or a separate optimization study for the power system would be necessary.

CONCLUSION

As a result of the conducted studies, the concept and detailed design of a VTOL unmanned aerial vehicle (UAV) were developed, and an engineering model was created. The designed aircraft features four vertical motors, one cruise motor, a 1.5-meter wingspan, and an inverted V-tail configuration. Based on the analyses and calculations, the aircraft meets the necessary aerodynamic parameters for flight. The body design reduces the flow stall point, preventing drag caused by pressure. Additionally, inspired by the shape of a dolphin, the body design stores the avionics at the front, balancing the tail moment. The choice of tail configuration aims to reduce drag resulting from the geometry.

RECOMMENDATIONS

To further develop the aircraft and enable it to perform new mission profiles, different materials could be used in the structure to make the aircraft lighter. By designing alternative power systems (e.g., solar panels), the efficiency of the battery could be improved, or power distribution optimization could be implemented. To increase the range of mission profiles and applications, modular ports could be added for integrating various devices.

Ethical Committee Approval

No human or animal subjects requiring ethical committee approval were used in this study. The research was conducted using publicly available data sets, literature reviews, or theoretical analyses. In accordance with ethical rules, full compliance with academic honesty and scientific ethical principles was maintained at every stage of the research process. Therefore, ethical committee approval was not required.

Yazar Katkıları

Research Design (CRediT 1) Yazar 1 (100%)

Data Collection (CRediT 2) Yazar 3 (50%) – Yazar 4 (50%)

Research - Data Analysis - Validation (CRediT 3-4-6-11) Yazar 2 (60%) – Yazar 4 (40%)

Writing of the Article (CRediT 12-13) Yazar 2 (60%) – Yazar 1 (40%)

Text Revision and Improvement (CRediT 14) Yazar 2 (30%) – Yazar 1 (40%) – Yazar 2 (30%)

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Sustainable Development Goals (SDG)

Sustainable Development Goals: 9 Industry, Innovation and Infrastructure

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