İSTANBUL UNIVERSITY CERRAHPAŞA

ORIGINAL ARTICLE
Electrica 2024; 24(1): 96-108

A Compact Three-Rotor VTOL Development for Medical Drug Transfer

Kursat Cicin[1], Ali Kankaya[1], Fatma Yalcinkaya[2], Hediye Orhan[3], Sena Turker[4], Ilknur Keskin[4], Enes Efe[5], Emrehan Yavsan[6]

[1]Department of Mechatronics Engineering, Necmettin Erbakan University, Konya, Turkey
[2]Department of Aircraft Engineering, Necmettin Erbakan University, Konya, Turkey
[3]Department of Computer Engineering, Necmettin Erbakan University, Konya, Turkey
[4]Department of Electrical and Electronics Engineering, Necmettin Erbakan University, Konya, Turkey
[5]Department of Electrical and Electronics Engineering, Hitit University, Corum, Turkey
[6]Department of Electronics and Automation, Tekirdağ Namık Kemal University, Tekirdağ, Turkey

Cite this article as: K. Cicin, et al. "A compact 3-rotor VTOL development for medical drug transfer," *Electrica*, 24(1), 96-108, 2024.

ABSTRACT

This work presents the development of a low-cost and low-power consumption vertical take-off and landing unmanned aerial vehicle (VTOL-UAV) with a simple and innovative design approach. The VTOL-UAV is capable of runway-independent flight and has the ability to carry payloads such as medical drug boxes. The hull volume of the UAV has been maximized to enhance its carrying capacity, while a three-rotor configuration has been implemented to simplify the design, reduce costs, extend flight time, and minimize weight. The wing-mounted rotors are strategically positioned in vertical and horizontal orientations to ensure stable flight during take-off, landing, and cruise phases. The wings are detachable, enabling rapid repairs in the event of accidents. Powered by an advanced flight controller, the VTOL-UAV is capable of autonomous flight, making it suitable for delivering supplies and medical provisions to remote, hazardous, or emergency areas. Moreover, the UAV has the capability to operate at higher altitudes, avoiding obstacles in urban transportation. Overall, this work demonstrates the feasibility of developing a cost-effective and efficient VTOL-UAV with a straightforward design approach for diverse applications, including medical delivery and urban transportation.
Index Terms—Aerodynamic structure, compact design, mechatronic systems, tilt rotor, UAV.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are aircrafts without a human pilot onboard and are controlled remotely by a ground-based operator. The UAVs are also sometimes referred to as drones. They are used in various missions, including surveillance, reconnaissance, target acquisition, and missile guidance. Unmanned aerial vehicles come in various shapes and sizes and are designed for civilian and military use. Some UAVs stay in the air for long periods, while others are designed to be disposable and only used for a single mission. Unmanned aerial vehicle technology is constantly evolving, and new applications for UAVs are being developed all the time [1].

There are two types of UAVs: fixed wing and rotary wing. Fixed-wing UAVs are more efficient in energy consumption and have a more extended range but are more difficult to control [2, 3]. Fixed-wing UAVs need large open areas for landing and take-off. This situation prevents UAVs from reaching rough terrain or urban transportation. Rotary-wing UAVs are more maneuverable but have shorter flight distances and are more susceptible to wind gusts. In rotary-wing UAVs that do not need a runway, only engines provide the lifting force. These motors draw a lot of current to create the lift force. Excessive current draw significantly reduces flight time. Unmanned aerial vehicles capable of vertical take-off, landing, and cruise flight, such as fixed-wing aircraft, do not experience these problems. This type of UAV can be called hybrid or UAV-vertical take-off and landing vehicle (VTOL) [4].

A hybrid UAV is an unmanned aerial vehicle using traditional propellers and jet engines. The jet engine provides power for take-off and horizontal flight, while the propellers are used for vertical take-off and landing. This design allows for more efficient fuel use and longer flight time than traditional propellers-only UAVs [5, 6].

Corresponding author:
Emrehan Yavsan

E-mail:
eyavsan@nku.edu.tr

Received: April 10, 2023

Revision Requested: July 3, 2023

Accepted: July 21, 2023

Publication Date: January 31, 2024

DOI: 10.5152/electrica.2024.23048

In this study, it is desired to develop a three-rotor VTOL-UAV with low power consumption, low cost, and a relatively simple design concept, especially for health-care and transportation. In particular, it is planned to produce the UAV by increasing its payload-carrying capacity. At the same time, the UAV will have full autonomous flight capability, and an avionics system will be installed. The developed UAV aims to transport drugs from one point to another at a distance of at least 1200 m. The specified points can be considered as hospitals whose coordinates are known. Besides, it is planned to increase it to a height of at least 100 m, considering its use in the city.

Although most UAVs are designed with five rotors, multi-rotor UAVs [7, 8] have several disadvantages compared to traditional UAVs. They tend to be slower and have a shorter range due to their lower energy efficiency. Moreover, they are more susceptible to turbulence and wind gusts, which makes them challenging to control. Additionally, multi-rotor UAVs are often noisier, which can be a concern for covert operations [9-11]. In this study, the preference for a three-rotor structure is intended to overcome these drawbacks. However, it is important to note that three-rotor VTOL-UAVs can be less stable during landing and take-off compared to four-rotor variants. Previous studies [12-15] have identified the instability caused by the fixed rotors positioned on the blades. To address this issue, a specially designed tilt mechanism will be implemented in this paper. This mechanism will enable the two rotors on the wings of the VTOL-UAV to move to a vertical position during take-off and a horizontal position during cruise flight. The fixed rotor in the tail will remain in a vertical position at all times to assist in maintaining altitude during cruise flight. By reducing the number of rotors, flight time and payload capacity can be increased. The proposed tilt mechanism sets the VTOL-UAV developed in this study apart from standard three-rotor VTOL-UAVs.

It is planned to increase the carrying capacity by accommodating the load inside the fuselage or on the wings of the VTOL-UAV. To optimize the airfoil selection, payload handling, and placement of electronic equipment, analysis programs will be utilized. This approach will enhance the maneuverability and stability of the VTOL-UAV. Furthermore, the VTOL-UAV will be capable of autonomous flight at high altitudes to ensure obstacle avoidance in urban transportation, such as buildings and trees. To achieve full autonomous capability, a highly advanced flight controller will be chosen. The significance and originality of this study can be summarized as follows:

- The presented VTOL-UAV has been developed with an original design approach, emphasizing low cost. Its unique feature is the ability to operate in rugged terrains and areas without the need for a runway, enabling efficient take-off and landing.
- The modular wing design allows for quick repairs in case of accidents and enhances the portability of the VTOL-UAV during transfers. This design also enables the attachment of various wing types, expanding its operational capabilities.
- The three-rotor design concept significantly reduces weight, production cost, complexity, and energy consumption of the VTOL-UAV.
- The proposed tilt mechanism enhances stability during flights, leading to smoother and more controlled operations.

II. METHODOLOGY

In this study, it is desired to develop a three-rotor VTOL-UAV that can be adapted to various fields such as military and civil aviation, especially health and transportation. Vertical take-off and landing unmanned aerial vehicle is planned to have a unique design that can carry payloads such as medicine and test tubes, take off, and land without needing a runway. For this, modeling processes will be made with various computer-aided design programs for both the fuselage and the tilt mechanism of the VTOL-UAV. The hull volume of the UAV will be kept as large as possible to increase the payload diversity and carrying capacity. It aims to reach an altitude of at least 100 m, considering that the VTOL-UAV will be used both in and outside the city on rough terrain. Furthermore, VTOL-UAV is planned to have a modular structure so that it can be easily transported and repaired as soon as possible against a possible accident failure. Designing the wings of the UAV in such a way that they can be disassembled and assembled from the fuselage will provide this modularity.

The tilt mechanism is the system that provides the vertical take-off and landing of the VTOL-UAV. This system will be mounted on the wings of the UAV through carbon pipes. Rotors will be mounted on it, and these rotors will be moved 180° on the pitch axis through servo motors. This tilting mechanism will hold the rotors vertically during take-off, landing, and horizontally during the cruise. The tilt mechanism will be modeled to meet the specified specifications with computer-aided design programs.

For the VTOL-UAV to perform the desired tasks autonomously, preflight task assignment must be possible. Task assignments are planned to be made through the open-source Mission Planner program [16]. A flight controller will be used so the VTOL-UAV assigned to the autonomous mission can fulfill the commands and provide information about its instantaneous status. This flight controller is planned to have the barometer, inertia measurement unit required for a healthy flight, and the necessary hardware elements to filter the data of these sensors. This way, it is considered safer than an external flight controller and a collection system installed from external sensors. Again, the same flight computer has a telemetry input to process and transmit sensor data. The data received from the flight computer will enable the flight dynamics to be decided and modified for a safe flight. The flight controller and electronic components required for these operations will be connected, and the avionics system will be installed. From the sensors in the avionics system, the data will be collected first before the flight for verification, then during the flight and transferred to the ground station by telemetry. In this way, the avionics system will be tested.

In order to increase the flight time of the VTOL-UAV and the payload it can carry, the fuselage structure should be large, durable, and light. Carbon fiber and epoxy resin will be used in fuselage production. Therefore, the composite fuselage will have a durable structure. It will be processed using the wooden machining method suitable for the fuselage model. Carbon fiber and epoxy resin will be laid on this mold, and a composite fuselage suitable for the design will be produced. In order to make the composite fuselage light, the vacuum infusion technique will be used together with the mold method. Excess epoxy resin deposited on the carbon fiber will be removed by vacuum infusion. Then, the wings will be cut from the foam-cutting machine. This way, a product suitable for the wing profile and a low error rate will be realized. It is thought that the wings will be covered with a composite material, which is a mixture of glass fiber and epoxy resin. This will increase the wing force.

Prototypes will be produced in three-dimensional printers for the moving part of the tilt mechanism to which the rotors are attached. Servo motor and rotor connections will be made, and tests will be carried out on this prototype. Unless there is an obstacle restricting

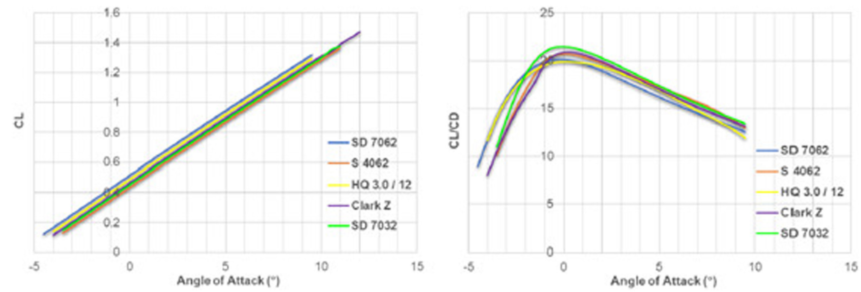


Fig. 1. CL vs. angle of attack and CL/CD vs. angle of attack charts. CD, drag coefficient; CL, lift coefficient.

the axial movement of the rotors, the prototype will be produced from aluminum sheets with a thickness of at least 1 mm with the exact machining and bending methods. Servo motors that will provide the axial movement of the rotors must be capable of carrying at least 20 kg of load. The tilt mechanism produced will be connected to the wings of the VTOL-UAV with carbon pipes, and care will be taken not to disturb the flight dynamics of the UAV.

After connecting the fuselage, wing, and tilt mechanism and providing the avionics system integration, the tests of the VTOL-UAV will begin. First, it will be tested whether the wings can lift the fuselage. For this test, the wings will be fixed at both ends, and all weights, including electronic and payloads, will be added to the fuselage. The wing structural test will be successful if the wings can carry the VTOL-UAV without damage. A vertical UAV needs to produce more thrust than its total weight, including payload. The engines counter this thrust in vertical and horizontal flights. Therefore, a voltage source of 22.2 V will power each engine to provide the desired thrust. For starting, the engine will be connected to the thrusting stand, and the thrust values will be measured. The thrust test will be passed successfully if the desired thrust value is reached.

The test flights will be carried out after the preflight tests are completed. In the first test flight, only vertical take-off and landing will be made on the VTOL-UAV, and the stability of the UAV will be tested. Then horizontal flight will begin. Proportional Integral Derivative (PID) gains will be adjusted practically by observing the flight of the VTOL-UAV in horizontal flight tests. PID gains will be changed considering the maneuverability and stability of the VTOL-UAV during the flight. Flight tests will be repeated at different times to increase the stability, maneuverability, flight time, flight speed, and take-off–landing speed of the VTOL-UAV. To increase these parameters, primarily software and, if necessary, mechanical improvements will be applied. In this way, it is planned to develop the VTOL-UAV.

A. Analysis

First, the literature was scanned during the dimensioning phase. In the literature review, we have observed that the flight performance of three-rotor UAVs decreases due to their high weight, resulting in a shorter range. To address this problem, we designed a lightweight UAV with high aerodynamic performance and achieved very successful results in our experiments. We determined the basic design parameters that are suitable for the job requirements, including take-off weight, speed, and wing surface area [17-19].

Next, we calculated the lift coefficient by applying the lift formula, and we selected the wing profile from the Airfoil Tools website [20] based on our data. At this stage, we selected four candidate airfoils from the dataset created with the XFLR5 program [21]. These airfoils had high CL_{max} and lift coefficient/drag coefficient values (CL/CD), as well as low pitching moment coefficient (CM) values. Unfortunately, airfoils with extremely curved and sharp trailing edges were not considered as candidates due to manufacturing challenges.

Based on the analyses obtained from XFLR5, we examined the graphics in Figs. 1 and 2. As a result, we chose the SD 7032 airfoil due to its higher CL/CD value, better longitudinal stability, and sufficient cruise speed compared to other profiles. During the profile selection stage for the tail, we considered certain parameters. The tail thickness should be lower than that of the wing, and the lift coefficient of the tail should be lower than the lift coefficient of the wing. Additionally, since the aircraft's center of gravity shifts during cruise flight, our aircraft should exhibit similar behavior in both positive and negative directions.

Among the tail profiles analyzed in XFLR5, we selected the thin and symmetrical NACA 0012 profile. Furthermore, we determined the *CL* using Equation (1), which is a fundamental formula in aerodynamics. Equation (1) relates the lift force to the air density (*d*), velocity

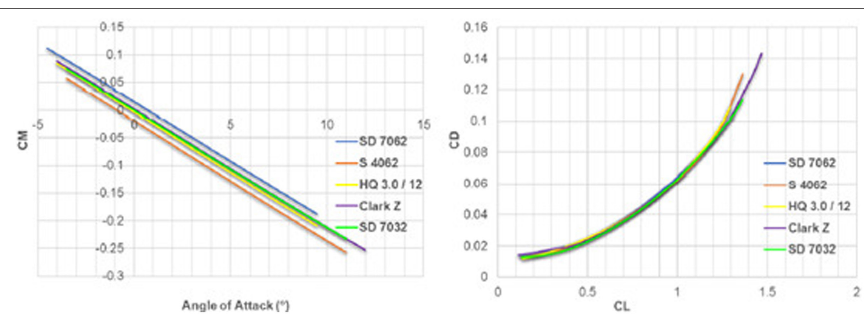


Fig. 2. CM vs. angle of attack and CD vs. CL charts. CD, drag coefficient; CL, lift coefficient; CM, pitching moment coefficient.

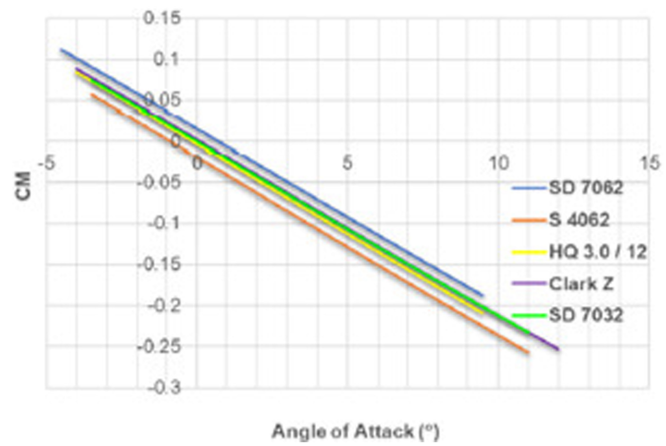


Fig. 3. Static stability analysis. CM, pitching moment coefficient.

TABLE I. DYNAMIC STABILITY MODES OF THE VTOL

Modes	Axes	Eigen Values	Damping Ratio	Undamped Frequency (Hz)
Short period	Longitudinal	$-5.257 \pm 8.468i$	0.527	1.586
Long period	Longitudinal	$-0.008 \pm 0.701i$	0.012	0.112
Dutch roll	Lateral	$-0.459 \pm 3.738i$	0.122	0.599
Roll	Lateral	−23.9108	–	–
Spiral	Lateral	0.1463	–	–

squared (v^2), reference area (s), and CL. By employing this equation, we were able to calculate the CL, a crucial parameter in assessing the aerodynamic performance of our UAV design.

$$Lift = \frac{1}{2} dv^2 sCL \quad (1)$$

1) Static Stability

There are two parameters for our aircraft to be statically stable. CM_0 positive, and the slope of the CM-angle of attack plot must be negative, or in other words, its derivative must be negative. The CM value should also be small because the smaller it is, the less torque our aircraft needs. The graph of the CM-angle of attack obtained as a result of the analysis performed on the XFLR5 with the UAV is shown in Fig. 3. As seen in this chart, the slope of the CM-angle of attack graph is negative.

2) Dynamic Stability

After providing the static stability of the UAV, the dynamic stability of the UAV was analyzed in XFLR5. To determine the longitudinal stability, the symmetric short-period mode and the symmetric long-period mode should be examined. In addition, Dutch roll, spiral, and roll modes should be studied to determine horizontal stability. The dynamic stability modes and their changes over time are illustrated in Table 1, Figs. 4 and 5, respectively. The values of our key performance parameters are shown in Table 2.

B. Modeling

1) Modeling of the Aircraft Fuselage

The hull of the UAV designed according to the analysis is shown in Fig. 6. While the fuselage was being designed, the wing structure was designed to be compatible with the moderate wing structure and to minimize friction. Later, the rear of the fuselage was designed with a thinner and narrower structure to match the boom-mounted tail

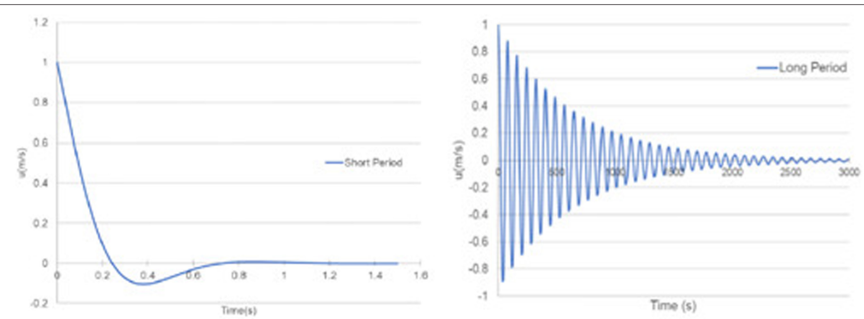


Fig. 4. The variations of the short and long period modes in time.

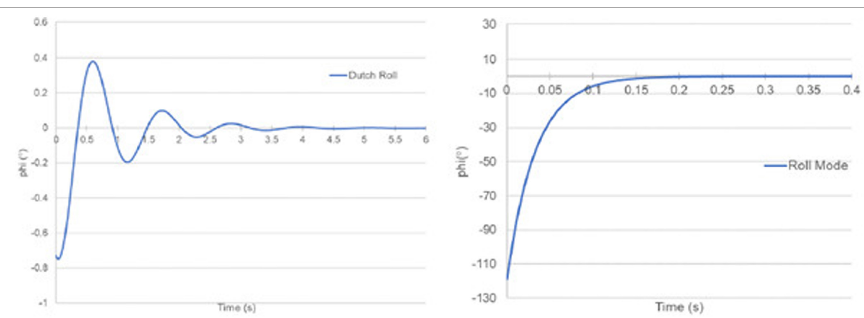


Fig. 5. The variations of the Dutch roll and the roll modes in time.

TABLE II. THE KEY PARAMETERS FOR THE FLIGHT PERFORMANCE OF THE VTOL

Parameters	Value	Units
Take-off weight	3.5	kg
Stall velocity	10	m/s
Wing loading	91.2625	N/m^2
CL_{max}	1.49	-
CD_0	0.0397	-
Power-to-weight ratio	0.325	W/g
Thrust-to-weight ratio	1.5	-
Cruise velocity	17.55	m/s
Maximum velocity	30.321	m/s
L/D_{cruise}	11.534	-
Endurance	19.788	min

structure. In this way, it is ensured that the fuselage is more resistant to the forces produced by the tail and rear engine. Another point to be considered while designing the fuselage is the placement of components on the UAV in a way that does not disturb the center of gravity of the UAV. Since the heaviest part of the UAV is the battery, the nose part of the UAV fuselage is designed to be wider to balance the weight, and the battery is placed here, as seen in Fig. 6. In this way, in case of any center of gravity problem in the UAV, the battery's position can be easily changed, and the UAV can be returned to its equilibrium position. The fuselage of the UAV is 78 cm long, 20 cm wide, and 13 cm high. This way, sufficient space is left inside the fuselage for electronic components and payload. In addition, the parts suitable for the fuselage structure in Fig. 4 are designed to fix the payload carried inside the fuselage.

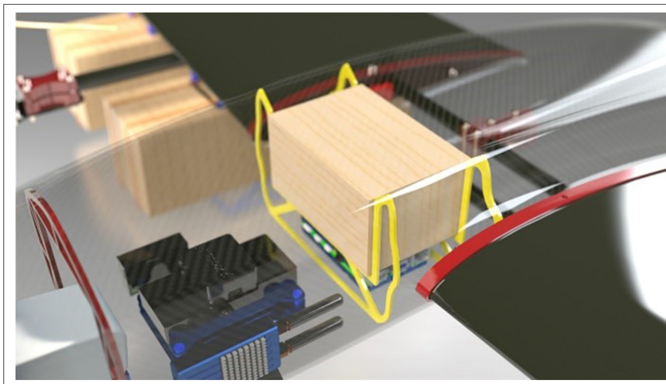


Fig. 6. VTOL-UAV fuselage design and payload layout.

While designing the wing and tail connections of the UAV, its wings and tails are designed to be separated from the fuselage to have a modular structure. This way, precautions were taken against possible accidents and breakages, and accessible transportation was provided. Fig. 7 shows parts designed for easy removal of wings and tails.

2) Modeling of Vertical Landing–Take-Off System (Tilt Mechanism)

The tilt mechanism is one of the essential mechanisms of the UAV. Therefore, there are several vital elements to consider when designing. One is that the mechanism is durable, and the other is light. As a result of the research, the adapter design was made suitable for the rotors so that we would obtain the necessary thrust. As in Fig. 8, servo motors provide 180° movement of the rotors. Finally, the fittings shown in Fig. 6 are designed to fix the tilt mechanism of the UAV fuselage.

C. Avionic System

1) System Architecture

Fig. 9 presents an overview of the system components of the developed UAV, which can be categorized into five subclasses. Each subclass is discussed in detail below.

Power system: The power system is responsible for supplying the necessary power to the UAV. It consists of a LiPo battery, power module, and power distribution board. The power system ensures the efficient distribution of power to all other subsystems of the UAV.

Propulsion system: The propulsion system includes electronic speed controllers (ESCs) that control the speed and direction of the motors. The UAV is equipped with a rear engine, right engine, and left engine, which work in conjunction with the ESCs to accelerate the aircraft.

Autonomous flight control system: The autonomous flight control system enables the UAV to perform autonomous operations such as take-off, landing, and flight. It comprises a flight controller, which serves as the central processing unit, and sensors that measure position, altitude, and airspeed. These sensors are connected to the flight controller, along with Global Positioning System (GPS) and telemetry systems. The flight controller processes the sensor data and GPS information to autonomously control the UAV's flight.

Ground control station system: The ground control station system acts as the command center for monitoring and controlling the UAV. It collects real-time flight status data from the UAV's sensors via telemetry. The control computer in the ground control station evaluates the commands given to the UAV and transmits them back to

Fig. 7. Wing and tail components.

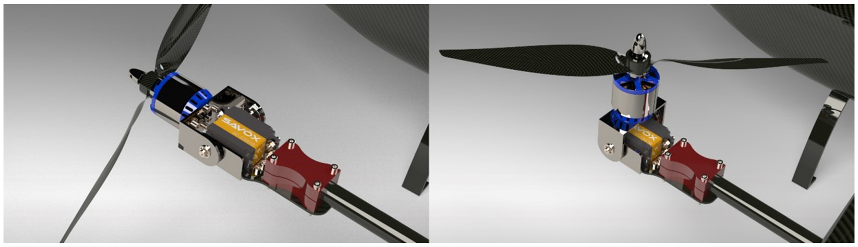


Fig. 8. Tilt mechanism.

the autonomous flight control system. The interface program in the control computer analyzes the telemetry data and facilitates interaction with the UAV. In case of disconnection or emergency, there is a pilot intervention command available.

Communication and imaging system: The communication and imaging system enables the UAV to perform its designated tasks effectively. It encompasses the communication equipment necessary for establishing connectivity between the UAV and the ground control station. Additionally, the imaging system provides capabilities for capturing and transmitting visual information from the UAV's onboard cameras or sensors.

Together, these subsystems and components enable the UAV to operate autonomously, execute tasks, and establish reliable communication with the ground control station, ensuring efficient mission performance.

2) Electrical System Components

The flight controller is the circuit element that contains the necessary sensors and connection paths for the UAV to perform semi-autonomous

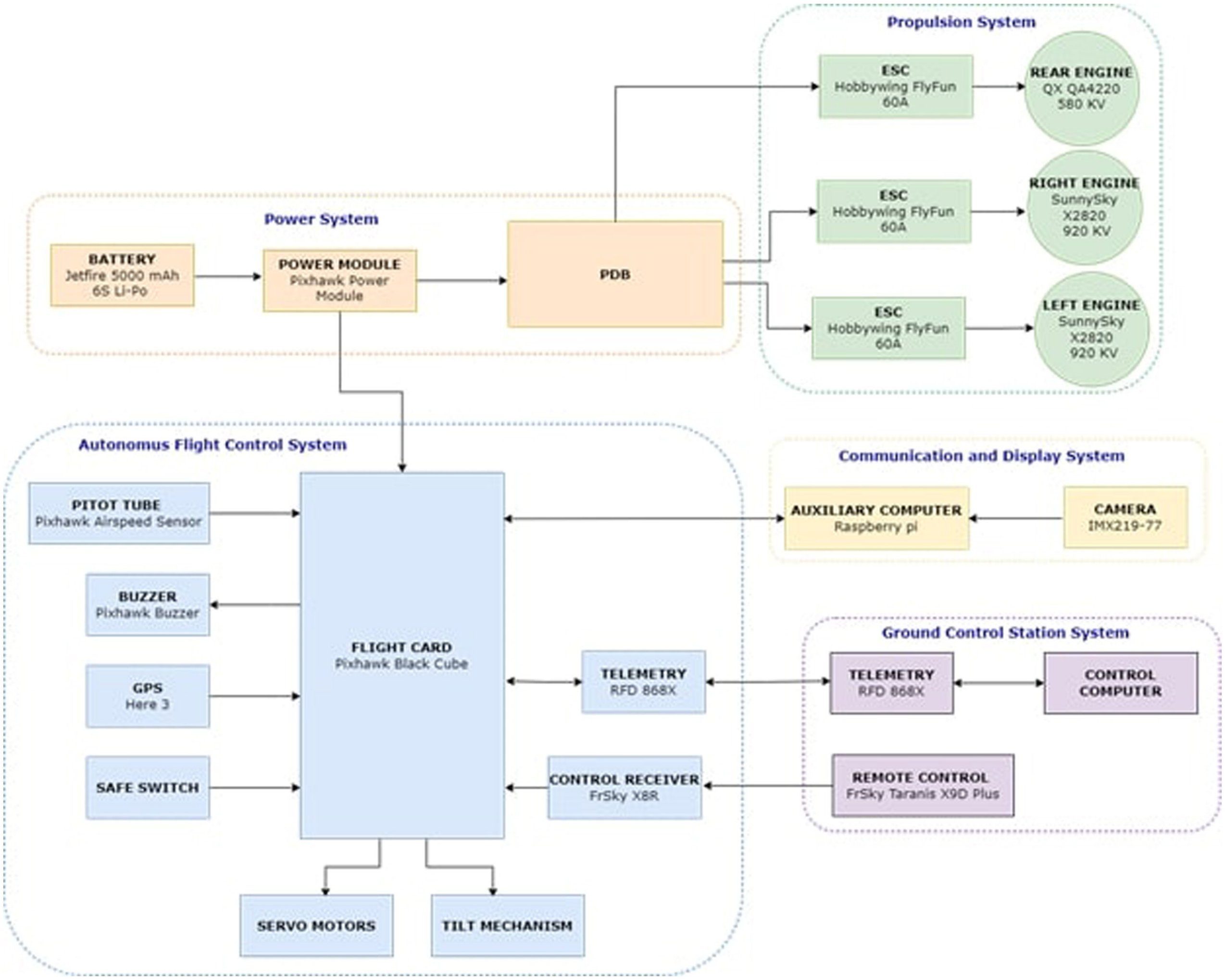


Fig. 9. The system architecture of the developed VTOL-UAV. ESC, electronic speed controllers; GPS, Global Positioning System; PDB, power distribution board.

or autonomous flights. There are flight computers with different sensitivity depending on the mission conditions. The flight computer we use has three iinertial measurement units (IMUs). In this way, IMU data comes as redundant. Data backup provides a high-accuracy measurement of angular velocity and linear acceleration data. Altitude data are essential for maintaining altitude or approaching the target during autonomous missions. The altitude data is verified with the help of two barometer sensors on our flight controller. External sensors can be added thanks to the port outputs on the flight controller.

Telemetry is used to exchange data between the flight controller and the ground station, to receive the desired flight data, to update the mission parameters during the flight, or to load new parameters. In the telemetry used, the transfer rate and bandwidth can be adjusted. It has a maximum range of 40 km. The telemetry used is called RFD 868 because it operates in the 868–869 Hz frequency range. The RFD 868 communicates over the universal asynchronous receiver/transmitter protocol. The Model X8R RC receiver with one-way messaging is used to communicate between the UAV and the controller. Thanks to the Serial Bus (SBUS) line on the receiver, it can be connected to the flight computer with a single output. In addition, GPS was used to determine the UAV's position and enable it to fly autonomously. The pitot tube instantly measured the airspeed so that the VTOL-UAV that takes off could switch to cruise flight. In addition, a buzzer gives an audible warning when electricity is supplied to the card and when the card is opened. A secure switch activates the signal transmission in the power system. An auxiliary computer is needed for the UAV to perform the desired task. For this, a Raspberry pi with high processing power was used as the auxiliary computer. The camera used to capture the image; The lens features of the camera were chosen considering its coverage and compatibility with the Raspberry Pi.

D. Production and System Integration

The VTOL-UAV production is divided into three main stages: 1) Wing and tail manufacturing, 2) Fuselage manufacturing, and 3) Tilting mechanism manufacturing. Different production methods and materials are utilized for each component. The specific methods employed are elaborated upon in detail under their respective headings.

1) Wing and Tail Production

The wings and tails of the VTOL-UAV were manufactured by cutting them from foam using a 3-axis hot wire cutter. During the cutting process, pipe holes were drilled into the wings to accommodate carbon fiber pipes. Once the cutting was complete, the wing, rudder, and elevator surfaces were separated from the main wing and tail using a utility knife. After the hot wire cutting, all surfaces were covered with a layer of glass fiber, as depicted in Fig. 10. Before applying the glass fiber coating, a thin mixture of epoxy and silica was applied to the surfaces to ensure the desired surface quality. This step helps in achieving a smooth and consistent surface finish. To provide the necessary strength, two carbon fiber pipes with an outer diameter of 12 mm and an inner diameter of 10 mm were placed on the wings. Similarly, a carbon fiber pipe with an outer diameter of 6 mm and an inner diameter of 4 mm was inserted into the tails. These carbon fiber pipes enhance the structural integrity of the wings and tails. The control surfaces, such as the ailerons and elevator, were hinged to the wings and tail respectively, allowing for controlled movement. Finally, the wing and tail fasteners were attached to the epoxy-coated surfaces, completing the manufacturing process. By following these steps, the wings and tails of the VTOL-UAV were constructed with the necessary strength, durability, and control surfaces in place.

Fig. 10. Covering the wings with fiberglass.

2) Fuselage Production

Once the design of the fuselage was finalized, molds were created to facilitate the manufacturing process. These molds were fabricated by machining wooden material using a three-axis milling process. To account for the wing profiles, present on the right and left surfaces of the fuselage, two separate molds were created, ensuring symmetry and ease of production. The hand-laying method was employed to apply glass fiber to the molds, ensuring that the fuselage structure would be reinforced and durable. After the glass fiber was applied, a vacuum process was used to remove any excess resin and ensure proper consolidation of the materials.

Upon completion of the parts production, internal supports were installed within the fuselage to enhance its structural integrity. The fusion of the fuselage was achieved by using a mixture of epoxy and silica, which provides strength and adhesion between the different components of the fuselage. In the final step of the fuselage production, a carbon fiber pipe was attached to the inner supports and surfaces. This carbon fiber pipe serves as reinforcement and further enhances the overall strength of the fuselage. By following these steps, the fuselage of the VTOL-UAV was manufactured using molds, glass fiber reinforcement, epoxy–silica mixture, and carbon fiber components. The result is a durable and structurally sound fuselage ready for further integration with other components of the UAV.

3) Manufacture of the Tilt Mechanism

To manufacture the tilt mechanism for the VTOL-UAV, an aluminum sheet was used. The production process involved cutting the required parts from the sheet metal using a plasma-cutting Computer Numerical Control (CNC) machine. These cut parts were then welded together to form the components of the tilt mechanism, as shown in Fig. 11. Once the tilt mechanism parts were produced, the necessary components such as bearings, servo motors, and other hardware for motor movement were assembled. This assembly process resulted in the complete manufacture of the tilt mechanism.

Following the production of the fuselage and wings of the VTOL-UAV, the assembly of the tilt mechanism onto the fuselage commenced. The tilt mechanism is connected to the wings using carbon pipes, ensuring proper integration between the tilt mechanism and the fuselage. Fig. 12 provides an illustration of the fully assembled fuselage, showcasing the integrated tilt mechanism. By following these

Fig. 11. Tilt mechanism assembled after CNC laser cutting.

steps, the tilt mechanism of the VTOL-UAV was successfully manufactured and integrated into the fuselage, allowing for controlled tilting of the rotors during flight operations.

III. RESULTS AND DISCUSSION

The VTOL demonstrated in this paper is characterized by its unique and modular design, rotor quantity, and tilt rotor features. These features contribute to the flight time, cost, and stability of the VTOL in take-off and landing. Table 3 lists VTOL aircraft similar to this study. Although the Mini Panther is one of the best commercial examples, our VTOL is close to it except for the duration of time in the air. Furthermore, since it is a prototype, its cost is low. Its payload capacity is higher than the organic air vehicle and its rotor count is lower than the Rotors Retractable (RR) VTOL I. As it can carry loads on its wings as well as inside the airframe (hull), it can carry loads of various geometries. Thus, it has an advantageous structure in terms of load carrying diversity compared to VTOLs such as J-Lion, which can only carry loads on its hull.

Fig. 12. Tilt mechanisms mounted on the VTOL-UAV fuselage.

A. Tests

The developed VTOL-UAV has passed various tests to perform successful missions and flights. These can be divided into structural and development tests.

1) Structural Test

The wing structure test was conducted to assess the wings' ability to withstand the counter loads experienced during flight. This test aimed to determine whether the UAV possessed sufficient structural strength to ensure safe operation during flight. For testing purposes, after installing all the components, including the loads intended for the UAV, they were removed from the wingtips, as shown in Fig. 13. Although there was some limited stretching observed at the wingtips during the test, no deformations were detected in the wings.

The engine assembly test was performed to verify the engine mounting component's ability to withstand the thrust generated by the engine. This test consisted of two stages. In the first stage, the spacer (coupling, key) used in the engine assembly was subjected to a load 50% higher than the engine's maximum thrust, as depicted in Fig. 14. The engine mount successfully passed this test, and no deformations were observed. In the second stage, the test involved connecting the engine to the chock. The chock attached to the engine was tested at 100% throttle, and no deformations were observed during this stage.

TABLE III. COMPARISON OF THE SIMILAR VTOL-UAVS IN THE MARKET AND THE LITERATURE

VTOL-UAVs	Type	Rotor Quantity	Payload (kg)	Take-Off Weight (kg)	Wing-Span (m)	Cruise Velocity (m/s)	Endurance (minutes)
J-Lion [5]	Laboratory, Tailsitter	2	-	2.83	1.5	15	30
Organic air vehicle [22]	Commercial, Tailsitter	1	0.5	10	-	-	15
RR VTOL I [23]	Laboratory, Fixed Rotor	5	0.2	2.5	1.2	20	15
Mini Panther [22]	Commercial, Tilt Rotor	3	2	12	1.5	18	120
Our VTOL-UAV	Laboratory, Tilt Rotor	3	1	3.5	1.8	17.55	19.79

Fig. 13. Wing structural test.

2) Development Tests

In order to enhance the flight performance of the VTOL-UAV, preliminary flights were conducted during the development tests. The flight data collected from these flights were utilized to improve the VTOL-UAV's flight performance.

The PID test was performed to evaluate the VTOL-UAV's in-flight response accuracy. The objective of this test was to determine the optimal PID gains for the VTOL-UAV. Additionally, an in-flight calibration was executed to establish the appropriate PID gains. Based on the test results, the most suitable P value for the VTOL-UAV was determined as 2.872, the optimal I value was found to be 4.281, and the appropriate D value was determined as 6.371.

Considering the usage of the VTOL-UAV in both urban and extra-urban rough terrains, a minimum altitude of 100 m was established for cruise flight. During flight tests, the desired altitude was incrementally achieved.

For the VTOL-UAV, which was designed to address emergency healthcare requirements in challenging terrains, a target range of 1200 m was determined. This range corresponds to the distance between the two hospitals specified in the scenario and illustrated in Fig. 15.

Fig. 14. Engine-assembly test.

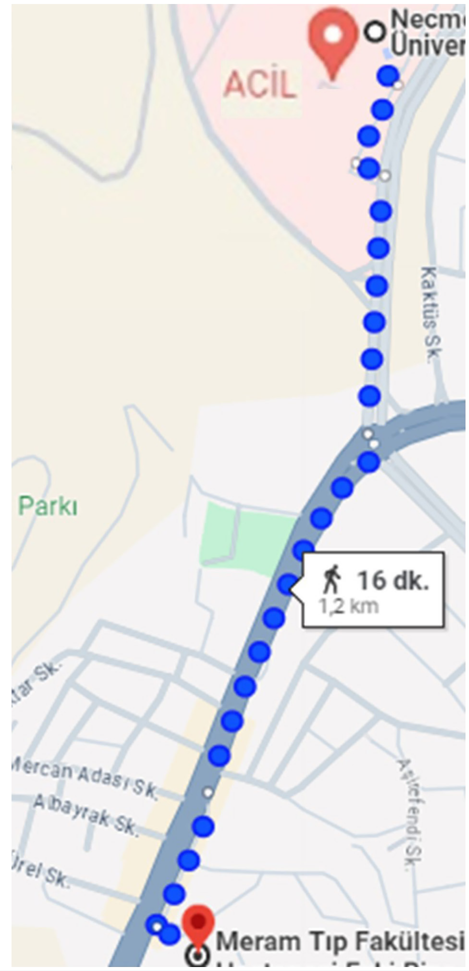


Fig. 15. The reference map used to determine the distance.

By employing preflight task assignments, VTOL-UAVs are capable of autonomously reaching the designated area. These mission assignments were made using the open-source Mission Planner program integrated into the ground control station. Consequently, the VTOL-UAV can operate autonomously throughout its flight, and its real-time status can be monitored through the interface displayed in Fig. 16. The interface provides data such as instantaneous altitude, distance to the mission, and speed, enabling real-time monitoring and interventions to the VTOL-UAV based on this information.

IV. CONCLUSION

This article presents the design, manufacturing, and flight of a low-cost, three-rotor VTOL-UAV with low power consumption, primarily intended for health and transportation applications. The utilization of a three-rotor structure in the UAV design eliminated structural and hardware complexity. The unique tilting mechanism facilitated part replacement and reduced production costs. With the tilt mechanism, the two rotors on the wings function in rotary wing mode during take-off and fixed-wing mode during cruise flight. This design feature enabled the use of a low number of engines in the VTOL-UAV, resulting in reduced costs and power consumption. Fig. 17 illustrates the produced VTOL-UAV.

Fig. 16. Mission assignment and route analysis of the developed VTOL-UAV.

The VTOL-UAV was designed to maximize payload capacity. It was modeled to accommodate a useful load within the fuselage and wings. Various analysis programs were employed to enhance the strength and load-carrying capability of the fuselage and wings. Emphasis was placed on creating a wide, durable, and lightweight fuselage, while the wings were designed to withstand the intended carrying capacity. The proposed design incorporates an avionic system within the voluminous fuselage.

Fig. 17. The prototyped VTOL-UAV.

An avionics system was established for the VTOL-UAV to fulfill its tasks at desired distances and altitudes. Preflight tests, as depicted in Fig. 18, were conducted to validate the established system, and necessary improvements were implemented during and after the test flights. Consequently, a low-power, cost-effective VTOL-UAV capable of taking off and landing without a runway was designed for the purposes outlined in this study. Furthermore, this UAV can autonomously fly to an altitude of 100 meters, carry payloads on its wings and fuselage, and operate autonomously.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – K.C., A.K., F.Y., H.O., S.T., I.K, E.Y.; Design – K.C., A.K., F.Y., H.O., S.T., I.K; Supervision – E.Y.; Resources – K.C., F.Y.; Materials – K.C., S.T., I.K; Data Collection and/or Processing – K.C., H.O., S.T., I.K.; Analysis and/or Interpretation – K.C., A.K., F.Y., E.Y.; Literature Search – K.C., E.E., E.Y.; Writing – K.C., A.K., F.Y., S.T., I.K., E.E., E.Y.; Critical Review – E.E., E.Y.

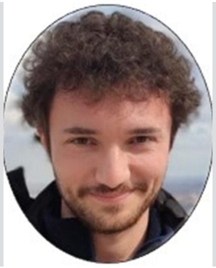
Declaration of Interests: The authors have no conflict of interest to declare.

Fig. 18. Medical payload boxes carried on the wings of the developed UAV.

Funding: This work was supported by the Necmettin Erbakan University Scientific Research Projects Unit [grant number 221219010].

REFERENCES

1. F. Santoso, M. A. Garratt, and S. G. Anavatti, "State-of-the-art intelligent flight control systems in unmanned aerial vehicles," *IEEE Trans. Autom. Sci. Eng.*, vol. 15, no. 2, pp. 613–627, 2017. [CrossRef]
2. M. Lungu, and R. Lungu, "Application of H2," *Asian J. Control*, vol. 17, no. 6, pp. 2153–2164, 2015. [CrossRef]
3. M. Lungu, "Auto-landing of fixed wing unmanned aerial vehicles using the backstepping control," *ISA Trans.*, vol. 95, pp. 194–210, 2019. [CrossRef]
4. Y. Zhou, H. Zhao, and Y. Liu, "An evaluative review of the VTOL technologies for unmanned and manned aerial vehicles," *Comput. Commun.*, vol. 149, pp. 356–369, 2020. [CrossRef]
5. Y. Ke, K. Wang, and B. M. Chen, "Design and implementation of a hybrid UAV with model-based flight capabilities," *IEEE ASME Trans. Mechatron.*, vol. 23, no. 3, pp. 1114–1125, 2018. [CrossRef]
6. P. Panagiotou, I. Tsavlidis, and K. Yakinthos, "Conceptual design of a hybrid solar MALE UAV," *Aerosp. Sci. Technol.*, vol. 53, pp. 207–219, 2016. [CrossRef]
7. Q. Shi, D. Liu, H. Mao, B. Shen, and M. Li, "Wind-induced response of rice under the action of the downwash flow field of a multi-rotor UAV," *Biosyst. Eng.*, vol. 203, pp. 60–69, 2021. [CrossRef]
8. Z. A. Ali, D. Wang, and M. Aamir, "Fuzzy-based hybrid control algorithm for the stabilization of a tri-rotor UAV," *Sensors (Basel)*, vol. 16, no. 5, p. 652, 2016. [CrossRef]
9. O. A. Jasim, and S. M. Veres, "A robust controller for multi rotor UAVs," *Aerosp. Sci. Technol.*, vol. 105, p. 106010, 2020. [CrossRef]
10. P. Ventura Diaz, and S. Yoon, "High-fidelity computational aerodynamics of multi-rotor unmanned aerial vehicles" AIAA Aerospace Sciences Meeting, 2018, p. 1266. [CrossRef]
11. D. Sartori, and W. Yu, "Experimental characterization of a propulsion system for multi-rotor UAVs," *J. Intell. Robot. Syst.*, vol. 96, no. 3–4, pp. 529–540, 2019. [CrossRef]
12. L. Derafa, A. Benallegue, and L. Fridman, "Super twisting control algorithm for the attitude tracking of a four rotors UAV," *J. Franklin Inst.*, vol. 349, no. 2, pp. 685–699, 2012. [CrossRef]
13. M. A. Boon, A. P. Drijfhout, and S. Tesfamichael, "Comparison of a fixed-wing and multi-rotor UAV for environmental mapping applications: A case study," *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, vol. XLII–2/W6, 47–54, 2017. [CrossRef]
14. M. Elfeky, M. Elshafei, A.-W. A. Saif, and M. F. Al-Malki, "Modeling and simulation of quadrotor UAV with tilting rotors," *Int. J. Control Autom. Syst.*, vol. 14, no. 4, pp. 1047–1055, 2016. [CrossRef]
15. L. Setlak, and R. Kowalik, "Studies of 4-rotor unmanned aerial vehicle UAV in the field of control system," *MATEC Web of Conferences, EDP Sciences*, vol. 210, p. 05009, 2018. [CrossRef]
16. A. Hasan, K. Fahmy, and I. Putri, "Detection of Paddy Leaves Healthiness Area Using UAV and Rasberry Pi 4, IOP Conference Series: Earth and Environmental Science,". IOP Publishing, vol. 1059, no. 1, p. 012011, 2022. [CrossRef]
17. Á. Gómez-Gutiérrez, and G. R. Gonçalves, "Surveying coastal cliffs using two UAV platforms (multirotor and fixed-wing) and three different approaches for the estimation of volumetric changes," *Int. J. Remote Sens.*, vol. 41, no. 21, pp. 8143–8175, 2020. [CrossRef]
18. K. K. Vaigandla, S. Thatipamula, and R. K. Karne, "Investigation on unmanned aerial vehicle (UAV): An overview, IRO," *J. Sustain. Wirel. Syst.*, vol. 4, pp. 130–148, 2022.
19. P. T. Dewi, G. S. Hadi, M. R. Kusnaedi, A. Budiyarto, and A. Budiyono, "Design of separate lift and thrust hybrid unmanned aerial vehicle," *J. Instrum. Autom. Syst.*, vol. 2, pp. 45–51, 2015.
20. A. Glaws, R. King, I. A. Tools, National Renewable Energy Lab.(NREL), and C. O. Golden. United States, 2022.
21. D. Communier, M. F. Salinas, O. Carranza Moyao, and R. M. Botez, *Aero Structural Modeling of a Wing Using CATIA V5 and XFLR5 Software and Experimental Validation Using the Price-Païdoussis Wing Tunnel, AIAA Atmospheric Flight Mechanics Conference*, 2015, p. 2558.
22. U. Ozdemir *et al.*, "Design of a commercial hybrid VTOL UAV system," *J. Intell. Robot. Syst.*, vol. 74, no. 1–2, pp. 371–393, 2014. [CrossRef]
23. Z. Xiong, Y. Xu, Z. Wang, X. Pian, and Y. Wang, "Preliminary design method and prototype testing of a novel rotors retractable hybrid VTOL UAV," *IEEE Access*, vol. 9, pp. 161141–161160, 2021. [CrossRef]



Kursat Cicin received a bachelor's degree in Mechatronics Engineering from Necmettin Erbakan University, Konya, Türkiye in 2023. During his undergraduate education, he worked on avionics of unmanned aerial vehicles. He is currently doing his master's degree in Energy Systems Engineering and working on the energy systems of air vehicles.

Ali Kankaya graduated from Necmettin Erbakan University, Department of Mechatronics Engineering, Konya, Türkiye in 2023. His research interests are flight and mission control systems of unmanned aerial vehicles.

Fatma Yalcinkaya currently continues her education as a senior aeronautical engineer with Necmettin Erbakan University, Konya, Turkey. Her research interests include aircraft design, structural analysis, fatigue and damage tolerance.

Hediye Orhan graduated from Necmettin Erbakan University, Department of Computer Engineering, Konya, Türkiye in 2023. Her research interests focus on data science, machine learning, deep learning and optimization algorithms.

Sena Turker is an undergraduate student at Konya Necmettin Erbakan University in Department of Electrical and Electronics Engineering. Her research interests are embedded systems, control systems, antennas and communication principles.

Ilknur Keskin is an undergraduate student in Department of Electrical and Electronics Engineering at Konya Necmettin Erbakan University. Her research interests are sensor technologies and circuit designs.

Enes Efe, who received his BS and MS degrees in electrical and electronics engineering in 2014 and 2018, respectively, is still continuing his doctoral education at Konya Technical University. He is currently working as a Research Assistant at Hitit Unsiversity, Department of Electrical and Electronics Engineering. His research interests are biomedical signal processing and artificial intelligence.

Emrehan Yavsan received the B.S. and M.S. degrees from Fırat University, Elazığ, Türkiye in 2012, 2014, respectively, and Ph.D. degree from Necmettin Erbakan University, Konya, Türkiye in 2020, all in Mechatronics.

He worked as a Research Assistant at Konya Necmettin Erbakan University in the Mechatronics Engineering Department between 2013 and 2023. He has been working as an Assistant Professor in the Department of Electronics and Automation at Tekirdağ Namık Kemal University, since 2023. His research interests include sensor technologies, mechatronic system design, and machine learning.