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Aircraft Designed for Cargo Transportation and Investigation of its Benefits

Enes Özen[1*], Tuğrul Oktay[2]

[1*] Hasan Kalyoncu University, Faculty of Engineering , Mechanical Engineering Department, Gaziantep, Turkey

[2] Erciyes University, Faculty of Aeronautics and Astronautics , Aeronautical Engineering Department, Kayseri, Turkey

ABSTRACT. In this study, an Octorotor UAV capable of carrying 10 desi/2 kg cargo was designed. It is an eight-rotor rotary wing aircraft and its body consists of eight arms connected to each other by two moving mechanisms. When requested in emergency situations, the fastest intervention can be provided by aircrafts. The auxiliary battery and generator system carried by the aircraft is to provide enough energy to reach the nearest electric charging station for the stranded vehicles. In cases such as disasters, the rapid delivery of health supplies can also be provided by this method. The aircraft designed for this purpose has a rotary wing and a feature that can change its body structure according to different load and weather conditions. The shape change improves its performance compared to conventional aircraft and increases its ability to fulfil its mission. For this purpose, the design of a shape-changing aircraft was realized.

Keywords: Octorotor UAV, Portable Battery, Cargo

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1. INTRODUCTION

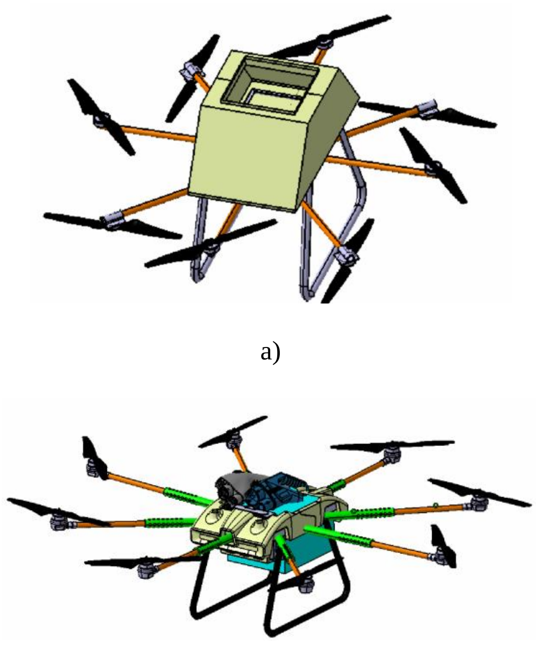
Unmanned aerial vehicles (UAVs), commonly known as drones, offer customers the advantage of speed, flexibility and convenience in delivering goods. They are particularly useful for tedious, dangerous or dirty tasks [1]. Delivery drones are unmanned aerial vehicles used to transport parcels, food, medicine or other goods. Due to the high demand for fast and efficient delivery, drone delivery system can be an effective solution for on-time deliveries and especially for emergency management [2]. "In recent years, significant progress has been made in various technologies designed for drone delivery of cargo. This progress has been primarily driven by industrial efforts. These deliveries can be by air, sea or land [3]. Shape-shifting drones can offer various advantages over conventional fixed structure drones and can become more effective for certain tasks [4]. The primary purpose of shape-shifting cargo drones is to increase the payload capacity. The drone's ability to change its shape enables it to carry loads of different sizes and weights more efficiently due to its changing geometry. This is especially important when large and heavy loads need to be transported. The drone's ability to change its shape increases its capacity to adapt to different missions. For example, it can be faster and more manoeuvrable for search and rescue operations, or more stable and safer for transporting medical supplies. Variable geometry can increase the drone's stability and adapt to different flight conditions. It can also increase the drone's maneuverability, improving its ability to fly in tight spaces. Shape-shifting cargo drones can be used for long-distance deliveries or urban deliveries. In these cases, it is important to transport large quantities of materials or packages quickly and efficiently. Such drones can contribute to advancing aviation technology. By developing innovative design and control systems, they can help shape the future of drone technology. Shape-shifting drones can consume less energy for certain missions, potentially leading to more environmentally friendly flights. This is an important advantage, especially in long-term or intensive use. Depending on the type of payload, multirotors can be effectively applied in a variety of missions, such as transportation, research, reconnaissance and life-saving. However, due to the nature of multirotor, the payload loaded on the multirotor is limited in terms of its location and weight. This limitation is a major disadvantage if the multirotor is used in various fields [15].

Electric vehicles continue to be an environmentally friendly and economical alternative. However, when vehicles need

*Corresponding author: enes.ozen@hku.edu.tr

to be charged during long journeys, a problem arises due to the lack of charging stations. To solve this problem, mobile charging station systems have been developed to meet the energy needs in emergency situations [5]. Another problem of electric cars is that battery performance decreases significantly in cold weather conditions. These situations can lead to vehicles remaining on the road longer than planned, causing disruptions to travel. These systems allow vehicles to be charged in emergency situations and thus prevent vehicles from being stranded. Mobile charging station systems consist of portable chargers. These devices are used to charge the batteries of vehicles. Mobile charging stations are designed to quickly charge the batteries of vehicles. In this way, vehicles are prevented from staying on the road and the safety of drivers is ensured. Offering a fast and effective solution for emergency access, mobile charging stations play an important role in meeting energy consumption, especially in long journeys or off-grid areas. These systems can be integrated with portable chargers and aerial vehicles, enabling access to electric vehicles from anywhere [6].

This paper presents the design of a deformable rotary wing aircraft, illustrated in Figure 1. The overall objective of the study is to discuss the design and geometry of the shape-shifting cargo drone (octorotor) in detail. Important features such as the body structure of the drone, the angle between the arms and their lengths are analyzed. The design and tuning of PID (Proportional-Integral-Derivative) controllers for controlling the drone's shape change are discussed. Advanced control systems for flight stability and safety are emphasized. The study emphasizes the variable geometry features designed to adapt the drone to different missions. These features optimize the payload, maneuverability and flight performance of the drone.



a)

b)

Fig. 1. a) Octorotor Unmanned Aerial Vehicle, **b)** Mobile Charging Station UAV

2. MATERIALS AND METHODS

2.1 General Structure and Components of Octorotor

The propulsion system of the rotary wing unmanned aerial vehicle consists of 8 rotors and propellers. The propellers rotate in opposite directions and the autopilot system on the aircraft controls the rotation speed of the propellers (Figure 2).

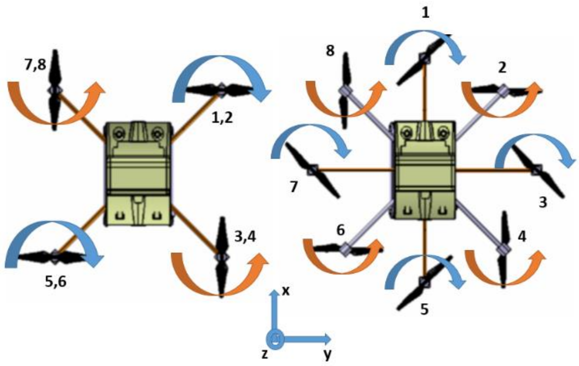


Fig. 2. Rotary Wing Aircraft Propeller Rotation Directions

Dynamic equations are obtained by using Newton Euler equations for modeling the aircraft system. Equation 1 is used to describe linear movements and equation 2 is used to describe angular movements. The octorotor has eight rotors and it is preferred that each rotor is equivalent. Rotors rotating at the same speeds create an upward force along the z-axis. The aircraft is stationary along the x and y axes and is considered to be in equilibrium. Rotation of the rotors at different speeds disrupts the equilibrium state in the x and y axes and the aircraft performs linear motion along the x, y and z axes and angular motion around these axes. These situations are expressed mathematically in equations 1 and 2.

$$F = ma \tag{1}$$

$$M = I\alpha \tag{2}$$

$$F_i = b\omega^2; i = 1,2,3,4,5,6,7,8 \tag{3}$$

Blade element theory is expressed in Equation 3. The rotation speed of the propellers is obtained by assuming that the air density, angle of attack and wing surface area are constants in the aerodynamic lift force equation. F_i is the equation that gives the aerodynamic force generated in each propeller. The U1 command is obtained by multiplying the square of the velocities of the rotors of the co-rotor by the coefficient b. When all the rotors of the aircraft with co-rotors rotate at the same speed, the ascent motion command input is obtained without any orientation as given in Equation 4. The b coefficient is calculated as a constant with the assumption that the aircraft is rotary winged, flies up to a certain altitude and the angles of attack of the propellers do not change, and is obtained from the engine-propeller manufacturer [7].

$$U_1 = b\left(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2 + \omega_5^2 + \omega_6^2 + \omega_7^2 + \omega_8^2\right) \quad (4)$$

The other command inputs to the octorotor are for pitch and roll motions and are given in equations 5 and 6. The input U2 required for pitching motion allows to realise angular motion around the x-axis. The speeds of the rotors on the right side of the x-axis are increased and the balance is disturbed. As a result, rolling moment is produced [8]. The speeds of the rotors in front with respect to the y-axis are increased and the balance is disturbed. A pitching moment is produced [9]. Generation of pitching and rolling moments and realisation of these movements are provided by U2 and U3 command inputs.

$$U_2 = bl\begin{pmatrix} \omega_5^2 \frac{\sqrt{2}}{2}\cos\alpha + \omega_6^2 \frac{\sqrt{2}}{2} + \omega_7^2 \frac{\sqrt{2}}{2}\cos\alpha + \omega_8^2 \frac{\sqrt{2}}{2} \\ -\omega_1^2 \frac{\sqrt{2}}{2}\cos\alpha - \omega_2^2 \frac{\sqrt{2}}{2} - \omega_3^2 \frac{\sqrt{2}}{2}\cos\alpha - \omega_4^2 \frac{\sqrt{2}}{2} \end{pmatrix} \quad (5)$$

$$U_3 = bl\begin{pmatrix} \omega_1^2 \frac{\sqrt{2}}{2}\sin\alpha + \omega_2^2 \frac{\sqrt{2}}{2} + \omega_7^2 \frac{\sqrt{2}}{2}\sin\alpha + \omega_8^2 \frac{\sqrt{2}}{2} \\ -\omega_5^2 \frac{\sqrt{2}}{2}\sin\alpha - \omega_6^2 \frac{\sqrt{2}}{2} - \omega_3^2 \frac{\sqrt{2}}{2}\sin\alpha - \omega_4^2 \frac{\sqrt{2}}{2} \end{pmatrix} \quad (6)$$

$$Q_i = d\omega_i^2; i = 1,2,3,4,5,6,7,8 \quad (7)$$

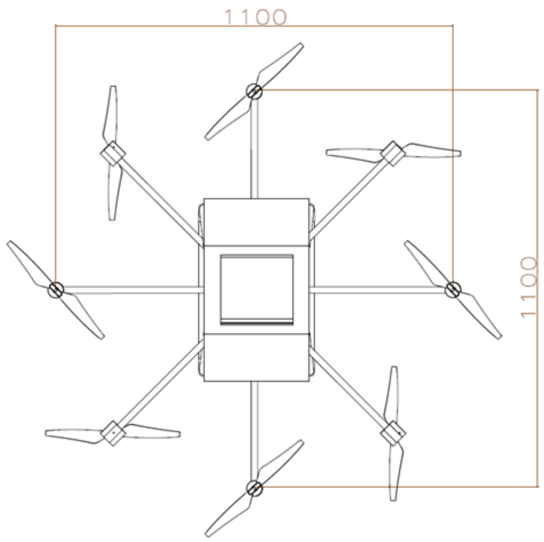
As the propellers rotate, they sweep the air and drag is created. This creates a moment opposite the direction of rotation. This value was expressed in equation 7. The parameters in the aerodynamic drag force equation are considered constant and are expressed with the coefficient d, considering that the aircraft can rise to a certain altitude and its speed has limits. The orientation movement of the quadrotor is provided by the U4 command input. Rotation of the propellers around the rotor axis creates torque due to drag. Since the rotors rotate at the same speed during ascent, 4 rotors rotate clockwise and 4 rotors rotate anti-clockwise, the total torque is zero. In helicopters, a tail rotor is also used to reset the torque produced by the propellers [10].

In Equation 8, the command input is given to generate the deflection moment [11]. In the equation given in Equation 7, the coefficient d is considered constant.

$$U_4 = d\left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2 + \omega_5^2 - \omega_6^2 + \omega_7^2 - \omega_8^2\right) \quad (8)$$

2.2 Multi-rotor Aircraft Design with Variable Geometry

X8-Octo narrows laterally and longitudinally (in y and x directions) by changing the angle between its arms in the longitudinal axis direction [12]. The shape change is named as two different configurations; configuration 1L (octo), configuration 2L (X8).



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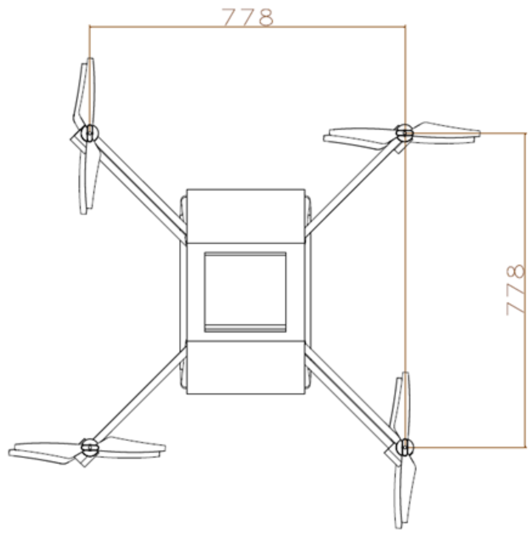


b)

Fig.3. Shape Changing Unmanned Aerial Vehicle **a)** Configuration 1L **b)** Configuration 2L

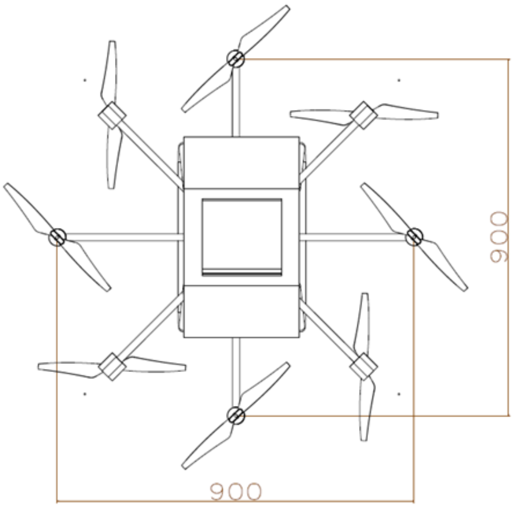
Changes in the geometry of the structure after the resulting shape change are given in Table 1.

Table 1. Dimensions of the Eight Rotor Aircraft

Aircraft Configuration	Width (mm)	Length (mm)
Configuration 1L	1100	1100
Configuration 2L	778	778

As seen in Eq.5 and 6, the distance of the rotor centre from the centre of gravity is effective in forward and lateral movements. These values will be taken into account when designing the controller in the next section.

The arms of the vehicle are lengthened and shortened and thus different configurations are created in different weather conditions. The shortening and lengthening of the arms also affect the flight performance values in previous studies [13]. The top view geometric dimensions of the aircraft in different configurations are shown in Figure 4.



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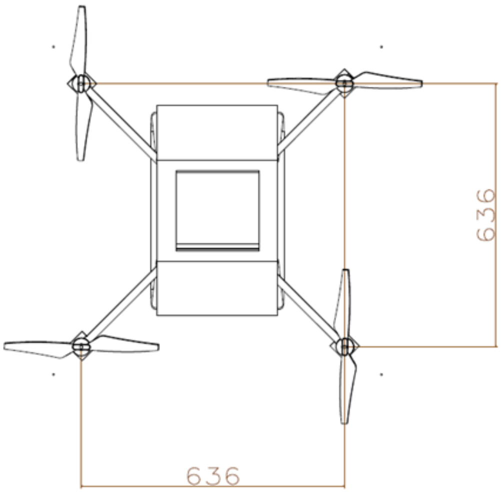

b)

Fig. 4. Shape Changing Unmanned Aerial **Vehicle a)** Configuration 3S **b)** Configuration 4S

The general characteristics of the 8-rotor aircraft before and after the shape change are given in Table 2.

Table 2. Octocopter Air Vehicle General Specifications

Aircraft Configuration	Width (mm)	Length (mm)
Configuration 3S	900	900
Configuration 4S	636	636

The stability and control behaviour of the aircraft differs in different configurations. In configuration 2, the vehicle has a narrow structure and is easier to control, while it is vulnerable to atmospheric disturbances. For this reason, when the wind speed is high, it turns into a more stable structure by extending its arms to increase wind resistance. In this case, manoeuvrability will decrease [13].

The change is realized by means of mechanisms in flight and on the ground. The signals received from the control system are transmitted to the relevant actuator and the angle between the arms is narrowed and widened and the arms are lengthened and shortened thanks to the screw-gear mechanism. The designed mechanism is given in Figure 5.

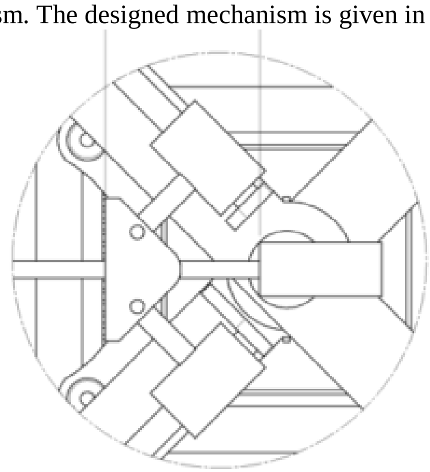

Fig.5. Mechanism enabling shape change

3. CONTROL SYSTEMS

3.1. Methods to Ensure Drone Stability during Shape Change

Aircraft perform 3 linear and 3 angular movements. It has 6 degrees of freedom mobility. According to this situation, the total forces and moments must be zero for the aircraft to remain in balance in the air. The commands that will ensure balance are control inputs. The rotary wing aircraft is controlled by both linear and angular accelerations. The aircraft uses the $U1$ command to ascend. It uses U2 command for roll motion (ϕ). It uses the U3 command for pitching motion (θ). Uses $U4$ command for yaw motion (ψ). 6 DOF says that there are 6 states for control but there are four control signals. The rotary wing aircraft is an incomplete actuator [16]. The aircraft performs the motion using elevation (z), roll (ϕ), pitch (θ) and yaw (ψ) commands. The control of the motion in the x and y direction is realized by the commands derived by the flight computer. When designing the aircraft controller, it can be divided into two subsystems. It controls the translational and angular motions of the aircraft. These are linear position, velocity and acceleration and angles, angular velocities and accelerations.

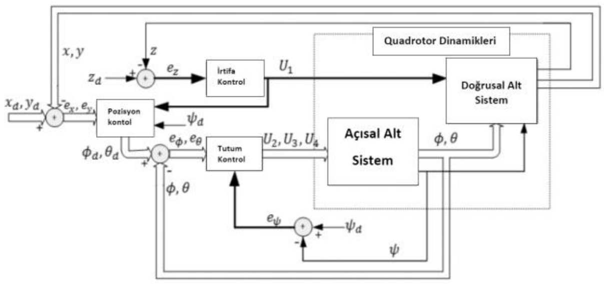

Fig. 5. Hierarchical Autopilot System Structure

As can be seen in the block diagram of the autopilot system, the differences between the desired data and the measured data are sent to the autopilot system via feedback. The PID controller processes this difference signal and adjusts the rotation speed of the engines to support stable flight.

4. RESULTS AND EVALUATION

In this study, a rotary wing aircraft was designed to deliver small cargo (10 desi / 2 kg) much faster in urban areas. The cargo may change the center of gravity of the aircraft, and in order to ensure control and stability of the aircraft in this case, a design is presented in which the arms can be extended and shortened and the belly angle can be changed. The fact that rotary wing aircraft are easy to use and require little maintenance, and that they do not need a runway for take-off and landing is an indication that they will be used more intensively in the future, and it is foreseen that the study can be used in systems that carry first aid supplies needed in emergency situations in larger capacities and can provide energy to electric vehicles in emergencies.

In this study, a design is presented to quickly meet the need for electrical energy in emergency situations. While DC-AC electric charging options of electric cars affect the time, DC electric energy method was preferred in this study. The biggest reason for this is the lightest solution for the electrical energy needed. With DC, cars will be able to gain 10 minutes of driving distance with 24 volt 7 kVA energy and 50Ah capacity battery and reach the nearest charging station [17].

Table 3. Charging Units and Features [17]

Charging Unit	Voltage	Current	Power Rating
House type	Single Phase	13-16-32 A	3-3,7—7,4 KVA
Normal	Single Phase	16 A	3,7 KVA
Fast	DC	up to 125 A	50 KW
	AC	up to 63 A	43 KVA

Higher capacity solutions can be offered with different portable energy sources. In future studies, larger aircraft with higher energy capacity will be designed by using the APU, which is also used in airplanes. Thanks to this system, the range of the aircraft will also increase significantly [18]. The design was prepared by examining similar aircraft that increase stability and controllability against different loads and variable weather conditions [19]. At this stage, it was concluded that the payload values presented could be transported safely.

5. CONCLUSION

In this study, improvements are presented by considering the disadvantages of cargo drones. These disadvantages include capacity limitations, range limitations, weather sensitivity, infrastructure requirements and legal barriers. The solutions to these problems; Compared to traditional cargo transportation, the carrying capacity of cargo drones is generally more limited, which can be improved by changing the shape. The flight range of cargo drones is directly related to battery life and payload capacity. Increased capacity provided a significant improvement to this problem. While bad weather conditions, especially strong winds and storms, can prevent cargo drones from operating safely and effectively, the advanced shape-shifting capability of the aircraft brings an important innovation. Cargo drones require appropriate infrastructure to operate. Infrastructure elements such as suitable landing and take-off areas, charging stations and logistics centers are important for cargo deliveries. Increased range and the ability to be used in emergencies, and the ability to take off and land vertically, are also important [20].

Disadvantages may hinder the widespread adoption of cargo drones or limit their use in certain application areas. However, with advances in technology and regulatory developments, these disadvantages may be overcome.

It is predicted that urban transportation will abandon traditional methods in favor of new approaches [21]. The aircraft structure designed and presented in this study appears to be well-suited for this anticipated shift.

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