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Design and Development of a Low-cost UAV for Pesticide Applications

Caner KOÇ[1]*

[1]Ankara University, Faculty of Agriculture, Department of Agricultural Machinery and Technologies, Ankara
*e-mail: ckoc@ankara.edu.tr

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Abstract: Intensive pesticide applications are used for plant protection in Turkey and in the world. Orchard sprayers, field sprayers and atomizers are commonly used machinery for pesticide applications. The recent developments in unmanned aerial vehicle (UAV) technologies have made multi rotor UAVs suitable for precision pesticide applications as these vehicles do not damage crop due to field traffic, can operate in sloping terrain freely and have data storage capabilities. Despite these advantages, their relatively high costs and requirements for technical skills to operate these vehicles are among the factors limiting their use in agriculture. In this research, a prototype multi rotor UAV for aerial pesticide applications was designed and manufactured. Computer aided design and analyses were used for the development of the UAV. The developed hexacopter UAV has an aluminum frame and carries a 5 liters pesticide tank and powered by a 222 W battery. The UAV is also equipped with an aerial camera, GPS and electronics a suitable for autonomous flights. The laboratory and field experiments were conducted to verify the features of the developed UAV successfully.

Keywords: Hexacopter, UAV, pesticide application, precision agriculture, image analysis.

Pestisit Uygulama Amacıyla Ekonomik Bir Drone Tasarımı ve İmalatı

Öz: Türkiye'de ve dünyada tarımsal mücadele amacıyla yoğun olarak pestisit kullanılmaktadır. Pestisit uygulamak için genellikle bağ-bahçe pülverizatörü, tarla pülverizatörleri ve atomizörler kullanılmaktadır. Son yıllarda ürüne zarar vermemesi, eğimli arazilerde rahat hareket edebilmesi ve hassas tarıma yönelik sahip olduğu veri depolama ve gönderme özelliklerinden dolayı insansız hava araçları pestisit uygulama amacıyla gündeme gelmiştir. Bu avantajlarına rağmen insansız hava araçlarının yaygınlaşamamalarının önemli sebeplerinden birisi de maliyetlerinin yüksek olmasıdır. Bu çalışmada, ekonomik olarak pestisit uygulamasında kullanılabilecek bir drone prototipi tasarımı yapılmış ve yapılarak imal edilmiştir. Geliştirilen drone, 5 litre depo hacmi, 222 W olan bir batarya, alüminyum malzemeden imal edilmiş özel bir çatı, kamera, GPS ve ilgili kontrol ünitelerinden oluşmaktadır. Geliştirilen dronenun laboratuvar ve tarla denemeleri başarılı bir şekilde gerçekleştirilmiştir.

Anahtar Kelimeler: Hekzakopter, UAV, pestisit uygulama, hassas tarım, imaj analizi

1. Introduction

The use unmanned aerial vehicles (UAVs) for precision agriculture have been increasing. Many unmanned aerial vehicles have been designed and used for agricultural activities (Clarke 2014). At first, UAVs were used for aerial image acquisition in agricultural activities (Candiago et al. 2015). With the developing technology, specially designed UAVs have been developed to perform certain tasks such as soil and water sampling, aerial imaging of the fields, pesticide and applications (Vasudevan, Kumar, and Bhuvaneswari 2016; Hoffmann et al. 2016; Huang et al. 2016; Faical et al. 2016). However, there are many obstacles preventing the widespread use of the UAVs in agriculture. The main ones include the complexity of the UAV structures relatively short flight times to the limited battery power, requirement of experience and programming skills to program and to fly

(Bin Junaid, Lee, and Kim 2016). Another important reason is their relatively high costs (Kim, Pergande, and Hughen 2003).

One of the most important inputs used to increase crop production is the application of pesticides to combat diseases and pests. Every year, 80 thousand tons of pesticide is used in Turkey (Yilmaz, Kart, and Demircan 2016). Various types and sizes of orchard sprayers, field sprayers and atomizers are used to apply pesticides in Turkey. Many of these machines are tractor pulled, tractor mounted or self-propelled machines(Çelik et al. 2008). Crop damage caused by the use of tractor and machine tires and difficulties in operating these machines in sloping terrains are among the major drawbacks of these machines (Koc and Keskin 2011).

In this research, a prototype multirotor UAV for aerial pesticide applications was designed, manufactured and tested in laboratory and field conditions. The developed UAV is suitable for manual and autonomous flights and has the ability to capture and store aerial images.

2. Materials and Methods

CAD Design and Manufacturing

Computer aided design (CAD) (Catia v5 R20) was used to design and develop a hexacopter frame for the UAV. Aluminum material was used as the frame material because of its light weigh. Six 1120 mm long, square aluminum profiles with the dimensions of 10 x 10 x 1 mm were used. Two sheets of hexagonal aluminum plates with an edge length of 300 mm and a thickness of 2 mm were used. The chassis of the UAV had four legs made of twisting 10 mm diameter aluminum pipe profiler. The height of the frame is 400 mm (Figure 1). A 5-liter capacity plastic tank was mounted under the UAV frame. A 12 VDC electric pump was used for the spraying.

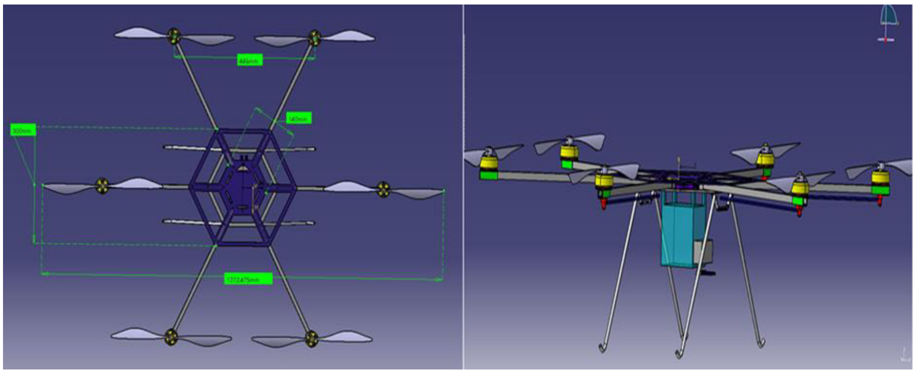

Figure 1. The top and side views of the hexacopter UAV
Şekil 1. *Hekzakopterin üstten ve yandan görünüşü.*

The designed frame was primarily analyzed for strength, deformation and safety factor in ANSYS 14.0 using finite element analysis (Yilmaz, Celik, and Akinci 2009). For the analyses, the frame was exposed to about 9 N of force acting in the -Z direction and about 68 N (6 x 1140) of the motor forces in the + Z direction through each motor (Figure 2).

In the design process, different parts are analyzed in various details according to the features. First of all, frame arms are positioned and assembled.

Next, the electronic and flight controller, electronic speed controllers (ESCs), motors, battery and the pesticide storage tank were assembled (Figure 3).

After the assembly process, the system was equipped with four arms at the rear in the direction of spraying nozzles.

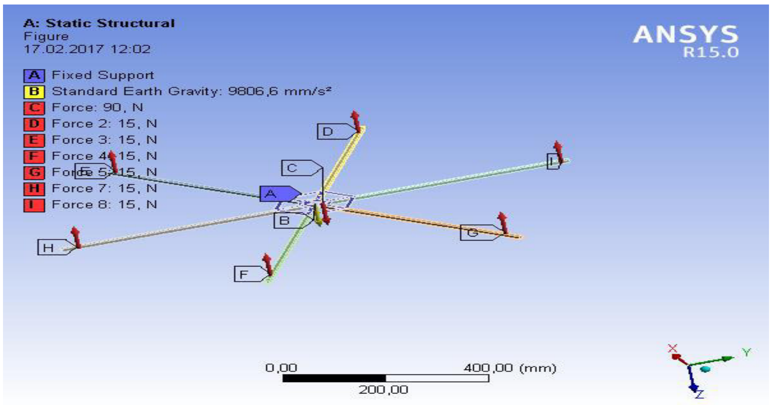

Figure 2. Schematic view of the force values used for the analysis.
Şekil 2. *Analizde kullanılan kuvvet verilerinin şematik görünümü.*

Figure 3. View of the developed hexacopter in the air.
Şekil 3. *Geliştirilen dronun havadaki görünümü.*

The UAV components and their weights are listed in Table 1. The total weight of the UAV with all of the components including the pesticide was 8720 g.

Table 1. The UAV components and their weights.
Çizelge 1. *UAV parçaları ve ağırlıkları.*

Components	Component Name	Weight (g)
Controller	APM Flight Controller Set APM 2.6 6M/H GPS & OSD & Radio Telemetry etc.	124
Connectors	20x Male+Female 4mm Banana Plug + 2x XT60 Connector	17
Frame	Aluminum Chassis, 6 Arms 56cm +2 Landing Skid+ Motor Coupling + Vibration Absorber	580
Tank	5 L Prismatic Tank 170*185*160mm	210
Pump	3 Bar 12V 3A Pump 0,4l/m + Pipes and Nozzles	182
Batterys	3s 11V 1Ah 30c +1,2Ah 30c Battery	70
Cargo	5Lt Pesticide ~5kg	5000
Others	Screws, Connectors, Jumpers, Plastic Cable Ties, Adhesive Tapes	50
Motors	6x SunnySky X4108S 480KV Brushless DC Motor	678
ESC	6x BLHeli 30A Brushless ESC With LED Light Support 2-6s For RC Multicopter	156
Propeller	6x Entire Carbon Fiber 1555 15 x 5.5 CW/CCW Propeller	113
Battery	Tunelsan 5s 18,5V 12Ah 35C Battery	1540
Total Weight:		8720

Electronic Components

An Arduino based flight controller, ArduPILOT (Mega 2.6 APM, China), was used for the UAV control. This flight controller contains a gyroscope, accelerometer, barometer and it can also be equipped with a wide range of sensors such as sonar, radar, lidar, GPS, telemetry, compass, Bluetooth and air speed sensor. A pair of telemetry broadcasting in the 433 MHz band was used (Pixhawk Radio Telemetry Kit 433Mhz, China) to enable data exchange between the UAV and the ground station. With telemetry, the data such as the UAV speed, battery status and position were monitored instantaneously. The position data required for manual or autonomous flights was provided by a GPS (U-blox, China) with a compass on it and a 50 cm sensitivity. A remote control (RC) (Turning 9X, Chine) was used to transmit data in the 2.4 GHz for remote control of the UAV. The RC had a rechargeable battery and a signal transmission capacity from 9 different channels. The system used a power distribution board for battery power monitoring and voltage control. In addition, this board was capable of distributing electrical currents up to 22.2 V and 120 A. The battery used on the UAV was rated at 222 W. At the same time, the UAV was equipped with an audible battery power warning alarm. The battery that was used for the UAV had approximately three hours of charging time. With the used battery, about 1.6 km can be sprayed at a speed of 6 kmh^{-1}. When applying pesticides, an ultrasonic distance sensor (Maxbotix, USA) was used to adjust the spraying height, a CCD (Sony 700 TVL FPV HD Ultralight) camera for image capture, a pump for spraying (Maher 85330-332020, Chine) and 8 conical spray nozzles were used.

Motor Selection

The motors for the UAV were selected to make up approximately 30-40 % of the total weight of the UAV. These motors were able to accommodate the additional needs for acceleration and environmental influences. If this overload is not taken into consideration, the UAV can cause difficulties in control and take off. Depending on the data, the total weight of 8720 was added at 35% and the selection was made at about 11287 g. Table 2 shows the data for the selected motors. In this table, the brushless DC motor with model number X4108S of 480 KV was selected. Each of these motors in combination with a propeller combination with a 381 mm wide and 127 mm wind sweep area, can theoretically carry a lifting force of 1900 g. Since there are a total of 6 motors on the UAV, it can carry approximately 11400 g. This value was optimal since the theoretical transport weight exceeds the total weight of 11287 g.

Table 2. Engine selection table (Anonymous, 2017a)
Çizelge 2. *Motor seçim tablosu.*

Prop Size (mm)	Voltage (V)	Throttle	Current (A)	Pull (g)	RPM	Power (W)	g/w Ratio	Temperature under 100 % throttle 10m
356 x120	SUNNYSKY X4108S 480KV 18.5V	50	4.0	750	3600	74	10.135140	102C (No 100 % throttle for log)
		65	6.7	1040	4180	123.95	8.390480	
		75	11.5	1450	4835	212.75	6.815511	
		85	14.6	1590	5130	270.1	5.886709	
		100	18.3	1820	5450	338.55	5.375868	
381 x127		50	3.4	730	3665	62.9	11.605720	78C
		65	6.0	1050	4398	111	9.459459	
		75	10.0	1410	5140	185	7.621622	
		85	13.3	1700	5570	246.05	6.909165	
		100	16.3	1900	5930	301.55	6.300779	

Electronic Speed Controller (ESC)

The motor control is done by an electronic speed controller (ESC). The ESCs set the required speed for the motor according to the signal from the flight controller. The two of the major parameters for ESC selection include the power range at which the ESC can operate and the maximum current it can deliver. For the selected motors, these values were 14.8 - 22.2V power supply support and maximum of 18.6 A. The SimonK 30 A type ESC was used in this design (Shenzhen Flycolor Electronic Co., Ltd., China).

Propeller Selection

Another important component of the UAV based on the motor size and ESC is the propeller selection. Within the scope of this study, propellers with 381 mm width and 140 mm wind screening capacity, which are manufactured from composite material, were selected. This provides 10 % more sweeping space from the propeller. However, energy consumption has also increased. With the selection made, motor power values and lift forces increased to 12540 g according to Table 3.

Table 3. New reference motor values (Anonymous, 2017b)
Çizelge 3. *Yeni motor referans değerleri.*

	Throttle	Amper	Pull (g)	Watt
Sunny Sky	100 %	17.93	2090	331.7
x4108s	85 %	14.63	1870	271.1
480kv	75 %	11	1551	203.5
18,5V	65 %	6.6	1163	122.1
CF 15x55	50 %	3.74	803	69.2
Re-derived Values				

Control Modes

The designed UAV can be used with two control modes of manual or autonomous. The flow diagram of the manual control system mode is shown in Figure 4. The manual flight plan was structurally based on the fact that the signals received from the RC reach the flight controller and evaluated. The APM v2.6 controller does not contain the functions to control the sprayer. For this reason, a separate relay system was developed to switch the sprayer on and off. Output signals from the 7 th channel of the RC was used to switch the relay controlling the nozzles manually. An important point in controlling the developed spraying system was the turn on and off of the spraying nozzles based on the position data from the GPS sensor. In this regard, a pair of FPV (First Person Video) and OSD (On Screen Display) were used on the UAV to monitor the device data and to observe the direction of movement in manual and autonomous flights. The FPV displays the stored data. In addition, the sensor on the tank was programmed to generate warning signals when the threshold pesticide level was reached.

The flight path for the autonomous flights for pesticide application was developed in Mission Planner program (Anonymous, 2017b). In the program, the area to be sprayed, the flight route, the on/off positions of the spraying nozzles and distance data were programmed and loaded on the flight controller. According to the created coordinates, the flight controller was able to detect the flight information in the autonomous flight mode from the control output 5 or to bring it to the "armed" position on the ground station.

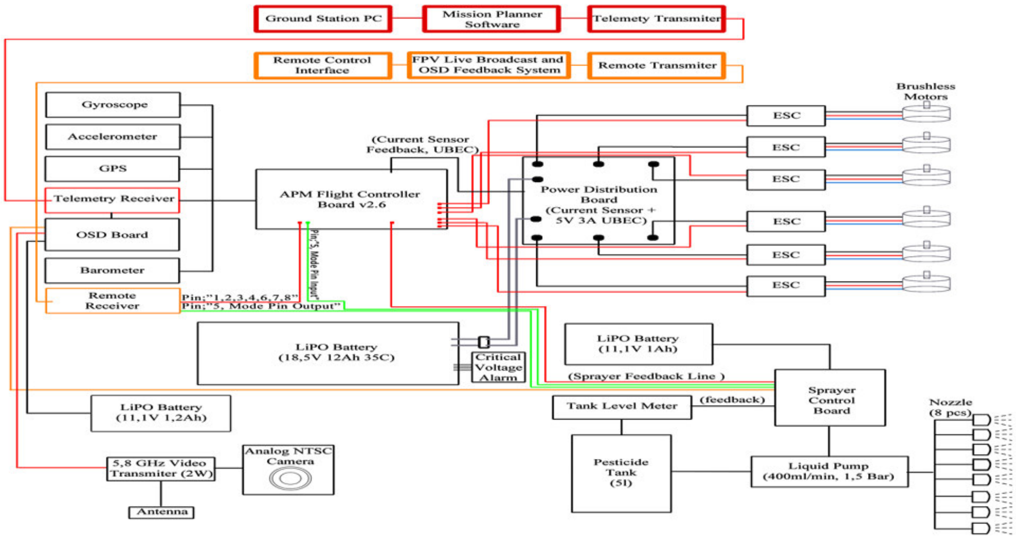

Figure 4. Flow diagram of the manual flight control.
***Şekil 4**. Manuel kontrol akış diyagramı.*

In addition, the UAV was also capable of automatically returning to its launching position when the pesticide tank was empty in this mode. The flow diagram for the autonomous flight is shown in Figure 5.

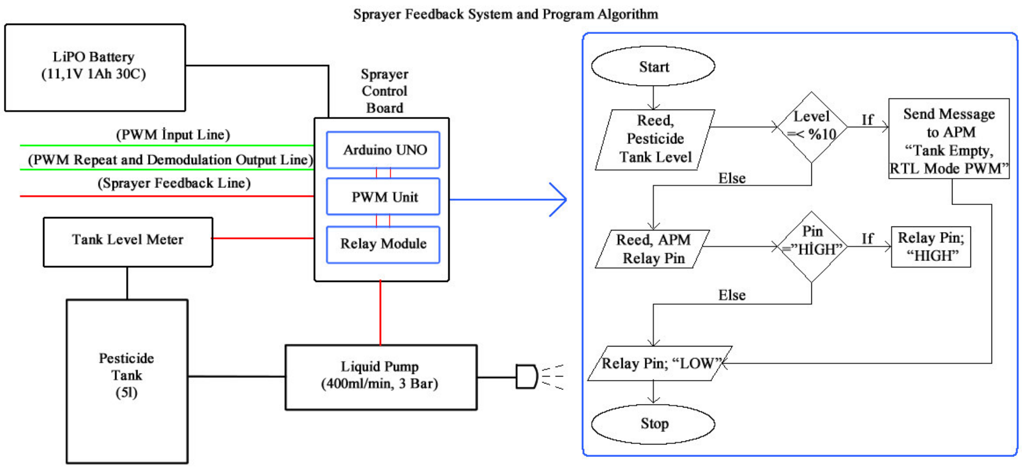

Figure 5. Flow diagram for the autonomous flight mode
***Şekil 5.** Otonomus uçuş akış diyagramı.*

Field Experiments

Field experiments to test the functions of the developed hexacopter UAV were conducted at Ankara University, Faculty of Agriculture. Flight path was determined using Mission Planner program (Figure 6). Three different throttle levels (55 %, 70 % and 85 %) on the field and 3 different UAV speeds (3.4 kmh^{-1}, 6.3 kmh^{-1}and 9.62 kmh^{-1}) were used for the field tests. Food coloring dye and water-sensitive papers were used to check the sprayed areas on the field. In the experiments, nozzles with conical orifices with a diameter of 0.5 mm were used (Chen, Zhu and Ozkan, 2012). The pump pressure used in the experiments was 1.5 bars. The water sensitive papers after the field tests were transferred to a computer environment by taking the photographs with the aid of the sensitive CCD camera. In order to determine the performance of the UAV, average droplet diameters and surface coverage ratios were calculated using the Image J (National Institute of Health, USA) program. Before these values are calculated on the scanned pictures, filtering was done to prevent noise.

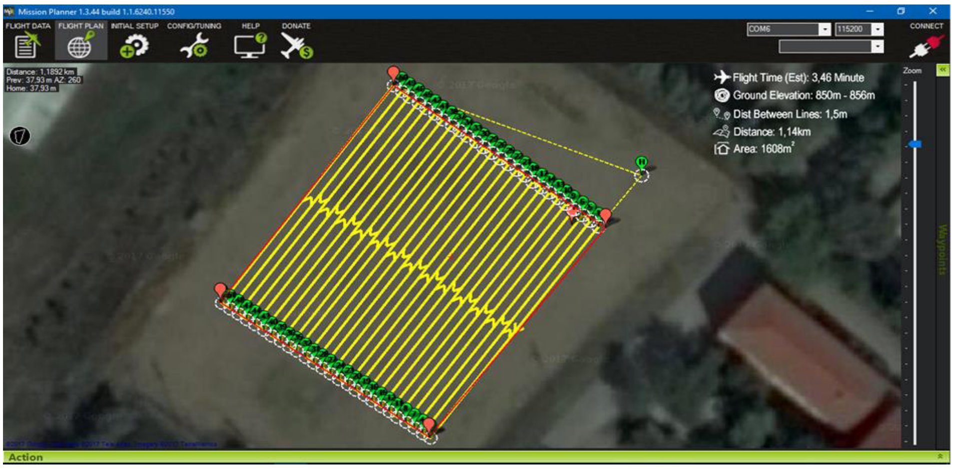

Figure 6. The marker path followed by the UAV during the experiments.
Şekil 6. *UAV'nin denemelerde takip ettiği markör yolu.*

3. Results and Discussion

As a result of the analysis with the help of ANSYS 14.0 program, the total maximum stress on the frame was found to be 66.46 MPa (Figure 7A). The critical points where stress was most intense were on the points where the reservoir and the battery were attached to the UAV arms. In terms of total deformation, the highest deformations were observed at the points of the motor connections. The total deformation was calculated as approximately 11.45 mm (Figure 7B). The other critical value in terms of frame manufacturing was the safety factor. As a result of the analysis, the minimum safety coefficient was found to be 1.24 (Figure 7C). Since this value was within the safety limits (Min Safety Factor > 1), it can be said that the developed frame was suitable for the design and manufacturing of UAV spraying system (Çelik et al. 2009).

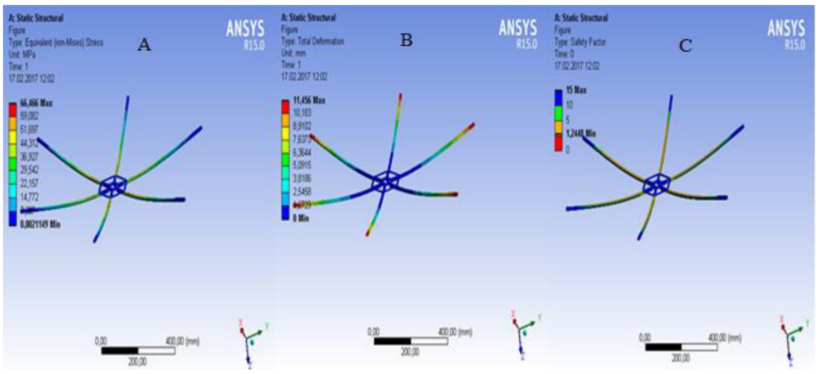

Figure 7. The values in the analysis results (A-Total stress, B-Total deformation, C- Safety factor).
Şekil 7. *Analiz sonuçlarında elde edilen değerler (A-Toplam gerilme, B-Toplam deformasyon, C-Güvenlik katsayısı).*

The liquid in the tank was discharged in 12.5 minutes at a flow rate of 0.4 liter/min. If the UAV was operated at 70 % throttle level, the UAV flew until the tank was empty. The time-dependent weight reduction is shown in Figure 8. The total flight time table was obtained by subtracting the power values from the total capacity of the battery and the power consumption values corresponding to the weight per minute. In Figure 7, between 14th and 18th minutes is seen as empty storage and return time. This protects both the battery life and the safety of the drones.

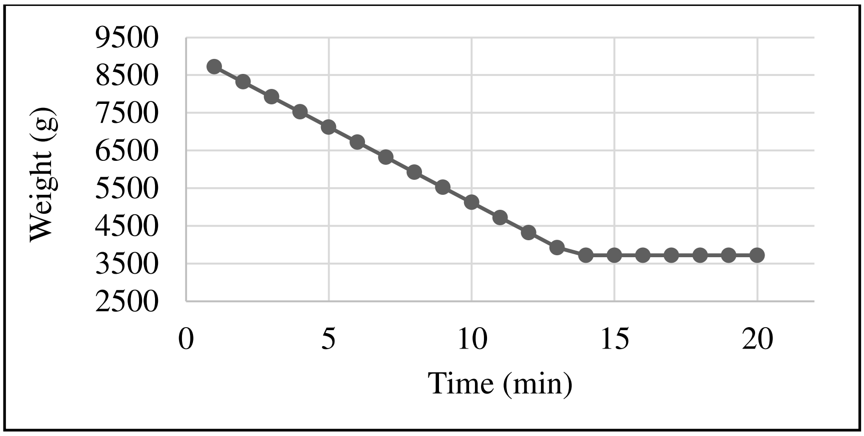

Figure 8. Time-dependent weight reduction during the UAV operation.
Şekil 8. *UAV' nin uçuş süresince görülen ağırlık azalması.*

To find the weight acting on each motor was calculated by dividing the total weight by 6. The power consumption of each motor is shown in Figure 9. As a result of the measurements, the drop diameter values n the water-sensitive papers varied from 80 µm to 900 µm. Surface coverage rates ranged from 8.89 % to 28.71 %. Surface coverage values decreased with increasing UAV speeds (Figure 9).

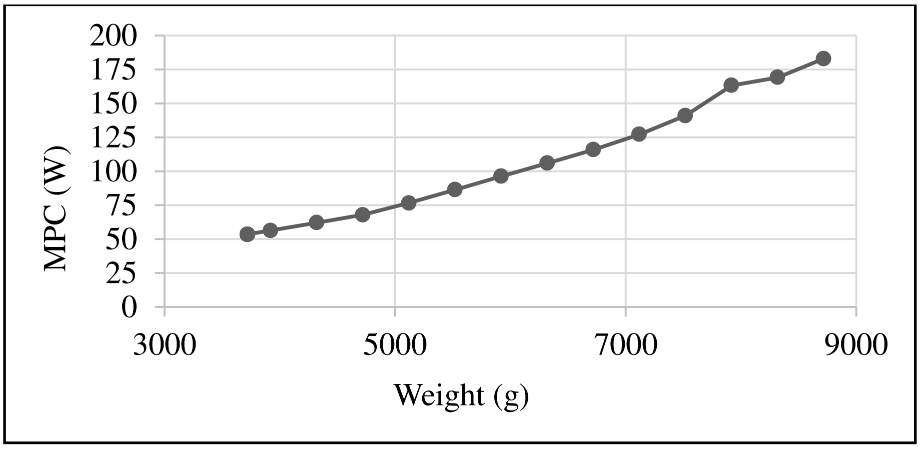

Figure 9. Weight-dependent motor power consumption.
Şekil 9. *Ağırlığa bağlı motor güç tüketimi.*

The cost of the developed UAV was approximately $1000. This amount was about one tenth of the cost of commercially available similar UAVs such as the ones sold by DJI (http://www.dji.com/mg^{-1}). Aluminum was used as the frame material in this prototype, as it was easy to machine, light weight and relatively inexpensive.

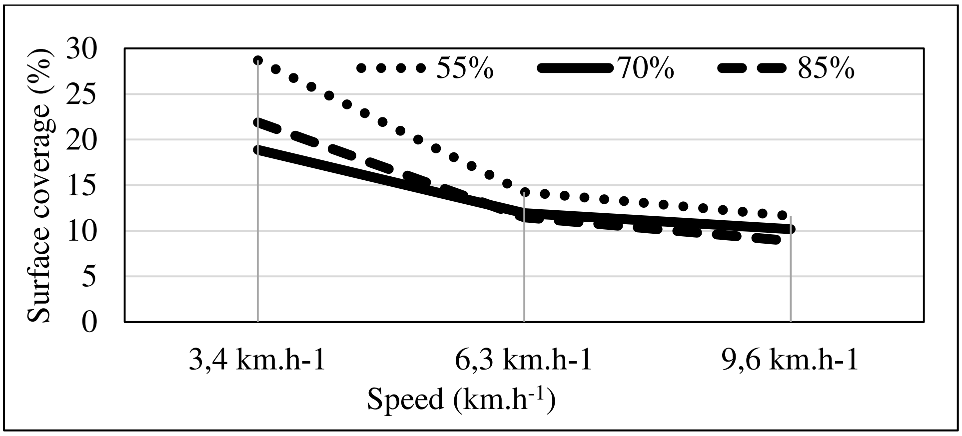

Figure 10. Surface coverage rate.
Şekil 10. *Yüzek kaplama oranı*

While the composite materials have high tensile strength, flexibility, lightness, permanent deformation, the composite materials have high costs (Cordill, Seguin, and Ewing 2011; Arasu, Krishnaraj, and Rambabu 2014).

ArduPILOT Mega 2.8 APM was used as prototype UAV flight controller. For unmanned aerial vehicles, there are flight controllers by many companies. However, ArduPilot Mega 2.8 APM controller was chosen because it was not only inexpensive but also allowed the use of open source software (Mission Planner 1.3.39) programs. Required programs for different purposes can be added to ArduPilot. The open source Mission Planner program also offers a fully automated flight capability with GPS.

On the UAV, conical beam nozzles were used. As a result of the experiments, the average drop diameters obtained ranged from 80 µm to 900 µm. These average drop diameters are not sufficient for efficient spraying. The irregularity of the drop diameters was due to the variations in spraying pressure. The selected pump for the spraying system did not provide enough pressure to provide the optimum average droplet sizes. A pump with a higher pressure rating would be more suitable for this type of application. However, the weight and power consumption of the pumps for UAV spraying applications would be the limiting factors.

One of the important problems encountered in aerial pesticide applications is the drift. There are methods to prevent drift such as using assisted air-flow atomizers and electrostatic charge nozzles (Chen et al. 2013). The developed UAV prototype offers a significant advantage due to the airflow created by the propellers against drift. During the application, the nozzles were sprayed from the bottom of the propellers, so the propellers served as auxiliary airflow in downward direction. There was also a reduction in the rate of surface coating depending on the UAV speed. As the UAV speed increased the surface coating ratio was decreased and this was in agreement with the study by Whitney et al. (1989).

4. Conclusion

In this study, an inexpensive UAV-assisted aerial spraying system with a capacity of 5.0-liter tank was designed and manufactured. Field experiments were carried out in order to apply pesticide in agriculture. In addition to taking aerial images with the developed UAV, the desired target was sprayed successfully with both manual and autonomous modes. While the developed prototype sprayer applied the pesticide successfully on the targeted areas, the average droplet size and the surface coverage ratios were not within the desired optimum levels. Therefore, the nozzles and the pump used for spraying need to be modified for optimal aerial spraying operations. More experiments with different nozzles and pumps would be necessary to determine the biological activity of the UAV spraying system. With that, the UAV aerial spraying systems have great potential in orchard, vineyard and field spraying applications especially in difficult to access fields and ground terrains.

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