

CONCEPTUAL AND FUNCTIONAL STUDY OF A MULTI-ROTOR DRONE PROTOTYPE USED FOR SECURITY APPLICATIONS

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ABSTRACT:

THIS PAPER PRESENTS THE DESIGN AND FUNCTIONAL STUDY OF THE PROTOTYPE OF A MULTI-ROTOR (HEXAROTOR) DRONE AND SUBSEQUENTLY OF ITS ACTUAL PROTOTYPE REALIZATION. THE DRONE IS INTENDED TO BE USED IN SECURITY APPLICATIONS FOR INDUSTRIAL FACILITIES OF STRATEGIC INTEREST, GOVERNMENTAL INSTITUTIONS, DETENTION CENTERS, BORDER SURVEILLANCE ETC.

KEY WORDS: HEXAROTOR PROTOTYPE, ELECTRONIC SPEED CONTROLLER, GPS, BRUSHLESS MOTOR, SECURITY APPLICATIONS.

INTRODUCTION

The paper presents the solution of a hexarotor drone, adopted for designing and practical implementation.

Following the elaborate calculation abstract and considering the experimental data obtained, the solution chosen, presented in this article, is a hexarotor in X model, given that this solution exhibits much higher air stability due to the resulting lift force created by the rotation of the six rotors (fig. 1)³.

A multirotor UAV (unmanned aerial vehicle) is an unstable dynamical six-degree of freedom system consisting of three-dimensional translation and three rotational movements. The translation motion is obtained by altering the direction and magnitude of the vertical traction force⁴.

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For fixed rotor blades (relatively to those mounted on drones) the rotational movement for drone tilting is accomplished by individual variations of the rotor speeds to create rotation torques around the rotation center. The magnitude of the rotor speeds results in the magnitude of the traction force vector⁵.

The movement of the multi-rotor vehicle in two dimensions is illustrated in fig.2-fig.4.

COORDINATE SYSTEMS ASSOCIATED WITH THE DRONE

To analyze the behavior of the drone, two coordinate systems were used to represent the position and orientation of the hexarotor in the three dimensions work space, namely: the ground coordinate system and the hexarotor coordinate system⁶.

The ground coordinate system is a fixed reference system, so that, if it is desired to define a spatial route of the drone it will be followed, by referring to this coordinate system.

The hexacopter coordinate system is chosen to be aligned with the drone mounted sensors, so that the x-axis will be oriented in the forward direction (the red mounting heads of the motors), the y-axis oriented to the left and the upward-facing axis, perpendicular to the plane determined by the axes x and y⁷. (See Figure 5)

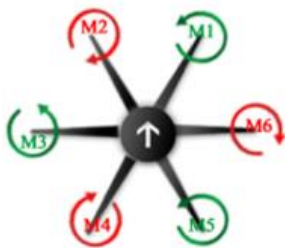


Fig.1 Hexarotor in X, highlighting the rotational direction of the propellers and the direction of the drone (white arrow)

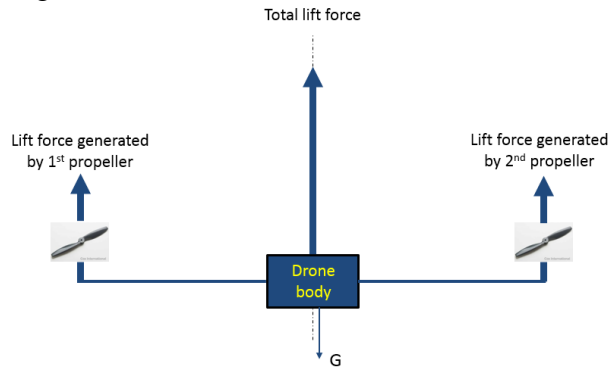


Fig.2 The propellers rotate at the same angular velocity so that the total lift force vector is in the same direction as the force of gravity vector

Cambridge University Press, 2000; Christian Månsson; Daniel Stenberg, *Model-based Design Development and Control of a Wind Resistant Multirotor UAV*, Department of Automatic Control, Lund University, 2014; V. Martínez, *Modelling of the Flight Dynamics of a Quadrotor Helicopter*, Department of Aerospace Sciences: Cranfield University, Cranfield, Bedfordshire, United Kingdom, 2007

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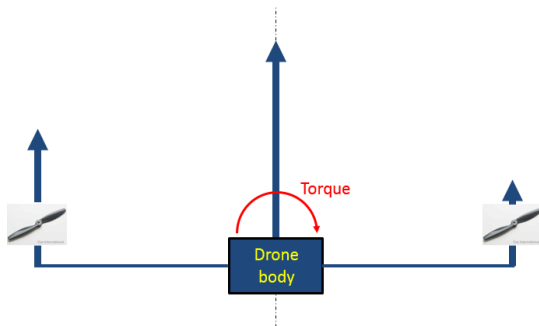


Fig.3 By varying the speed of rotation of the propellers result in a torque of rotation

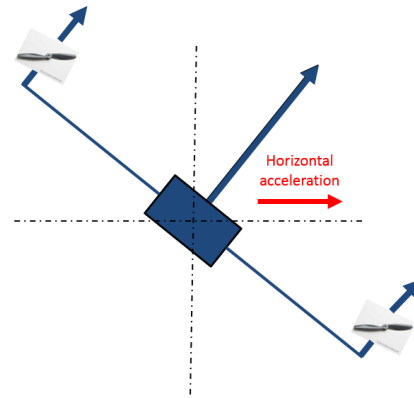


Fig.4 The direction of the total thrust vector does not coincide with the direction of the gravitational force, resulting in a horizontal acceleration

THE ROTATION AXES

The attitude of the drone is defined as the orientation of the drone's coordinate system to the Earth's coordinate system. This represents the rotation of the drone around its x, y and z axes, by using the right-hand rule, and consists of three movements: roll, pitch, and yaw⁸ (See Figure 6)

The attitude is controlled by changing the speed of the motors, implicitly by the speed of rotation of the propellers, the rotors being numbered clockwise, with the rotor number 1 being in the right front position of the hexacopter⁹ (See Figure 5)

The roll (roll) represents the rotation movement around the x axis, obtained by increasing / decreasing the speeds 1, 2 and 3, and simultaneously by increasing / decreasing the rotation speed of the rotors 4, 5 and 6. During this maneuver a torque of rotation around the x-axis and thus an angular acceleration occurs. The rotation angle for roll motion is noted with φ and is measured in rad/s¹⁰.

The pitch is the rotational movement around the y-axis and is achieved by increasing / decreasing the speed of the rotors 1 and 6 and simultaneously by increasing / decreasing the rotation of the rotors 3 and 4. Since the y-axis direction coincides with the position of the

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rotors 2 and 5, they do not affect the pitch rotational motion. The pitch motion is noted with θ and is also measured in rad/s¹¹.

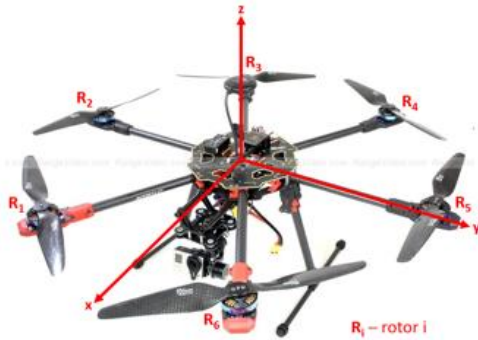


Fig.5 The hexacopter coordinate system and numbering of the rotors

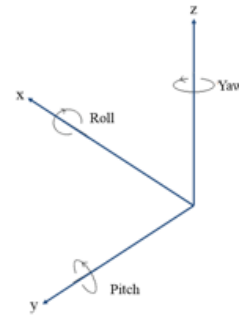


Fig.6 The hexacopter rotation axis: roll (x-axis), pitch (y-axis), yaw (z-axis)

The yaw represents the rotation movement around the z axis. In the case of this movement, each propeller creates a torque around the z-axis when rotating. Thus, this torque is directed in the opposite direction to the rotation direction of the rotor. If the propeller rotates clockwise, it will create a trigonometric rotation around the z-axis¹².

To maintain a stable hexacopter, it is necessary to rotate the rotors in different directions so that the three rotors rotate clockwise and the other three in the trigonometric sense. The rotation movement is achieved by decreasing / increasing the speed of the rotors 1, 3 and 5 and simultaneously increasing/decreasing the rotation speed of the rotors 2, 4 and 6. The rotation angle for the rotation motion is noted with ψ and is measured in rad/s¹³.

THE VIRTUAL PROTOTYPE OF THE HEXACOPTER

The virtual 3D prototype of the hexacopter was realized using SOLIDWORKS CAD software (See fig. 8-fig.9).

In order to achieve the best performance of the hexacopter, a calculation algorithm was developed in order to analyze the behavior of the drone in all flight modes (hover, ascending flight, forward flight, rotation around the center axis, lateral flight). The calculations results were correlated and validated with the data obtained from the dedicated software platform

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existing on the website www.ecalc.ch, which allows, based on the user's inputs, to verify if the chosen version of the drone's motors is correct and able to fly without errors¹⁴.

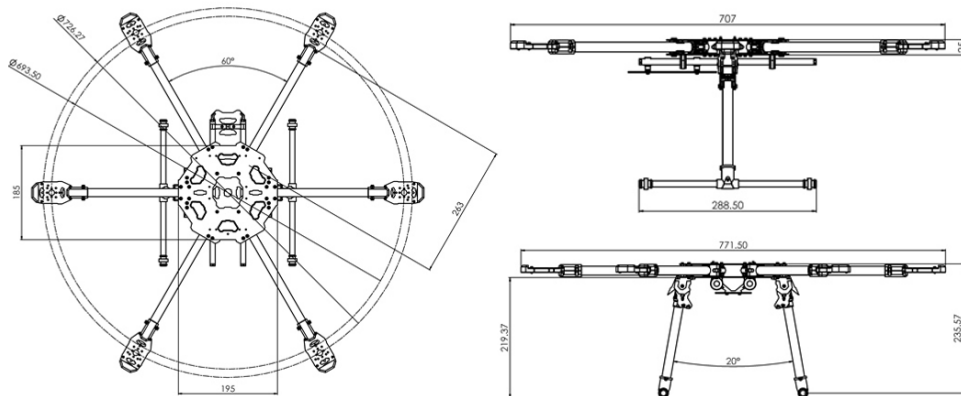


Fig.7 The hexacopter dimension figures

Figure 9 illustrates the fully equipped PROTOTYPE of the hexacopter including: 13” carbon fiber propellers, brushless motors, 4S LiPo battery, ESCs (Electronic Speed Controller), main controller, tilt-pan orienting system, camera, PMU (Power Module Unit), GPS antenna and receiver [6].



Fig.8 The CAD prototype of the hexacopter

¹⁴ Drone configuration calculation checking, range estimator, motor characteristic at full throttle evaluation; [Online]. Site: <https://www.ecalc.ch/xcoptercalc.php>

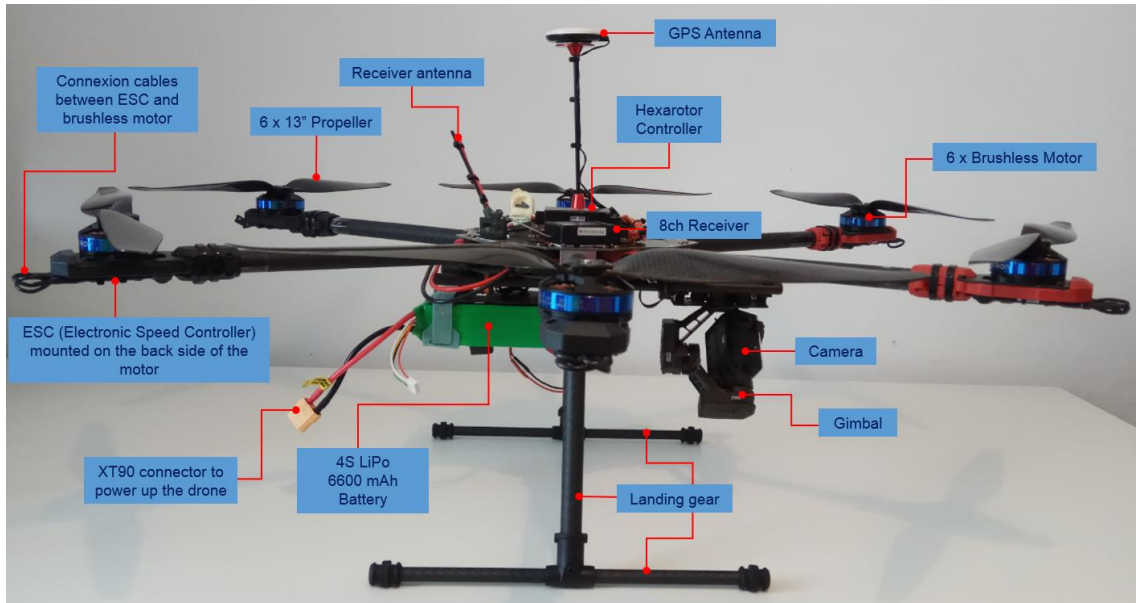


Fig.9 Hexacopter PROTOTYPE fully equipped



Fig.10 Choosing the components that equip the drone¹⁵

Remarks:							
Battery	Motor @ Optimum Efficiency	Motor @ Maximum	Motor @ Hover	Total Drive	Multicopter		
Load: 19.44 C	Current: 8.44 A	Current: 19.44 A	Current: 4.09 A	Drive Weight: 1430 g	All-up Weight: 2845 g		
Voltage: 13.03 V	Voltage: 13.96 V	Voltage: 12.87 V	Voltage: 14.39 V	50.4 oz	100.4 oz		
Rated Voltage: 14.80 V	Revolutions*: 7941 rpm	Revolutions*: 6331 rpm	Revolutions*: 3504 rpm	Thrust-Weight: 2.6 : 1	add. Payload: 3483 g		
Energy: 88.8 Wh	electric Power: 117.8 W	electric Power: 250.3 W	Throttle (log): 36 %	Current @ Hover: 24.53 A	122.9 oz		
Total Capacity: 6000 mAh	mech. Power: 99.0 W	mech. Power: 192.3 W	Throttle (linear): 47 %	P(in) @ Hover: 363.0 W	max Tilt: 63 °		
Used Capacity: 5100 mAh	Efficiency: 84.0 %	Power-Weight: 527.8 W/kg	electric Power: 58.8 W	P(out) @ Hover: 275.2 W	max. Speed: 45 km/h		
min. Flight Time: 2.6 min		239.4 W/lb	mech. Power: 45.9 W	Efficiency @ Hover: 75.8 %	28 mph		
Mixed Flight Time: 9.0 min		Efficiency: 76.8 %	Power-Weight: 127.6 W/kg	Current @ max: 116.66 A	est. rate of climb: 8.5 m/s		
Hover Flight Time: 12.5 min		est. Temperature: 50 °C	57.9 W/lb	P(in) @ max: 1726.5 W	1673 ft/min		
Weight: 568 g		122 °F	Efficiency: 77.9 %	P(out) @ max: 1153.7 W	Total Disc Area: 51.38 dm ²		
20 oz		Wattmeter readings	est. Temperature: 31 °C	Efficiency @ max: 68.8 %	796.39 in ²		
		Current: 116.64 A	88 °F		with Rotor fail:		
		Voltage: 13.03 V	specific Thrust: 8.06 g/W				
		Power: 1519.8 W	0.28 oz/W				

Fig.11 Verifying the actual configuration¹⁶

(the green circle with white check mark indicates that the actual configuration has been properly chosen)

¹⁵ Drone configuration calculation checking, range estimator, motor characteristic at full throttle evaluation; [Online]. Site: <https://www.ecalc.ch/xcoptercalc.php>

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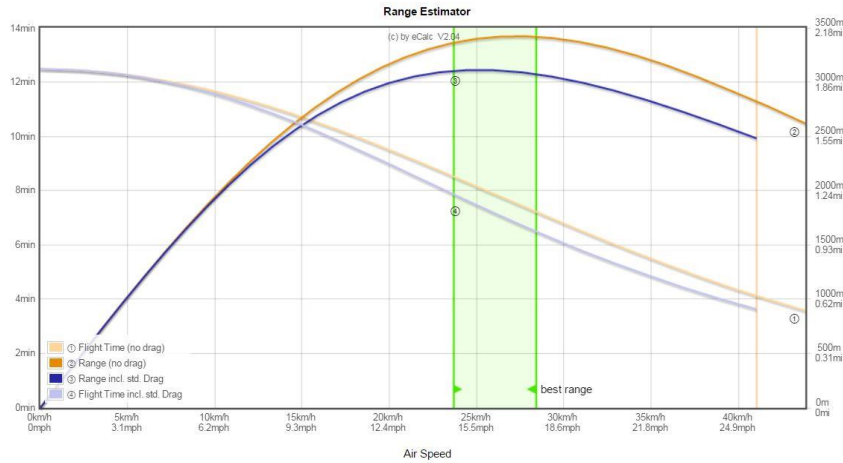


Fig.12 Hexacopter range estimator¹⁷

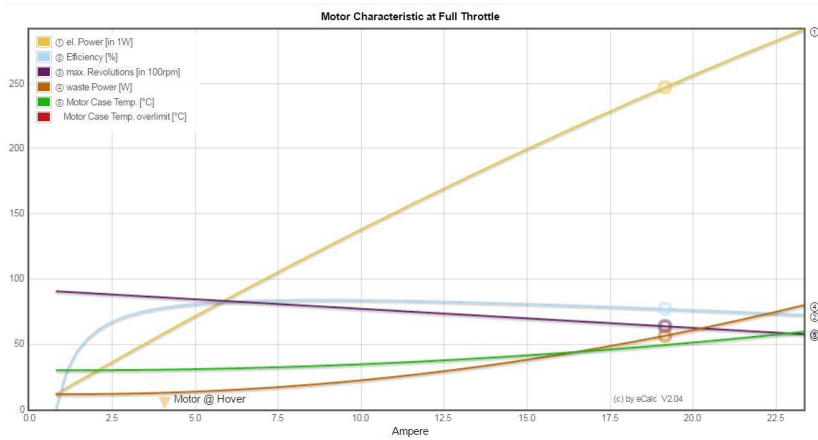


Fig.13 Brushless motor characteristics at full throttle¹⁸

Prop-Kv-Wizard

All-up Weight: g

of Rotors:

Frame Size: mm

Battery - Rated Voltage: V

Propeller - Diameter: inch max. 13.6"

Propeller - Pitch: inch max. 8.6"

Propeller - # Blades:

recommended KV: **460 ... 670** rpm/V

min. Motor Power: **250 ... 435** W+

min. ESC size: **20 ... 35** A+

Fig.14 Choosing the right motor-propeller combination¹⁹

Figures 10-14 illustrate the data obtained from the simulations performed on the www.ecalc.ch platform, using the chosen variant of the driving equipment mounted on the hexarotor, to identify any inconsistencies or errors that may occur during its flight²⁰.

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¹⁸ Drone configuration calculation checking, range estimator, motor characteristic at full throttle evaluation; [Online]. Site: <https://www.ecalc.ch/xcoptercalc.php>

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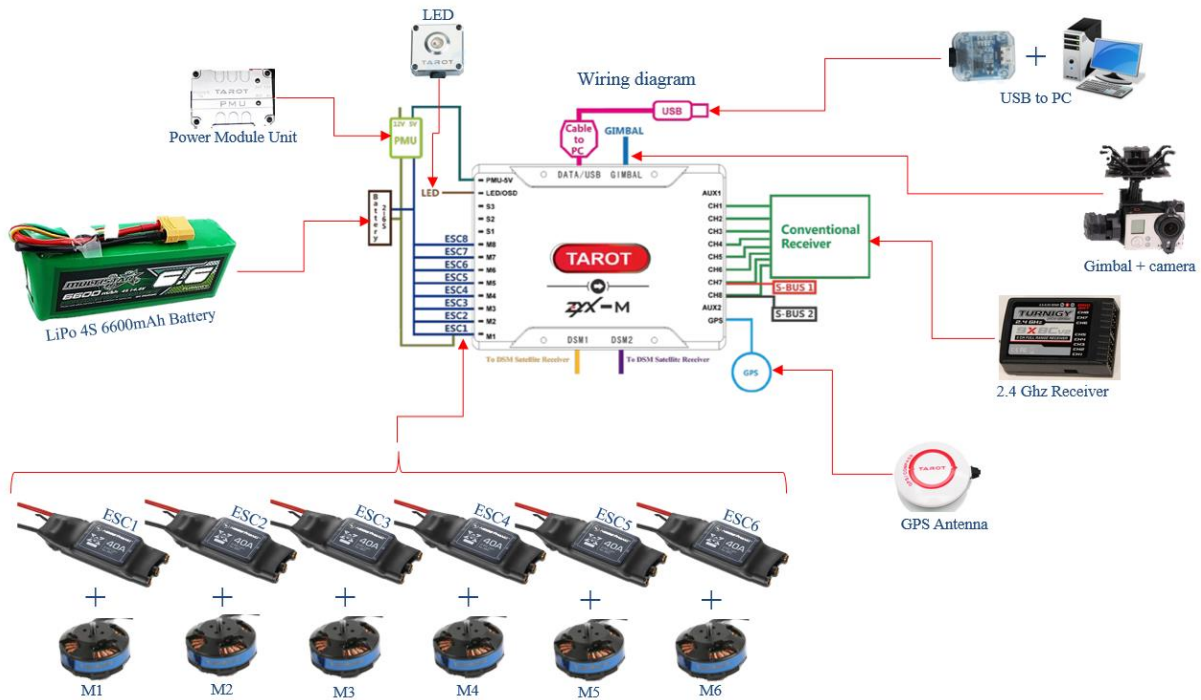


Fig.15 Wiring diagram

CONSTRUCTIVE AND FUNCTIONAL ASPECTS OF THE HEXAROTOR

Figure 15 shows the wiring diagram, where the connection of the avionics components is highlighted. They connect to the central element of the hexarotor - the main controller, which provides the processing power required for the evolution of the drone during flight and is equipped with intelligent computing and navigation control systems, a 32-bit processor, integrated anti-vibration sensor, metal housing, supports dual S-BUS reception, sends warnings in case of failure.

Power is provided by a 4S LiPo battery pack with a capacity of 6600 mAh, voltage - 14.8V. From the battery (indicated on the Battery 2-6S circuit diagram), a fraction of the voltage is distributed through the upper plate (which also acts as the voltage distribution board) to the 6 Electronic Speed Controllers (ESC), which, in turn, through the engine control software distributes the voltage to brushless electric motors.

The other fraction of the voltage supplied by the battery passes through the power distribution module (PMU) from where it is divided into 2 bus lines: the 5V bus provides the voltage required for the main controller (coupled to the PMU-5V slot) and the other, a 12-volt bus system provides power to the tilt-pan camera system. For the 3-axis tilt-pan control part, the power supplying cable is inserted into the tilt-pan system slot and on the controller.

Motor's control is achieved by coupling servo cables to the M1-M6 ports on the controller (corresponding to the 6 ESCs). At the other end of the controller, the servo cables are inserted into the appropriate CH1-CH8 slots, and the opposite end of the servo cables is inserted into the slots on the receiver.

In the case of the hexarotor, the control of the motors is made through channel 3 on the receiver.

²⁰ Drone configuration calculation checking, range estimator, motor characteristic at full throttle evaluation; [Online]. Site: <https://www.ecalc.ch/xcoptercalc.php>

The GPS antenna connects to the GPS slot on the controller. To program the different flight modes and set the control limits on the 3 axes: pitch, roll, rotation, via a USB cable, the drone is connected to the PC and the software can be programmed (on the pink cable scheme - Cable to PC). To indicate the operation modes with the help of light signals, a LED unit has been installed, connecting it to the LED / OSD slot on the controller. Optionally, if a FPV - First Person View system is installed, it will require an OSD - On Screen Display equipment, which will also connect to the LED / OSD slot on the controller.

In the following, there are briefly presented the components used for the practical realization of the above mentioned hexarotor solution.

For the frame side, carbon fiber tubes were used, like the landing gear arms for engine mounts due to the reduced weight of the material. As a support of the above-mentioned arms, landing gear and avionics and camera equipment, two carbon fiber plates (upper and lower) were used, which are assembled with screws. After checking the obtained data, the next step was to equip the drone, as shown in the following lines. For propulsion, the hexarotor was equipped with Tarot 4006/620KV brushless electric motors. To control the engine start/stop phases, speed and rotating direction ESCs (Electronic Speed Controller) were mounted at the bottom side of the motors. The type of the ESC chosen is Hobbywing XRotor 40A-OPTO.

To produce lift 13" carbon fiber propellers, Tarot 1355 type, were used, and as a power source the hexarotor was equipped with a 4 cell LiPo 6600 mAh battery, Multistar 6600mAh Lipo type.

For the avionics part, the drone was equipped with a main controller (the central component that also provides the automatic pilot function and controls the flight modes of the drone), Tarot ZXY-M model, a GPS antenna, a voltage distribution module, to supply power from battery to consumers, a USB module to program the drone, and, of course, the Tx-Rx radio frequency transmission equipment pack, Turnigy TGY 9x model.

Considering the purpose of this hexarotor, namely, perimeter surveillance, it is mandatory to equip the drone with a surveillance camera. For this purpose, it was used a 3-axis steering and position control system from an integrated Tarot T4-3D controller. Surveillance is achieved with a Turnigy Action Cam video camera, which can shoot at a resolution of 1080p, and its autonomy is ensured by a battery.

As an auxiliary solution, the drone can be equipped with infrared surveillance camera (FLIR – Forward Looking Infrared) or thermal imaging camera for surveillance in difficult visibility conditions (at night or in dense conditions).

CONCLUSION

The mechanical structure of the hexarotor, the elaborated calculation algorithm which shows the behavior of the drone during various flight maneuvers (hover flight, forward flight, lateral flight, ascensional flight, rotation around the vertical axis), the selection of the number and type of the motors equipping the drone, the correlation of the payload to be mounted on the hexarotor and driving system component;s selection, as well as the integration of the avionics components and the Tx remote control, represent original contributions to this work.

From the cost point of view, compared to a similar constructive-functional solution available on the market at a price of approximately EUR 3,800 - 4,500, the solution presented in this paper has a final price of about EUR 1,500, resulted by cumulating the price of the components that equip the drone, the materials and tools used for construction. Thus, one may conclude too that this drone represents a better financial solution to be used in perimeter securing applications, for the surveillance of industrial facilities of strategic interest, government buildings, detention centers, borders, illegal border crossing.

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