DEVELOPMENT OF A TRICOPTER-HEXAROTOR AGRICULTURAL UAV DESTINED FOR THE REALIZATION OF PRECISION SPRAYING WORKS
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DEZVOLTAREA UNUI UAV TRICOPTER-HEXAROTOR DESTINAT REALIZĂRII LUCRĂRILOR DE STROPIRE DE PRECIZIE

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ABSTRACT

The utilization of unmanned aerial vehicles (UAVs) for chemical application has become a topic of great interest to both researchers and the market in recent times. Producers have proposed the use of drones for joint spraying as a means of enhancing precision agriculture and productivity. However, chemical spraying is a highly specialized field where the quality of the spray is critical so the used UAV have to be precise and reliable. Within this paper will be presented the process of developing a tricopter-hexarotor chassis type UAV, electrically driven, fitted with a 66 litres tank and 6 anti-drift nozzles which will be used for precision spraying of agricultural crops based on preprogrammed flying missions.

ABSTRACT

Utilizarea vehiculelor aeriene fără pilot (UAV-uri) pentru aplicarea chimicalelor a devenit un subiect de interes în ultimul timp atât pentru cercetători cât și pentru piață. Producătorii au propus folosirea dronelor pentru stropirea integrată ca o modalitate de a îmbunătății productivitatea și agricultura de precizie. Totuși, stropirea cu substanțe chimice reprezintă un domeniu specializat în care calitatea stropirii este esențială astfel încât UAV-ul folosit trebuie să fie precis și fiabil. În cadrul acestei lucrări va fi prezentat procesul de dezvoltare al unui UAV având șasiul de tip tricopter-hexarotor, acționat electric, dotat cu un rezervor de 66 litri și 6 duze antidrift care va fi folosit pentru stropirea de precizie a culturilor agricole pe baza unor misiuni de zbor preprogramate.

INTRODUCTION

Main applications areas in the use of UAV are filming and photography, inspection and maintenance, mapping and surveying, surveillance and monitoring and precision agriculture, in addition to other miscellaneous applications (*del Cerro et al., 2021*).

One important component of Agriculture-4.0 is represented by drones and other mechatronic systems available to increase the Return on Investment, ensure the sustainability of the farming process and reduce environmental pollution near to "zero pollution". So, the role of UAV platforms is crucial in precision farming for sustainable agriculture. Aerial monitoring of crop vegetation status is a major factor in precision agricultural management. The health status of crops is analysed based on vegetation indices determined by reliable measurements performed with optical sensors installed onboard drones or through sampling devices mounted on UAV (*Zhang et al., 2022*). The monitoring of the resources and the state of the vegetation is performed aerially with non-contact sensors, the automatic data acquisition being correlated with the GPS coordinates and their processing in the GIS system for making spectral maps, all necessary in spatial and precision management (*de Castro et al., 2021; del Cerro et al., 2021; Wang et al., 2023*). Detection, identification, and quantification of crop diseases are therefore done by monitoring, the best results are obtained by thermography, chlorophyll-fluorescence, or with multi- and hyperspectral sensors.

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Basically, by aerial mapping of the arable area concerned, the following technological aspects of agricultural crops can be managed much better:

- Control of applied fertilizers, implicitly can be observed areas where increased attention is needed in terms of pollution or reducing the amount of waste that could have a detrimental effect on the environment;
- Neutralization of harmful plants that can infiltrate crops, consequently measures can be taken quickly to act in order to eliminate weeds and solve the harmful situation;
- Early detection of diseases and pests of agricultural crops leaves farmers the opportunity to adopt the best solutions to reduce them promptly.

After the online aerial monitoring of agricultural crops, the next stage is the offline processing of recording data to produce spectral maps. These maps are made by processing images using a dedicated programming medium. The spectral maps obtained from the processing of images recorded by the multispectral camera onboard the drone contain information on the state of crop vegetation. Afterwards, the use of specialized UAV platforms to precisely apply the phytosanitary treatments based on the obtained maps ensure sustainable development in agriculture. There were performed researches regarding the quality of the spraying process of different types of drones, taking into consideration aspects as pesticide load, downwash of multi-rotor UAV, droplet deposition, flight speed and height, number of drones etc (*Qi et al., 2023; Chen et al., 2022; Yang et al., 2022*), all these results contributing to the optimization of drone development in order to be used during spraying works.

In order to build an agridrone minimal knowledge of mechanics, electronics and IT or in a word mechatronics is required. The first step in designing a drone is to know the components of the drones and the materials they will be made of. Generally, an aerial drone is made up of hardware and software components. Most systems and components can be purchased, other simple parts can be made on a 3D printer with high manufacturing volume. A preliminary design flow for high payload aerial drones is recommended in the literature (*Ong et al., 2019*). The flowchart of the design flow for these UAS platforms is shown in Figure 1.

The design methodology is relatively new, it includes coaxial rotor propulsion systems that have the best pressure-to-volume ratio.

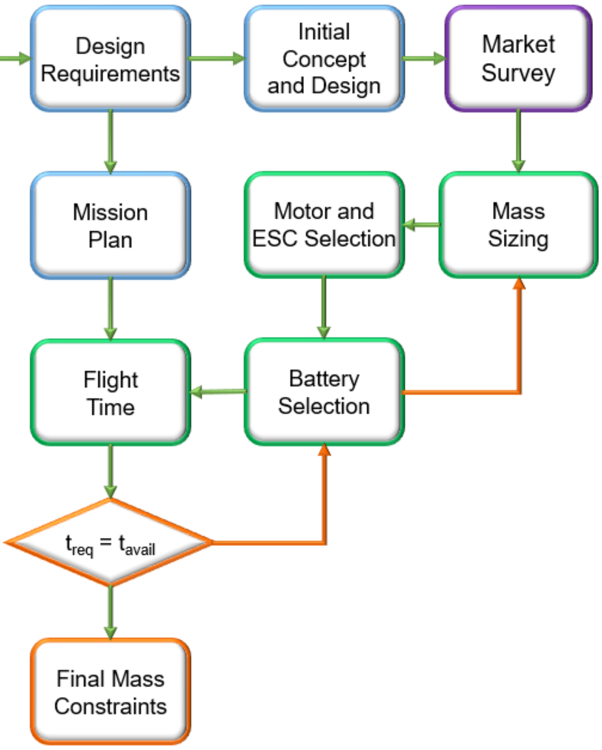


Fig. 1 - UAV system preliminary design flow chart (adapted from *Ong et al., 2019*)

Recently, UAVs for utility applications have the limits of the available flight time, considerable as operating autonomy values for various industrial applications of inspection, agriculture, surveillance and transportation.

Heavy UAS platforms are dominant in the logistics sector because their capabilities facilitate the autonomous transport of goods and reduce time in dangerous work missions. Payload mass is unpredictable in such applications. Therefore, to ensure that these drones are suitable for a wide range of actions, it is essential that the aerial vehicle has heavy lifting capabilities.

The process adapted to heavy drones can be applied to the design of conventional multi-functional tricopter-hexarotor configurations and then it is compared with other sizing methods proposed in this paper. It is important to note that both the flight mission plan and the design requirements must be met individually and will be addressed in parallel. From the mission profile the required flight time (t_{req}) can be calculated and compared to the available flight time (t_{avail}) given the capacity of the selected battery pack. The approach is iterative. Instead of the empty drone weight (available/required) used in the conventional fixed-wing drone mass sizing methodology, the multirotor UAV design methodology was modified by comparing the flight time (available/required) on mass sizing by battery pack selection (*Ong et al., 2019*).

Agridrones intended for spraying agricultural crops generally have a frame structure, with 3 or more arms arranged radially and equidistantly for the installation of each propulsion system (motor + propeller) as well as a landing gear and other elements for fixing the equipment necessary for the flight mission on the structure.

The payload of the drone is ensured by the power of the propulsion system and the number of drone motors determines the shape of the frame for the UAV platform. The classification according to the number of motors of the structures of the most common multicopters used in precision agriculture is presented in Figure 2.

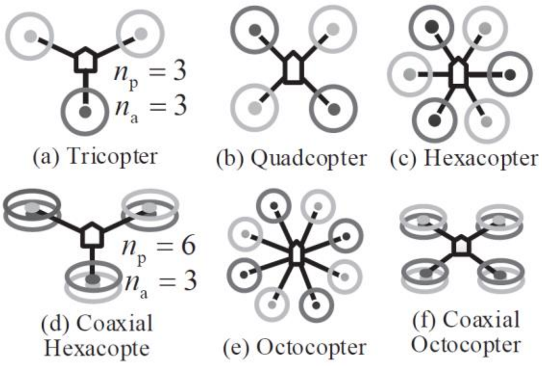


Fig. 2 - Schematic representation of current UAV multicopter structures (*Xunhua et al., 2019*)

n_p – number of motors; n_a- number of arms

Coaxial drones have several advantages over traditional multi-rotors drones, as stated by *Karman Drones, (2023)*, as:

- enhanced stability due to their opposing rotor system, which cancels out rotation momentum, fact which allows for easier control of the UAV and to maintain a steady hover;
- increased lift capacity: a coaxial multi-rotor drone generates more thrust than a traditional one similar in size, due to its coaxial rotors spinning in opposite directions but having added thrust vectors. Thus, heavier payloads could be lifted, like bigger fluid tanks, without sacrificing flight performance;
- redundancy and reliability: coaxial drones offer a high level of redundancy in the event of a rotor failure. With rotors spinning in opposite directions, the drone can maintain stability and control even if one rotor fails.
- low noise: the opposing rotation of the rotors in a coaxial system produces less noise than a traditional one, making it a quieter option for applications that require low noise emissions, such as wildlife monitoring or urban surveillance.

Regarding development of tricopter – hexarotors, also called co-axial Y6 or coaxial hexacopters, there are results in the relevant literature which present the stages of development and testing of such UAVs, relevant for the state of the art from which present paper was inspired (*Czyba et al., 2015; Ong et al., 2019; Hamandi et al., 2020*)

Within this paper are presented the development and initial tests performed for a high capacity agricultural coaxial tricopter UAV, called 4.0-MHRT.66L, which was designed after point d) architecture from figure 2, for a payload of 66 litres of phytosanitary fluid, with 6 anti-drift nozzles and an electric double-pump for creating hydraulic pressure in the boom ramp. The initial test consisted in maximum thrust measurement, spraying system characterization and coverage degree assessment in different flying conditions.

MATERIALS AND METHODS

3D design

The 3D CAD design for the 4.0-MHRT.66L variant is presented in Figure 3. The mechanical structure is the novelty element for the 4.0-MHRT.66L agridrone, the structure chosen for the drone being outlined around the Y6 tricopter hexarotor concept. The arms of the drone were designed in the form of parallel aluminium tubes stiffened by means of a support, at the end of each tube being mounted the electric motor with a double propeller. The liquid substance tank was designed as a body composed of a truncated cone and a cylinder with rounded edges, constructed of fiberglass and mounted on top of the drone's main structure. Under the tank, the battery housing and flight equipment supports were designed. The spraying ramp together with the spraying nozzles were designed in a circular shape and mounted on supports, below the level of the lower motors.

a) Isometric view b) Top view

Fig. 3 – Functional model 3D design, 4.0-MHRT.66L

CAE analysis of 4.0 MHRT.66L functional model

Static FEM analysis was performed on the 3D model of the 4.0-MHRT.66 L functional model to verify the mechanical strength of the drone frame.

A structural analysis was performed in static mode, using the solid meshing type. The meshed structure totalled a number of 150199 nodes, with 71375 standard elements. The minimum size of the elements was 0.982496 mm and the maximum size was 16.9811 mm. The finite element analysis was made in the SolidWorks program. Figure 4 shows the meshed structure.

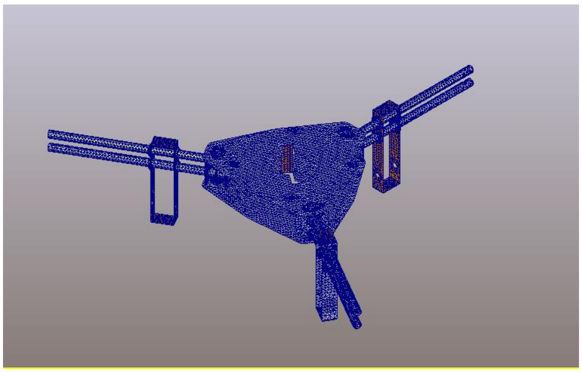
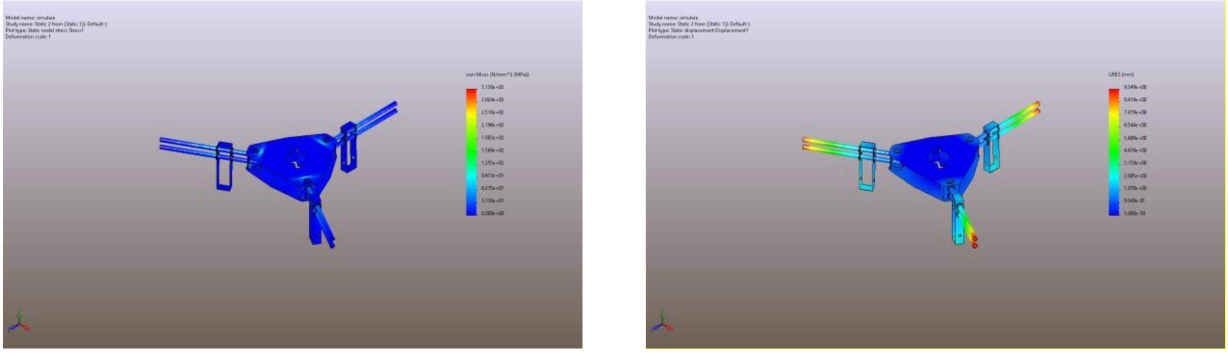


Fig. 4 - Structural model of functional model 4.0-MHRT.66L: discretization

The loading forces were applied to the motor mounts. The loading force had a value of 300 N. Thus, the total reaction force from the fixing points had a value of 1800 N. The minimum and maximum values of the equivalent stress state (Figure 5, a)) in the structural model of the drone were determined after performing the static analysis according to the fixings and loads presented previously. The maximum value of the equivalent stress was 313.8 MPa and was located at the point of contact between the drone arm and the landing gear leg, node 145839, which is located in the cylindrical joint of the drone arms through which they are connected to the drone body.



a) Von Misses equivalent stress b) Equivalent displacing

Fig. 5 – Static study results

The distribution of the resultant relative displacement field values in the structural model of the functional model MHRT.66L is graphically represented in Figure 5, b). The representation is made on the deformed shape of the structure. The maximum displacement related to the simulation was 9,349 mm at the tip of the drone arms, which can be taken up by the flexible nature of the frame. Following the study, the structural integrity of the drone's frame was validated up to loads of 1800 N, loads that exceed by 80% the maximum load for which the drone was designed.

Execution of the functional model 4.0-MHRT.66L

The agridrone functional model for applying phytosanitary treatments in field crops, MHRT.66L, is a Y hexarotor type drone powered by two AB2-17500mAh-51.8V, 14S Lithium batteries, it is equipped with 6 8700 W motors, type X9 Series Power System for Heavy Lift Drones X9PLus 36inch, whose rotation speed is controlled by 6 electronic speed controllers (ESC) of 120 A nominal (150 A maximum), three motors having two CCW blade propellers (rotating counterclockwise) and the other three motors having two CW blade propellers (rotating clockwise), all propellers having dimensions of 36", has a 66-liter tank from which a 12 V DC electric pump, powered by 2 separate 12 V DC batteries, pumps with a pressure of up to 7.5 bar phytosanitary substances to a circular spray ramp on which 6 nozzle holders equipped with calibrated spray nozzles are mounted. The drone is equipped with a Pixhawk 4 Orange cube autopilot with Here 3 GNSS GPS module for precise positioning in the field and can be programmed to operate the electric pump to spray agricultural crops only on predefined areas based on the mission profile entered by the operator. Flight system settings were made using Mission Planner software.

Figure 6 shows the connection diagram of the control elements of the drone, based on which the wiring was done during the execution stage.

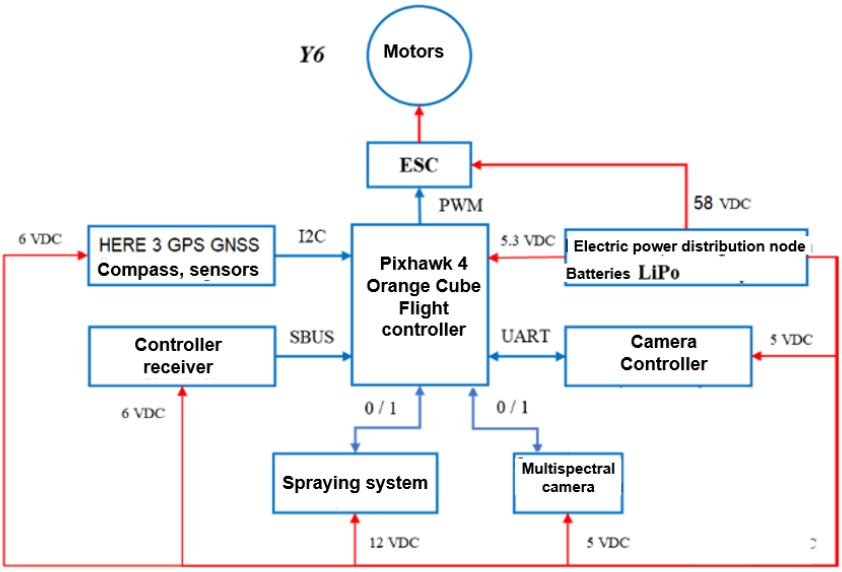


Fig. 6 – Wiring diagram of avionics elements 4.0-MHRT.66L

Figure 7 shows the central frame and the battery holder and how the drone arms are attached to the central frame.

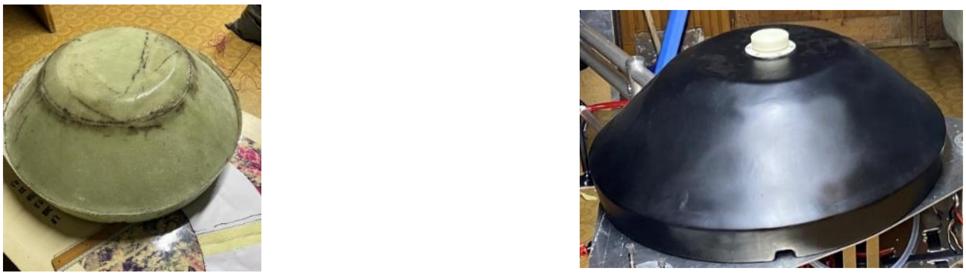
Fig. 7 –MHRT.66L elements– main frame, arm - central frame assembly

Figure 8 shows aspects during the manufacturing process of the 66 litres tank made of composite material consisting of glass fibre and carbon fibre laminated with epoxy resin. The tank cap is equipped with a vent valve and inside it wave breakers have been created to reduce liquid movements and ensure stability during flight.

a) Mold lamination of the tank upper body

b) Tank bottom

c) Wave breaker building



d) Tank upper body

e) Assembled tank

Fig. 8 – 4.0-MHRT.66L components – tank

Figure 9 shows the functional model 4.0-MHRT, fully assembled, in the folded transport position and in the working position.

a) Functional model - folded for transport

b) Functional model - operating position

Fig. 9 – 4.0-MHRT.66L Functional model

In order to determine the main characteristics and operational parameters of the functional model, a series of tests were conducted. The experiments were carried out in the laboratory to determine the dimensions of the drone, the maximum take-off mass and the characteristics of the spraying system.

The **dimensions** of the 4.0 MHRT.66L drone functional model were determined by measuring using calibrated laboratory tape measures and scales.

The maximum take-off mass was determined by measuring the maximum takeoff force between the drone and a fixed point on the ground by means of a 5 KN load cell placed between the drone and the ground.

The flow rate through the nozzles of 4.0 MHRT agridrone functional model was determined by direct method, using a digital flowmeter and by volumetric method, measuring the liquid flowed for each nozzle in a 1-minute interval, at the working pressure. The pressure drop across the ramp on which the six nozzle holders are located was measured by means of a pressure transducer mounted in the place of a nozzle, on the nozzle holder.

In-situ experiments to determine spray uniformity and degree of coverage were conducted to demonstrate the functionality of the functional model. To carry out the tests, the following test methodology was applied:

- the tank of the drone was loaded with water solution and methylene blue;
- blue 0.3 type nozzles were installed on the drone's spraying ramp;
- water-soluble paper was applied to the ground to capture water droplets from the drone's nozzles;
- altitude and working speed were set, from the base station software, Mission Planner;
- transitions to 2 working speeds (3 and 5 m/s) and 3 working heights (3, 6, respectively 9 m) were made.

After these steps, high-definition images of the water-sensitive paper - 4962x7019 pixels (Figure 10) were taken using an EPSON L220 scanner for each test. Images were processed using software to obtain the coverage degree. For image processing, first the contrast between the colour of the droplets (blue) and the background colour (white) was increased. The blue pixels were then extracted as a percentage of the total pixels and thus the percentage coverage was measured.

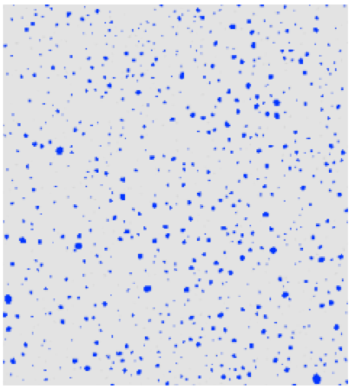


Fig. 10 – Scanned image of water-sensitive paper for determining the degree of coverage

Thus, with the drone set in automatic flight mode - ALTHOLD (automatic flight altitude maintenance) and commanded from the remote control, test flights were carried out with the tank loaded, with different flight speeds and working heights, the results obtained being presented in the following table.

The nozzle holders of the drone were equipped with blue 03 type nozzles and it worked at a pressure of 1.5 bar.

RESULTS

Dimensions of the 4.0 MHRT.66L drone functional model

After conducting the tests to determine the dimensions of the 4.0 MHRT.66L drone functional model, the following results were obtained:

- Diameter at the centre of the motors: 2.76 m
- Distance between motor centres: 2.30 m
- Height: 0.94 m
- Own mass without battery: 50 kg
- Weight of batteries: 12 kg
- Maximum mass with full liquid tank: 128 kg

Maximum thrust force

Table 1 shows the average values obtained regarding the maximum thrust force.

Table 1

Maximum thrust force

Acceleration (%)	ESC power (A)	Drone thrust force (N)
25%	37.5	389
50%	75	765
75%	112.5	1125
100%	150	1505

The maximum thrust force corresponds to a maximum ESC current level of 150 A at a battery charge level of 58 V and a maximum electric power of 8700 W/motor.

Characteristics of the spraying system

Figure 9 shows aspects of laboratory experiments to determine nozzle flow, total flow and working pressure. The following figure shows aspects of laboratory experiments to determine nozzle flow, total flow and working pressure.

Fig. 9 – Determination of flow rate and working pressure achieved by the 4.0-MHRT.66L drone functional model

The following table presents the average experimental results obtained for the work flow achieved by the 4.0 MHRT agridrone according to the size of the nozzle used. 4 types of nozzles with the following characteristics were used for experiments: spray angle: 120 °, made of plastic material, working pressure range 1-6 bar. The type of nozzles was coded by colour and number, depending on the diameter of the respective nozzle.

Table 2

Spraying system characteristics

Working pressure (bar)	**1.5**			
Nozzle type	orange – 01	yellow-02	blue-03	red – 04
Flow rate per nozzle (l/min)	0.27	0.49	0.66	0.87
Total flow rate (l/min)	1.62	2.94	3.96	5.22

Determination of spray uniformity

Table 3 presents the experimental results obtained for the distribution uniformity.

Table 3

Uniformity of distribution under different working conditions

Crt. No.	Working speed - set (m/s)	Working altitude (m)	Working width (m)	Degree of coverage (%)
1.	3	3	4	48.2
2.	3	6	8	40.1
3.	3	9	10	38.2
4.	5	3	4	44.6
5.	5	6	8	39.2
6.	5	9	10	36.1

From the results obtained, it was found that the best uniformity of distribution was obtained for a 4 m working width and a 3 m altitude for both operating speeds.

CONCLUSIONS

In this paper, the stages of development of an agricultural UAV for carrying out phytosanitary treatments were presented. The agricultural drone made has the following advantages:

- constructive simplicity and the possibility of folding the arms for transport;
- operational safety (allows safe landing, even with a major failure of one of the motors);
- ease of use and performance;
- due to the use of CCW-type propellers above and CW-type propellers below, the Y-type hexarotor drone is much more stable and manoeuvrable;
- due to the special arrangement of the drone’s supports in Y at 120º and the arrangement of the spray nozzles between the supports, the angle of the jet of the nozzles is directed directly downwards by the air currents related to the drone’s motors, so that a uniform spraying of the crop plants is achieved;
- the precise application of phytosanitary treatments by means of the drone leads to a reduced consumption of phytosanitary substances and implicitly reduced costs;
- the possibility for farmers to treat agricultural crops targeted with phytosanitary substances only in the areas previously identified as needing phytosanitary treatment, without using machines on the ground, which compact the land and destroy part of the crop plants.

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