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# Analysis of Preliminary Design Requirements of a Heavy Lift Multirotor Drone for Agricultural Use

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Within the civil aviation cluster, the technological applications in agriculture represent a booming field consisting in acquisition of data through remote sensing and integration of sensor networks (crop status detection) or development of chemical and biological treatment applications. Drones in agriculture can be used for a variety of task, aimed to increase farm crop yields and accurately monitor fields, simultaneously decreasing time, labour and resources. While for some specific task a medium size drone can be chosen, on the other hand for other task like precision spraying of pesticide or fertilizer heavy lift drone are required. Prior to the approval of Yamaha R-MAX, an UAV helicopter which will be allowed to operate with a maximum payload of 98 kg, the Federal Aviation Administration (FAA) had only issued exemptions for much smaller drones weighing less than 55 pounds (24.98 kg). In Europe national legislations still lack of harmonization, and in Italy at the moment the local legislation restricts the possible choices to a maximum allowed take-off weight of 25kg without the necessity to submit a “permit to fly” documentation which is equivalent to the one required for a full scale commercial vehicle. Depending on the required task, one of the more important tasks of designing a multirotor Unmanned Aerial Vehicle (UAV) is the selection of a propulsion system that will provide desired performance in terms of payload and flight length or duration. Rigorous methods for selecting these drive components, that is, the motors, propellers, and batteries for electric UAVs are not readily available. A possible choice relies on using a Ready To Fly (RTF) UAV, but rapid changes in components and a fast evolution of the performance of engines and batteries allow possible updates of the existing UAV using aftermarket part to increase the flight envelope, a particularly interesting feature for heavy lift drone if a proper design method is adopted. Moreover, integration of technologies like LIDAR is easier to implement on UAV in which the design is not proprietary. In this work the technical requirements for agricultural tasks are investigated, and the state of the art of drone design method is presented, reporting an analysis of actual possibilities in terms of payload/flight envelope.

## 1. Introduction

The UAS (Unmanned Air System, an all-encompassing description that encapsulates the aircraft or UAV, the ground-based controller, and the system of communications connecting the two), also commonly known as drones (Dynamic Remotely Operated Navigation Equipment), now represent a commercial reality on a European and worldwide scale. The UAV market is experiencing a time of great expansion and growing interest. The world market for drones is valued at approximately $6 billion in 2017 and it is supposed to grow to more than $11.2 billion by 2020, according to a new forecast from Gartner, Inc.; in terms of growth, the residential sector for civil applications presents annual growth forecasts of 19%, compared with the modest 5% of the civilian/defence sector. Within the civil aviation cluster, the technological applications in agriculture are a booming field and will consist of:

• acquisition of data through remote sensing and integration of sensor networks;

• environmental monitoring (detection of fires, presence of weeds );

• development of chemical and biological treatment applications.

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In this sense, the use of precision agriculture introduces considerable advantages that can be simply summarized as follows:

• optimization of treatments with fertilizers, with a possible overall reduction of 20-40% in terms of overall distributed products;

• reduction and prevention of water waste, reducing the use of water resources (water consumption will be reduced in some cases up to almost 90%);

• reduction of labour and material costs;

• reduction of pollution in the UAV powered by electric motors;

• reduction of risks through the automatic analysis of the state of the crop production processes on the field, supplemented by prevention activities.

As regards the use of the UAV, the sensors activity turns out to be at the basis of subsequent applications, such as the control of the distribution of pesticides. The remote sensing activities, is defined as the acquisition of information about an object or surface by means of propagated signals (eg. Electromagnetic, or microwave signals), typically emitted and / or received via aerial vehicles (eg. Satellites, airplanes, UAV ). However, for such activities there are some major limitations in the use of satellites and aircraft, arising mainly from:

- capacity existence of high technical sector;
- need for appropriate weather conditions;
- availability of multi-temporal data.

The use of UAVs can fly at low altitude makes it much more accessible remote sensing, through the following main technologies(Zhang & Kovacs 2012):

• analysis in the visible and infrared, in multi-spectral or hyper-spectral, through which it is possible to carry out:

- analysis of the plant and soil;
- height indices, growth, health, acquisition of vegetation indices;
- control of irrigation, soil properties, moisture analysis, erosion control;
- analysis of specific chemical components;

• thermographic analysis, using which it is possible to integrate the analysis of the plant and soil, and acquire irrigation indexes, ripening and leaf temperature;

• laser beam scanning, which allows the acquisition of vegetative height indices, growth, generation of topographic .carte.

With the same services, the use of drones has undeniable advantages over classical techniques satellite monitoring, on the ground or to traditional aerial photogrammetry with unmanned aircraft:

- Imaging: substantially cheaper to fields of less than 50 hectares in size, since the drones are much less expensive satellites or drones of manned surveillance drones;
- Greater precision: the drone cameras are able to resume high-resolution images up to 1 centimetre, detecting also the elements in greater detail of the crop;
- Early detection of problems: the drones allow to carry out more frequent analyses, with early surveys of weeds, pests and other abnormalities;
- Field Control / Scouting: it is possible the full recognition of the field (including weeds infestation preliminary warning) through the use of the drone, in spite of the modest 5%, measured by means of the piloting of an Automated Terrestrial Vehicle (ATV);
- 3D / Volumetric Data Analysis: the drone images can be used to calculate volumes present on the field, and thus detect the density problems and / or contour such as those related shading due to exposure hilly.

• a more frequent index of report analysis: drones offer a cost-effective way to monitor at frequent intervals crops and detect some key indices as CCCIs (global index of chlorophyll content), CWSI (water stress index) and NDVI (index of normalized difference vegetation).

As a matter of fact attention is often focused on the single UAV operation, rather than on the global implementation of the technology in order to make it really “ready to use”, i.e. on the global requirements to make the system reliable, safe and in agreement with regulations, which is basically the integrated . Actually the technology requires an advanced knowledge of the flying systems, and the necessity to provide a safety operational framework in case of accidents involve the use of a significant amount of resources both in in term of human resources and economical as well. In addition to the flying machine, the industry of drones also includes a wide supply chain of enabling technologies. In particular, it is considered strategic for companies investing in smart technologies in a broader context, having a direct implication on their ability to build a completely autonomous flight and optimize mission with an intelligent control. The same concern is evident for Detect and Avoid technology, essential for flying in uncontrolled airspace, and its smart features additional character (such as the Health Monitoring and the self recovery systems). The same smart technologies are used in many other non-aviation sectors and can contribute to characterize the product of interest. In the context of development and automation of the various arrangements for monitoring the health of crops, connectivity and use of Big Data represents an aspect in line with the technological trends that will emerge clearly. In theory, the major market drivers that may influence the choice of an unmanned aircraft are as follows:

- Payload Suite;
- Cost;
- Flight Hours;
- Payload Weight;
- Datalink Bandwidth;
- Stabilization of payload;
- Aircraft Weight;
- Range / Radius of Action;
- Operational Ceiling;
- Speed;
- Endurance;
- Weather Rating;
- LOS Operations;
- Sensor Resolution;
- Launch / Recovery Modes;
- Base of Operations.

In the following sections an example of possible payload and performance of a drone with limit weight of 25 kg are computed, and briefly compared with service requirements.

## 2. Materials and Methods

In recent decades, significant efforts have been devoted to increase flight duration, payload, and tolerance to various weather conditions, resulting in different UAV configurations with different sizes, duration of autonomy and competencies. A key criterion currently used to distinguish among UAV is the size and flight duration:

- Class1: Large autonomy, high altitude UAV such as Northrop- Grumman Ryan 's Global Hawks (65.000 feet altitude, flight time 35 hours, payload 950 kg).
- Class2: Medium Altitude Long Endurance UAV, such as the General Atomics Predator (9.000 m high, 30/40 hour flight, and beneficial load 250 kg).
- Class3: Regular use UAVs as Hunter, Shadow 200, and Pioneer (5000 m high, Flight time is 5-6 hours, and 25 kg payload)
- Class4: Small and portable UAVs from a man as the Pointer / Ranen (AeroVironment), Janelin (BAL) or Black Pack Mini (Mission Technologies).

While Class1 and Class2 vehicle are restricted to military use, Class 3 vehicle with actual regulations in Italy requires a quite strict permit to fly, and the documentation required is basically restricted at the moment to companies with experience in aerospace, as almost no UAV in such class is at the moment allowed to fly freely. Intermediate vehicles between Class 3 and Class 4 up to a maximum of 25 kg are allowed to fly (a licence is required but requirements are less strict) and aim of this paper is to investigate the actual endurance and payload using state of the art component in terms of electronic equipment, engines, propellers and materials. In this sense the “heavy lift” considered here is the maximum amount of payload that can be deployed using a Class 3 vehicle.

A complex strategic tasks in designing a multirotor unmanned aerial vehicle (UAV) is the selection of a propulsion system that can provide desired performance. As matter of fact rigorous methods for selecting these essential components ( motors, propellers, and batteries) for electric UAVs are not readily available, and many UAV designs are currently based on legacy selections or limited and sometimes inaccurate manufacturer data (Ampatis and Papadopulos, 2014). The motors used in multicopter UAV (MUAV) applications are usually Brushless Direct Current (BLDC), due to their high efficiency. Outrunners motors, spinning their outer shell around its windings, are generally used for their high torque constant ($K_T$) allowing direct propeller coupling, unlike inrunners motors, in which their rotational core is contained within the motor's can, and requiring a gearbox. BLDC motors are usually synchronous 3-phase permanent magnet motors, but in the simplified approach proposed by Ampatis and Papadopulos, motors can be modelled as a permanent magnet DC motor inside the framework of a three-constant model. The model requires the knowledge of $V_k$, the supply voltage (V), of $i_\alpha$ , the current through the motor coils (A), and $e_\alpha$ , the back-electromotive force (EMF) (V). Additional required parameters are $R_\alpha$, the armature resistance (Ω) and ω, the shaft angular velocity expressed in rad/s. Then the motor equations can be written as:

$$V_k = e_\alpha + i_\alpha R_\alpha \quad (1)$$

$$e_\alpha = K_e\omega = K_T\,\omega = N/KV \quad (2)$$

where $K_e$ is the motor back EMF constant (Vs/rad), $K_T$ is the motor torque constant (Nm/A), N is the motor rpm, and KV is motor speed constant (rpm/V). The $K_T$ is related to KV by:

$$K_e = K_T = 30/(\pi KV) \quad (3)$$

while the output torque is given by:

$$M_{mot} = K_T\,(i_a - i_0) \quad (4)$$

where $i_0$ is the current at zero load. The motor input power is described by:

$$P_m = V_k\, i_a \quad (5)$$

and the motor output power is:

$$P_{mot} = M_{mot}\,\omega = K_T\,(i_a - i_0)\,\omega = (V_k - i_\alpha R_\alpha)\,(i_a - i_0) \quad (6)$$

The motor speed in rpm is expressed by:

$$N = (V_k - i_\alpha R_\alpha)\,KV \quad (7)$$

The performance of the motor can be obtained if KT, $R_\alpha$ and $i_0$, are known. Depending on load and battery voltage, electronic speed controllers (ESC) regulate motor speed within a certain range, and the most important variable in ESC modelling is the power loss, caused by its power MOSFETs and transistor drain-to-source "ON" state resistance RDS (ON). The range of RDS(ON) is generally between 3 and 15 mΩ, depending on transistor size. As ESC manufacturers often do not include in ESC documentation the type of transistors used, so a constant value resistor of RDS(ON)=5 mΩ was adopted. .

BLDC motor ESCs generally use three pairs of transistors to manage the three phase currents, so the total resistance of the ESC will be equal to $R_{ESC} = 3 \times R_{DS(ON)} = 15$ mΩ

The maximum current $i_{ESC}$ they can handle, a design constraint, was obtained by using manufacturer data.

Propeller performance can described by its thrust T (N), power P (W) and torque M (Nm). To model performance in static conditions, manufacturer data such as propeller diameter $D_p$ and its pitch p at 75% of its radius were adopted. Performance quantities can be related to propeller speed, diameter and pitch, and this calculation is achieved through a number of coefficients.

The thrust coefficient is given by:

$$C_T = T/\rho\,(N/60)^2\,D^4 \quad (9)$$

where T is thrust (N), ρ is air density (kg/m$^3$), N is propeller speed (rpm), and D is propeller diameter (m).

The power coefficient is given by:

$$C_p = 2\pi C_M = P/\rho\,(N/60)^3 D^5 \quad (10)$$

where P is power (W) and $C_M$ the torque coefficient.

These coefficients can be related to propeller diameter and pitch using the Blade Element Momentum Theory (BEMT) and a series of mild assumptions (Leishman ,2006) obtaining the following equations for thrust and power coefficients:

$$C_T = \frac{\pi^3}{4}\frac{1}{2}\sigma C_{i\alpha}\left[\frac{\theta_{0.75}}{3} - \frac{1}{2}\sqrt{\frac{4}{\pi^3}\frac{C_T}{2}}\right] \quad (11)$$

$$C_P = \frac{2}{\pi^2}\frac{{C_T}^{3/2}}{\sqrt{2}} + \frac{1}{8}\sigma C_{d0} \quad (12)$$

where σ is propeller solidity, $C_{l\alpha}$ is the slope of blade airfoil lift coefficient – incidence angle curve, $\theta_{0.75}$ is propeller pitch angle at 75% of the propeller radius R, and $C_{d0}$ is the blade airfoil drag coefficient for zero lift.

## 3. Results and Discussion

Integration of components already present on the market would allow increasing the operational framework of UAV to perform more advanced tasks like fertilizer and pesticide distribution, and lidar analysis. A key component in such applications is the possibility to maximize the lift at take off to minimize operational cost.
After applying the previously described models, a sub- optimal design, obtained using standard state of the art component that can be acquired on the market, an UAV characterized by an approximate take-off weight of 25 kg, is shown in Table 1.

*Table 1: Optimized payload and with a state-of-the art octacopter in coaxial configuration.(continue)*

| | | | | | |
|---|---|---|---|---|---|
| Battery | | LiPo 16000mAh - 55/80C | Motor @ Hovering | | |
| Configuration: | | 3S8P | Propeller | T-Motor CF (0°) 28" x 9,2" | |
| Load: | C | 4.16 | # of blades: | | 2 |
| Tension: | V | 10.94 | Current | A | 32.48 |
| Nominal tension: | V | 11.1 | Tension: | V | 10.98 |
| Energy: | Wh | 1420,8 | RPM | rpm | 2002 |
| Total capacity: | mAh | 128000 | Power - Weight: | W/kg | 161.8 |
| max discharge: | | 85% | | W/lb | 73.4 |
| Used capacity: | mAh | 108800 | Efficiency | % | 75.7 |
| Min. flying time | min | 12.3 | Specific Thrust | g/W | 6.25 |
| Mixed Flying time | min | 23.6 | Total engine weight | g | 15822 |
| Flight time in hovering: | min | 25.1 | | oz | 558.1 |
| weight: | g | 10296 | Power-weight: | W/kg | 324.2 |
| ESC | | max 200A | | W/lb | 147,1 |
| Current: | A continuous | 200 | Thrust-Weight: | : 1 | 1.6 |
| Mechanical Power | W | 548,9 | Ampere @ Hovering: | A | 259.8 |
| Weight: | g | 260 | P(in) @ Hovering: | W | 2883.8 |
| Motor @ max | | LDPower OP6110-340 (340) | P(out) @ Hovering: | W | 2160.7 |

*Table 1: Optimized payload and with a state-of-the art octacopter in coaxial configuration.*

| | | | | | |
|---|---|---|---|---|---|
| Transmission ratio: | : 1 | 1 | Efficiency @ Hovering: | % | 74.9 |
| weight: | g | 251 | Ampere @ max: | A | 532.03 |
| | | | P(in) @ max: | W | 5905.5 |
| Current | A | 66.5 | P(out) @ max: | W | 4391.2 |
| Tension | V | 10.86 | Efficiency @ max: | % | 74.4 |
| RPM | rpm | 2845 | Efficiency | % | 76 |
| Electrical power | W | 722.3 | Temperature (estimate): | °C | 69 |

| Multicopter | | |
|---|---|---|
| # of rotors: | | 8 coaxial |
| Totale weight (frame+engines+batteries): | g | 18078 |
| Adjuntive Payload : | g | 26299 |
| Tilt max: | ° | 66 |
| Maximum speed: | km/h | 40 |
| Estimated climbing rate: | m/s | 7.6 |
| Total Surface: | dm² | 158.9 |

Results show that using today technology it is possible to develop an UAV with a useful payload equal to 26 kg and an estimated flying time equal to 23 min. Such performance can be considered satisfactory not only to fulfil imaging and crop diagnostic missions, but also to perform more challenging one like plantation or pesticide distribution.

## 4. Conclusions

Integration of components is not a straightforward task due to a lack of an integrated theory, application is challenging since it requires expert knowledge in aerodynamics and control theory, and the commercial development of heavy lift drones it is still today limited to few companies, often with export limitations on aircraft and sensors (i.e. frequency of IR sensors) due to military implications. Nonetheless it is possible, using simplified theories on standard configurations (X or Y design), to develop and optimize the design of heavy lift UAVs for agricultural use with significant performance in terms of payload and flight envelope. State of the art components, freely available on the market, would allow today to perform not only recognition task but also more challenging tasks such as seeds, pesticide and fertilizer distribution, but in order to guarantee an economical return the limit of 25 kg at take-off present today in several countries(including Italy) should be lifted as it represents a strong deterrent to possible extensive use of UAV in agriculture.

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