Chapter

Design Considerations for Autonomous Cargo Transportation Multirotor UAVs

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Abstract

Unmanned aerial vehicles (UAVs) have proven to be an advanced tool for a variety of applications in the civilian and military sectors. Different categories of UAVs are used in various missions and are also the subject of numerous researches. Due to their characteristics and potential in specific conditions, multirotor UAVs imposes itself as a solution for many tasks, including transport. This chapter presents a conceptual solution of autonomous cargo transportation where the primary research objective is the design of a heavy lift multirotor UAV system. The process of designing a multirotor UAV that can carry heavy lift cargo is quite challenging due to many parameters and constraints. Five selected series of electric propulsion systems are analyzed, with different multirotor configurations, and results are graphically displayed for payloads from 10 kg up to 100 kg.

Keywords: multirotor UAV, autonomous cargo transportation, heavy lift transport, electric propulsion system, configuration parameters analysis

1. Introduction

In recent decades, technology has enabled the development of components and systems that have numerous capabilities in the field of autonomous vehicles and robots. From the aspect of the control system, developed control components with higher processing speed and integrated MEMS sensors allow a certain degree of autonomy of the vehicle. On the other hand, the development of the propulsion system and batteries has enabled a wide range of applications in various missions on the ground, in water, or in the air. Such as autonomous cars, unmanned ground vehicles (UGVs) can use existing infrastructure which is vulnerable to failure, and congestion that can be caused by other vehicles. These problems can potentially be overcome by using unmanned aerial vehicles (UAVs) as autonomous vehicles or/and robots.

There are different categories of UAVs that are used in various missions such as construction management [1, 2], agriculture [3], surveillance [4], search and rescue [5, 6], firefighting [7, 8], transport (delivery) [9] and many others. Aircraft can generally be divided according to the lifting mechanism into fixed-wing [10], rotary-wing [11, 12], and hybrid aircraft [13]. Because of its ability to vertically take-off and land (VTOL), rotary-wing (rotorcraft) UAVs do not need a launchpad or runway so the degree of autonomy can be higher and the cost of supporting infrastructure lower. Rotary-wing UAVs can be further divided into aircraft with variable-pitch propellers where the typical representative is a helicopter, and multirotor (multicopter) aircraft with fixed-pitch propellers. The advantages of the multirotor UAVs over other categories of aircraft are agility and maneuverability which is important in missions that include interaction with the environment and precise movements. Therefore this type of UAV is increasingly being considered as an alternative to UGVs in delivery and transport. The design of an autonomous heavy lift cargo transportation multirotor UAV is a quite challenging process since this type of aircraft is characterized by high energy consumption. Various conventional aircraft configurations such as quadrotor [14], hexarotor [15], or octorotor [16], allow a wide range of applications. Numerous research has recently been conducted with the aim of the design and development of new configurations with improved performance [17, 18].

There are several groups of researchers and companies engaged in the research and development of multirotor UAVs for the transportation of heavy loads. Brar et al. in their technical report [19] addressed several aspects of UAVs for deliveries such as the current market, available technology, regulation, and the impact on society. In general, multirotor cargo transport can be achieved with two basic transport strategies. The load can be attached to the multirotor body, or suspended through cables [20]. Ong at al presented design methodology for heavy-lift UAVs with coaxial rotors [21]. Several companies deal with the production of aircraft for the transportation of heavy cargo [22, 23]. The motivation to design an autonomous system stems from the fact that such a system can improve some aspects of society. Life on the islands is specific given the needs of the population and the infrastructure and institutions that exist on certain islands. On the larger islands, there are schools, ambulance, post offices. All other needs of the island's inhabitants are met through the connections that exist with the mainland and are mostly met by sea. Transport of passengers, goods, transport vehicles, and others takes place by ferries and ships. The existing type of transport is characterized by limited line frequency and high transportation costs.

In this chapter, a conceptual solution of on-demand autonomous heavy lift cargo transportation is presented which can reduce operational costs and carbon emissions. The overall system consists of a network of multirotor UAVs and docking facilities with the purpose of transportation from the mainland to the islands and vice versa. Based on the distance analysis and the existing infrastructure on the considered central Adriatic islands in Croatia, the topology (network) of the system was proposed whose endpoints are Zadar ports (mainland). The main focus of this research is on the design of heavy lift multirotor UAVs which can carry loads from 10 kg up to 100 kg. The multirotor UAV system divided into four key subsystems allows a methodological approach to aircraft design. The performance of the multirotor UAV is determined by the parameters and components of the propulsion and energy subsystem. The parameter analysis of conventional configurations for five selected setups of electric propulsion units was performed and presented. Based on the analysis, it is possible to select the aircraft parameters and components for a particular cargo and planned flight route. Furthermore, the parametric design of the aircraft is presented and preliminary simulations are performed.

2. Autonomous cargo transportation system concept

In this research, the aim is to show the benefits of the autonomous cargo transportation system (ACTS). The implementation of on-demand ACTS using multirotor UAVs can potentially reduce transport costs and increase the frequency and speed of transportation. This is of particular importance for the inhabitants of the islands, for whom such a system would enable better communication with the mainland, and thus would improve the standard of living on the islands. The concept of the system allows for a multi-purpose character and could be used for missions involving the delivery of postal packages, the transport of goods such as fresh fish and fruit, and such a system could even be used for fire prevention purposes. The system consists of docking facilities on certain islands and a fleet of multirotor UAVs deployed on an on-demand basis that connect islands facilities to the overall system.

A case study was considered for the central Adriatic islands, which administratively belong to the city of Zadar, which is located on the coast of the Croatian mainland (**Figure 1**). The archipelago consists of ten smaller and three larger inhabited islands, two of which are connected by a bridge. Common to all islands is that there is the infrastructure to accommodate smaller and/or larger ships and ferries. On these islands, among other facilities, there are 21 post offices as shown in **Table 1**, which is important from the aspect of the delivery and distribution of postal packages. The ACTS can consist of several to several dozen multirotor UAVs, depending on the needs and scope of purposes that such a system can perform. A fleet of aircraft is considered, consisting of five series of aircraft that can carry from 10 kg up to 100 kg of cargo. This also enables the modular character of the overall system, and the use of different aircraft series depending on the cargo they need to carry can potentially reduce the energy consumption. The idea is that the smaller islands are connected to the larger islands with the possibility of using particular islands as an intermediate docking, and the aircraft with the largest payload are provided for connection to the mainland.

Docking facilities have several functions, among others, they need to perform a user-friendly interface that makes it simple to use for the residents of the island and the services bear in mind that this is an on-demand system. Taking into account the current state of available components and technologies, the docking facility could consist

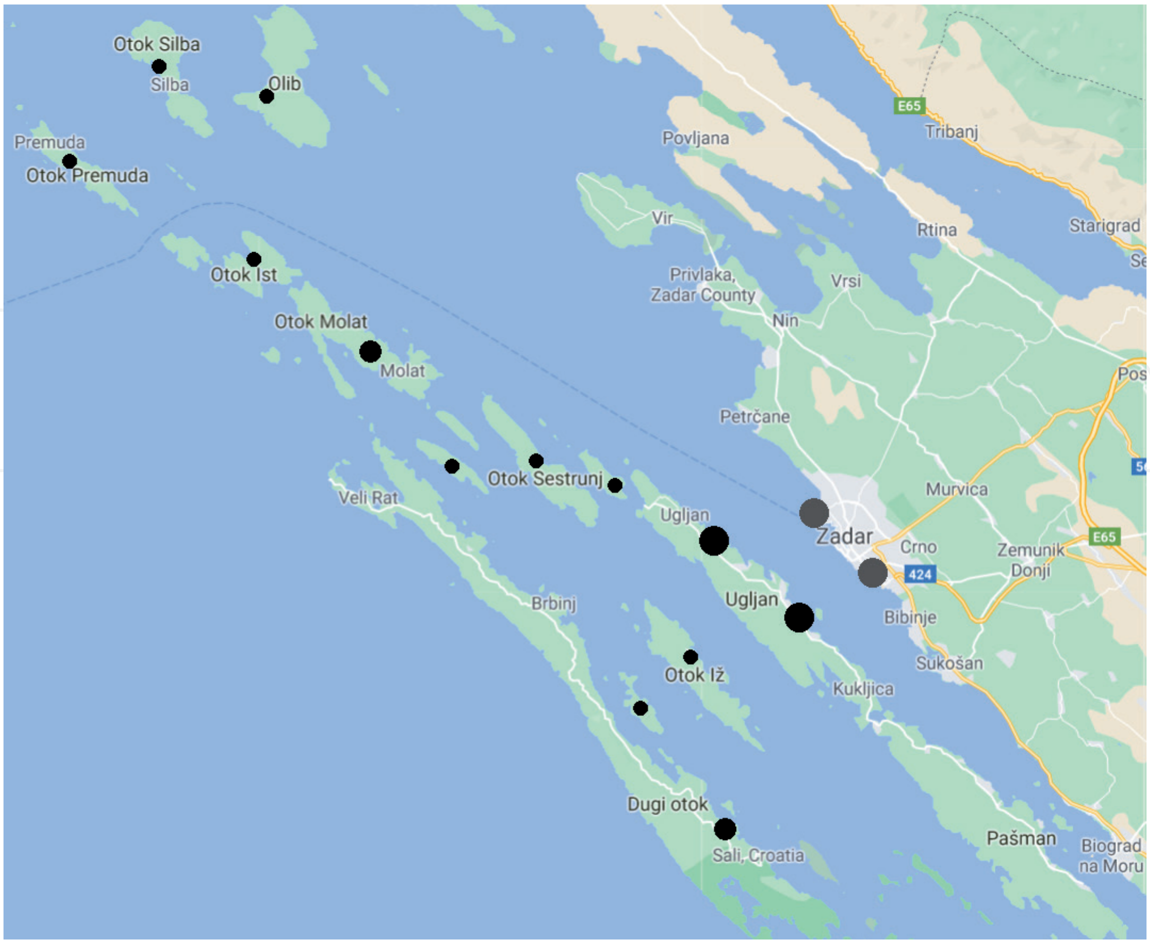

Figure 1.
Considered archipelago of central Adriatic islands in Croatia.

Pašman	23,262	Ugljan	23,275	Veli Rat	23,287
Ždrelac	23,263	Sali	23,281	Sestrunj	23,291
Neviđane	23,264	Žman	23,282	Molat	23,292
Kukljica	23,271	Rava	23,283	Ist	23,293
Kali	23,272	Veli Iž	23,284	Premuda	23,294
Preko	23,273	Brbinj	23,285	Silba	23,295
Lukoran	23,274	Božava	23,286	Olib	23,296

Table 1.
Post offices located on the central Adriatic islands.

of a multirotor UAV docking assembly and storage for depositing or retrieving cargo. It can additionally be contained with other features such as a mini solar power plant or a battery charging module for electric cars or UGVs. The multirotor UAV docking assembly is connected to the aircraft via sensors and telemetry and have to be designed to allow take-off and landing of the aircraft. It consists of a module to recharge the multirotor UAV batteries or additionally replace the batteries when the aircraft needs to be used urgently. The storage for depositing or retrieving cargo is associated with the user interface and is connected to the docking assembly to allow the exchange of cargo between the user and the aircraft. **Figure 2** schematically shows the possible topology of the overall ACTS where the most distant islands are connected to the mainland by three connections. It is important to note that the marked distances are for planned routes where flight over settlements and infrastructure is avoided.

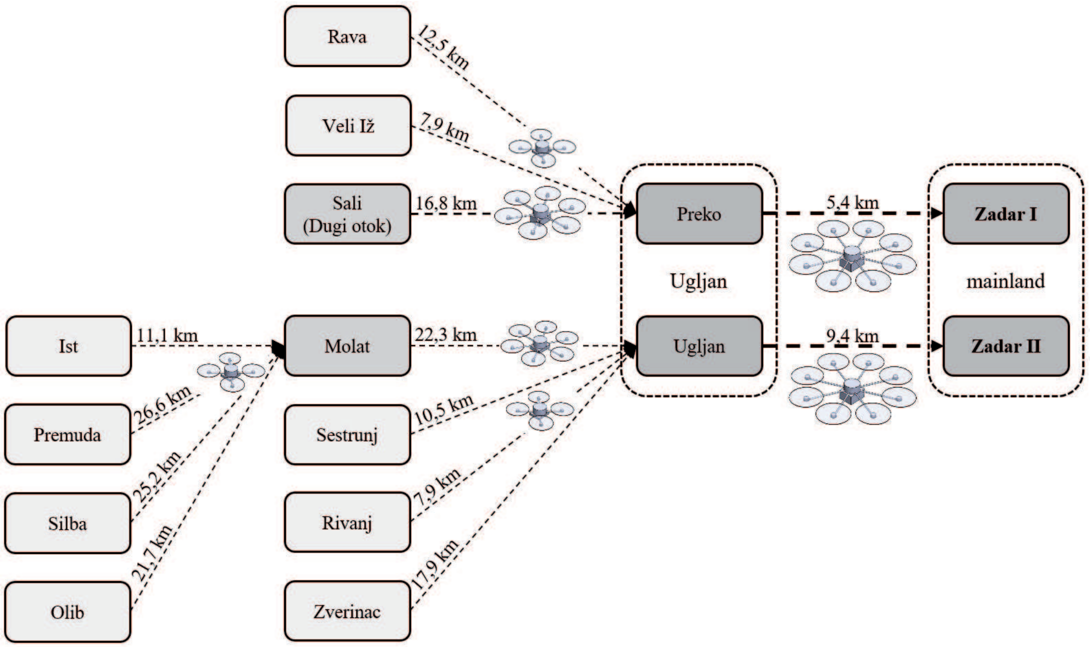

Figure 2.
Considered topology of the overall ACTS system.

3. Multirotor UAV system description

Multirotor UAVs are mechanical systems represented as rigid bodies with six degrees of freedom. Common to all designs is that they consist of N rotors (propulsion units) whose geometric arrangement also determines the configuration of the aircraft. They are mathematically described by a dynamic model of a rigid body with six second-order differential equations, twelve state variables, and N input variables, making them a multivariable system. Conventional configurations are characterized by a planar arrangement of the rotors, where the typical and most common configurations with four (quadrotor), six (hexarotor), and eight (octorotor) rotors are shown in **Figure 3**. The propulsion units mainly consist of an electric motor, suitable motor driver, and fixed-pitch propeller. It follows that the rotor's angular velocities are the only variables that have a direct impact on flight dynamics since propellers by their rotation create aerodynamic forces and moments.

The development and design of multirotor UAVs are significantly limited by both their size and energy consumption. For simpler analysis, design, and construction of this type of UAV, the aircraft system is divided into four key subsystems regardless of the configuration or purpose of the aircraft. The propulsion subsystem consists of N rotors that generate the necessary forces and moments for the movement of the aircraft in 3D space. The energy subsystem consists of one or more lithium-polymer batteries with joined components that need to deliver a large amount of energy essential to achieve the desired performance. The control subsystem takes care of UAV navigation and the functioning of the overall system by managing and monitoring other subsystems. Another task for the control subsystem is to be the interface between the aircraft and the base station (docking facility). The multirotor payload subsystem includes all equipment and cargo required to perform a particular mission whereby, this paper discusses the missions of heavy lift cargo transportation. Generally, it can be said that the performance of the multirotor UAV is determined by the parameters and components of the propulsion and energy subsystem. **Figure 4** schematically shows the multirotor UAV system which consists of four key subsystems.

From a control point of view, multirotor UAVs are inherently unstable and highly nonlinear systems. The inherent instability stems from the fact that this type of UAV cannot return to the equilibrium point on its own if it loses the functionality of the control loops. Furthermore, multirotor UAVs are highly nonlinear systems since the propulsion aerodynamic forces and moments are proportional to the square of the rotor angular velocity, and the transformations of the coordinate systems involve trigonometric functions. The basic task of the control subsystem is to navigate the multirotor UAV according to the given mission. The considered control subsystem is based on PX4 Autopilot. Generated control signals by the PX4 Autopilot, are sent to the electric propulsion units in order to achieve the desired movement in 3D space, ie to perform the mission. Orientation sensors are integrated into the PX4 Autopilot, while the position is estimated using compatible peripheral sensors. In considered concept, a global positioning system (GPS) and sensors for precise docking are incorporated in the control system. Given that the cargo mass in transport missions is unpredictable and there are real external disturbances such as wind gusts, it is necessary to consider robust control algorithms.

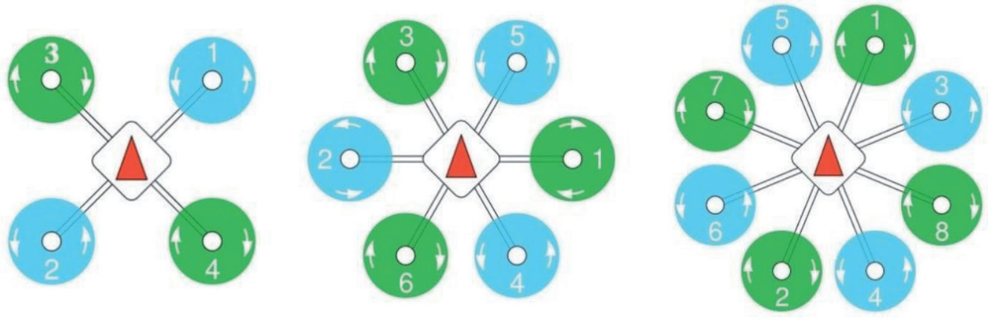

Figure 3.
Conventional multirotor UAV configurations [24].

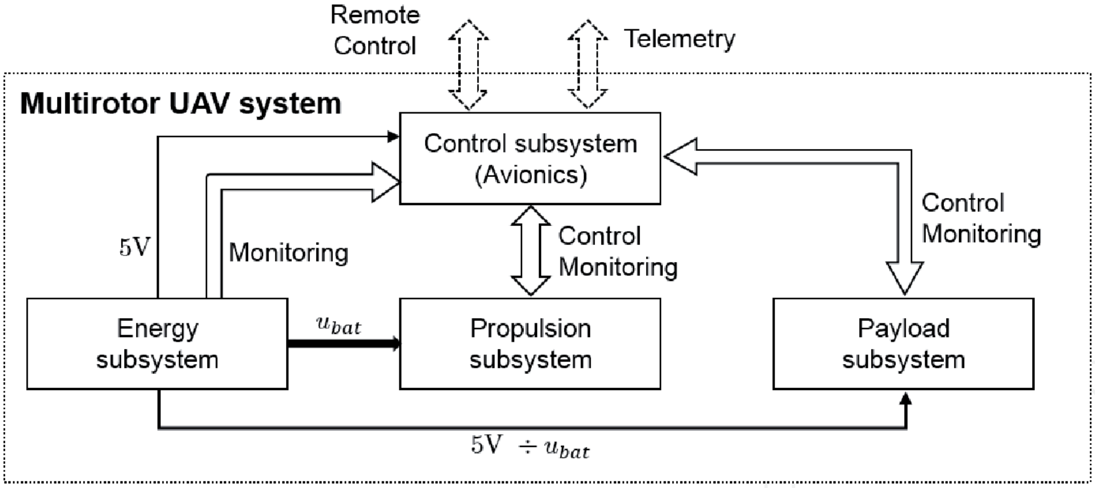

Figure 4.
Schematic representation of an electric multirotor UAV system.

3.1 Electric propulsion subsystem

The propulsion subsystem provides the aircraft system with the necessary power to move in 3D space. The choice of propulsion subsystem configuration and propulsion unit type affects flight performance and it is a key step in designing a multirotor type of UAV. Electric motor based propulsion unit enables precise and fast control of forces and moments which directly affect the position and orientation of the aircraft. The reliability of electrical systems reduces the possibility of aircraft crash due to motor failure. The required performance of the aircraft, which depends on the type and profile of the mission, determines the choice of propulsion configuration and components. The electric propulsion unit consists of a control unit and a mechanical assembly of the motor on whose rotor a fixed-pitch propeller is mounted, which creates forces and moments by its rotation. Propulsion units with brushless DC (BLDC) motors coupled with electronic speed controllers (ESCs) are suitable for a wide range of tasks, including missions with heavy lift transportation (**Figure 5**).

In this case study, seven setups of electric propulsion units were considered which will be paired with the high voltage (HV) setup of the energy subsystem. Based on the component manufacturer's specification, it is possible to characterize the propulsion units which is the first step in designing the aircraft propulsion subsystem for heavy lift multirotor system. **Table 2** shows the considered electric propulsion components for which characterization is presented. Motor velocity constant (back EMF constant) Kv of motors intended for heavy payloads is typically small (Kv < 200), resulting in lower speeds and higher torques. The propeller designations in the table describe its geometry where the first two numbers indicate the diameter of the propeller, and the other two the propeller pitch, both in inch.

Figure 5.
Multirotor UAV electric propulsion unit.

Characterization is necessary for the appropriate selection of propulsion components and analysis of the electric propulsion system which further allows system optimization. **Figure 6** shows thrust force as a function of rotor angular velocity for seven considered setups. As expected, setups consisting of motors with a lower Kv achieve lower angular velocities, and propellers with larger diameter achieve higher thrust forces. **Figure 7** shows the electric current as a function of the required thrust force, which is very important from the aspect of estimating the flight time. **Figure 8** shows the overall efficiency of the propulsion unit which is expressed by the ratio of thrust and electric power. In this case, efficiency is represented as a function of electric power. From the graph, it can be concluded that the increase in efficiency can generally be achieved by choosing propulsion units consisting of a larger diameter propeller combined with a suitable motor.

BLDC motor	Kv	ESC	Propeller
U15 II	100	FLAME 180A HV	4013 (40 × 13.1)
U13 II	130	ALPHA 120A HV	3211 (32 × 11)
U11 II	120	ALPHA 80A HV	2892 (28 × 9.2)
P80	100	ALPHA 80A HV	3211 (32 × 11)
P60	170	FLAME 60A HV	2266 (22x6.6)
Antigravity 1005	90	FLAME 60A HV	3211 (32 × 11)
Antigravity 7005	115	FLAME 60A HV	2472 (24 × 7.2)

Table 2.
Considered electric propulsion unit setups [25].

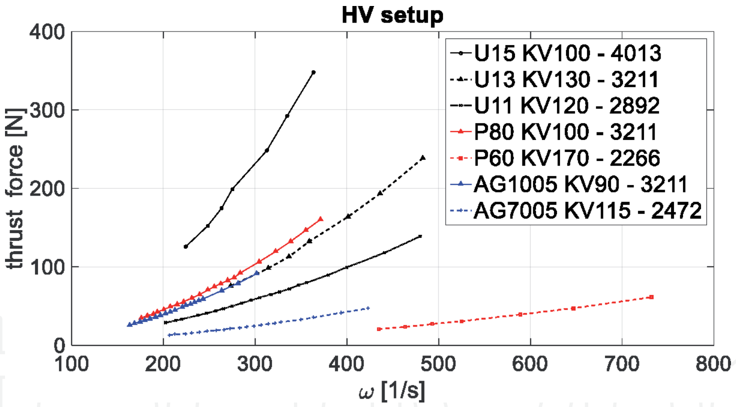

Figure 6.
Thrust force with respect to rotor angular velocity.

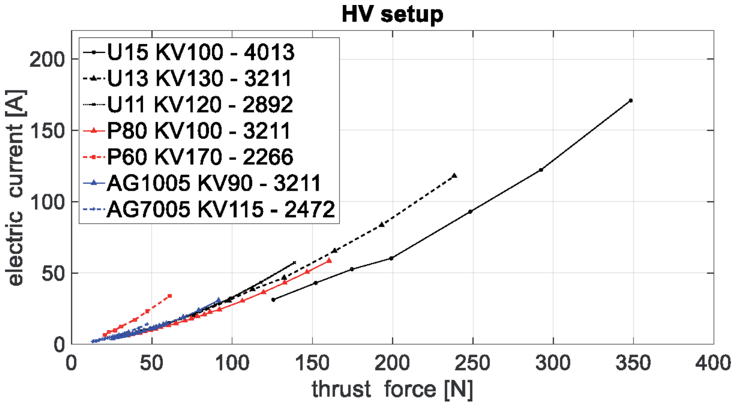

Figure 7.
Electric current with respect to the thrust force.

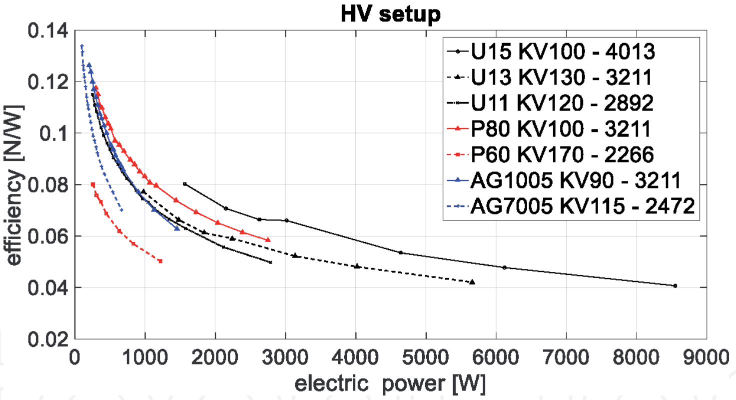

Figure 8.
The overall efficiency of the electric propulsion unit with respect to electric power.

3.2 Electric energy subsystem

The energy subsystem must provide sufficient energy for multirotor UAV system in order to perform the intended missions. Multirotor UAVs are characterized by high energy consumption as they consist of a minimum of four propulsion units. When choosing an energy subsystem, it is necessary to take into account several parameters, the most important of which is the type of propulsion subsystem. Electric propulsion units based on BLDC motors are combined with an energy subsystem consisting of one or more lithium-polymer (LiPo) batteries. Each LiPo battery contains one or more electrochemical cells to ensure a continuous flow of energy to power the propulsion and other subsystems. A very important feature of a LiPo battery is high energy density. Compared to other types of batteries such as nickel-metal hydride (NiMh), LiPo batteries have a higher discharge rate, which allows more power and consistent energy flow to the propulsion. LiPo batteries are defined by the capacity, discharge rate (C), and the number of cells that determine the operating voltage (S). The nominal voltage of a single battery cell is 3.7 V, and the voltage of a fully charged cell is 4.2 V.

When selecting batteries, the energy requirements of the propulsion subsystem must be taken into account, which in turn depends on the mass and size of the aircraft and the number of propulsion units. It follows that when designing a system, the relationship between mass and battery capacity is one of the

Figure 9.
LiPo battery Tattu plus 12S, 22,000 mAh, 25C.

Figure 10.
Power hub MAUCH power cube 4.

key data. For the characterized propulsion units, commercial high voltage (12S) LiPo batteries of capacity 8000 mAh, 16,000 mAh, and 22,000 mAh, as shown in **Figure 9**, were selected for further analysis [26]. Since the mass of the batteries in relation to other system masses dominantly affects the aircraft dynamics, it is desirable to place the energy subsystem centrally, as close as possible to the aircraft center of gravity. Energy subsystems of large aircraft, such as in this research, have more sophisticated energy distribution circuits (**Figure 10**) that provide different voltage levels and also have the function of measuring the battery's electrical parameters.

4. Design considerations for heavy lift multirotor UAV

To ensure overall flight performance, it is necessary to determine the required thrust-to-weight ratio (TWR). As a rule, aircraft are designed with approximately twice the thrust force in comparison with aircraft weight, from which it can be concluded that the mass of the aircraft is a key parameter in the design of the system. The division of the multirotor UAV system into four key subsystems, where the subsystems are determined by masses as the basic parameters, represents the first step in the design of the aircraft. The equipment subsystem is directly determined by the type of mission which in this research is heavy lift transportation. The mass of this subsystem directly affects the selection of the propulsion and energy subsystem. These two subsystems are interdependent and when choosing components it is necessary to maintain a balance with the existing constraints defined by the mission. Parameters which significantly influence the dynamics and duration of the flight were analyzed for five selected aircraft series. The design of the propulsion subsystem affects the performance of the aircraft. Given the interdependence of the propulsion and energy subsystems, the parameters of LiPo batteries are included in the analysis.

4.1 Mass distribution of the aircraft system

Based on the division of the aircraft system into four key subsystems, the mass distributions of conventional multirotor configurations for five selected aircraft series (S, M, L, XL, XXL) are graphically shown. To ensure basic flight performance, the required TWR was determined according to the propulsion manufacturer's recommendations and is approximately 1.8 for all five series. **Figures 11–15** show the mass distributions of payload mass (m_{PL}), energy subsystem mass (m_{ES}), propulsion subsystem mass (m_{PS}), and control subsystem (avionics) mass (m_{AV}) for five generic series of aircraft whose propulsion subsystem consists of four, six, and eight rotors. For the selected battery capacities and the number of rotors, the maximum masses of the payload subsystems for the assumed TWR are expressed in kilograms. The first aircraft series – S (**Figure 11**) whose propulsion subsystem is based on propulsion units with P60 BLDC motors, is considered for payloads up to 10 kg. The second series – M (**Figure 12**) based on propulsion units with Antigravity 1005 motors, is considered for payloads from 10 kg up to 15 kg. The third series – L (**Figure 13**) based on propulsion units with P80 motors, is considered for payloads from 15 kg up to 25 kg. The fourth series – XL (**Figure 14**) based on propulsion units with U13 motors, is considered for payloads from 25 kg up to 50 kg. And lastly, the fifth series – XXL (**Figure 15**) based on propulsion units with U15 motors, is considered for payloads from 50 kg up to 100 kg.

The analysis of the multirotor UAV system mass distribution and the graphical representation, shown in **Figures 11–15**, was performed using a script written in the Matlab software package.

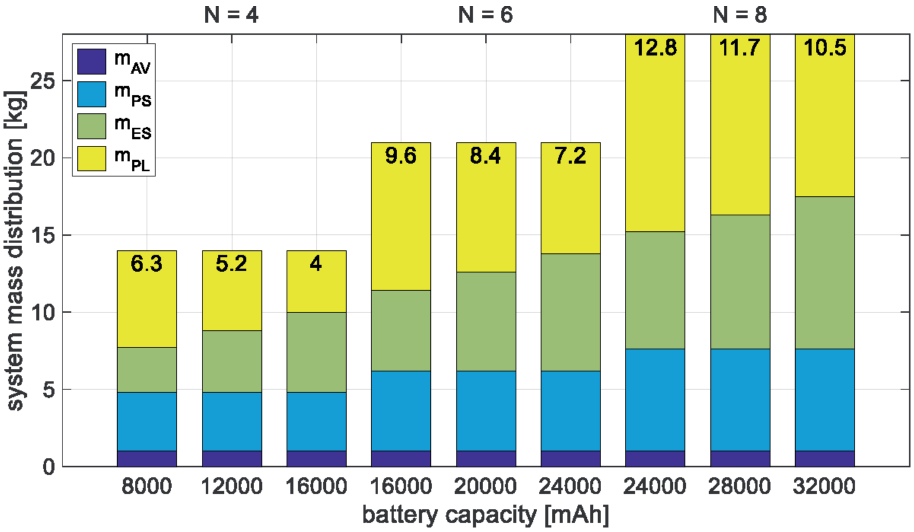

Figure 11.
Mass distribution of the S aircraft series system (TWR = 1.8).

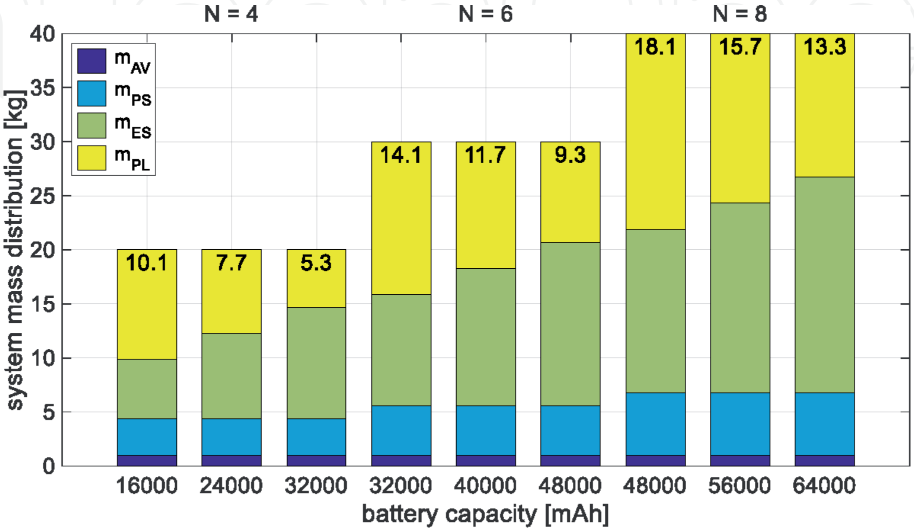

Figure 12.
Mass distribution of the M aircraft series system (TWR = 1.8).

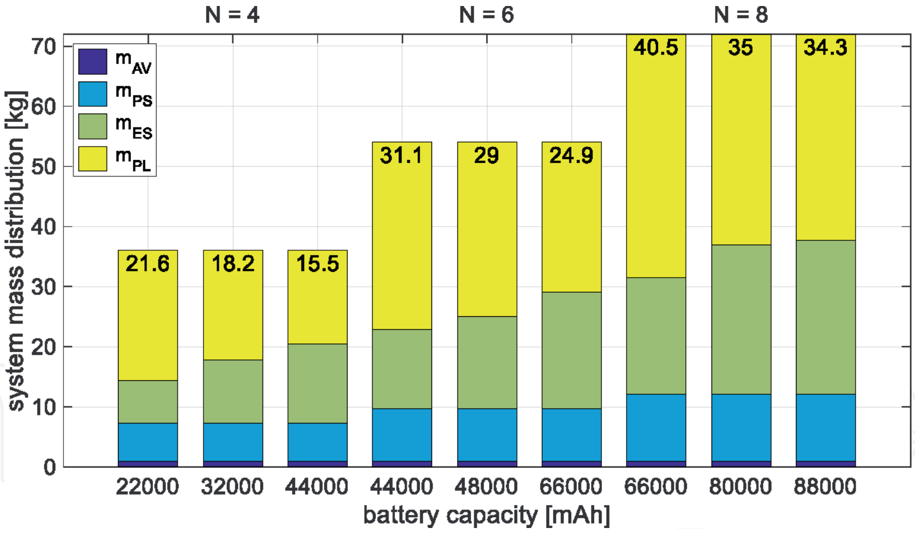

Figure 13.
Mass distribution of the L aircraft series system (TWR = 1.8).

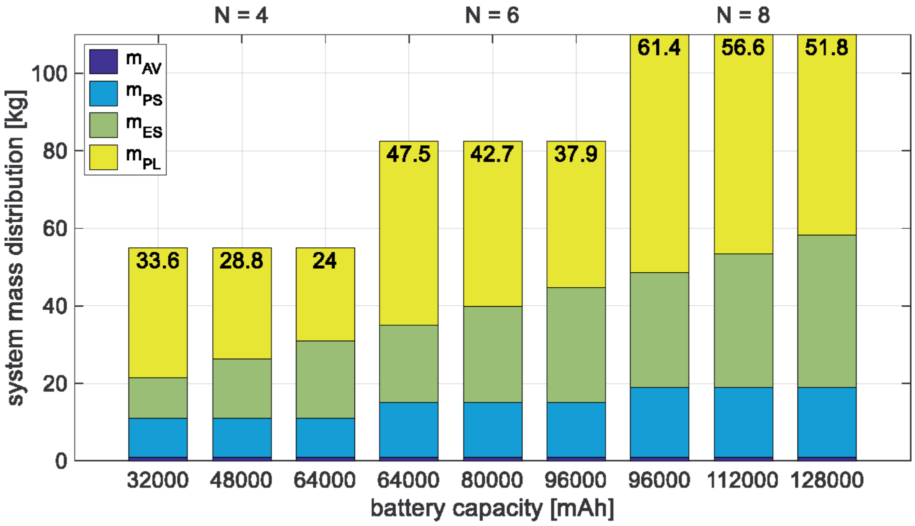

Figure 14.
Mass distribution of the XL aircraft series system (TWR = 1.8).

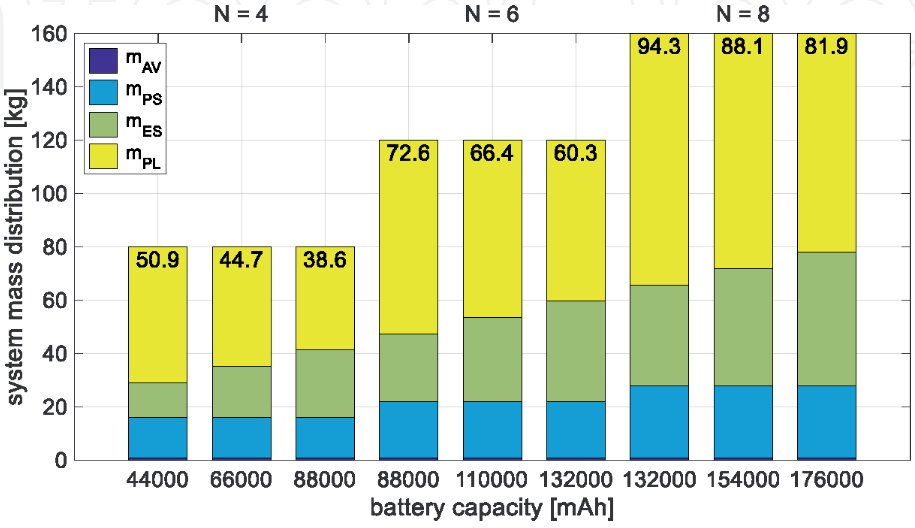

Figure 15.
Mass distribution of the XXL aircraft series system (TWR = 1.8).

4.2 Numerical estimation of stationary flight time

Very important information is the total time that the aircraft can be in the air, which depends on the mission itself, ie on the required flight performance and the cargo that the aircraft carries. Based on the characteristics of the propulsion units, an estimate of the flight time was performed for selected series of aircraft defined by the parameters of the propulsion and energy subsystem. The basic case is considered, a stationary flight of conventional configurations, assuming that the drop in battery voltage and the power consumption by the control subsystem (possibly also the payload subsystem) are ignored. The estimated flight time is calculated based on the available battery capacity and the electric current required to generate adequate thrust force. It is also important to note that the complete battery capacities were used in the calculation, which is not possible in practice since the batteries must not be completely discharged. The required thrust force to reach the steady state of the aircraft depends on the mass of the system.

Figure 16 shows the estimated stationary flight time for possible nine configurations of the first aircraft series – S. Configurations for each series are determined by the number of rotors (N) which is a parameter of the propulsion subsystem, and by battery capacity ie the number of considered batteries which is a parameter of the energy subsystem. The first series (S), as mentioned in the last subsection, is considered for payloads up to 10 kg. Furthermore, **Figures 16**–**19** show the estimated stationary flight time for other aircraft series (M, L, XL, and XXL) which were considered and analyzed in the last subsection.

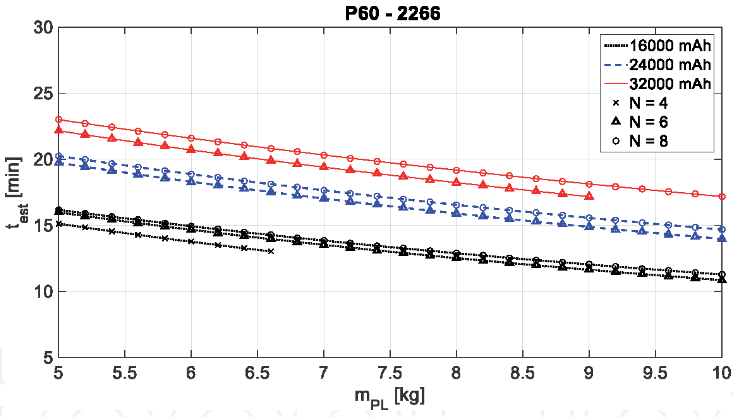

Figure 16.
Estimated stationary flight time of the S aircraft series.

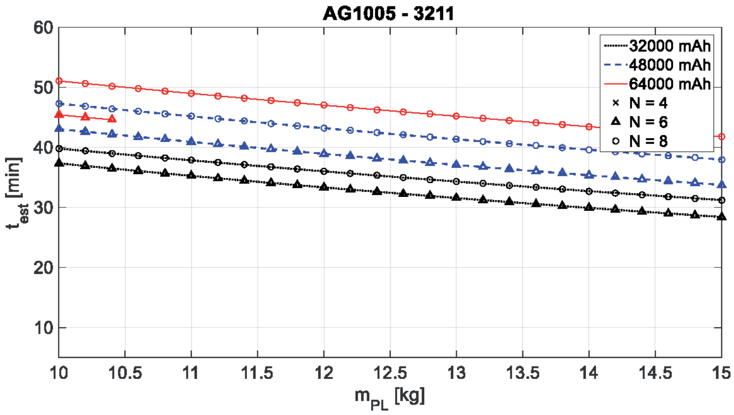

Figure 17.
Estimated stationary flight time of the M aircraft series.

The estimation of the multirotor UAV system stationary flight time and the graphical representation, shown in **Figures 16–20**, based on the parameters of the propulsion and energy subsystems, was performed using a script written in the Matlab software package.

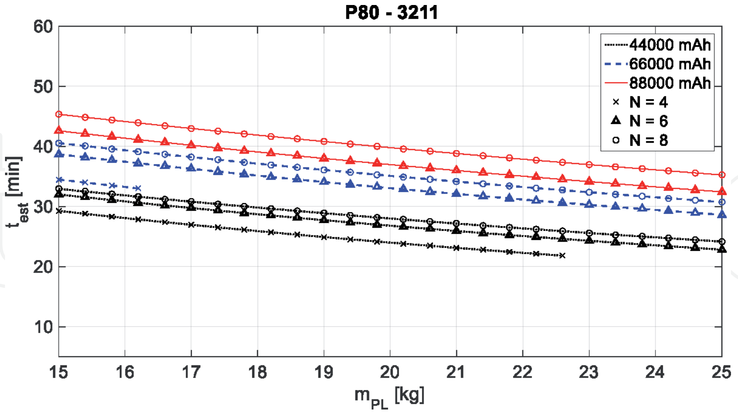

Figure 18.
Estimated stationary flight time of the L aircraft series.

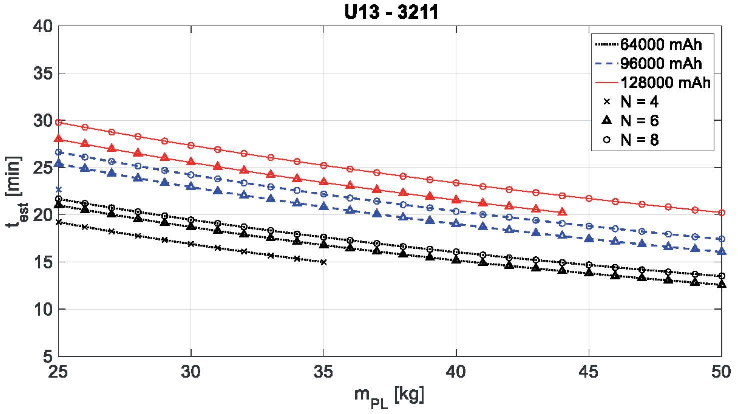

Figure 19.
Estimated stationary flight time of the XL aircraft series.

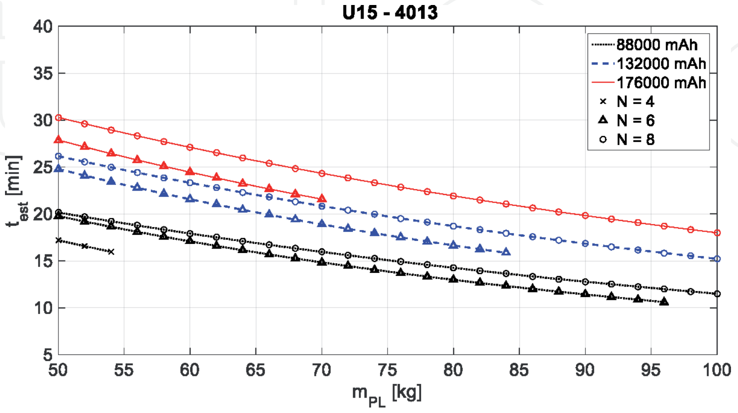

Figure 20.
Estimated stationary flight time of the XXL aircraft series.

4.3 Parametric design of a multirotor UAV

Based on the analysis, it is possible to select the aircraft parameters and components for a particular cargo and planned flight route. In considered design, the propulsion unit (rotor) is defined by the propeller diameter and the propulsion subsystem by the number of rotors. The size of the aircraft, which is defined by the aircraft diameter, derives from these two parameters. For given propulsion units defined with propeller diameter (d) in inch, and with the number of rotors (N), **Table 3** shows the propulsion subsystem diameter (D) in mm, which actually defines the construction parameters of the aircraft. In order to reduce the cost of prototyping and the potential production of system parts, it is necessary to achieve a certain degree of modularity. The idea is to turn predefined aircraft subsystems into modules that can be easily connected to each other. Of particular importance is the modularity of the propulsion subsystem. One of the ways to achieve this goal is by parameterizing the propulsion construction that connects the propulsion components with other subsystems.

	d = 22″	**d = 24″**	**d = 28″**	**d = 32″**	**d = 40″**
N = 4	1100	1200	1400	1600	2000
N = 6	1400	1600	1800	2000	2500
N = 8	1800	2000	2200	2500	3000

Table 3.
Conventional multirotor configuration sizes (D).

5. Conclusion

In this chapter, the concept of on-demand autonomous cargo transportation is presented by employing multirotor UAVs. The topology of a network of docking facilities and a multirotor UAV fleet was proposed for the considered autonomous transport within the central Adriatic islands in Croatia. Currently available technologies allow relatively simple implementation of the proposed concept, however, regulations applicable in a particular area should also be considered in the future. The market of commercially available components for propulsion and energy subsystem was investigated and it was found that it is possible to develop multirotor UAVs that can carry up to 100 kg of cargo. Based on the considered setups of electric propulsion units, the analysis of the Multirotor UAV propulsion and energy subsystems parameters were performed. In the multirotor UAV design process, the mass of five series of aircraft is considered and the flight time with respect to the payload mass is approximated and shown. The proposed concept of an autonomous cargo transportation system has great potential for future development and implementation since it can reduce transport costs, increase the frequency and speed of transport, and reduce carbon emissions.

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Appendices and Nomenclature

UAV	unmanned aerial vehicle
MEMS	micro-electromechanical systems

UGV	unmanned ground vehicle
VTOL	vertically take-off and land
ACTS	autonomous cargo transportation system
GPS	global positioning system
BLDC	brushless direct current
ESC	electronic speed controller
HV	high voltage
EMF	electromotive force
LiPo	lithium-polymer
NiMh	nickel-metal hydride
TWR	thrust-to-weight ratio

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