Chapter

Framework for Design and Additive Manufacturing of Specialised Multirotor UAV Parts

Petar Piljek, Nino Krznar, Matija Krznar and Denis Kotarski

Abstract

Rapid prototyping technologies have enabled a major step forward in the development of a very wide range of products, especially in the field of mechatronic systems. These technologies are largely related to additive manufacturing (AM), so-called 3D printing which is, in addition to product development, also suitable for the fabrication of mechatronic systems that are not intended for series production. In this chapter, a framework for the AM of specialised multirotor unmanned aerial vehicles (UAVs) parts is proposed and described for three AM technologies—fused deposition modelling (FDM), selective laser sintering (SLS), and stereolithography (SLA). A different approach to parts design is shown where the main problems are addressed and guidelines for parts manufacturing are given. Special emphasis is related to the mechanical characteristics and low weight of the manufactured parts that are merged with carbon fibre segments. The manufactured (printed) parts are mounted in functional assemblies and preliminarily tested.

Keywords: specialised multirotor UAV, additive manufacturing, fused deposition modelling, selective laser sintering, stereolithography

1. Introduction

In the last 10 years, the market for unmanned aerial vehicles (UAVs) in the civil sector has been growing enormously. This was certainly preceded by a period of intensive research that continues to this day, so, an even greater step forward is expected in the future. Technological advances in the design and manufacture of mechatronic system components have enabled many applications from the aspect of automation. The development of control, propulsion, power supply components, and other subsystems has contributed to greater speed of data processing and greater autonomy, which enables the performance of complex flight missions. The development of propulsion components and numerous studies of propulsion configurations have facilitated applications in various sectors, such as precision agriculture [1, 2], surveillance [3], and aerial photography [4]. The application possibilities of UAVs are plentiful in many other sectors, such as transport [5], construction [6], fire protection [7], and more.

The propulsion configuration defines how the aircraft will move in three-dimensional space and it depends on the type of application or mission that the UAV needs to perform. Numerous types of aircraft with various propulsion configurations are used to perform different tasks, activities, and for research and development. In addition to conventional types of UAVs with fixed wings [8, 9] and rotary wings [10–12], a number of hybrid configurations [13, 14] and bioinspired propulsion configurations [15, 16] are being investigated. Fixed-wing aircraft can achieve high speeds and compared to other types, consume less energy to achieve movement, but on the other hand, unable to perform the stationary flight. Generally, they need a runway or special launchpad to be able to take off. Aircraft with rotary wings do not have this problem because they have the ability to take off and land vertically (VTOL), and thus stationary flight and flight at moderate speed. This makes them suitable for missions that require complex manoeuvres and a higher degree of system autonomy. Within the rotary-wing UAV type, there are numerous subtypes of aircraft. It is important to highlight two typical representatives, aircraft with variable pitch propellers, such as helicopter aircraft [17] and multirotor aircraft (multicopter) [18], consisting of N rotors on which fixed-pitch propellers are mounted.

Multirotor type of UAV has greater agility and manoeuvrability, which allows them to perform missions that involve precise and complex movements. On the other hand, they are characterised by high-energy consumption, so it is extremely important to choose the right components and parameters of the system. The most commonly used configuration utilises four rotors (so-called quadrotor) and to a lesser extent the configuration with six (hexarotor), and eight rotors (octorotor). Generally, conventional configurations are characterised by a planar geometric arrangement of an even number of rotors. In addition to conventional purposes, a variety of propulsion configurations makes the multirotor type of UAV suitable for usage as aerial robotic systems. Since this type of application is expected for specialised tasks, there is a need to design custom aircraft and make small series or customised systems. It is also important to save time in the design and production phase and lower production costs compared to conventional manufacturing technologies. Rapid prototyping technologies, such as additive manufacturing (AM), allow the fabrication of assembly parts of such systems [19–21]. Numerous studies have shown the possibilities of rapid prototyping technologies and their application [22, 23].

In this chapter, the framework for design and AM of specialised multirotor UAV parts is presented. In the system design phase, it is necessary to select components and design multirotor UAV based on the purpose of the aircraft. The division into modules (subsystems) allows a greater degree of modularity that leads to a wider range of applications (by fitting the aircraft with different equipment). In the prototyping and production phase, the procedure for making parts using three different AM technologies is described. Depending on the mechanical and other requirements, which are defined in the system design phase, FDM, SLS, and SLA technologies are used within this framework. Professional and hobby 3D printers and related software packages were used in the production process. The procedure was validated for two considered case studies, for a small fully-actuated modular aircraft, and a heavy-lift multirotor UAV. The last part of this chapter presents experimental testing in certain phases of the specialised UAV development, which is necessary for this type of aircraft to be safely used.

2. Multirotor UAV system description

Multirotor type of UAV is classified as rotary-wing UAV, aircraft that are heavier than air and are powered by motors. The ability to take off and land vertically, hover, and fly at moderate speeds, amongst other flight manoeuvres, allows multirotor UAVs to perform complex movements, making them suitable for a wide range of tasks. From a mechanical point of view, the multirotor type of UAV system is described as a rigid body consisting of N rotors (propulsion units) that exist in 3D space; hence, it has six degrees of freedom (DOF). Such a multivariable system is mathematically described by a dynamic model with six second-order differential equations. The geometric arrangement of the propulsion subsystem defines the aircraft configuration. To perform missions such as aerial filming, conventional configurations characterised by a planar arrangement of the even number of rotors are generally used. Commercial aircraft for these and similar purposes are mainly quadrotor (quadcopter), hexarotor (hexacopter), and octorotor (octocopter) aircraft. The listed configurations can be in + and × arrangement (layout), such as configurations shown in **Figure 1**.

The design of the aircraft system primarily depends on the purpose, respectively, the mission profile that the aircraft should typically perform. To allow easier analysis of aircraft parameters and design, the aircraft system can be divided into four key subsystems (**Figure 2**). The equipment and payload to be carried by aircraft dictate the choice of parameters and components of other subsystems. The rotors of the propulsion subsystem are mainly electric propulsion units (EPUs) whose central part is a brushless DC (BLDC) motor with a corresponding electronic speed controller (ESC), and a fixed-pitch propeller mounted on a motor rotor. By their rotation, the propellers create aerodynamic forces and moments and directly affect the flight dynamics, which means that the rotors angular velocities are the input variables of the propulsion subsystem. The characteristic of the multirotor UAVs is high-energy consumption, so an energy subsystem must deliver a large amount of energy. In conventional

Figure 1.
Conventional multirotor UAV configurations in ×-layout.

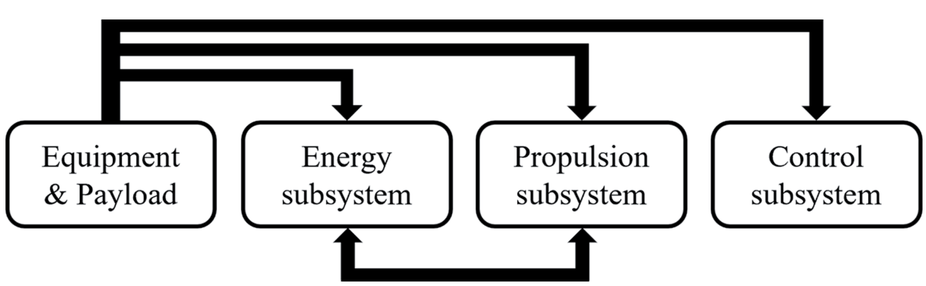

Figure 2.
Multirotor UAV main subsystems.

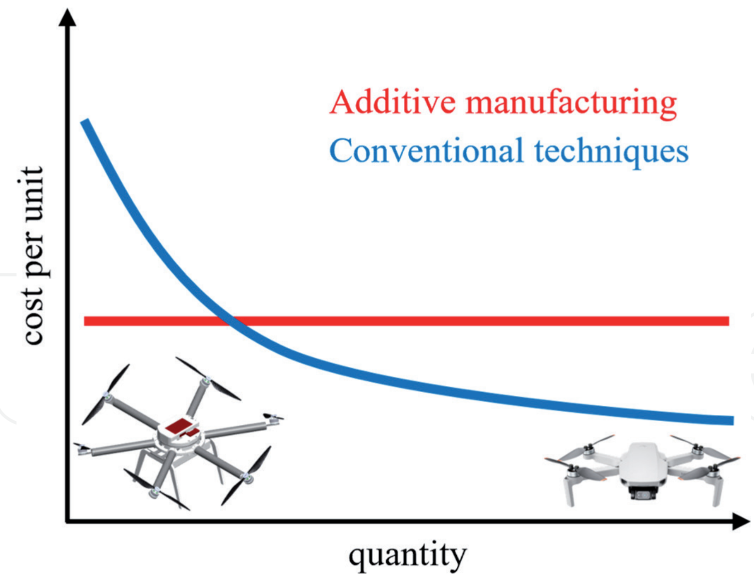

Figure 3.
Cost per unit with respect to quantity for conventional and additive manufacturing technologies.

EPUs, the power subsystem mainly consists of one or more lithium-polymer (LiPo) batteries with associated electronics. The design of the control subsystem or the selection of components primarily depends on the mission or the degree of autonomy that determines the selection of the flight controller, sensors, and other peripheral modules (telemetry, RC, VTx, and others). It follows that the performance of a multirotor type of UAV is determined by the parameters and components of the propulsion and energy subsystems. These two subsystems are interdependent because, for example, as the power of the aircraft increases, the energy demand increases, resulting in a higher mass of the aircraft. The energy requirements of the propulsion subsystem must be taken into account when selecting batteries, which, in turn, depends on the weight and size of the aircraft and the number of EPUs. When designing a system, the ratio of mass and capacity of the battery is one of the key data.

In this chapter, the design of specialised multirotor aircraft is considered, and two case studies are presented through the design, production, and testing phases. Aircraft, such as those used in the case study, cannot be procured in form of commercial aircraft produced in large series. They are produced in small series or even as unique models designed to perform a specialised task. The first case is an experimental modular multirotor (EMMR) UAV with a power of 350–700 W, which has so far been proposed as an engineering educational platform [18]. EMMR can be used as an aerial robotic system since fully-actuated UAV configurations can be assembled. Such a platform represents a suitable engineering educational tool due to the complexity of the system, which requires an interdisciplinary approach in the field of mechanical engineering, electrical engineering, and computing. The second case is a heavy lift aircraft that can be a power of approximately 10–20 kW, depending on the number of rotors. Such an aircraft is considered for use in precision agriculture for smart spraying tasks. In addition to the fact that these aircraft are not commercially available in a form that would allow change of the parameters within open-source software, it is also important to point out that in small series production the cost per unit increases dramatically. For this reason, technologies for rapid prototyping were chosen, mostly AM in which the cost per unit is the same regardless of the number of units produced (**Figure 3**), which is a known fact described in numerous studies [24, 25]. AM is often appropriate for small to medium-sized production series but there is always an inflexion point at which other manufacturing methods become more cost-effective.

3. Additive manufacturing technologies

In this chapter, AM technologies are used for the rapid prototyping and development of specialised multirotor UAVs. In addition to the fact that for small batches AM is cheaper compared to conventional processes, it also significantly shortens the development time by rapid iteration and the possibility of early and often testing many different designs or partial designs with critical features, which further reduce the cost of the final product. Conventional production technologies are much more expensive for small batches due to preparation, tool selection, manufacturing of tools, and other costs. AM, on the other hand, allows the production of parts directly from solid CAD models using software packages, so-called slicers. AM is also suitable for the production of spare parts for damaged aircraft.

There are a large number of low-cost 3D printers on the market, so for low-power multirotor aircraft, parts can be produced very cheaply and quickly. 3D printers may vary greatly in price, size, material, and AM technology used. The paper further considers three AM technologies: FDM, SLS, and SLA. 3D printing uses a wide range of materials, the choice of which is related to AM technology and the purpose of the part. In the case of aircraft parts, plastic materials in the raw form of filament, powder, or resin are mainly used. To determine whether certain materials and AM technologies are suitable for the production of a particular part, the desired strength, stiffness, and weight of the part must be taken into account, but the influence of environmental conditions and the expected duration of the part must also be considered. In addition to the choice of material, the mechanical properties of the part can be alternated and adjusted by changing the printing parameters and the orientation of the printed part. Because parts are fabricated gradually, layer by layer, the inevitable result is the anisotropic properties of printed parts. Better mechanical properties are achieved along with the printing layer and worse in a direction normal to the printing layer. There are many ways in which the mechanical properties of materials can be tested [26–28]. Also, greater precision and greater detailed geometry can be achieved in planes parallel to the print layer where print accuracy is higher. **Table 1** shows the main characteristic of the used 3D printers in combination with the associated software.

AM technology	3D printer	Raw material form	Build volume	Software
FDM	Prusa i3 MK3S+	Continuous thermoplastic filaments	250 × 210 × 210 mm	PrusaSlicer
FDM	Markforged Onyx Pro	Composite base filaments	320 × 132 × 154 mm	Eiger
SLS	Sinterit Lisa Pro	Powder	150 × 200 × 260 mm	Sinterit Studio
SLA	Formlabs Form 3	Resin	145 × 145 × 185 mm	PreForm

Table 1.
Used 3D printers with associated software.

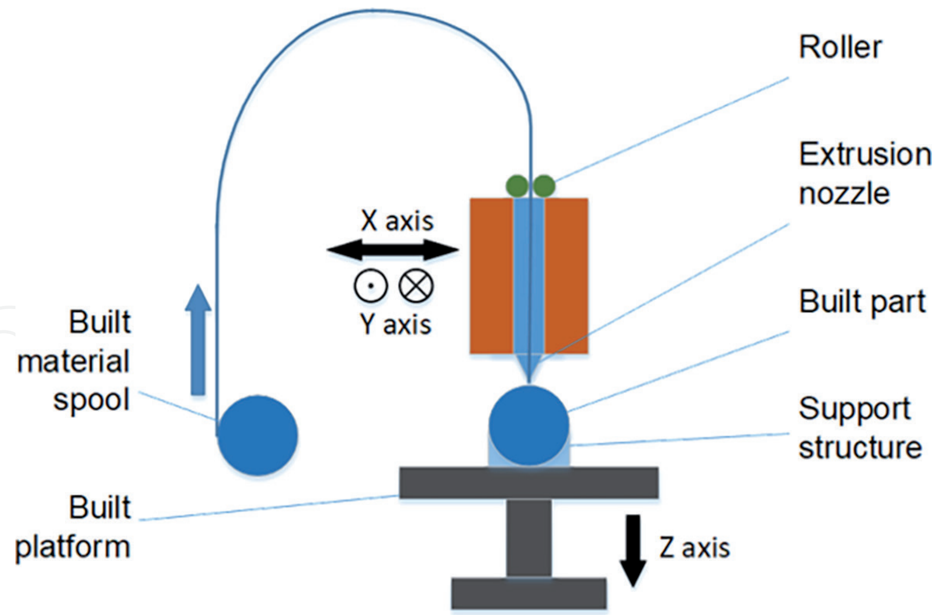

Figure 4.
The principle of operation of FDM technology.

3.1 Fused deposition modelling

Fused deposition modelling (FDM) or known as fused filament fabrication (FFF) is a manufacturing technology in which objects are created by extruding polymer filament onto a built platform through a heated nozzle. There are numerous versions of FDM printers with various price ranges. In this research, Prusa i3 MK3 is used as a low-cost FDM printer where the platform moves in the Y-axis and the nozzle in the X- and Z-axes. When one layer is done, the nozzle will move up vertically to allow a new layer to be applied to the previous one. The thickness of the layer (slice) depends on the print parameters, and in the case of the used Prusa printer, the slices are between 0.05 and 0.30 mm thick [29]. Prior to the AM process, the constructed CAD model must be exported in a compatible file format, such as STL. Such a model is then cut into horizontal slices in a software package (so-called slicer). The paths of the platform and the nozzle are calculated by the software according to the parameters set by the user. In addition to the mentioned layer thickness, which significantly affects the accuracy, some of the other variable parameters are the number of layers in the outer wall and the number of layers at the bottom and top of the part, the percentage and structure of the filling, extrusion speed, and others. Because the next printing layer prints on top of the last one, supporting structures are required to print large overhangs or holes. They are printed together with the part and removed after printing is done. In general, overhangs should be avoided by proper orientation of the part or by using angled overhangs where possible. The most common materials used in FDM technology are ABS, PLA, PC, ASA, PPSF/PPSU, ULTEM, PH-HD. PE-LD, PET, TPU, and others. **Figure 4** shows a working principle of the FDM technology.

3.1.1 Continuous fibre fabrication

In addition to classic FDM technology, devices that can produce parts from composite materials using FDM processes are known as continuous fibre fabrication (CFF). In this paper, Markforged Onyx Pro is used, in which the platform moves in the Z-axis and the nozzle in the X- and Y-axes. Compared to the Prusa printer, it is a much more expensive device but allows 3D printing of composite materials made of plastic matrix and inlaid

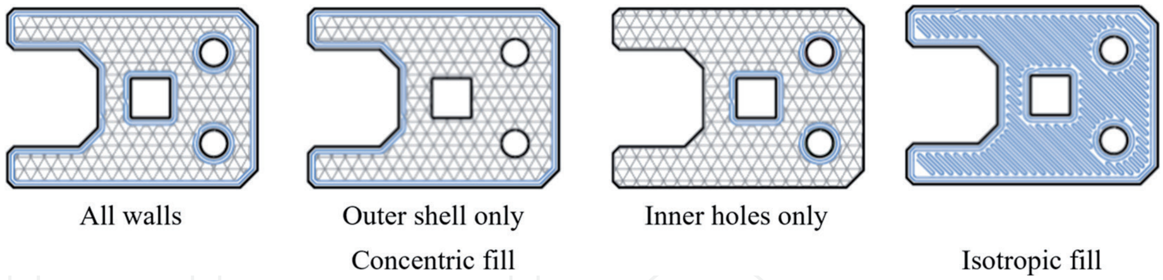

Figure 5.
Fibre reinforcement layout—CFF technology [30].

fibreglass fibres for better mechanical properties and increased lifetime, compared to plastic alone. The strength and stiffness of a fibre-reinforced part can be comparable to aluminium. The software package allows adjustment of the classic print parameters and further adjustment of the composite reinforcements parameters as shown in **Figure 5**.

3.2 Selective laser sintering

The next AM technology considered in the chapter is selective laser sintering, which with the advent of cheaper 3D printer systems allows the application not only for industrial purposes but also for research. The material used in this technology is available in the form of powder that is laser-sintered to create a designed geometry. The powder delivery mechanism consists of two chambers, in the first, there is construction powder that is delivered to the second chamber through rollers and a piston in form of a powder layer. In the second chamber, a layer is precisely sintered to the desired shape utilising laser beams. This technology does not require a support structure, as the unsintered powder provides support to the object under construction. This allows the production of parts of more complex geometry from different types of materials, and it is possible to produce prefabricated assemblies with movable joints. After the production process, further

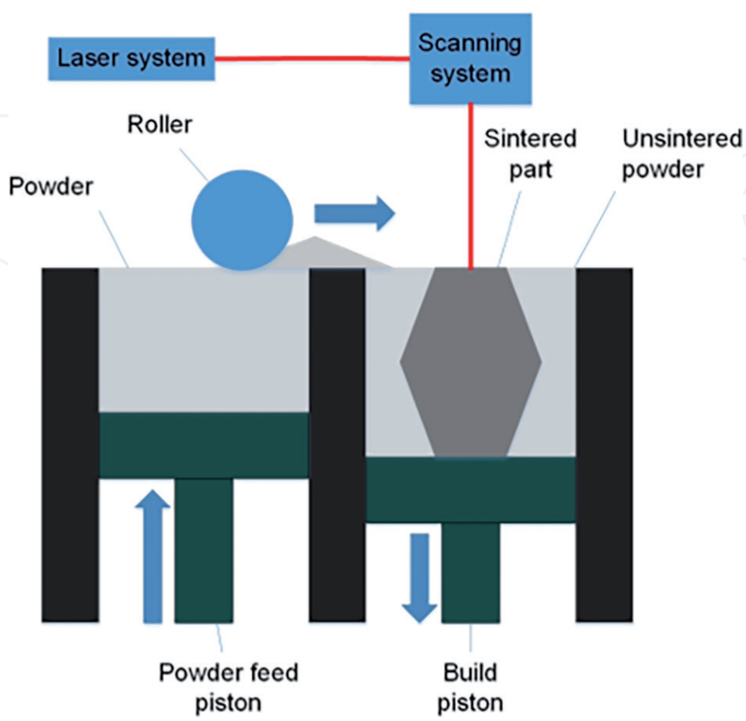

Figure 6.
The principle of operation of SLS technology.

processing of the part or assembly is required to achieve certain mechanical properties of the finishing quality. In this chapter, the SLS system is discussed, which consists of the SLS 3D printer Sinterit Lisa Pro and the associated equipment for the preparation of powder materials (nylon 11, nylon 12, TPU, TPE, and polypropylene) and processing of parts and assemblies. **Figure 6** shows the working principle of the SLS.

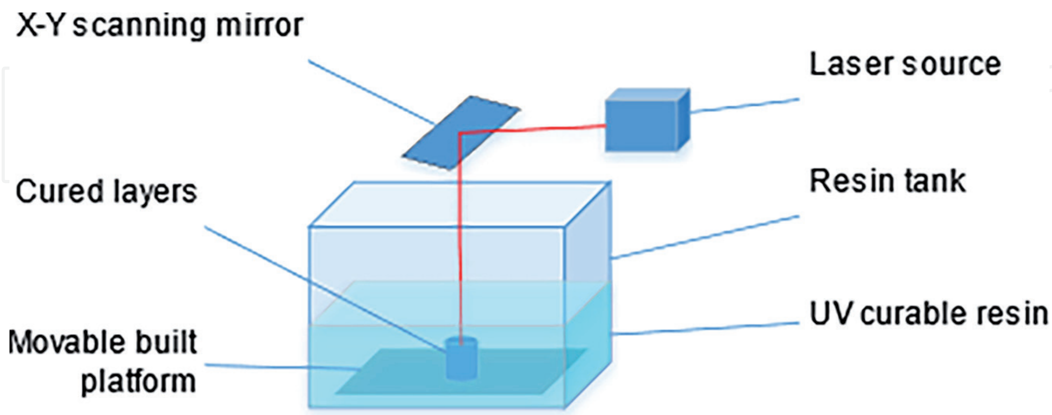

Figure 7.
The principle of operation of SLA technology.

3.3 Stereolithography

Stereolithography (SLA) is the first commercially available AM technology developed in 1986 by 3D Systems. With this technology, CAD models are created by curing polymer resin using a laser beam system. With SLA technology, the laser is focussed on a mirror scanning system that cures polymer resin with very high precision. When one layer is cured by laser, the built platform moves upwards in the z-direction and the new layer can be treated. The materials for SLA are thermoset photosensitive resin-shaped polymers. SLA technology makes it possible to achieve high accuracy and a smooth surface, making it the most cost-effective AM technology. Compared to the previously considered technologies, SLA parts have poorer mechanical properties; therefore, SLA technology is not recommended for structurally loaded parts. **Figure 7** shows the scheme of the SLA procedure.

4. Framework for additive manufacturing of specialised UAV parts

The design of the multirotor type of UAV propulsion subsystem is considered and the additive manufacturing framework is shown. This framework can also be used for rapid prototyping of parts from carbon fibre plates. The process of making parts is presented for two experimental aircraft that can be used for specialised purposes, such as performing tasks involving complex and precise movements and in tasks involving the transfer of heavy cargo.

4.1 Propulsion subsystem design considerations

The propulsion subsystem is defined by the parameters of the geometric arrangement and characteristics of the EPUs. A suitable fixed-pitch propeller is mounted on the rotor of the outrunner BLDC motor (**Figure 8**). The basic parameter of a propeller is its diameter. As the diameter of the propeller increases, the angular velocity of the

Figure 8.
Electric propulsion unit of multirotor type of UAV [31].

motor rotor decreases. The motor is defined by a motor velocity constant kV. Motors with a lower motor constant are used in combination with larger diameter propellers and are driven at higher voltages. The ESC is responsible for starting the motor and, depending on the control signal, controls the motor speed. The EPUs are connected to one or more LiPo batteries of the appropriate number of cells and capacity.

The motor stator must be connected to the aircraft assembly which consists of a central part and the rotor arms. Propulsion assembly design is the most complex part of the overall design in terms of the mechanical properties that assembly parts should possess. The aircraft can be used in a wide range of powers, from a few tens of watts to several tens of kilowatts. It is necessary to choose materials and technologies concerning the selected propulsion components. **Figure 9a** shows the stator geometry which is important from the aspect of mounting the motor to the aircraft assembly. **Figure 9b** shows the characteristics of the propulsion unit considered in the case of a heavy-lift aircraft.

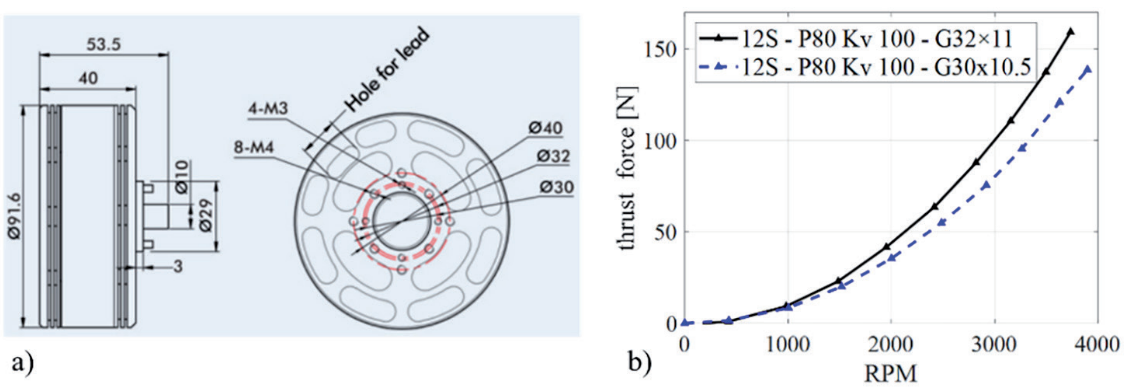

Figure 9.
Electric propulsion unit: (a) BLDC motor geometry [31]; (b) characteristics.

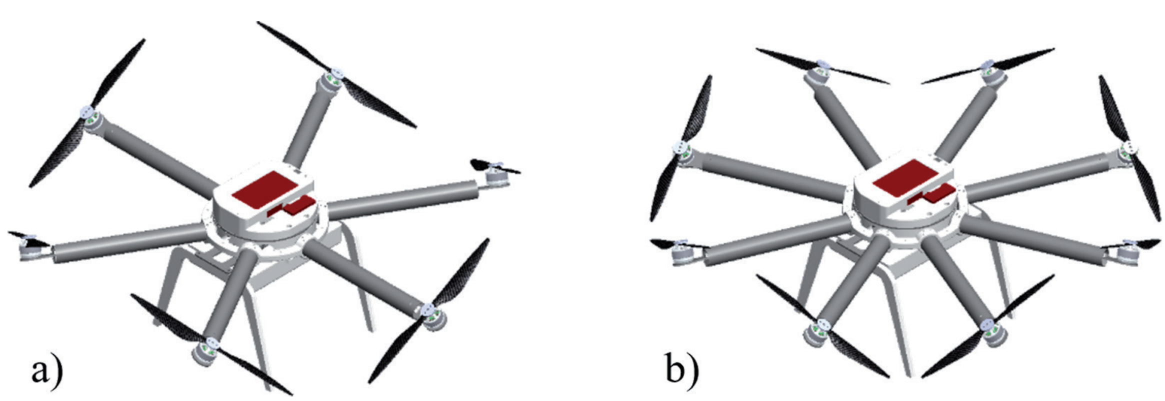

Figure 10.
Fully-actuated multirotor configurations with passively tilted rotors: (a) PTX6; (b) PTX8.

The configuration of the multirotor UAV is defined by the geometric arrangement of the rotors. Mostly conventional configurations with a planar rotor layout are commercially available. It is possible to select configuration parameters that will result in an increased degree of actuation, which potentially allows the performance of complex tasks in the field of aerial robotics. A fully-actuated aircraft with passively tilted rotor arms are considered in this research (**Figure 10**).

4.2 Additive manufacturing procedure

A framework for the production of parts for specialised multirotor UAVs using additive manufacturing is presented. It consists of an aircraft design stage in which various software packages can be used for the needs of 3D modelling of parts and

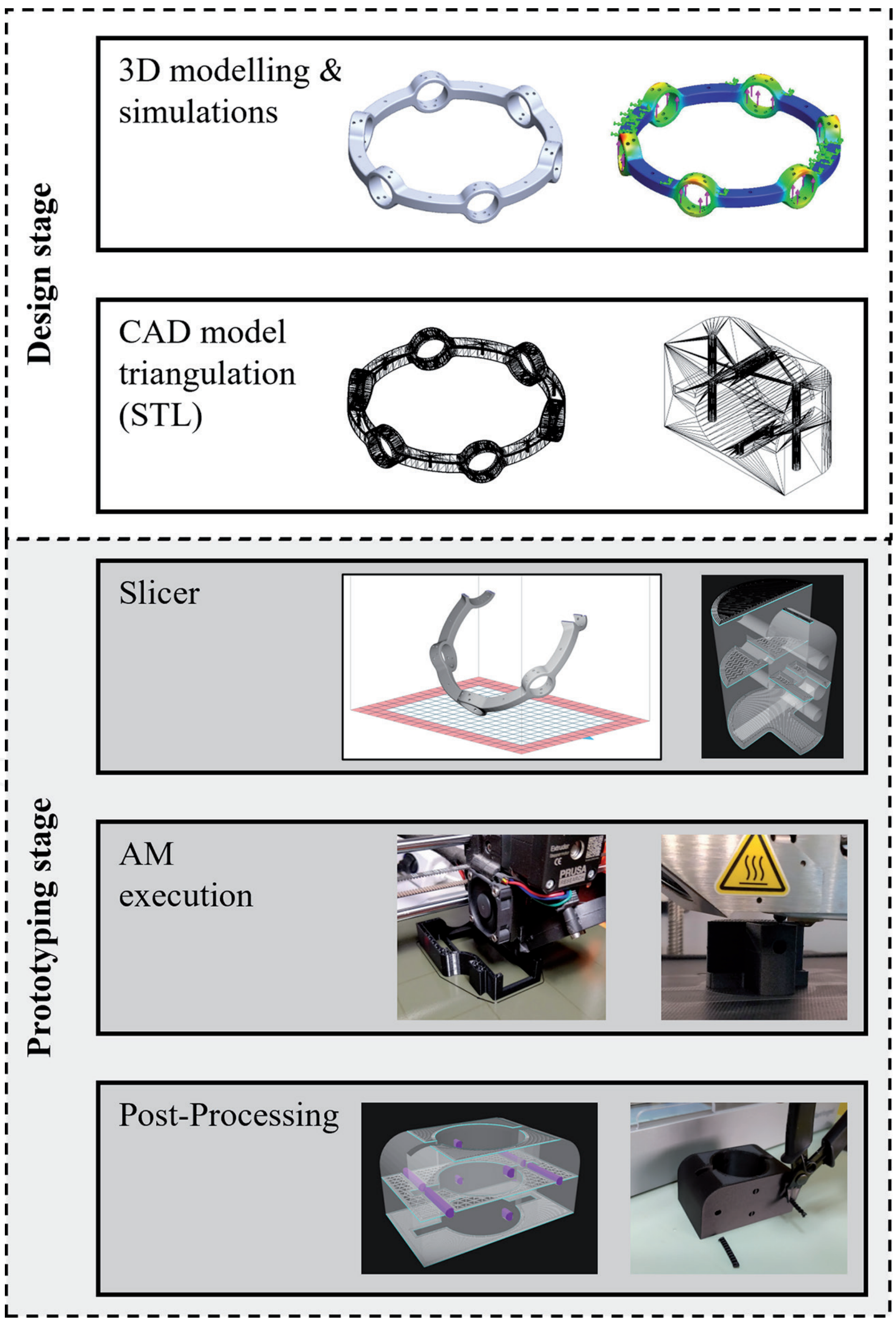

Figure 11.
Additive manufacturing procedure.

assemblies, and also for simulations. In this research, the SOLIDWORKS software package is used in the design stage. After the process of creating a model is done, triangulation of the 3D CAD model is performed and the model is exported into an STL format. In the prototyping stage, it is necessary to adjust the parameters of the 3D print in accordance with the selected AM technology using associated software, the so-called slicer. The next step is the execution of the g-code by which the given parts are produced. After finishing the print, the parts need to be post-processed (**Figure 11**).

4.3 Experimental verification

Manufactured parts of specialised multirotor UAVs are connected together with other components into functional assemblies. Through the prototyping phase, different test phases were conducted for the two aircraft based on propulsion units with the parameters given in **Table 2**. By assembling and testing individual subsystems, potential design errors can be identified, and improvements offered.

The control subsystem of the experimental aircraft is based on the open-source Pixhawk FC. To operate a fully-actuated aircraft, custom firmware has been developed.

Multirotor configuration	BLDC motor	Propeller	ESC
PTX6 D = 500 mm	MN1806 1400 Kv	CF7024 d = 7″	Air 10A 3S
X4 D = 1500 mm	P80 100 Kv	G32x11 d = 32″	Flame 80A 12S

Table 2.
Considered multirotor configuration main parameters.

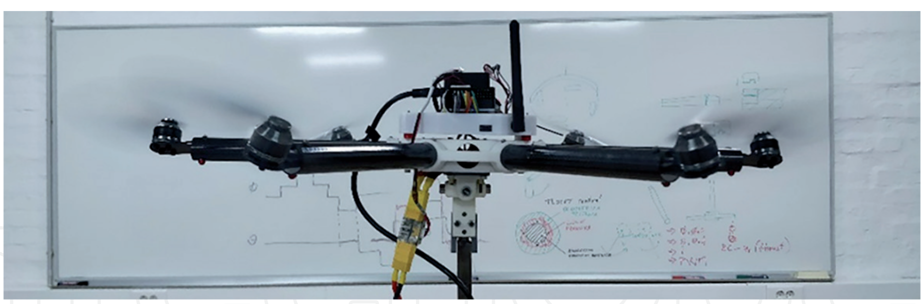

Figure 12.
Experimental testing of PTX6 configuration in case of attitude control.

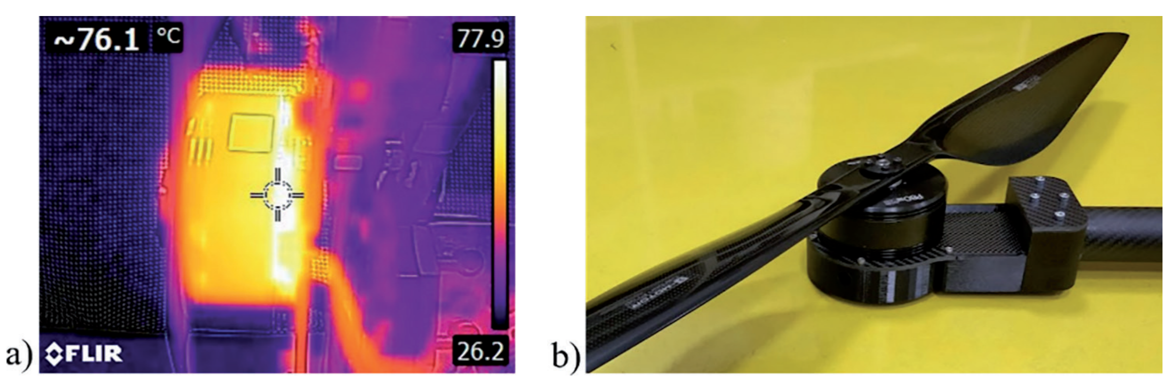

Figure 13.
Heavy-lift aircraft propulsion: (a) EPU testing; (b) EPU assembly.

Figure 12 shows the indoor testing phase where attitude control experiments were conducted. Indoor testing provides a safe way to set the basic parameters of the control subsystem and set up and test all safety elements. It is also possible to tune the parameters of the control algorithm. After the indoor phase, the remote control of the aircraft was tested in two cases that differ by control inputs from the RC transmitter. The first case is represented with conventional control inputs (thrust, roll, pitch, and yaw), while in the second, control inputs were three forces and yaw moment with respect to body axes.

For the second experimental aircraft, the propulsion unit was tested in different operating regimes at the full power range. Characteristics were obtained (**Figure 9b**) and other parameters, such as heating, were monitored (**Figure 13a**). Given the power of the aircraft, the described framework is used in a wider range of rapid prototyping, which includes cutting carbon plates, which together with printed parts and prefabricated tubes form the rotor arm assembly (**Figure 13b**). In the coming period, it is planned to assemble the propulsion subsystem into a functional assembly so that tests can be carried out as in the case of the first experimental aircraft.

5. Conclusion

This chapter demonstrates the application of three different AM technologies for the development of customised parts for the specialised multirotor UAVs—fused deposition modelling (FDM), selective laser sintering (SLS), and stereolithography (SLA). Special purpose multirotor UAVs are often produced in small series, with the option of personalization and modular design. In the case of prototyping or individual production, conventional manufacturing technologies are too expensive and not flexible enough to be able to make parts quickly and put them into exploitation. AM offers new possibilities for rapid development of UAV multirotor reducing costs and time of research, development, and production. To take full advantage of AM, a new design approach for AM is needed to achieve lightweight and durable structures of UAV parts. Preliminary tests have shown that the use of the proposed AM technologies is very promising in terms of designing parts of specialised aircraft, as many factors (i.e., geometry, strength, firmness, and weight) often have to be changed and adjusted during the design process. In future work, it is planned to use AM technologies to make parts of other aircraft subsystems and to integrate them in the overall multirotor UAV system. Furthermore, the oncoming tests of mechanical properties are expected to have a great significance for frame structure optimisation.

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Appendices and nomenclature

AM	additive manufacturing
UAV	unmanned aerial vehicle

FDM	fused deposition modelling
SLS	selective laser sintering
SLA	stereolithography
VTOL	vertically take-off and land
DOF	degrees of freedom
EPU	electric propulsion unit
BLDC	brushless direct current
ESC	electronic speed controller
FFF	fused filament fabrication
CFF	continuous fibre fabrication
LiPo	lithium-polymer

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