Mission-Oriented Additive Manufacturing of Modular Mini-UAVs

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Recent developments in fast additive manufacturing, such as rapid 3D printing of composite materials, present opportunities for the manufacturing of small unmanned aerial vehicles (UAVs) that are tailor-made for the specific mission needs. This paper presents a novel framework for mission-oriented, modular design and construction of mini-UAVs using additive manufacturing. The outcome is a manufacturing method which is suitable for a parametric design that can be tailored for specific mission requirements, and rapidly constructed using additive manufacturing techniques. We show how additive manufacturing enables an agile design methodology by allowing fast and efficient iteration of prototypes during the design process. The proposed framework is demonstrated by the design of a tail-sitter hybrid VTOL vehicle, for which wing-tip geometry and wing dihedral angle were optimized over several iterations of rapid prototyping. Additionally, we present a flight performance validation of the resulting vehicle design through flight tests in a motion capture facility and outdoors. Finally we show several other vehicle configurations, such as quadrotors and a fixed-wing aircraft, that also take advantage of the proposed design and manufacturing methods.

Introduction

Advances in accuracy, affordability, and material range have made additive manufacturing (AM), or *3D printing*, a viable choice for industrial manufacturing [1]. In the aerospace industry, its applicability was initially limited to the manufacturing of small items and support structures, such as tooling and jigs. However, in recent years, the industrial use of AM has expanded to include, e.g., wing components and engine parts. Concurrently, the use of AM for rapid prototyping in academic and industrial research and design settings has greatly increased [2]. We anticipate that this trend will accelerate even further as accessibility and affordability continue to improve.

Several key aspects of AM make it an eminent option for research and design of mini unmanned aerial vehicles (UAVs), i.e. UAVs with wingspan up to 2 m. Most prominently, it is accessible for organizations with limited manufacturing facilities and manpower, as the 3D printing process is typically fully automated and does not require specific tooling. After the design is completed, all components can be manufactured on a single 3D printer at a click of the mouse. If a printer is not available, designs can be ordered from a third-party printing service. These services often offer much shorter turnaround times than more traditional parts manufacturers. In practice, AM enables a *crash and continue* approach to experimentation with novel designs and prototypes. The fact that prototypes can be manufactured quickly and at low cost allows for an *agile design philosophy*, where experimental data, e.g., from wind tunnel and flight tests, can immediately be integrated in subsequent design iterations [3]. This enables an increased synergy between the

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design process and flight testing, for example by supplementing numerical methods with practical experiments in the multi-disciplinary design, analysis, and optimization (MDAO) stage. At the same time, AM provides geometric design freedom that is not limited by the constraints of traditional manufacturing methods [1]. Thereby it enables research into virtually all aspects of UAV design, such as airfoil geometry, experimental control surface design, and structural analysis [4].

In manufacturing and deployment, AM's quick turnaround and limited use of design-specific tooling enables the application of modular, mission-oriented UAV designs. Opposed to traditional design, which typically embodies design compromises that lead to acceptable performance over a range of mission scenarios, mission-oriented design is tailored for specific mission requirements, such as endurance, maneuverability, or payload. One could foresee a scenario where mission requirements are set, the specific mission-oriented aircraft is printed overnight, and the mission is flown the very next day.

In this paper, first, we present a novel agile framework for design and construction of mission-oriented mini UAVs using modular design and additive manufacturing. The outcome of the framework is a manufacturing method that is parametric and can be tailored as specific mission requirements arise. We show how additive manufacturing enables such an agile design methodology by allowing fast and efficient iteration of prototypes during the design process. Second, demonstrate our methodology by presenting the iterative design of a tail-sitter hybrid VTOL vehicle, including validation of flight performance through flight testing. Finally, we highlight the advantages of modular airframe design by presenting its application to control robustness, and show several other vehicles manufactured using the proposed design framework, including quadrotors and fixed-wing configurations.

(a) University of Southampton SULSA [5]

(b) MIT VAST [6]

(c) University of Virginia Razor [7]

(d) University of Sheffield Blended-Wing Body [8]

Fig. 1 Mini-UAVs constructed using additive manufacturing.

Additive Manufacturing for Mini-UAVs

Additive manufacturing is an umbrella term that encompasses a large variety of manufacturing techniques. The commonality being that AM techniques produce 3D objects by material addition based on automatic control and digitally defined designs. These designs can be created using computer-aided-design (CAD) software, 3D scanning, or a combination of both. The application of AM to the manufacturing of a complete air vehicle was pioneered at Southampton University with the construction of the SULSA in 2009 [5]. In the ten years since, several other mini-UAVs have been constructed using AM in both academia and industry. The majority of these vehicles were constructed using techniques from three of the seven AM process categories defined in the appropriate ISO/ASTM standard [9]. An overview of these techniques is given in Table 1. Each has specific advantages and disadvantages that affect its suitability for certain vehicle designs.

SULSA, shown in Fig. 1a, was manufactured out of nylon using selective laser sintering (SLS) [5]. In this process, parts are built by fusing thin layers of material powder by laser sintering [1]. The powder is transformed into a solid mass by heating, without reaching the point of liquefaction. After sintering, the build platform is lowered and a new layer of powder is applied. The unfused powder remains as support material and is removed once the part is completed. SLS results in strong and tough parts with good structural properties. It is relatively affordable and can accommodate large built volumes without the need for support structure, which makes it also suitable for larger UAVs [10]. A major downside of SLS is the rough surface finish, which may make additional treatment required in certain aerodynamic applications [11].

In multijet modeling (MJM), material and binder liquids are jetted onto a build platform [1]. After jetting of a layer, the material is solidified through photo-polymerization using an ultraviolet (UV) curing lamp. The process of polyjet modeling (PJM) is similar, but incorporates the use of multiple material liquids. Both techniques are capable of printing fine details and result in smooth surface finishes. However, material selection is quite limited, and structural properties are often inferior and further degrade as the part is exposed to UV light. Consequently, material jetting is typically not suitable for construction of UAV fuselage parts or fixed wings. However, it has been used for the construction flapping wings, e.g, by [12].

Fused filament fabrication (FFF), also known by the proprietary term fused deposition modeling (FDM), based on the deposition of material filament through a moving, heated nozzle [13]. The nozzle heat causes the material to melt and fuse with the growing part. Support structures are printed in the same manner and have to be removed afterwards. FFF is by far the most popular technique amongst the hobbyist community, mainly due to the availability of relatively simple and affordable printers. High strength polymers can be used to obtain parts with good structural properties. FFF has also been applied to ceramics, metals, and carbon-fiber nanotubes, e.g., for the printing of an electronics circuit in a multicopter body [14]. A clear disadvantage of FFF is the relatively poor surface finish and stair stepping effect due to the layered deposition of filament.

Table 1 Overview AM techniques applied in mini-UAV construction.

Technique(s)	Process category	Fusion mechanism	Material(s)
Selective laser sintering (SLS)	Powder bed fusion	Sintering	Polymers
Multijet modeling (MJM), Polyjet modeling (PJM)	Material jetting	Photo-polymerization	Polymers
Fused filament fabrication (FFF)	Material extrusion	Melting	Polymers, Metals, Ceramics

Mini-UAV Designs using Additive Manufacturing

As mentioned above, the SULSA, shown in Fig. 1a, is the first published UAV that was produced using AM [5]. It was constructed at University of Southampton in 2009. The design exploits several key advantages of AM. Freedom in design geometry was leveraged to construct the aerodynamically efficient elliptical wing planform that is challenging to manufacture using traditional methods. The design also incorporated simple and tool-less assembly through parts consolidation, e.g., by manufacturing the wing with hinges and control surfaces in place.

University of Malaysia Pahang developed a modular UAV testbed for evaluation of mission-specific hardware [15]. In the project, AM enabled modular design and rapid prototyping to enable switching of on-board components with relatively low effort. The vehicle featured structural parts constructed out of acrylonitril-butadieen-styreen (ABS) using FFF. In 2012, University of Virginia and MITRE Corporation collaborated to design and build a somewhat similar UAV that combined structural parts produced using AM with a tightly applied plastic skin [16]. While the aircraft still needed significant assembly, it featured design geometry that could not be manufactured using traditional methods and balsa wood [6, 16].

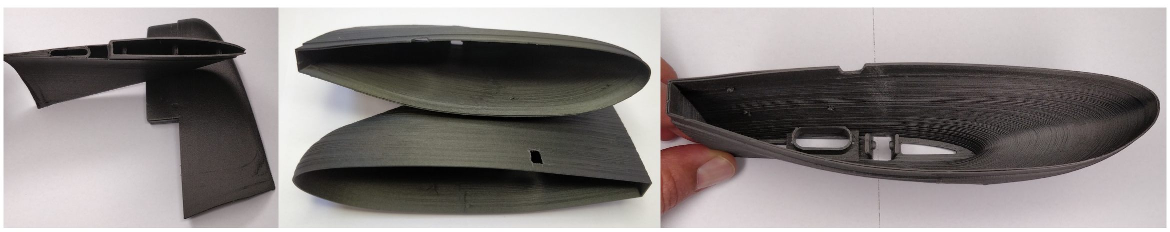
The VAST UAV, shown in Fig. 1b, was developed at MIT Lincoln Laboratory in 2013 [6]. It features a modular, integrated structural and aerodynamic design with reconfigurable payload bay, and was constructed out of ABS using FFF. The design combines its modularity with designed failure locations to limit damage to replaceable parts. It features a telescopic wing design to enable operation over a wide range of air speeds.

The Razor, depicted in Fig. 1c, is an early example of a flying wing constructed using AM [7]. It was developed by University of Virginia and MITRE Corporation in 2014. The aircraft was designed using a process of quick successive iterations, which was enabled by using only AM and off-the-shelf parts.

The blended-wing body was designed An AM blended-wing body glider UAV was designed at University of Sheffield in 2014. Its airframe is constructed entirely out of ABS using FFF, which was chosen over other AM techniques due to its simple process, and lower initial investment and material costs [8]. By specifically optimizing the design of AM, the use of support material was eliminated and production time reduced from over 120 hours to less than 24 hours [8]. Within the same year, a powered version was constructed. This vehicle featured two ducted-fan engines and is shown in Fig. 1d. AM, now depending on limited support material, enabled the use of complicated geometry to improve efficiency, e.g., of the ducted fan inlets.

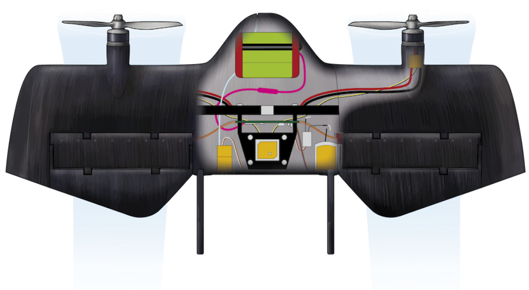
In 2015, Aurora Flight Sciences partnered with 3D printer manufacturer Stratasys to build the first jet-powered UAV manufactured using AM [17]. The design consisted for 80% of AM parts, most of which were constructed out of polymers using FFF. Additionally, SLS was used to produce the nylon fuel tank, and the thrust vectoring exhaust nozzle was 3D printed in metal. Aurora Flight Sciences claims that the use of AM reduced design and build time by 50% [17].

The Phoebe UAV was designed at Oklahoma State University in 2016, specifically to enable production on a desktop-size, consumer-grade FFF printer using ABS [18]. The airframe is assembled out of 24 separately printed components, in order to fit in the small print volume. The wing consists of an AM structure with off-the-shelf carbon spars and is covered in film. Consequently, its aerodynamics are not affected by the poor surface finish from which most consumer-grade FFF printers suffer.



(a) Wingtips **(b) Fuselage halves** **(c) Thin wall fuselage skin and inner details**

Fig. 2 Fuselage and wingtip parts manufactured by *Onyx* material with MarkForged Mark-Two machine.



Mass	0.492 Kg
Wingspan	0.55 m
Mean Chord	0.13 m
Propellers	2-blades Bullnose 5x4.5
Motors	T-Motor Brushless F30 2800KV
Servos	MKS DS65K 0.2s/60°
Battery	3 cells 12V 3500 mAh

Fig. 3 General DarkO hybrid MAV's specifications.

Design for Fused Filament Fabrication with Carbon Fiber Reinforced Nylon

In the current work we focus on rapid prototyping and modular design of flight vehicles. Therefore, we value the favorable structural properties, along with the relative affordability and accessibility of FFF. Traditionally, the major disadvantages of FFF are the poor surface finish with obvious stair stepping effect, and limited part size [11]. The development of modern FFF equipment with reduced layer heights enables manufacturing at finer resolutions, which (partially) alleviates the first disadvantage. The second disadvantage can be addressed by modular design, as described in subsequent sections.

We selected FFF not only based on the properties of the manufacturing process, but also based on our material choice. The composite material Onyx consists of chopped carbon fiber embedded in a nylon matrix [19]. As such, it is able to combine the properties of traditionally popular thermoplastic polymers with the strength and stiffness of carbon fiber. The resulting material is tough, stiff, heat tolerant and dimensionally stable, and has been extensively used in the prototypes that are shown in this paper. Its high internal layer bonding makes it suitable for the creation of thin wall structures, as shown in Fig. 2. The flexibility of the nylon also provides a structural benefit, as it absorbs the high impact energy of hard landings.

In addition to chopped carbon fiber, Onyx can also embed continuous fibers using the proprietary Continuous Filament Fabrication (CFF) technology developed by MarkForged [19]. Using this technology, layers can be programmed individually by selecting amount, orientation, and type of reinforcing fiber.

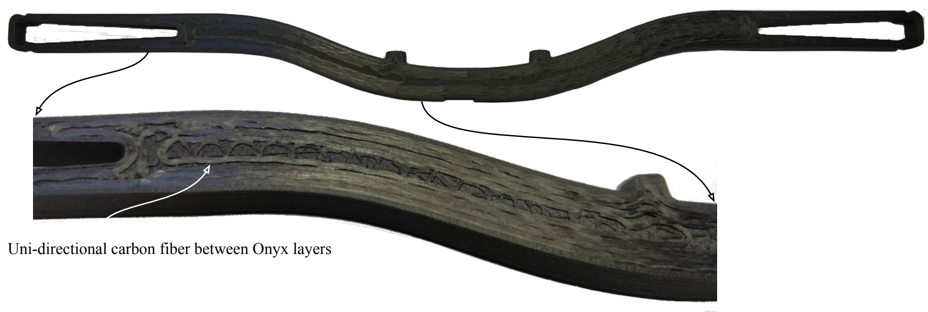


Fig. 4 3D printed spar structure, shown with inner layer materials.

Unique Aspects of Design for Additive Manufacturing with Onyx

Understanding the properties of AM enables an effective use. Once understood, the structural design of the frame can be done accordingly. Typical structural designs used in aerospace structures are based on *monocoque* or *stressed-skin* methods. In the former both the tensile and compressive forces are supported through the skin; while in the latter the skin carries most of the tensile forces, while compressive forces are supported through additional elements. Both of these methods can be applied successfully with AM.

As it is mentioned before, in this paper, we are mainly sharing the experience using the Onyx material, and therefore will be mentioning related problems. One of the most important design criteria is the wing skin thickness. For a small-scale full monocoque structure, e.g., a quadrotor frame, $2-3$ mm works the best, however for a thin layer of skin, e.g., for a wing or fuselage as shown in Fig. 2b and Fig. 2c, we want to have the minimum thickness that is practically achievable and operational. After several print trials, a 0.7 mm thickness showed the best fit for internal layer bonding, and continuous curvature following. In the case of sudden curvature change, such as the one that is usually seen around wingtips, the thickness needs to be changed close to 2.0 mm, otherwise inter-layer connections fail to create a continuous surface.

Additionally, the flexibility of the Onyx needs to be used correctly. It can give a huge advantage during the assembly of separately printed pieces. We have experienced that a small offset of around 0.1 mm is usually enough for interlacing pieces that are wider than 5 cm in width or length, however for smaller pieces, an offset of up to 0.3 mm may be required.

For pieces with open ends, such as seen in Fig. 2a, the Onyx material tends to enlarge with humidity and time. This can be addressed by adding a small vertical connection between the upper and bottom layer, which helps to increase the stability of the skin. The thin skin can sustain the aerodynamic torsional loads easily for a vehicle of around 1 m wing-span, with around 1 kg of total mass. However, the bending moments have to be supported by an additional structural element, such as a spar. AM is usually not a viable option with ABS, or even with metallic material. However, with the new CFF technology from MarkForged, it is possible to reinforce the nylon-based Onyx material with unidirectional carbon fiber [19]. The inner structure of such a CFF spar is shown in Fig. 4, where the unidirectional carbon fibers are clearly visible. With the use of the CFF technique, it is possible to design custom spar shapes that are lightweight and yet strong enough to support the bending moments.

Design Iterations of the Tail-Sitter Hybrid VTOL Vehicle

As an example case, we present the DarkO vehicle, which is a tail-sitter configuration with two motors, positioned in front of the wing, and two exceptionally large double-flapped control surfaces. Mission definition of DarkO has been mainly oriented towards forward flight with the capability of taking-off and landing vertically. The frame completely is manufactured by AM using the Onyx material on a MarkForged Mark-Two printer.

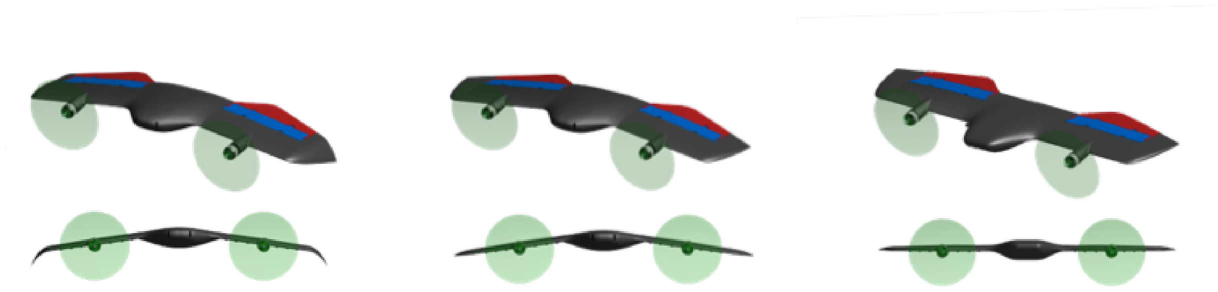
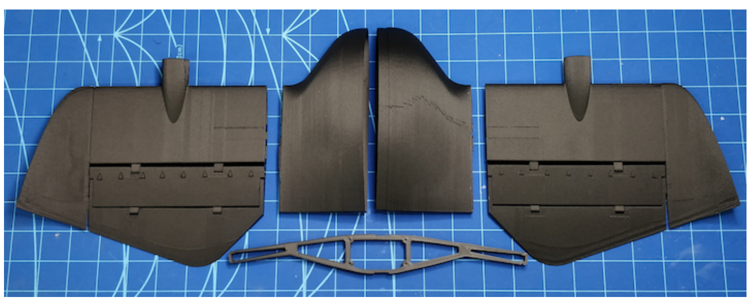
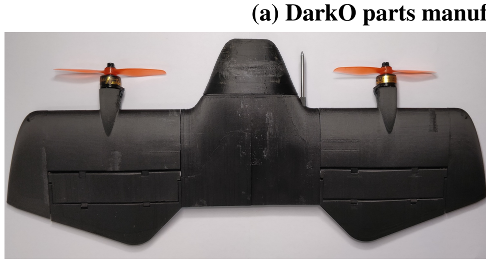


Fig. 5 Evolution of the DarkO Hybrid Tail-sitter VTOL design.

The vehicle's specifications are listed in the Fig. 3. An overview of the complete set of printed pieces is shown in Fig. 6a. The shell structure for the wing and the fuselage halves are manufactured with 0.7 mm thick skins, as discussed earlier, and the spar is manufactured with the addition of unidirectional concentric carbon fibers embedded into Onyx material. This method ensures to have a sufficiently rigid airframe that supports aerodynamic forces and yet also flexible enough to absorb harsh impacts during landing and test flights. Modularity of the design and AM method can also be seen in the Fig. 6c, where the right wing is detached from the main body, giving the possibility of interchanging different types of parametric wings, control surfaces, or wingtip geometries.



(a) DarkO parts manufactured using AM.



(b) Fully mounted, ready to fly DarkO frame.

(c) Modularity of removable DarkO wings.

Fig. 6 Aircraft constructed using additive manufacturing.

As can be seen in Fig. 5, the initial DarkO design had a significant amount of anhedral and downward curved wing-tips. The purpose of these design features was enabling the capability to roll with less control deflection. This would increase efficiency and keep the airfoil as smooth as possible. However, limited yaw authority during the take-off and landing phase, combined with side wind and gusts made it too hard to control vehicle. As a first solution, we flattened the wing-tips in order to reduce the equivalent anhedral. However, this solution was still not sufficient for windy days, therefore the wing root anhedral was also flattened, which resulted in a more stable outdoor flight. This process of rapid design iterations was enabled by the use of AM and modular design. If traditional manufacturing techniques would have been used the re-designs would have resulted significant time and cost penalties.

Validation and Experiments

The proposed AM method for vehicle design and fabrication has several advantages:

- Agile design and rapid prototype iterations
- Modular design for interchangeable parts, e.g., control surfaces and wingtips
- Mission-oriented design for real-life applications

In order to validate these points, we present flight performance of the DarkO tailsitter in both indoor and outdoor environments. We show the use of modular design for control performance analysis, and finally present several other vehicle designs that that were constructed using our design methodology. The indoor and outdoor flight experiment results in this section were obtained using the airframe shown in Fig. 7.

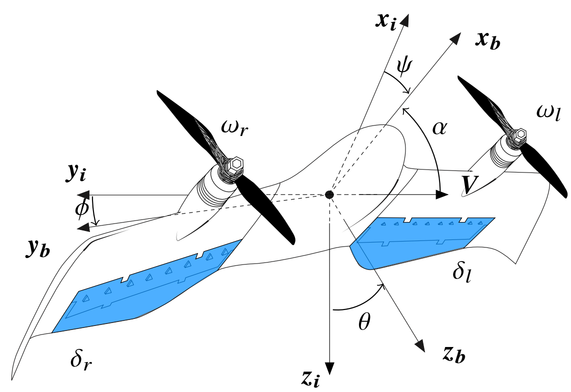


Fig. 7 Illustration of the used coordinate frames, angles and actuators. The inertial coordinate frame is represented by $\mathcal{R}_i = \{x_i, y_i, z_i\}$ and the body coordinate frame by $\mathcal{R}_b = \{x_b, y_b, z_b\}$.

Indoor Flight Experiment in front of WindShape (Gust Generator)

Initial indoor flight tests have been conducted inside ENAC's motion capture facility called *Voliere*.

Fig. 8 WindShape wind generation unit.

Fig. 9 presents the DarkO's attitude measurements during an indoor transitioning flight, which is controlled according to the Model-Free Control algorithms described in [20]. The DarkO starts the experiment in hovering flight mode faced to the *WindShape* gust generator. Then the wind speed started to increase incrementally, while the pitch angle set point was being imposed by the security pilot to perform the transition from hover to forward flight, following the increasing wind speeds from zero to 9 m/s. The use of WindShape wind generator enables the validation of this transitioning capability of DarkO during indoor flights. The shaded area in the figure highlights the transitioning flight domain where the pitch angle decreases while approaching to the forward flight domain.

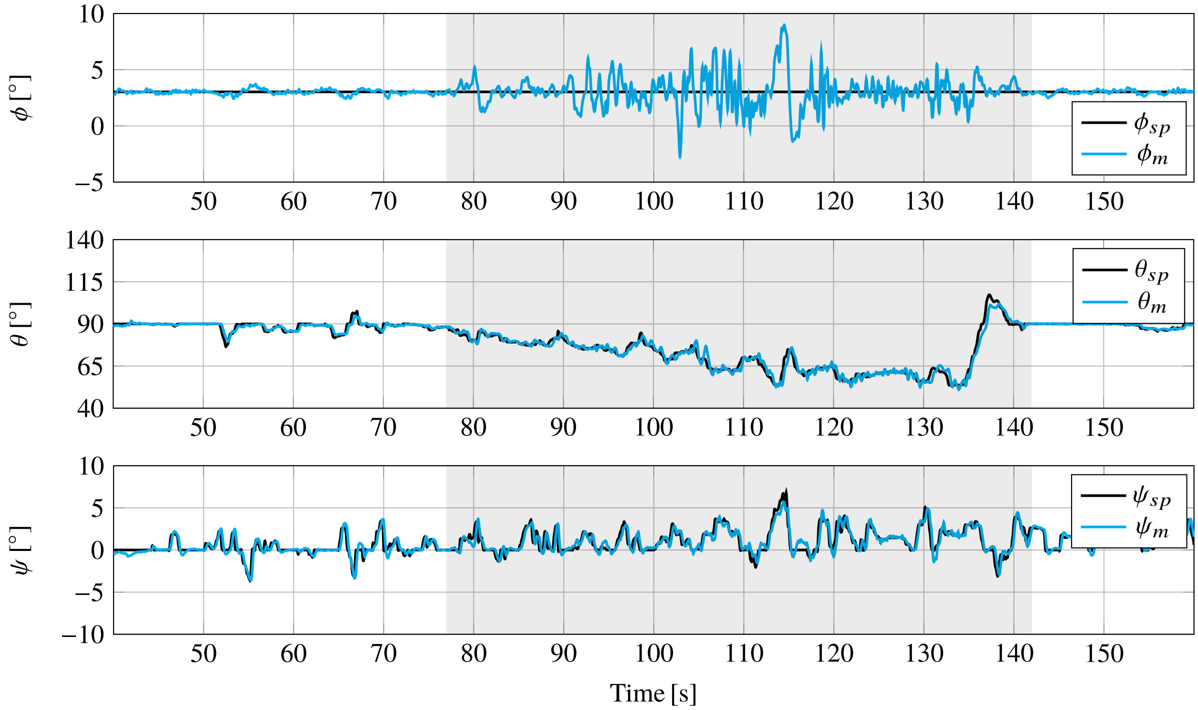


Fig. 9 Experimental transitioning flight faced to the *WindShape* gust generator.

Control Performance Analysis using the Modularity of AM

Fig. 10 shows the modular nature of the DarkO frame, where the control performance analysis can be made by modifying the geometry of the aircraft. Flying with half of the control surface taken out or without the wingtips is made as easy as changing the propeller type of the vehicle thanks to AM design method.

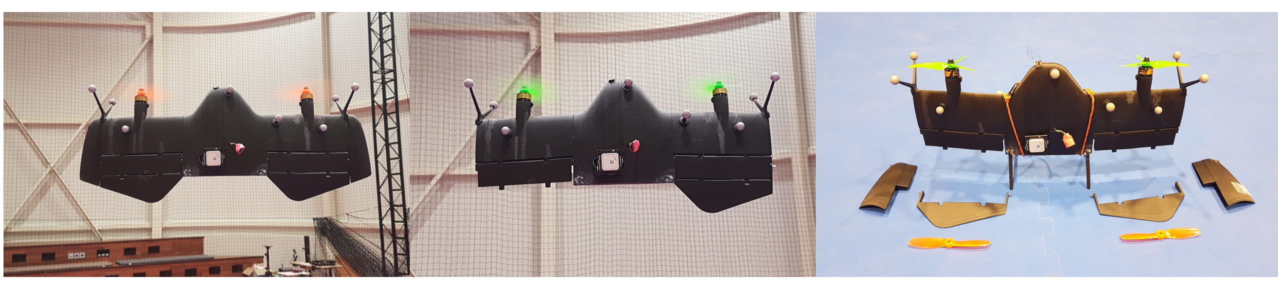


Fig. 10 DarkO configurations.

Another use of modular design is shown in the Fig. 11 where the vehicle is made up of several individual pieces that can be changed while keeping the main body fixed. This enables having modular performance according to the mission requirements. For example, wing span can be enlarged by using extensions which will lead to higher endurance, or middle wing section including the motor mount can be replaced with a different propulsion system which may increase the maximum flight speed of the vehicle in case of high speed flights are required.

Outdoor Flight Tests

A demonstration flight of the DarkO was performed during GIS meeting on 7th of June 2019, using the control and guidance algorithms described in [21], in the south of France, where the vehicle briefly demonstrated a vertical take-off, transitioned to cruise flight with circle patterns, and transitioned back to hover for a vertical landing, as shown in Fig. 12. Cruise flight capability of the DarkO can be seen on the right hand side of the plot in Fig. 12 where the pitch θ angle goes close to zero (in shaded areas).

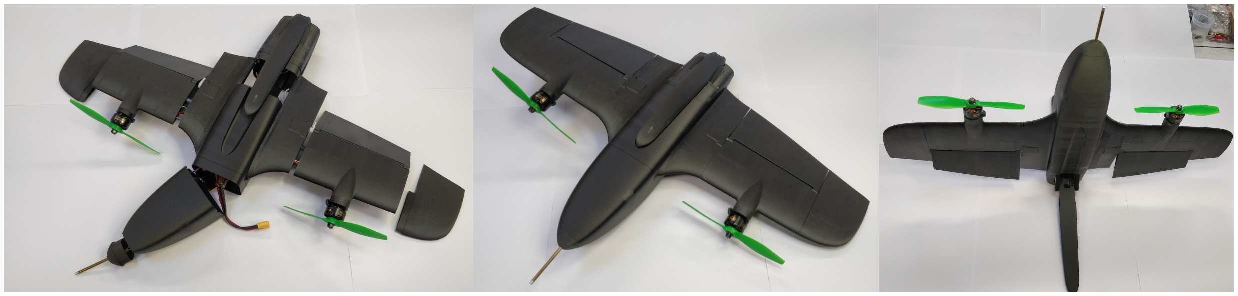
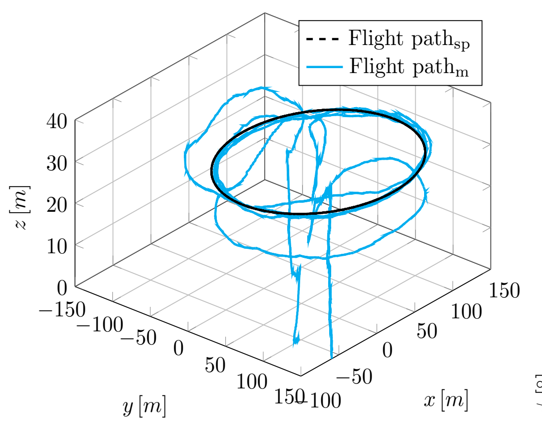
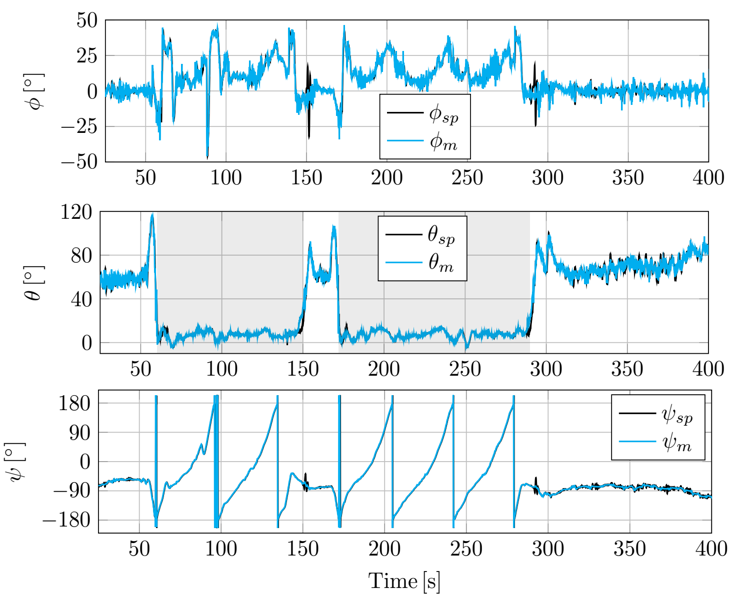


Fig. 11 Alpha tail-sitter configuration featuring the modular design advantages.



(a) Flight path trajectory tracking.



(b) Attitude stabilization.

Fig. 12 GPS trajectory of an actual demonstration flight of the DarkO.

AM Applied to Different Vehicle Configurations

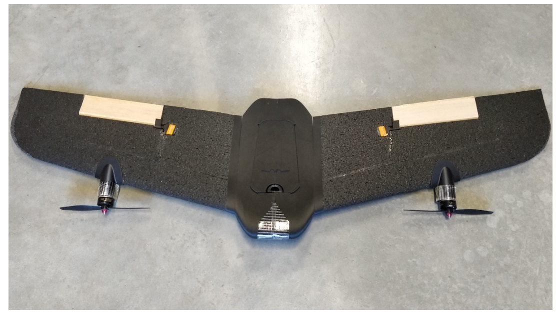
We have demonstrated the application of AM on tail-sitter configuration on the previous sections, however other configurations can also utilize the same technique, such as the quad-rotor designs shown in Fig. 13. Those quad-rotor designs can carry different type of payload equipment on the top of their frame which makes them very attractive for initial development phase of a new system where the final shape of the system has not been optimized. Additionally, the motor holder bar can be replaced to accommodate larger diameter propeller and accompanying motor in order to improve the flight time, or carrying capacity.

A fixed-wing configuration is shown in Fig. 13b, where the wings are manufactured by hot-wire cut from EPP foam, and the rest of the part are 3D-printed from Onyx material (except the flaps, which are reinforced balsa wood).

Conclusion

We presented a novel framework for mission-oriented, modular design and construction of mini-UAVs using additive manufacturing. This manufacturing method proved to be very suitable for parametric design and can be tailored for the specific mission requirements. After presenting the design specific tips on the use of Onyx material and the continuous filament fabrication, we demonstrated the feasibility of the proposed additive manufacturing by presenting an iterative design of a tail-sitter hybrid VTOL vehicle, where the wing-tip geometry and the wing dihedral angle went through several changes. As a validation, we showed indoor and outdoor flight experiment performance of the resulting vehicle

(a) 3D printed vehicles including quad-rotors, tail-sitters



(b) A fixed-wing configuration featuring 3D-printed parts

Fig. 13 Different vehicle configurations, manufactured by AM.

design. Finally we have shown several other vehicle configurations such as quad-rotors, and a fixed-wing that also take advantage of the proposed manufacturing method.

With the proposed type of agile design and iterative prototyping method, we believe that one-click design and overnight manufacturing of mission-tailored vehicles will be feasible in very close future.

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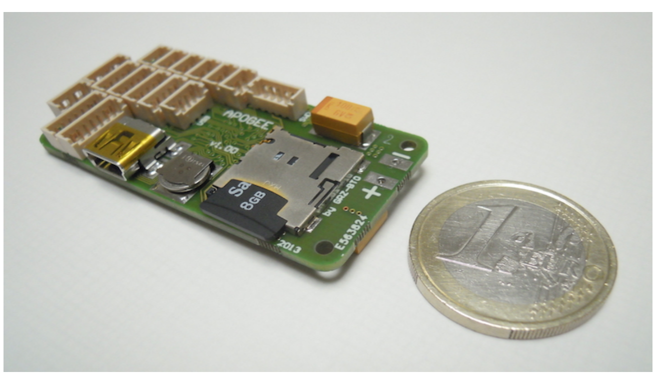
Appendix

On-board avionics

During the experimental flights presented above, the DarkO MAV was equipped with an *Apogee v1.00* board, presented in the Fig. 14, that contains a Cortex M4 168 MHZ processor to run the *Paparazzi* open-source autopilot system, which includes algorithms for state estimation, control laws, servo and motor drivers, software for communication, etc. In addition, the *Apogee v1.00* board is equipped with an SD logger which allows to record data for post-processing of the flight.



STM32F405RGT6 Cortex M4 168MHz processor
9(6) DOF integrated IMU MPU-9150(6050)
1 x Barometer/altimeter MPL3115A2
1 x MicroSD card slot
4-bit SDIO interface (high-speed data logging)
6 x Servo PWM outputs
3 x UART, 2 x I2C bus, 1 x SPI bus
10.4 grams
53 mm x 25 mm

Fig. 14 Overview of *Apogee v1.00* autopilot from *Paparazzi Autopilot system*.