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<td>Author(s)</td>
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FIXED-WING VERTICAL-TAKEOFF-AND-LANDING UAV WITH ADDITIVE MANUFACTURING: A DUAL-ROTOR VERSION

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ABSTRACT: Amongst the two main types of fixed-wing vertical-takeoff-and-landing (FW-VTOL) unmanned aerial vehicles (UAVs) namely, hybrid fixed-wing multicopter UAVs and tilt-rotor FW-VTOL UAVs, the latter is usually preferred due to its efficient propulsion system that is utilized for all flight phases. Howbeit, in the currently available tilt-rotor FW-VTOL UAVs, one or more rotors are turned off during the FW mode, which eventually acts as a dead weight for the UAV. Therefore, in this paper, we design a tilt-rotor FW-VTOL UAV which encompasses a dual-rotor configuration. The enticing features of this UAV includes its weight optimized design along with the inclusion of flaperons that serve three purposes: provide roll control during FW mode, generates additional lift during transition, and reduces blockage to the airflow of the main rotors during VTOL mode. In addition, we prototype it utilizing additive manufacturing (AM) as the primary manufacturing method. The high strength and rapid prototyping features of AM are utilized in our design to achieve adequate structural strength without inducing weight penalties. What is more, experimental tests in the VTOL mode are conducted to verify the design feasibility. The results exhibit that AM is a promising manufacturing method for complex FW-VTOL UAVs, wherein its on-demand printing ability significantly lowers the overall development cost.

KEYWORDS: Fixed-wing VTOL UAV, Dual-rotor, Tilt-rotor, Additive manufacturing

1. INTRODUCTION

With the developments in sensor and actuation technology, unmanned aerial vehicles (UAVs) are becoming increasingly popular for a wide variety of applications (Tuominen, et. al., 2011; Barmpounakis et. al., 2017; Mehndiratta et. al., 2018). They are mainly categorized as: fixed-wing (FW) and rotary-wing (also known as multicopter) UAVs. The FW UAVs have wings to generate lift but requires a runway to takeoff/land. On the other hand, multicopter UAVs incorporate multiple rotors to generate thrust in vertical direction, which facilitates a runway free takeoff/landing, also known as vertical-takeoff-and-landing (VTOL). Additionally, owing to the wings of the FW UAVs, their endurance is significantly higher than multicopter UAVs. Hence, to mitigate the limitations of both, a third type, known as fixed-wing vertical-takeoff-and-landing (FW-VTOL) UAV, is developed. It possesses VTOL ability and yet perform cruise flight at high speeds. Due to such capabilities, it shows better flight performance with less power consumption (Boon et. al., 2017) when compared to its FW and rotary-wing counterparts.

Based on the transition between the two flight modes namely, VTOL mode and FW mode, FW-VTOL UAVs are classified as: hybrid fixed-wing multicopter UAVs (Gu et. al., 2017) – utilize different airframe configurations during the two modes, and tilt-rotor FW-VTOL UAVs
(Papachristos et al., 2011) – utilize tilting parts to achieve the transition in between the two modes. While the former is comparatively easier to manufacture and control, the latter comprises of few tilting assemblies which complicates the design. Howbeit, the unused rotors of the hybrid fixed-wing multicopter UAVs within the FW mode acts as a dead weight which is avoided by tilting the rotors in tilt-rotor FW-VTOL UAVs. On account of this advantage, numerous FW-VTOL UAVs have been built and presented in the literature. One amongst them is the TURAC UAV (Ozdemir et al., 2014) which comprises of two rotors in the front and a coaxial rotor set at the back. Another famous example of the tilt-rotor FW-VTOL UAV is presented in (Czyba et al., 2015), where three coaxial rotor sets are incorporated in a ‘Y’ frame configuration. Both of these UAVs utilize all the rotors during the VTOL mode but the back rotors get turned off after transition into the FW mode. This implies that they also carry some sort of dead weight during the FW mode, which is in contradiction to the stated advantage of the tilt-rotor FW-VTOL UAVs. Hence, in this work, we develop and prototype a tilt-rotor FW-VTOL UAV incorporating a dual-rotor configuration. The main advantage of the developed system is its flying without any dead weight capability which results is an optimal flight performance. In addition, due to the presence of less number of rotors, its overall power requirement is the least in comparison to the other tilt-rotor FW-VTOL UAVs.

Additive manufacturing (AM), commonly known as 3D printing, is a rapid prototyping method which is used to add material layer by layer to produce a full part (Wong et al., 2012). It is an increasingly popular yet well-established method to synthesize robust and complex shapes incorporated in UAV applications (Ferro et al., 2016; Govdeli et al., 2016). It has also been demonstrated for manufacturing multicopter UAVs that demand adjustable parts with customized functionalities (Brishchetto et al., 2016; Mehndiratta et al., 2018). Since a FW-VTOL UAV is composed of complex parts and assemblies, 3D printing is the most suitable candidate for its manufacturing. Moreover, it facilitates easy and on-demand replacement of parts, which eventually reduces the repair cost in the event of damage (Goh et al., 2017). Thus, it is used as the primary manufacturing method for the FW-VTOL UAV presented in this paper.

2. COMPONENT DESIGN

The overall design and prototyping of the dual-rotor FW-VTOL UAV is realized via a step-wise procedure namely: (i) defining design requisites, (ii) determination of wing planform based on aerodynamic considerations, (iii) computer aided design (CAD) of the UAV, and (iv) printing of the designed parts utilizing a desktop 3D printer. Based on the pre-defined mission/flight requirements, the design requisites are listed as such: the FW-VTOL UAV should (i) weigh $2.3 - 2.4$ kg, (ii) measure within $1 \times 1$ m, (iii) produce a minimum thrust of $4$ kgf, and (iv) house the required electronics – 4S battery, power distribution board, Pixhawk (flight controller) and its peripherals, two brushless DC motors and their electronic speed controllers, two servos for tilting assembly, and four servos for control surfaces. The overall electronic connections diagram is presented in Fig. 1.

The UAV structure, shown in Fig. 2, is composed of four main components: supporting structure, tilting mechanism, lifting and control surfaces, and fuselage. Solidworks is used as the main CAD software. Apart from being designed with the aforementioned requisites, the CAD-modelled parts are also designed to be minimalistic, weight-optimized, and fitting to the dimensions of the utilized desktop 3D printer: $240 \times 190 \times 200$ mm. Each of these components are discussed in detail next.
2.1. Supporting Structure:
The supporting structure forms the main skeleton of the UAV. It is designed to be light weight, yet rigid enough to bear the structural loads during flight. Hence, a four-perpendicular-rod configuration, two along each side, is preferred to support the entire frame, as shown in Fig. 2. The lateral and longitudinal frames are joined by a simple structure having slots that serve two main purposes namely, keeping the structure in place, and providing platforms for the mounting of control boards and other parts of the electronic circuit.

2.2. Tilting Mechanism:
The two main rotors of the UAV provide both horizontal thrust during FW mode and vertical thrust during VTOL mode. The transition of the thrust in between horizontal and vertical plane is realized by a tilting mechanism (one for each rotor) located at the wing tip, as shown in Fig. 2. The tilting mechanism consists of a rotary assembly where the main rotor sits on a stationary supporting structure. The moment of inertia of the rotary assembly is minimized to reduce the reactive torque acting on the main frame when it is tilting. This is realized by placing the main rotor and servo very close to the rotational axis of the rotary assembly. The stationary supporting structure is designed to elevate the tilting axis to increase the moment arm caused by thrust vectoring. Two equal pitch gears are utilized to transmit servo shaft rotation to the tilting motion of the rotary assembly. Other constraints such as propeller clearance from ground during FW mode and ease of assembly are also considered in the tilting mechanism design.

2.3. Lifting and Control Surfaces:
To carry the entire weight of the UAV, a few candidate airfoils are selected for the wing cross-section namely, NACA 2408, 2410, 2411 and 2412 (airfoiltools, n.d.). Although all of them satisfy the required aerodynamic characteristics at the trim point in the FW mode, NACA 2412 is preferred in this work due to its highest lift coefficient value which eventually implies the least stall speed. Having low stall speed is extremely desirable for FW-VTOL UAVs, in particular tilt-rotor versions, as the speed during the VTOL mode is negligible and stall should not occur during the transition. In addition, the wing planform is designed in two parts: the fixed part and the flaperon. While the former starts from the wing root and continues until 50% of the span, the latter mainly forms the part of the wing which is directly below the propellers, as depicted in Fig. 2. During VTOL mode, these flaperons are extended to the maximum (almost by 60°) to make space for airflow of the main rotors, whereas during the transition, they smoothly return to their neutral position to complete the airfoil shape of the wing. Hence, in total the flaperons serves three purposes: provide roll control during FW mode, (ii) generate additional lift during transition, and (iii) reduces blockage to the airflow of the main rotors during VTOL mode. In addition to the wing, the tail is selected to be a

Figure 1. Electronic circuit diagram
Figure 2. Exploded view of the dual-rotor FW-VTOL UAV
conventional tail with NACA 0012 airfoil cross-section. While the vertical section of the tail is composed of a stabilizer and a rudder, the horizontal section is designed to be an all-moving-tail to achieve the maximum pitch control from the elevator. The overall tail assembly is shown in Fig. 2.

2.4 Fuselage:
Fuselage forms the main body of the UAV which encloses the on-board electronics. In this work, the aerodynamic prospects for fuselage are not taken into consideration, whereas a light weight design along with the ease of manufacturing is preferred. Hence, it is designed to be composed of two vertical plates which are joined by intermediate links as can be visualized in Fig. 2. In addition, some rectangular slots are enclosed to reduce the overall weight. Furthermore, the location of each component in the final assembly is adjusted such that the center of gravity of the entire UAV is in line with the thrust during the VTOL mode.

3. PROTOTYPING WITH ADDITIVE MANUFACTURING

Thermoplastics are preferred for manufacturing of the lifting surfaces to realize a low-cost and light weight fabrication of the UAV. In that vein, the most convenient method is AM that is of mainly two types: fused deposition modelling (FDM) and selective laser sintering. While the former melts the thermoplastic filament tube and extrudes the molten material in layers onto the print bed to form the shape of the model, the latter utilizes laser to fuse powder particles together to form layers of material. Owing to its lower manufacturing cost and enhanced reliability, the FDM-based 3D printing, incorporated in the Cubicon 3D printer, is utilized in this work. Moreover, amongst the two most common FDM materials - acrylonitrile butadiene styrene and polylactic acid (PLA) – PLA is used for printing the structural components because of its higher strength in comparison to the other.

Most of the structural components of the UAV are 3D printed, except the supporting structure which is made from light weight carbon fiber rods. As mentioned in Section 2, 3D printed joints are utilized to fix and rigidly secure the overall supporting structure throughout the flight. Next crucial structural component is the tilting assembly, wherein all the subcomponents, including gears and mounts, are printed as solid parts. Since the rotors are tilted by 90° within the FW mode, wings serve the main purpose, i.e., to generate lift for supporting the UAV weight in the air. This implies the need to obtain rigid parts which are realized by varying the infill percentage (amount of material to be filled inside a solid component) within the desktop printer. After numerous design iterations, the most optimal infill percentage and wall thickness (another printing parameter) to result light weight wings and control surfaces are found to be 3% and 0.4mm, respectively. In addition, the components for the tail of the UAV is also printed in a similar manner. However, the weight of the tail is even more crucial as it significantly affects the center of gravity of the UAV. Therefore, most suitable printing properties for the tails is also obtained by the trial-and-error method, where a few iterations are illustrated in Table 1. As can be seen, the print with 3% infill is the most desired setting, due to its less weight. Other structural components including fuselage, elevator, rudder and flaperons are also fabricated utilizing the similar printing properties. Since the printing bed size of the available desktop 3D printer is limited, most of the components are printed in multiple parts which are later welded together utilizing a 3D printing pen. Furthermore, a foam is attached over both sides of the fuselage to cover the electronic components and hence, minimize the overall aerodynamic drag experienced by the UAV.
Table 1. Variation in infill percentage

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<th>Weight (g)</th>
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<th>Tail heavy</th>
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<td>8</td>
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<td>5</td>
<td>80.1</td>
<td>&lt;2</td>
<td>no</td>
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4. EXPERIMENTAL TEST RESULTS IN VTOL MODE

In this section, we provide the real-time testing results for the prototyped FW-VTOL UAV, depicted in Fig. 3. In this work, we test it for the VTOL mode within an indoor environment. In order to fly the UAV, control commands in the form of attitude (roll, pitch and yaw) angles and throttle are given via a radio transmitter. In the presented dual-rotor configuration within the VTOL mode, roll, pitch and yaw controls are achieved by differential thrust, differential tilting and collective tilting of the main rotors, respectively. Additionally, the position flight data is recorded utilizing an Optitrack motion capture system at Nanyang Technological University, Singapore. In terms of the flown trajectory, the UAV first takes off, then hovers at certain altitude for a while and finally lands at another location. The overall position response of the UAV is presented in Fig. 4. As demonstrated from the experiment, 3D printing is a feasible and promising candidate for manufacturing tilt-rotor FW-VTOL UAVs.

5. CONCLUSION

The available tilt-rotor FW-VTOL UAV configurations possess an inherent limitation of carrying additional dead weight during FW mode. Hence, this paper manifests the design, prototyping and experimental testing of a tilt-rotor FW-VTOL UAV in a dual-rotor configuration. Additionally, AM is utilized as the main fabrication method on account of its rapid and low-cost productability. The design manages to utilize the fast and complex shaping feature of AM to construct most of the critical UAV parts such as supporting structures, tilting mechanisms, wings and fuselage. The design is optimized to achieve a good balance between structural strength and weight. Experimental tests are conducted to verify that the 3D printed prototype is a feasible platform for UAV operations. The future work for this UAV includes further optimization of its flight performance and various VTOL UAV applications including autonomous operations.

Figure 3. Prototyped dual-rotor FW-VTOL UAV in flight

Figure 4. Real-time testing of the UAV in VTOL mode
6. ACKNOWLEDGEMENTS

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7. REFERENCES


