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Defining a conceptual design for a tilt-rotor micro air vehicle for a well-defined mission

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The conceptual design for a tilt-rotor micro air vehicle (MAV) is carried out with the purpose of decreasing the design time to efficiently create a functioning tilt-rotor drone. First, a mission flight plan along with the planform are defined. Second, the weights of the electrical and structural components are determined. Then, using criterion from the weight estimation, wing dimensions are specified. The final wing dimensions yield an aspect ratio of 2.32. Recreating the wing in XLFR5, the aerodynamic properties of the wing are determined along with the airfoil selection. Once all previous parts are successfully completed, the body is defined. Finally, the aerodynamic center is determined for the wing in order to define the control surfaces and dimension the tail.

I. Introduction

The need to miniaturize multifunctional drones capable of complex flying missions has increased due to the diverse flying scenarios these unmanned air vehicles (UAV) can perform[1-3]. The use of micro air vehicles (MAVs) has risen because of their ability for data collection from stabilizing optics and sensors like those proposed by Kjenstad[4]. As the popularity for these drones increases so does the desire to optimize the performance of these flying drones[1]. Efforts by those like VanderMey[5] try to increase the endurance of these drones which expand the capabilities of these MAVs. Drone design is initially based on the flight mission and objectives. The drone must functionally and efficiently be able to navigate in diverse situations[3,6]. Tilt drones have the capability of vertical takeoff and landing (VTOL), hovering, high altitude flight, and increased endurance[1,3,4]. These capabilities allow tilt drones to be exploited in a wide range of missions with specific objectives[1,3].

The different classifications of tilt drones are, namely, rotor, wing, body, and ducted fan[3]. Comparing the similar tilt-rotor and tilt-wing drones. Investigators like Carlson[7] have implemented a flying wing into a tricopter tilt-rotor design. Tilt wing drones have been designed to utilize the quadcopter design for stability and increased power[8,9]. The most important differences between the tilt-rotor and tilt-wing during VTOL are the drag forces of the wings and energy consumption of the motors [9-12]. The wings for the tilt-rotor aircraft are fixed at a neutral position for the optimum forward flight efficiency[7,11]. Therefore, during takeoff or vertical hovering elevation change, the wings become a body with a larger coefficient of drag. This equates to a higher energy expended in order to change elevation while hovering[7]. The tilt-wing design disadvantage is that the endurance is decreased relative to the tilt-rotor design due to more energy expended for extra motors for all flight modes[5,9,10]. The advantage of both designs is that they maintain stability of flight during transition from hovering to forward flights[10-13].

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The tilt-rotor/flying-wing UAV is chosen for its VTOL/hovering capabilities, high altitude cruising speed, and cargo transportation capabilities[2,4,8]. Stability is highly desired for the drone to be easily controllable during hovering, normal flight, and transition. The coefficient of drag needs to be minimized for the wing in order to maximize its endurance and flight performance. The goal of this design is to maximize the flight time by minimizing losses and to create an efficient design. The rest of this paper is organized as follows: In section 2, conceptual design process for the tilt-rotor MAV is defined using different statistical and computational analyses. Finally, summary and conclusions are shown in section 3.

II. Design of tilt-rotor MAV

The conceptual design of a tilt-rotor MAV is carried out in this study. The sizing process of a tilt-rotor MAV involves (1) specification of the mission and aviation plan; (2) determination of the planform and aspect ratio; (3) constraint analysis and weight estimation using previously verified methods. It should be mentioned that Hassanalian and his coauthors[16-19] recently designed and fabricated fixed and flapping wings micro air vehicles by considering similar conceptual designs. Accomplishing all these phases lead to the determination of the wing dimensions and airfoil shape. After that, the fuselage and propulsion systems are designed and selected. The determination of the tail properties and center of gravity (CG) of the MAV can be carried out after calculating the position of the aerodynamic center (AC) and simulating the equilibrium and stability equations for vertical and horizontal modes.

The determination of the flight mission is carried out by creating a simulated 2-D flight path showing the flight distance and objective distances. Using a constraining time of thirty minutes and assumed flight speeds, flight objective times are determined. The MAV's capability for VTOL allows for the mission to be carried out without the need for a runway. The take-off can occur in a small area which gives this drone a greater facility for deployment. The transition of the rotors allows the MAV to have hovering capabilities as well. The fixed wing design gives the drone a higher cruising altitude at a higher speed than conventional copter aircraft. The flight plan includes cruise and loitering objectives in order to show the diverse flight capabilities of this MAV. The flight path is estimated to be 15,500 meters and the flight time to be 30 minutes. The proposed flight mission is shown in Figure 1.

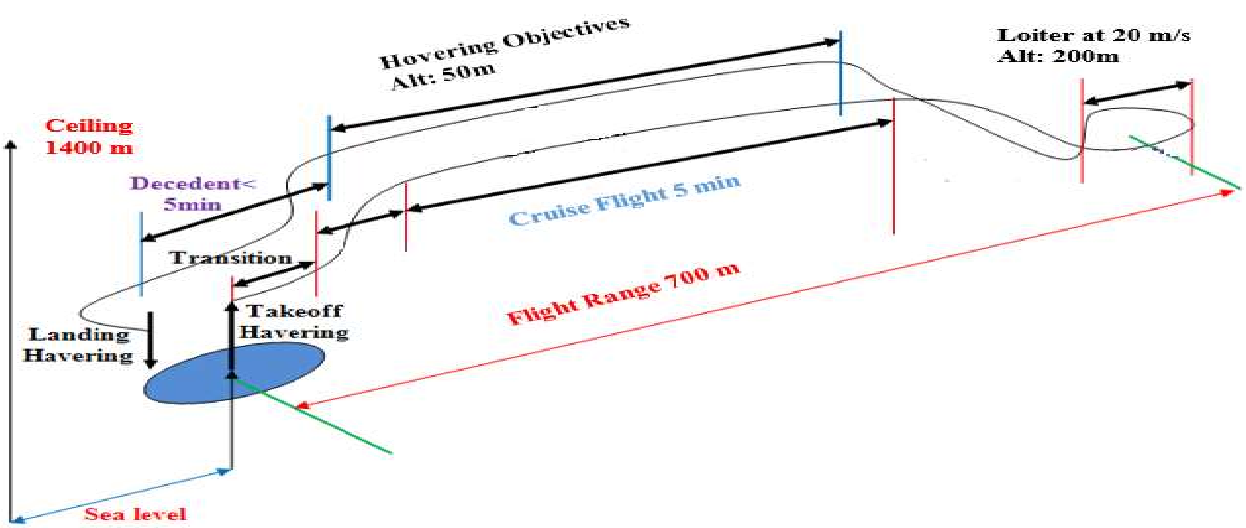

Figure 1: Flight mission for tilt-rotor MAV.

The shape selection for the tilt-rotor MAV is performed by searching through conceptual aircraft designs. A shape is selected with bio-inspiration from a bat wing shape based on the need for rotor mounting points. The complex planform of the MAV required multiple conceptual models to be created in order to obtain a visual representation of what the final product could look like. NX-10 is used in order to create an initial shape, to scale the wing shape, and to model a final visual that could be utilized for the design process. NX-10 is a CAD modeling software created by Siemens. Using NX, wing shape area is determined, and in conjunction with the wingspan yields the aspect ratio of 2.32. In Figure 3, a schematic view of the modeled planform is shown.

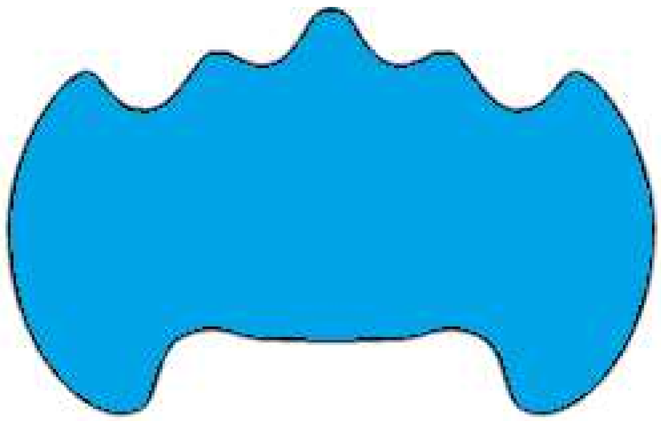

Figure 2: Complex wing shape of the tilt-rotor MAV.

In order to determine the final dimensions of the wing, the proposed methods for the weight estimation of the electrical and structural parts as well as the determination of the wing loadings by Hassanalian and Abdelkefi are used[16,18]. In this effort, the determined estimated weight (W= 0.85 Kg) is used in conjunction with the wing loading (W/S=3.46 Kg/m^2) yields the wing surface (S=0.25 m^2). When using the determined wing aspect ratio (AR=2.32), with this determined wing surface the final wingspan is obtained as b=0.76 m. When the shape is generated in XLFR5, the root chord is extracted as C_r=0.394 m. Using the determined weight which is equal to the lift (W=L), wing surface (S), speed (V), and density (ρ) yield the coefficient of lift (C_L) by using L=0.5ρ V^2SC_L. In this study, the lift coefficient is determined as C_L≈0.14.

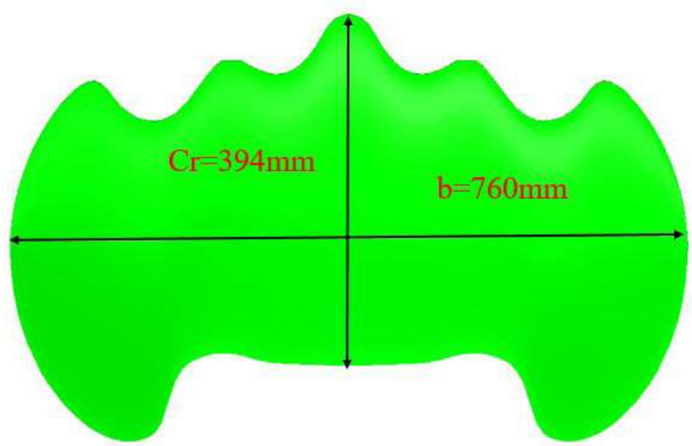

Figure 3: Dimensioning of the wing of the tilt-rotor MAV.

In order to select the optimal airfoil based on specific criteria: (1) the optimal airfoil must generate the required lift with minimized drag, (2) has a maximum lift coefficient in order to maximize the stall angle, (3) the thickness of the airfoil must be as thin as possible to negate the possibility of a boundary layer separation. Utilizing the generated model in XLFR5, comparing a selection of airfoils based on their angle of attack for a flow speed of V=20m/s, Reynolds number Re≈500,000, and utilizing a 3D Panel analysis. The 3D panel analysis in XLFR5 is the most accurate due to the inclusion of downstream effects of the fluid flow over the wing[24,25]. The 3D panel analysis yields the most accurate predicted results for the tested airfoils. The results for the airfoils from XLFR5 analysis are represented in Table 1. The following criteria were examined: the angle of attack, lift coefficient, drag coefficient, lift to drag ratio, maximum lift coefficient, stall angle of attack (in a two dimensional analysis), the pitch moment coefficient, and the thickness of the airfoil.

Table 1: Comparison between possible reflex airfoils when AR=2.32 and V=20m/s.

	α (deg)	C_L	C_D	C_L/C_D	C_{Lmax}	C_M	t_{max}
E221	2.1	0.142	0.008	16.817	1	-0.066	9.48
EH2510	2	0.144	0.01	14.247	1.046	-0.062	9.99
MH20	2	0.141	0.008	18.225	0.986	-0.065	9.00
S3	1.8	0.143	0.009	15.267	1.102	-0.07	10.99
S3014	0.8	0.141	0.008	16.679	0.997	-0.089	9.46
S5010	2.1	0.142	0.009	15.062	1.023	-0.059	9.82
S5020	1.9	0.142	0.011	12.769	1.029	-0.06	8.4

Using XFLR5 software, the distributions of the pressure coefficient (C_p), lift coefficient, and viscous and induced drag coefficients for S3014 can be simulated as shown in Figure 4. These results from Table 1 along with the visual observations like those shown in Figure 3 are used when selecting an optimum airfoil.

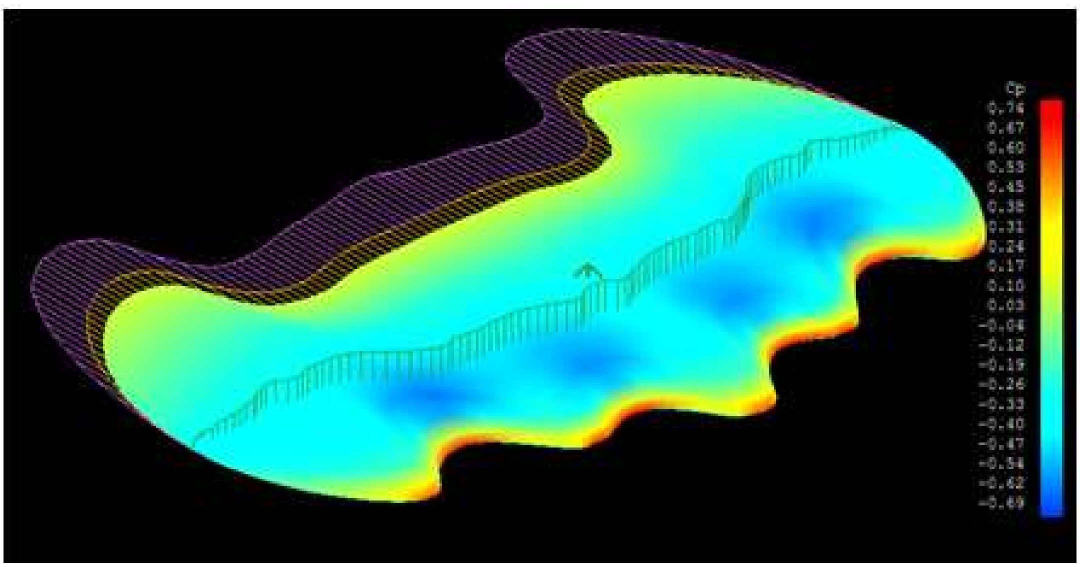

Figure 4: Variations of the pressure, lift, and drag distributions on the designed tilt-rotor MAV wings S3014 airfoil.

Utilizing the determined criteria from Table 1, a graph can be produced to display the performance of each airfoil by plotting C_L/C_D as show in Figure 5. Using Table 1 and Figure 5, the S3104 airfoil displays an optimal performance. Although this airfoil does not have the most minimal drag, it has a high C_L in comparison with other airfoils. Therefore, its overall performance in the C_L/C_D is acceptable. As it can be noted in Figure 5 that, for certain value of C_L, a sudden increase in the C_D is observed. This result may be due to the boundary layer separation. It can be seen that this event occurs later for the thinner airfoils including S3014.

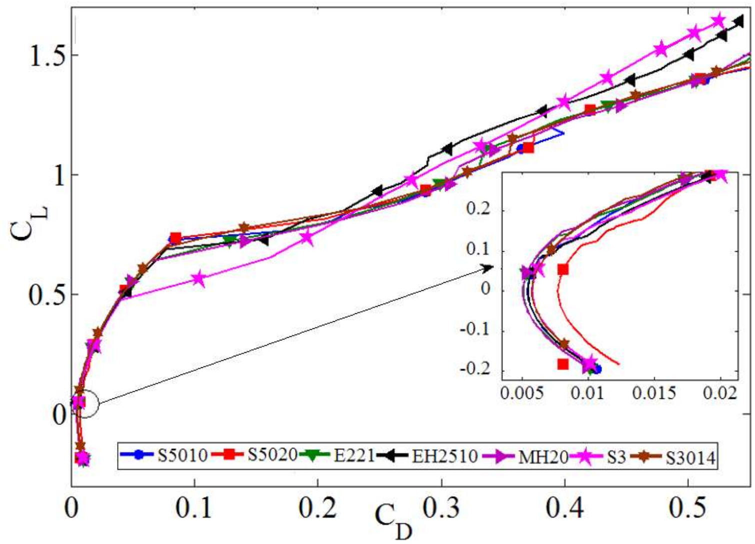

Figure 5: Variation of the lift coefficient as a function of the drag coefficient for the seven considered airfoils.

Based on the obtained results from Table 1 and Figures 4 and 5, S3014 is selected as the airfoil for our design. A schematic view of the airfoil is shown in Figure 6.

Figure 6: A schematic view of S3014 airfoil.

After designing the wing, the next step is the fuselage design. There is an interest of creating a simple fuselage design with the importance of carriage of sensors, battery, transmitters, and aft motor in one compartment. The size and number of components is based on the weight estimation which was proposed by Hassanalian and Abdelkefi[16,18]. To house these components in the simplest design and be easily fabricated, a modified box design will be implemented. The design will slide over the wing, be attached at a neutral angle, and consider the wing dimensions in order to maintain stability. A schematic view of the designed fuselage is shown in Figure 7.

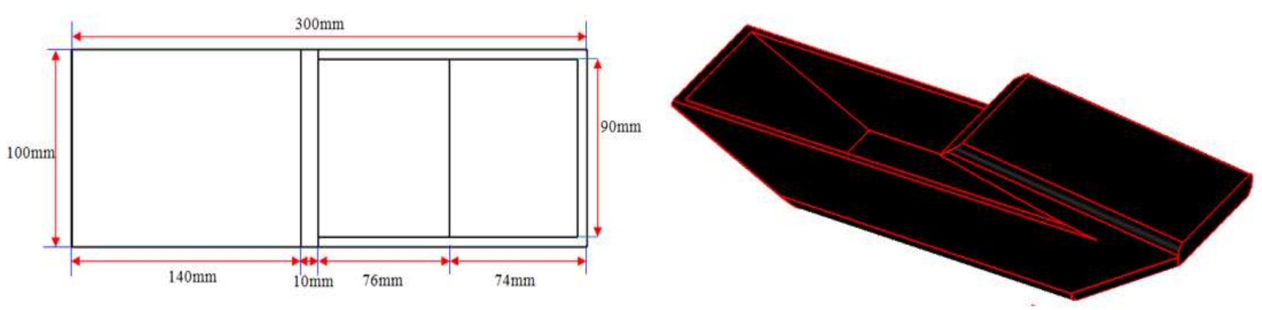

Figure 7: Top, and schematic views of the designed fuselage.

Applying A.C. Calculator software, the position of the aerodynamic center (AC), from the wing's leading edge is determined to be equal to 170mm. In addition, using Raymer statistical diagram[26] to estimate the placement and dimensions of the control surfaces of the designed tilt-rotor MAV, we present in Figure 8, the top view of the wing including the dimensions and locations of the control surfaces.

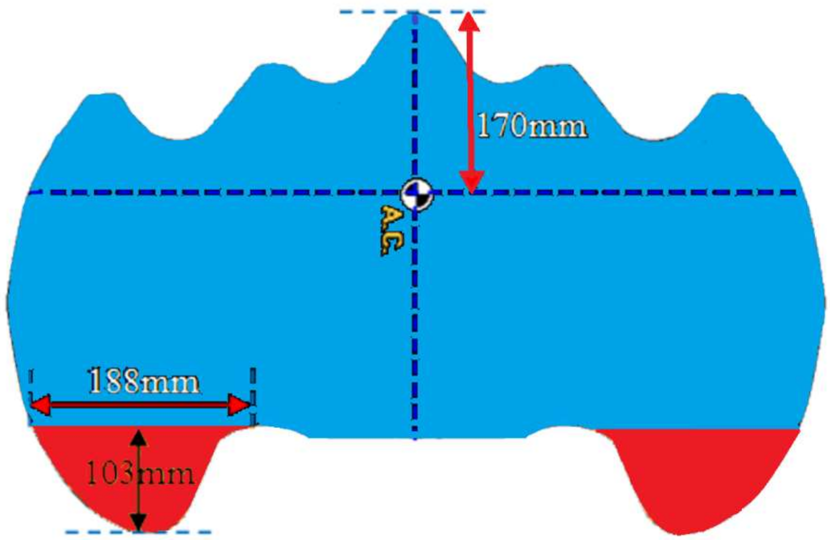

Figure 8: Dimensions and locations of the control surface of the designed tilt-rotor MAV.

The next step in the design is tails' design. Due to the use of reflexed airfoil and reduction of the size of the drone, we do not need to design horizontal tail. Therefore, we should just design a vertical tail. As for the vertical tail, the main parameter to design it is its surface (S_v). The tail arm (l_v) in flying wing drones is considered equal to the distance from the end of the wing at the point that is 0.1(*MAC*) until wing aerodynamic chord (*AC*)[18]. The vertical volume coefficient (V_V) is considered 0.03 in this design process[27]. Considering these values, the surface of the vertical tail can be calculated. In this design process, instead of using one vertical tail in center line of the tilt-rotor, we design two tails in tips of the wing with half surface. Generally, the tail aspect ratio is between 1.2 and 1.8 and the taper ratio is between 0.4 and 0.6 [16]. In this sizing process, the tail aspect ratio and taper ratio are considered to be equal to 1.5 and 0.5, respectively. Finally, the dimensions of the vertical tails and their position on the wing are determined, as shown, respectively, in Figures 7(a) and 7(b). As for the airfoil type in these tails, a symmetrical airfoil NACA0006 is used.

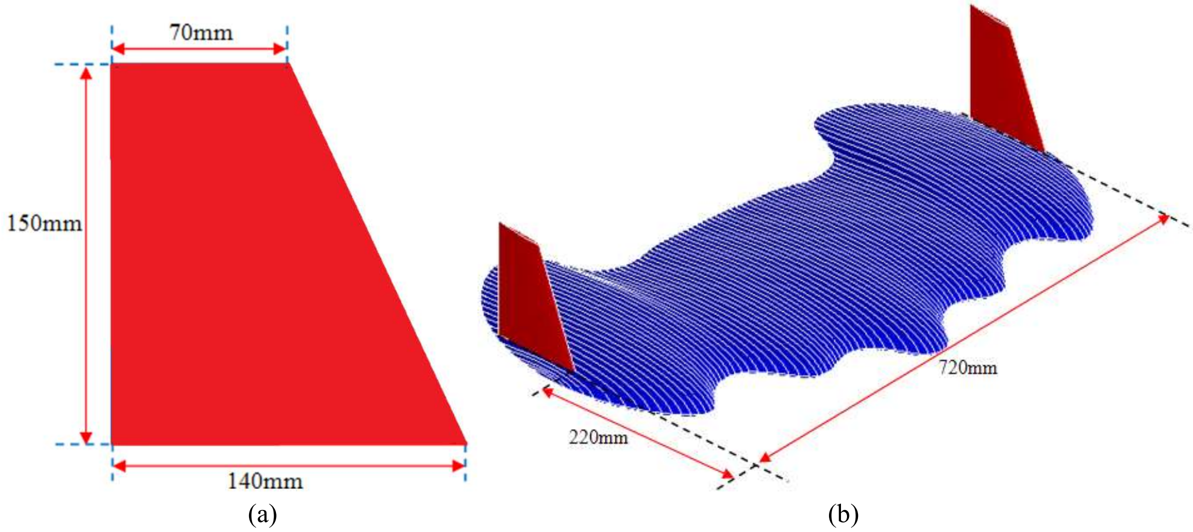

Figure 8: Dimensions and locations of the control surface of the designed tilt-rotor MAV.

III- Conclusions

The design cycle for the optimization of tilt-rotor MAV has been carried out. In this study, design criteria were defined and a complex wing was chosen and modeled. Dimensions of the wing were derived from the weight estimation. This allows to determine the aerodynamic coefficients of the wing to be analyzed in XLFR5. An airfoil was selected that has the best lift coefficient to a minimized drag coefficient. Once this was completed the dimensions of the fuselage were determined. This allows for the determination of the location of the aerodynamic center and the control surfaces. Two tails on the wing tips were selected due to flying wing design and their position was determined. All parts completed thus far yield the results for a conceptual design of wing, body, tail, and control surfaces of a tilt-rotor MAV.

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