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Conceptual Design of Tactical Solar Power UAV

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Abstract. The purpose of this research is to study and design a concept of the tactical solar power UAV. The mission requirements derived from military applications: Intelligence, Surveillance, and Reconnaissance)ISR(which including a longer operation time)8 hours(, 350-1000 meters service ceiling, and less than 5 kg for take-off weight. This paper, a conceptual design of solar power UAV mainly based on Noth's methodology. A simple program coding created for sizing solar power UAV by using Scilab. In addition, the vortex lattice method)XFLR5 program(also employed to evaluate the basic aerodynamic characteristics for three different low-Reynolds number airfoils. The wing incident angle was then designed. From the conceptual design results, the coding indicated that the solar power UAV is the conventional type of aircraft, which is provided 4 meters in wingspan)Aspect ratio 13(, 3.88 kg for take-off weight, and 69.13% for solar area to wing area ratio.

1. Introduction

The Royal Thai Air Force (RTAF) is responsible for the preparation of its capabilities to defend the kingdom using the air operations and the operations related to those capabilities. RTAF aims at being one of the best air forces in ASEAN by 2020. In addition, the policy of RTAF commander-in-chief year 2016-2018, particularly in the intelligence aspect focused on the enhancements of intelligence, surveillance and reconnaissance (ISR) mission. It is obvious that UAV is the useful platform for the ISR military operations. Currently, there are some problems about RTAF's UAV. Firstly, most RTAF's tactical UAV have limited endurance because of using power solely from battery. Secondly, the high frequency of take-off and landing affect the life cycle period of the avionics and payload that result in high risk to damage of those payload. Lastly, to participate in the global warming concern, which help reducing the amount of CO₂ emission to the atmosphere.

To date there are several approaches to have UAV stay flying theirs mission in the sky as long as possible like aerial refueling [1-3], energy gaining from environment by using efficient maneuvering [4-5], air launch [6] and alternative energy such as solar cell [7-11], fuel cell [12] etc.. Each approach has their own strength and weakness depend on mission requirements and figure of merit. However, for tactical UAV the exploitation of solar power is the most efficient approach.

Therefore, this paper proposes the conceptual design of the solar power UAV for tactical mission in order to enhance the endurance. The mission requirements derived from military applications specific to ISR mission which including a longer operation time, i.e. greater than 8 hours, 350-1000 meters service ceiling, and less than 5 kg for take-off weight.



The rest of this paper organized as follow, the first section explains the mission requirement and conceptual design methodology. The next section deals with airfoil selection. After that, initial sizing of wing and tail is described. Finally, conclusions are drawn for further studies.

2. Solar Power UAV

The configuration of the solar power UAV is indifference to battery powered UAV in terms of aerodynamics efficiency, which is dependent on the mission requirements and the design criterion. The only different is the propulsion system, i.e. the photovoltaic cell or solar cell are placed on the upper surface of wing, fuselage or empennage to harvest the energy from sun ray and convert to electrical energy during the day. The obtained electrical energy supply to the motor-propeller, the onboard electronic and the excess energy charge to battery. The first solar power UAV, Sunrise I with 3.2 m wingspan, soared in the sky on 1974 [13]. Since then, there are several successes in design and development of the solar power UAV [14-18].

2.1. Mission Requirements

The mission requirement is the important input that drives the conceptual design phase in order to come up with the fundamental 3-D drawing of the UAV. This paper focuses on ISR, which generally refers to continuous monitoring target by using imagery obtained from camera payload [18]. The mission profile of the tactical solar power UAV illustrated in figure 1. This UAV is hand launched to take-off, then climb to cruise altitude, then loitering over target area performing ISR, then cruising back to base, after that descending and net landing, respectively. It is obvious that the tactical solar power UAV spent most of the time in cruising and loitering flight phase, which is steady and level flight.

The list of performance requirements are as the followings,

1. Take-off weight less than or equal to 5 kg
2. Camera payload weight 0.17 kg
3. Wingspan greater than or equal to 4 m
4. Operating altitude 300 – 1,000 m
5. Endurance greater than or equal to 8 hours
6. Cruise speed range between 8-9 m/s
7. Stall speed 6 m/s

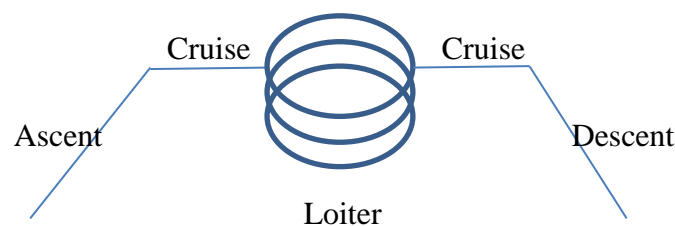


Figure 1 The Mission Profile of the tactical Solar Power UAV

2.2. Conceptual Design of Tactical Solar Power UAV

The principles of the UAV design are similar to the principles developed for the design of manned aircraft. The design process is divided into three phases, i.e. the conceptual design, the preliminary design and the detail design. Each phase has different inputs, calculations and outputs in systematic method [19]. The size of UAV varies according to the required mission and their performance as well. However, the conceptual design of the solar power UAV has many aspects different from traditional conceptual design methods [20-21]. There are two approaches in the conceptual design

method [17], which are the iterative approach and the analytical approach. This paper used the analytical approach because of the ease of implementation and the proof of successful flight of Sky-Sailor. This method relies on the analytical equations describing the characteristics of each component on board UAV, i.e. Maximum Power Point Tracker (MPPT), motor-propeller, solar cell etc. and 2 balance equations that is to say, mass balance and energy balance as shown in figure 2. The total take-off weight of the UAV is the sum of the mass of each component on board, e.g. payload, structure, propulsive unit, solar cell, MPPT, battery. Once the total take-off weight is obtained, the aerodynamic lift and drag can be estimated. These aerodynamic forces then converted to power required for steady and level flight. This amount of mechanical energy is then balance by the electrical energy required for daily operation time, which come from solar panel.

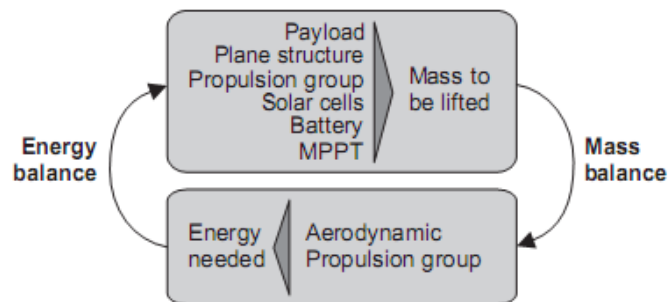


Figure 2 The Mass balance and Energy balance [17]

As mention in section 2.1, the tactical solar power UAV mostly fly in steady and level flight, such that lift force need to balance the total weight of the UAV in order to fly at constant altitude and drag force need to balance the thrust from electric motor and propeller in order to fly at constant airspeed. In addition, the electrical energy consumption needs to balance by the solar energy obtained from the solar panel. Therefore, the amount of solar energy must be greater than the electrical energy required to fly steady and level flight, moreover safely complete the mission. Figure 3 show the schematic diagram of the analytical conceptual design methodology in details. This diagram illustrated the mathematical calculation as a loop to solve for realistic solar power UAV's configuration in terms of wing aspect ratio (AR), wingspan (b), and mass (m), given a complete list of all the parameters shown in the table A1 - A2 in the appendix.

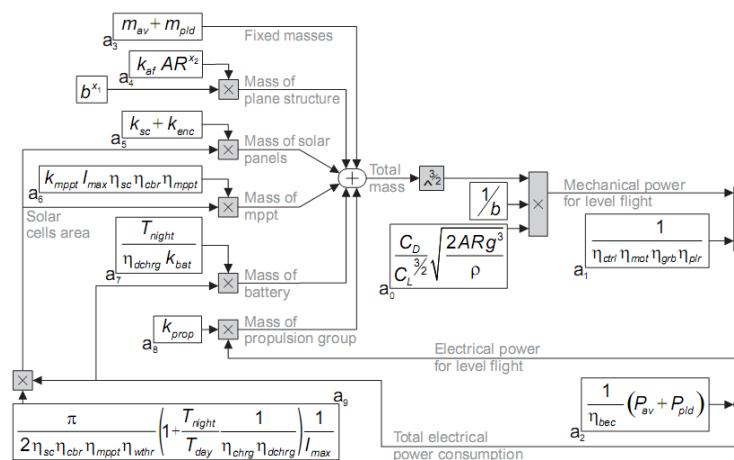


Figure 3 The analytical conceptual design methodology of the solar power UAV [17]

The conceptual design methodology explained in section 2.1 originally coded in MATLAB. This paper, the design algorithm is converted and written in Scilab, which is comparable to MATLAB and freeware under GNU license.

2.3. AERO Sun Surfer Design

The AERO Sun Surfer, tactical solar power UAV, was designed base on the mission and performance requirements in section 2.1 and the methodology in section 2.2. This prototype aircraft is required to fly at least 8 hours in scattered cloud sky condition. The payload for ISR mission is EO/IR camera, which weighs 170 g and consumes power 1.5 W.

The possible configurations of the UAV represent by, i.e. wingspan, aspect ratio, speed, power and the percentage of wing area required to install the solar cell. The results show in figure 4-5. Figure 4 (a) shows the possible wingspan versus total mass of the solar power UAV. Figure 4 (b) shows the magnifying version of figure 4 (a) for more details, notice that this graph focuses on the 4 m wingspan because UAV of this size is suitable for hand launch take-off. The corresponding total mass of 4 m wingspan is 3.88 kg for aspect ratio 13. Notice also that, the increasing aspect ratio results in the higher total mass of the UAV.

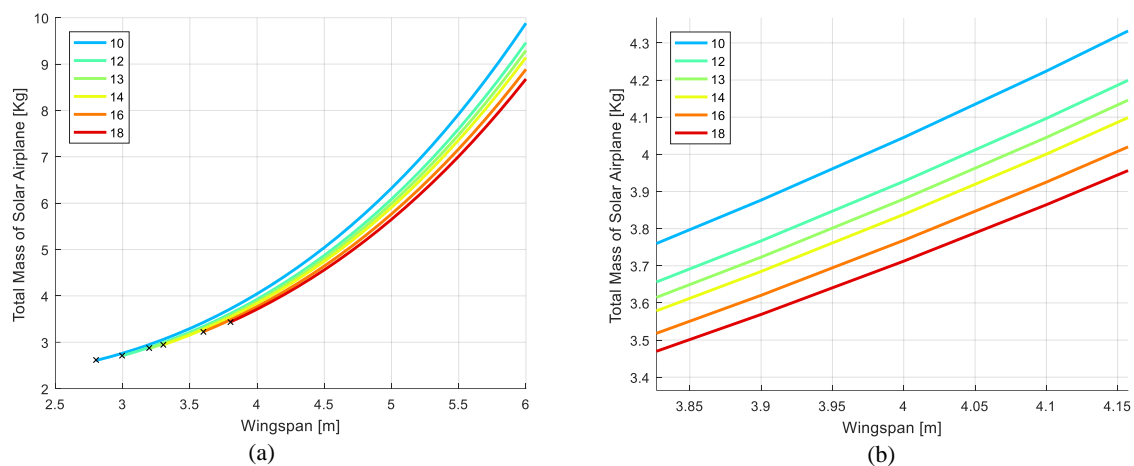


Figure 4 The possible solar power UAV's wingspan versus total mass with variation of aspect ratio

The results in figure 5 show various important design variables versus wingspan and corresponding to aspect ratio. Figure 5 (a) shows UAV's speeds vary with wingspan for a given aspect ratio and the 'x' mark denotes the minimum UAV's speed. Figure 5 (b) shows wing areas vary with wingspan for a given aspect ratio. Figure 5 (c) shows the mechanical power generated by propeller, varying with wingspan for a given aspect ratio and figure 5 (d) shows the percentage of wing area need to install solar cell, varying with wingspan for a given aspect ratio.

From the various candidates, the considerations and figure of merits were trade-off, i.e. mobility, manufacturing cost. Finally, the AERO Sun Surfer conceptual prototype has the total mass 3.88 kg. The wingspan equal to 4 m with aspect ratio equal to 13 with cruise speed equal to 8.144 m/s, wing area equal to 1.231 m², required 69.13% of wing area to install solar cells in order to fly steady and level flight, and the corresponding power from propeller is 14.14 W.

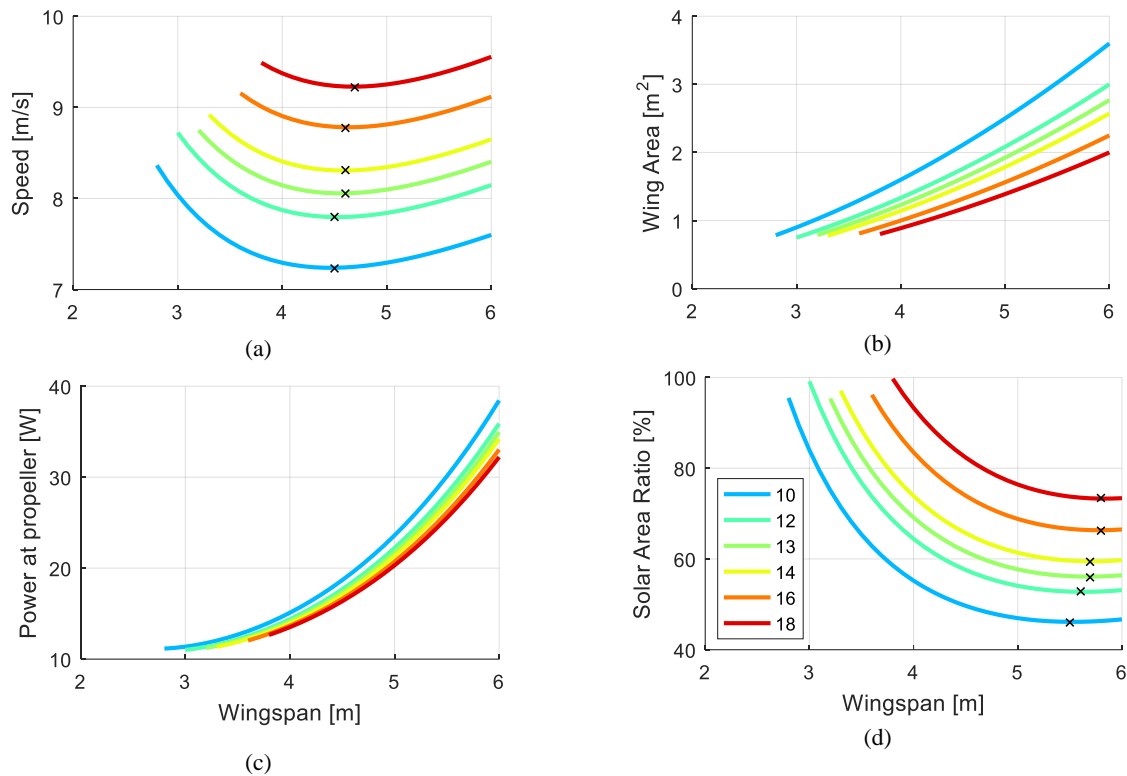


Figure 5 The possible solar power UAV's speed, wing area, propeller power, and area required for solar cell versus wingspan for a given aspect ratio

3. Airfoil Selection

Recall that the mission requirement for the tactical solar power UAV is to fly ISR mission for at least 8 hours. The conceptual design configuration obtained from section 2.3 is then passing to the preliminary design phase. To make this UAV soar to the sky, the wing is the main contributor component, therefore this section explains some detail of airfoil selection for the tactical solar power UAV. Recall also that this UAV spend time mostly in cruising and loitering, this conceptual configuration design to cruise at slow speed. This is the main reason of selecting 3 low Reynolds number airfoil, i.e. S1223, SG6043, and SD7032 to perform aerodynamic characteristics analysis with XFLR5 program. The basic aerodynamic required compose of i) lift coefficient, ii) drag coefficient, and iii) pitching moment coefficient versus angle of attack. The airfoil sections show in figure 6, where figure 6 (a) - (c) are the cross section contour of S1223, SG6043, and SD7032 respectively. The analyses consider the low speed flow where the Reynolds number equal to 250,000.

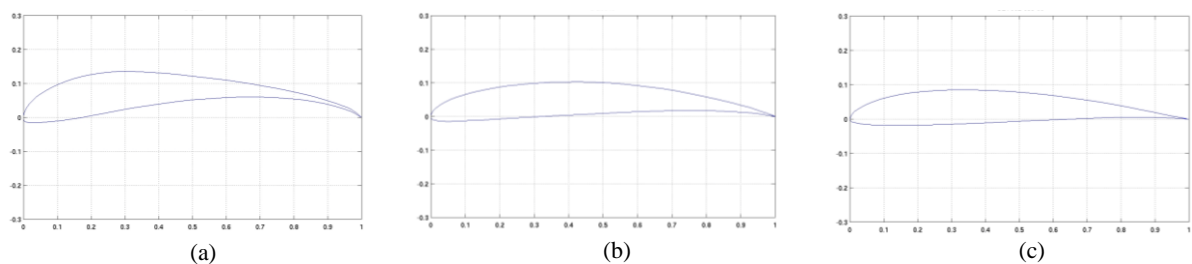


Figure 6 The low Reynolds number airfoil section contour of S1223, SG6043, and SD7032

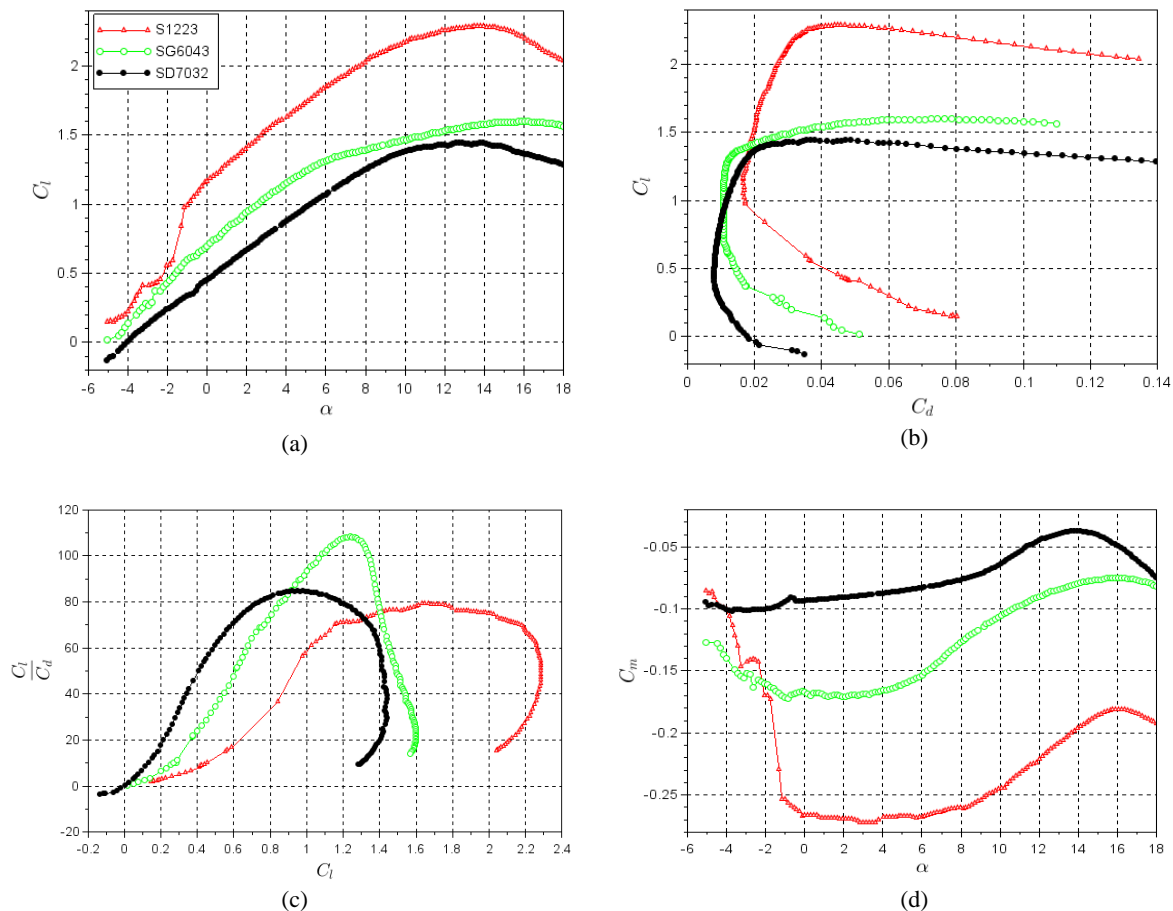


Figure 7 The basic aerodynamic characteristics of S1223, SG6043, and SD7032 airfoil

The results show in figure 7 (a) - (d). Figure 7 (a) shows the comparison of lift coefficient vary with respect to the angle of attack from -5 degree to 18 degree among these threes. It is obvious that S1223 airfoil gives the maximum lift coefficient at angle of attack 14 degree, which is equal to 2.25. SG6043 airfoil is the runner up and gives the maximum lift coefficient at angle of attack 16 degree, which is equal to 1.6. SD7032 airfoil is the third, which gives the maximum lift coefficient equal to 1.4 at the angle of attack 14 degree. Figure 7 (b) shows the comparison of drag polar or the plot showing between lift and drag coefficient of these airfoils. Notice the fact that, despite the highest lift coefficient of S1123 airfoil nonetheless drag coefficient is also the highest, which is the lowest aerodynamic efficiency among the threes. SD7032 and SG6043 have lift coefficient range from 0.6 – 1.0 and 0.7 – 1.3 in cruising condition, however SD7032 has lower drag coefficient range from 0.01 – 0.13 compare to 0.013 – 0.014 of SG6043 corresponding to the cruising condition. Figure 7 (c) shows the lift-to-drag ratio or aerodynamic efficiency of airfoil shape. It reveals that at the design point, where lift coefficient equal to 0.8, SD7032 airfoil gives the highest lift-to-drag ratio, 82 for this case and 78 for SG6043 airfoil. Figure 7 (d) shows the comparison of pitching moment coefficient vary with respect to the angle of attack of three airfoils. It can be noticed that SD7032 has the lowest negative pitching moment during linear operating spectrum among the threes, which means this airfoil has the least nose down moments. The results show that SG6043 airfoil is the suitable airfoil to be selected for utilizing as wing section of the tactical solar power UAV because of having wider range of lift coefficient, while drag coefficient is almost constant corresponding to this range of lift.

4. Initial Wing and Tail Sizing

In order to design the wing for solar power UAV, the important consideration is the shape and area for installing solar cell on the upper surface of the wing. There are many possible wing planform configurations, however the straight wing planform seem to be the simplest configuration for calculation and installing solar cell. Therefore, the straight wing with aspect ratio equal to 13 and wingspan of 4 m is considered as starting candidate for initial wing sizing. This section explains the initial wing and tail sizing by using XFLR5.

Given wingspan, aspect ratio, and wing area therefore the chord can be calculated. All these design parameters need to be input in the XFLR5 to estimate the basic aerodynamic characteristics and wing incidence angle at design point. Recalls that the initial lift coefficient in conceptual design phase is assume to be 0.8. Having define the vortex lattice method for Reynolds number 250,000 and varying angle of attack from -5 to 15 degree, the results showed that at angle of attack equal to 2 degree gives lift coefficient equal to 0.808 and drag coefficient equal to 0.017. Therefore, the wing incidence angle is set to 2 degree. Figure 8 shows the physical of the wing and the results from XFLR5.

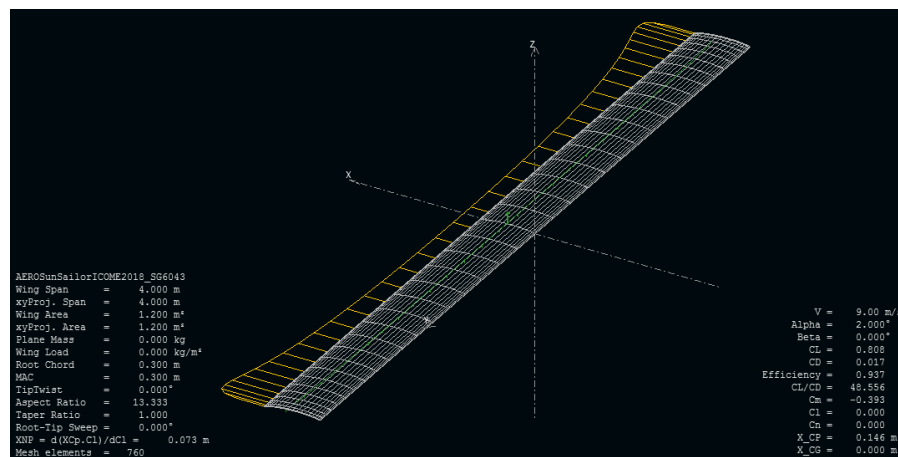


Figure 8 The basic aerodynamic characteristics of the straight wing with SG6043 airfoil

Generally, the conventional aircraft configuration is unstable without having empennage or tail. The tail is the most important component to make the whole aircraft stable or flyable. However, there are several tail configurations, i.e. T-tail, Y-tail, V-tail, H-tail etc., to be selected for the UAV. The consideration is based on the mission and performance requirements. This paper chose T-tail configuration because of two reasons, the one is this type of empennage avoiding the effect of downwash of airflow downstream from the wing. The other is the horizontal stabilizer, which is placed on top of the vertical stabilizer, expose the whole area to the sun, and hence give some extra area for solar cell installation. However, the higher weight is the penalty of this type of empennage. This point should be taken into consideration in the design review phase. As mention above, the empennage is the most important component to yield the stability of UAV. However, it will be given more details analysis in the preliminary design phase paper, particularly, in stability and control analysis of this UAV. Therefore, the first layout of the conceptual design phase of the tactical solar power UAV is shown in Figure 9. This prototype named AERO Sun Surfer. It was designed to have the conventional configuration, where the wing is the straight wing and is the top wing with 4 m span and 0.3 m chord length. The whole wing area is 1.231 m², which 69.13% of this area is occupied by solar cell. The solar cell efficiency is 22%, which is a flexible mono crystalline type. This type of solar cell is not expensive; therefore, it is suitable for academic research project. It has T-tail shape empennage. Table 1 shows basic data of the AERO Sun Surfer UAV.

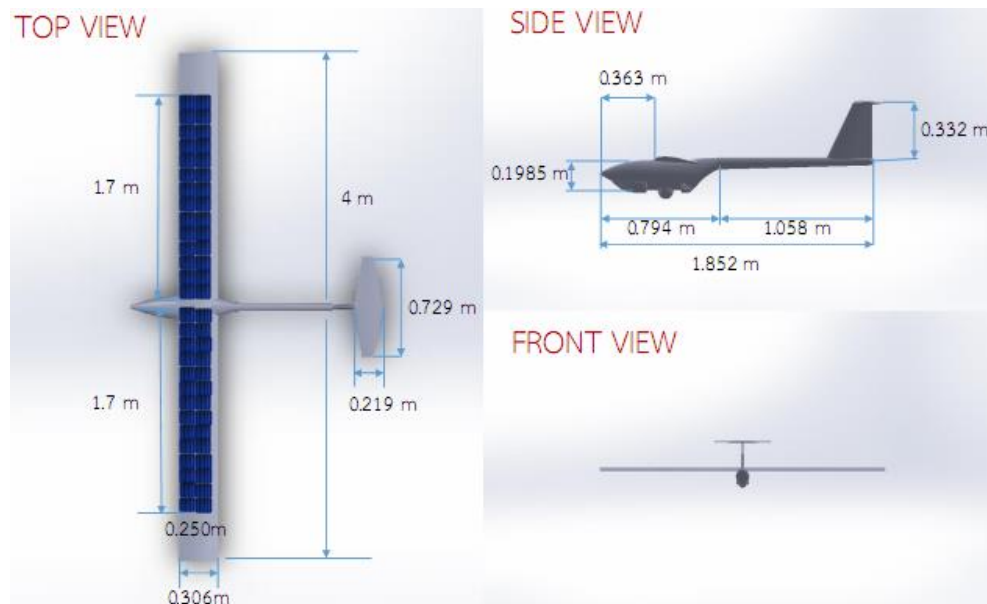


Figure 9 The conceptual layout of the AERO Sun Surfer UAV 3-D drawings

Table 1 The Basic data of AERO Sun Surfer UAV.

Main Geometric Data	AERO Sun Surfer
Wingspan	4.00 (m)
Wing Chord	0.30 (m)
Wing Area	1.23 (m ²)
Solar Area	0.85 (m ²)

Conclusions

This work presented the conceptual design of AERO Sun Surfer, the tactical solar power UAV, which has longer endurance to complete ISR mission and to enhance the performance of RTAF's existing tactical UAV. The conceptual design utilized Noth's methodology. This methodology has been proven for several successful flight of solar power UAV range from small to large scale UAV. However, the further step is to move all efforts to preliminary design phase where each part of UAV will be closely look into more details.

Acknowledges

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Appendix

Table A1 The Variable of AERO Sun Surfer UAV.

Variable	Value	Description
AR	13	Aspect ratio
b	4 [m]	Wing span
m	3.88 [kg]	Total mass

Table A2 The Parameter of AERO Sun Surfer UAV (constant)

Parameter	Value	Description
C_L	0.8	Airfoil lift coefficient
C_{Daf}	0.0013	Airfoil drag coefficient
C_{Dpar}	0.006	Parasitic drag coefficient
e	0.9	Oswald's efficiency factor
I_{max}	650	Maximum irradiance
k_{bat}	190.3600 [J/kg]	Energy density of lithium-ion
k_{sc}	0.32 [kg/m ²]	Mass density of solar cells
k_{enc}	0.26 [kg/m ²]	Mass density of encapsulation
k_{mppt}	0.00042 [kg/W]	Mass to power ratio of MPPT
k_{prop}	0.008 [kg/W]	Mass to power ratio of propeller group
k_{af}	0.44/9.81 [kg/m ³]	Structural mass constant
m_{av}	0.85 [kg]	Mass of autopilot system
η_{bec}	0.65	Efficiency of step-down converter
η_{sc}	0.222	Efficiency of solar cells
η_{cbr}	0.90	Efficiency of the curved solar panels
η_{chrg}	0.95	Efficiency of battery charge
η_{ctrl}	0.95	Efficiency of motor controller
η_{dchrg}	0.95	Efficiency of battery discharge
η_{grb}	0.97	Efficiency of gearbox
η_{mot}	0.85	Efficiency of motor
η_{mppt}	0.97	Efficiency of MPPT
η_{plr}	0.85	Efficiency of propeller
P_{av}	1.5 [W]	Power of autopilot system
x_1	3.1	Airframe mass wingspan exponent
x_2	- 0.25	Airframe mass aspect ratio exponent
m_{pld}	0.17 [kg]	Payload mass
η_{wthr}	0.7	Irradiance margin factor
P_{pld}	9 [W]	Payload power consumption
$T_{reserve}$	2*3600 [s]	Reserve time
T_{day}	8*3600 [s]	Day duration (Operation time)
ρ	1.1655 [kg/m ³]	Air density (500 m)

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