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Conceptual design of a Solar HALE UAV

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ABSTRACT

The aim of this research work is to realize the concepts of solar High Altitude Long Endurance Unmanned Aerial Vehicle and design a prototype before manufacturing with available technologies in order to take steps to reach eternal flight. The experience gained from former versions, Sun falcon 1 - a monoplane with solar powered and fuel cell system designed for day flight and Sun falcon 2 -an upgraded model capable of flight during night from energy saved in daytime were used to gain experience to introduce the HALE concept. This work proposes a conceptual design methodology of solar UAV with high operating altitude and long endurance characteristics from the state of art. A model of an UAV is presented which have 150 kg payload mass and a day and night endurance.

1. Introduction

High Altitude Long Endurance (HALE) aircrafts in Unmanned Aerial Vehicle (UAV) sector of aerospace industry can have wide applications including toys and racers, remote sensing, internet drones, crowd management, civil protection and real-time monitoring, border security surveillance in land and sea, sounding, rescue operations, disaster control and extra-terrestrial exploration. High altitude also provides the applicability of low-cost pseudo satellites with large coverage area. It can also be easily launched and recovered using normal self-take-off and landing or glider drop and recovery.

As the renewable energy technology domain including solar cells, thin film photovoltaic arrays, fuel cells, electrolysers, batteries like Gallium Arsenide (GaAs), power management systems, sensors, etc., got better improvements, solar powered UAVs can achieve longer endurance than ever before by even covering night flights where there is no solar power source. This can be achieved through a well compromise between the energy obtained during day, energy consumed in day and energy consumed in night.

Some literatures are reviewed to understand specification and capabilities of solar powered HALE UAVs since 1970 including the first solar aircrafts, Sunrise I and II to solar MALE UAVs, SunFalcon 1

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and 2 manufactured by Harasani *et al.,* [1-2] of King Abdul-Aziz University from the state of art. SunFalcon has 87 kg mass and day flight capability at altitude of 500−2000 m. Noth [3-4] proposed a design algorithm for various types of solar aircrafts. Romeo *et al.,* [5-6] developed solar monoplane trapezoid wing body (TWB) HALE UAV with 17-20 km altitude (stratosphere platform) for continuous operation of 9 months. It is equipped with eight brushless electric motors, a twin boom tail with sized horizontal stabiliser and two rudders. High modulus CFRP composite material has been employed extensively to minimize airframe weight. Many airfoils are optimized to obtain most favourable aerodynamic efficiency using integrated panel/ boundary layer methods, to achieve reduced induced drag and showed the capability of operating in low speed and low Reynolds number. Some wind tunnel experiments were carried out to ensure the analytically predicted airfoil performances. FEA were also carried out on both full size and scaled models of structure to predict static and dynamic behaviour. A scaled model of technological demonstrator was created to undergo static tests for ensuring the predicted behaviour. Cestino *et al.,* [7-8] carried out preliminary research on solar BWB HALE UAV (SHAMPO) with altitude of 17 km and several months of continuous operation for earth observation and telecommunication purposes in low latitude sites of Europe. It adopted efficient solar cells for power generation and energy storage system for propulsion module and graphite/epoxy - CFRP structures of sandwich wing-box spar demonstrated low structural weight and satisfactory classical flutter behaviour. BWB contribute best performance and proper availability of surface area and volume. Hajianmaleki [9] carried out a modified conceptual design method for solar UAV with traditional design methodologies to incorporate the characteristics of solar powered aircrafts and came with a successful model.

2. Solar Energy Generation

Regional availability of solar energy has to be checked for understanding the available maximum solar irradiance before designing the solar model to determine the required area for power generation. Figure 1 shows the solar diurnal cycle of the region with a maximum solar irradiance around 1000 W/m^2 supply on summer (June) and minimum of 800 W/m^2 on winter (December).

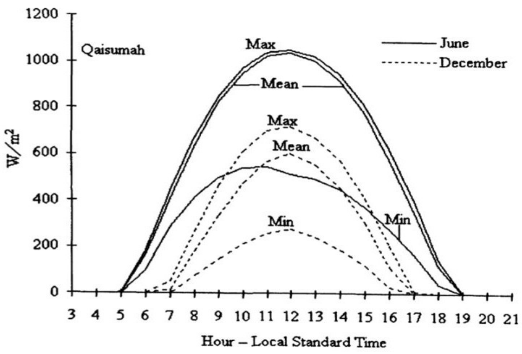

Fig. 1. Solar diurnal cycle in Summer and Winter

Figure 2 shows the global horizontal irradiation and direct normal irradiation as reported by solargis.info in the region. It shows that global horizontal irradiation supply of 2000 - 2200 kWh/m^2 and direct normal irradiation supply of 1600 – 2000 kWh/m^2 generally.

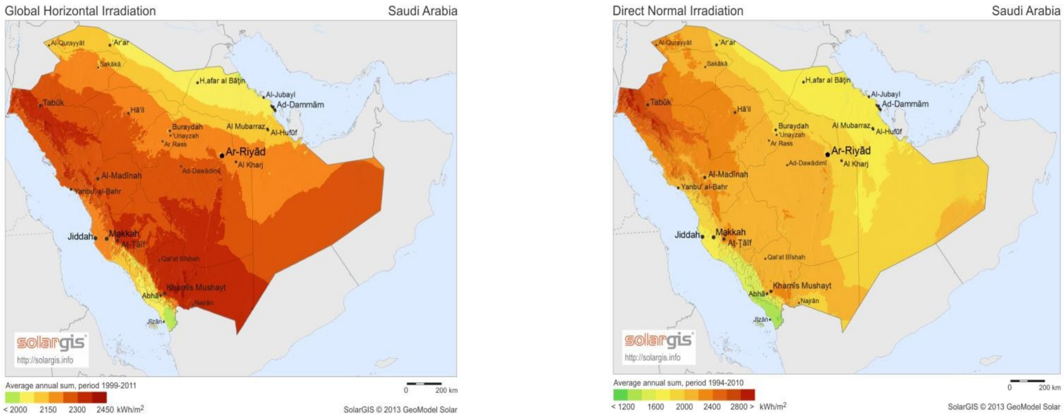

Fig. 2. Global horizontal irradiation and Direct Normal irradiation

Solar UAVs generate required electrical energy from the solar panels according to the regional supply. Solar panels comprised of mini solar cells connected in a certain configuration attached in part of the aircraft, mostly wing and empennage generates required power for level flight. Depending on the proper supply of solar irradiance and the inclination of sun rays, panels convert light into electrical energy in daytime. Maximum Power Point Tracker, a converter ensures that maximum amount of power is obtained from the solar panels. This power is used to run propulsion system and onboard electronics, and surplus energy is transferred to energy storage system, mostly batteries. During the night, energy stored is used to run as there is no power supply from solar panels.

3. Methodology

3.1 Benchmarks

Past research in solar powered UAV project 'Sunfalcon' have provided the needed data in medium altitude program and energy required blocks. Pathfinder and Helios UAVs were evaluated as benchmarks and the basic requirements were selected for HALE concept. This platform will accommodate an overall payload mass of 150 kg with an altitude of 9000 m. Table 1 provides the specifications and Figure 3 presents the images of benchmarks.

Table 1
Benchmarks

Parameters	**Pathfinder**	**Pathfinder Plus**	**Centurion**	**Helios HP01**	**Helios HP03**
Length(m)	3.66				5
Chord(m)	2.4				
Wingspan(m)	30	36	63	75	
Aspect Ratio	12 to 1	15 to 1	26 to 1	30.9 to 1	
Max.Altitude(km)	22	24	27	30	20
Max. Weight(kg)	254	317	862	930	1110
Payload(kg)	45	150	45 - 270	330	
Engines	Electric, 2 hp (1.5kW) each				
No. of Engines	6	8	14	14	10
Supplementary Power	Batteries	Batteries	Batteries	Li Batteries	Li Batteries, Fuel Cell

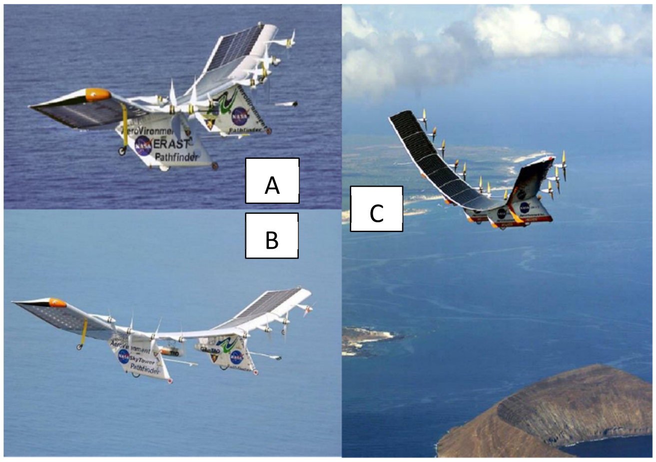

Fig. 3. Benchmarks: A) Pathfinder B) Pathfinder Plus C) Helios

3.2 Airfoil Selection

Table 2 shows the selected airfoils and characteristics; FX63 137sm, MH78, mhmi3 and S1223RTL.

Table 2
Selected airfoils

Name	Details	Characteristics
FX63 137sm	Wortmann FX 63-137 airfoil smoothed	Max thickness 13.7% at 30.9% chord Max camber 5.8% at 56.5% chord
MH78	Martin Hepperle, MH 78 for flying wings (hang glider)	Max thickness 14.4% at 22.1% chord Max camber 1.9% at 17.9% chord
Mhmi3	Matteo Gallizia	Max thickness 9.31% at 23.7% chord Max camber 2.4% at 27.2% chord
S1223RTL	Richard T. LaSalle modification of the S1223 to S1223RTL	Max thickness 13.5% at 19.9% chord Max camber 8.3% at 55.2% chord

To properly analyse the airfoil performance, a 2D analysis was conducted on XFLR5 at altitude 9000m with velocity of 20 m/s in inviscid flow. S1223RTL showed highest C_L with high C_D.

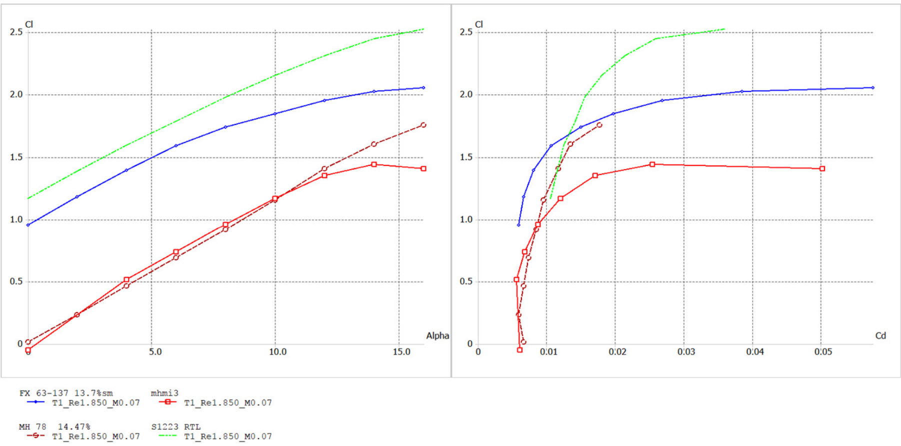

Fig. 4. Airfoil derivatives; Coefficient of lift (C_L) vs angle of attack (alpha) and coefficient of lift (C_L)Vs coefficient of drag (C_D)

FX 63 137 and S1223 RTL have C_L of 1.5 and 1.7 and C_D of 0.01 and 0.0125 at angle of attack of 5^0. Both showed higher compatibility, but FX 63 137 have higher aerodynamic efficiency (C_L/C_D) being exceptional in high altitude. MH78 and mhmi3 were showing poor compatibility in early angle of attacks (0 - 6) while exceeding quality in higher operating angles.

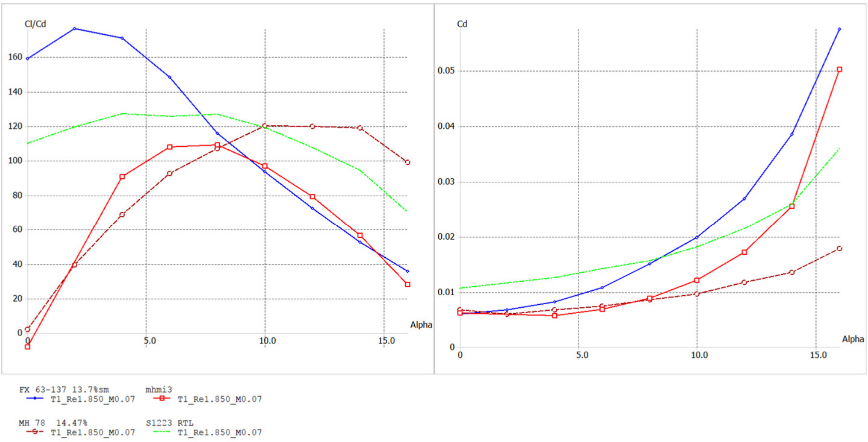

Fig. 4. Airfoil derivatives; coefficient of lift to drag ratio (C_L/C_D) vs angle of attack (alpha) and coefficient of drag (C_D) vs angle of attack (alpha)

FX 63 137 sm was selected due to its higher C_L/C_D ratio.

3.3 Required Electrical Energy and Obtained Solar Energy

1) Formulation of power equation for level flight: Forces are assumed to be in equilibrium state at level flight, lift force equates with weight and thrust force equates with drag force as depicted in Eq.1 and 2,

Weight = Lift force,

$$Mg = \frac{1}{2} C_L \rho S v^2; \tag{1}$$

Thrust = Drag force,

$$T = \frac{1}{2} C_D \rho S v^2; \tag{2}$$

To calculate power for level flight,

$$P_{lev} = Tv; \tag{3}$$

Where, M is total mass of UAV, C_L is coefficient of lift, C_D is coefficient of drag, reference area, v is velocity at level flight, T is thrust.
By solving Eq.1, 2 and 3, Power can be written in terms of aspect ratio, AR and wingspan, b from $= b^2/S$; as,

$$P_{lev} = \frac{C_D}{C_L^{3/2}} \sqrt{\frac{2ARg^3}{\rho}} \frac{m^{3/2}}{b}; \tag{2}$$

Formulation of daily electrical power required,

$$P_{electot} = \frac{1}{\eta_{mot}\eta_{grb}\eta_{plr}\eta_{ctrl}} P_{lev} + \frac{1}{\eta_{bec}} (P_{av} + P_{pld}); \tag{3}$$

First part of the equation is power consumed by electronic controller, motor, gear box and propeller while second term constitutes for power consumed by avionic system and payload instruments. η_{mot} is motor efficiency, η_{grb} is gearbox efficiency, η_{plr} is propeller efficiency and η_{ctrl} is controller efficiency and η_{bec} is battery eliminator circuit efficiency.

2) Solar Irradiance: It is the power generated per unit area from the exposure to sun in the form of electromagnetic radiation. Irradiance level varies according to measuring altitude with maximum at space and minima at sea level due to atmospheric absorption and scattering and depending on the inclination angle of the ray and falling surface.

3) Daily solar energy obtained: Total electrical energy is the product of energy density gained in day time, the area of solar cells and marginalized with efficiencies of weather), solar cells (η_{sc}), camber (η_{cbr}) and MPPT (η_{mppt}).

$$E_{electot} = E_{daydensity} A_{sc} \eta_{wthr} \eta_{sc} \eta_{cbr} \eta_{mppt}; \tag{4}$$

where energy density gained in day time is, $E_{daydensity} = \frac{I_{max} T_{day}}{\pi/2} \eta_{wthr};$ (5)

η_{wthr} is used in the equation while taking clouds in to consideration and η_{cbr} is considered due to the camber of airfoil as the equation for obtained electrical energy density assumes the surface is flat. It also denotes airfoil selection must be done with careful observations and its explained elsewhere.

3.4 Mass Prediction Models

Mass estimation method is adopted from A. Noth [1] after verifying the applicability of the design requirement with great flight diagram and our scenario of high aspect ratio and high altitude. Total mass is classified into various sub-groups as mentioned in Eq. 8.

$$M = M_{fixed} + M_{af} + M_{sc} + M_{mppt} + M_{bat} + M_{prop} \tag{6}$$

Figure 4 presents a flowchart of mass estimation model from mission requirements and required power for level flight. Process of mass estimation was done using MATLAB Simulink through continuous iteration.

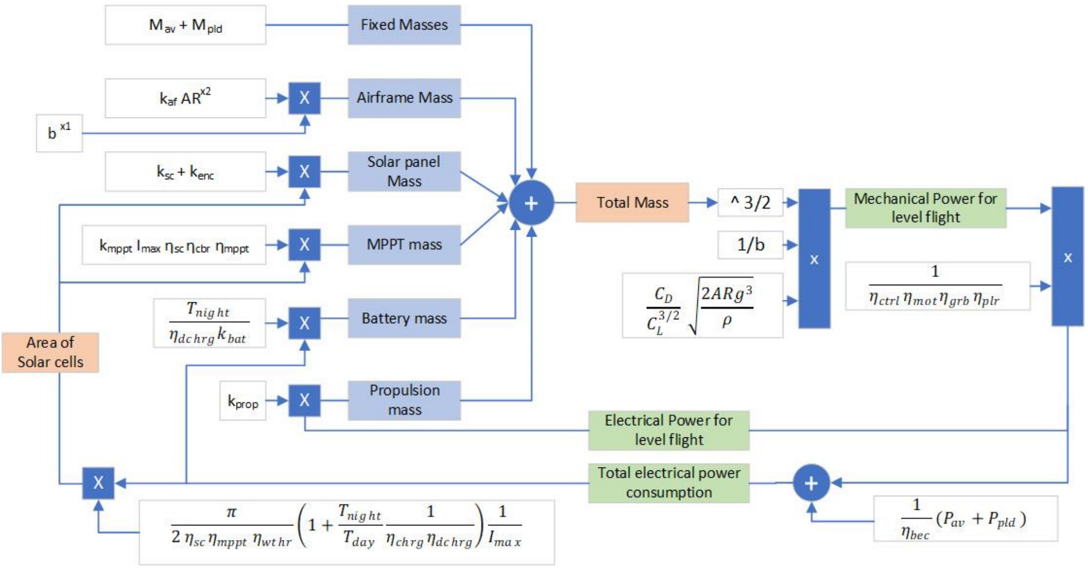

Fig. 5. Mass estimation model for solar UAV [1]

Inputs of the process are presented in Table 3.

Table 3
Inputs

Abbv	Name	Units	Value	Input Abbv	Name	Units	Value
	Design Variables				Airfoil data		
AR	Aspect Ratio	m	30.5	CL	Airfoil coefficient of lift at Angle of attack 3 deg and Reynold no. 500,000		1.228
b	Wingspan	m	75	$CDafl$	Airfoil coefficient of drag at Angle of attack 3 deg and		0.0115
$Mpld$	Payload mass	kg	150	$CDpar$	Fuselage drag coefficient		0.005
$Pav{+}pld$	Power consumed by avionics and payload equipments	W	175	e	Oswald efficiency		0.9
				Efficiencies			
$\eta wthr$	Margin factor for clouds		0.9	$\eta chrg$	Efficiency of charge process		0.95
kaf	Airframe mass sizing constant		0.022/9.81	$\eta dchrg$	Efficiency of discharge process		0.95
$x1$	Airframe mass sizing constant		3.1	ηbec	Efficiency of bec (5V stepdown)		0.65
$x2$	Airframe mass sizing constant		-0.25	$kbat$	Energy density of LiPo	J/kg	190*3600
$\eta ctrl$	Efficiency of motor controller		0.98	ksc	Mass density of solar cells	Kg/m2	0.32
ηmot	Efficiency of motor		0.88	$kenc$	Mass density of encapsulation	Kg/W	0.26
ηgrb	Efficiency of		0.97	$kmppt$	Mass/Power ratio of	Kg/W	1/2368

	gearbox				mppt		
η_{plr}	Efficiency of propeller		0.87	η_{sc}	Efficiency of solar cells		0.25
k_{prop}	Mass/Power ratio of	Kg/W	0.000121	η_{mppt}	Efficiency of mppt		0.99
η_{cbr}	Efficiency of cambered configuration		0.9				
Conditions							
alt	Altitude	m	9000	T_{day}	Duration of day	sec	13.75*3600
I_{max}	Solar Irradiance	W/m^2	1000	T_{night}	Duration of night	sec	(24-13.75) * 3600
Output							
T_{mass}	Total mass	kg	1340	P_{level}	Power required for level flight	W	5273
M_{af}	Airframe mass	kg	620	$P_{electot}$	Total electric power (propulsion + payload + avionics)	W	7515
M_{bat}	Battery mass	kg	426.7	P_{sc}	Max solar cells power output	W	23950
M_{sc}	Mass of solar cells	kg	62.36	V	Level flight velocity	m/s	16
M_{mppt}	Mass of MPPT	kg	10.11	D	Drag	N	336.2
M_{prop}	Mass of propulsion system	kg	8.7				
A_{sc}	Area of solar cells	m^2	107.5	A	Wing surface area	m^2	184.4

4. Optimization

Disciplines of UAV optimization process requires the calculation of various physical characteristics including payload capability, empty weight and total mass. These quantities were predicted using a multidisciplinary subsystem analysis that included propulsion, mass estimation, and aerodynamics and formulated system design problem as a mathematical optimization problem. An optimization problem consists of objective function which needs to be maximized or minimized controlled by design variables subject to various constraints. Optimization techniques are applied to find a set of design parameters, that can in some way be defined as optimal. This work adopted multi-discipline feasible (MDF) as the multidisciplinary design optimization (MDO) method after reviewing some early works [10-13].

A population-based metaheuristic algorithm called genetic algorithm (GA) was used in the optimizer. GA begins the search with random population initialization with capability of evolving after successive generation without any user defined initial point. It starts the search process from an assumed lower and upper bound and narrow down the design space to the optimal variables.GA uses the following operators based on biological evolution: selection, crossover and mutation. Selection operator uses stochastic uniform option imitating the principle of Survival of the Fittest. The Crossover operator propagates features of exemplary surviving designs from the current generation into the succeeding generation imitating mating populations. Eighty percent of the population is used for matting on a single point basis. Mutation operator allows for global search, preventing the algorithm from getting trapped in local minima of the design space and promoting diversity in population characteristics.

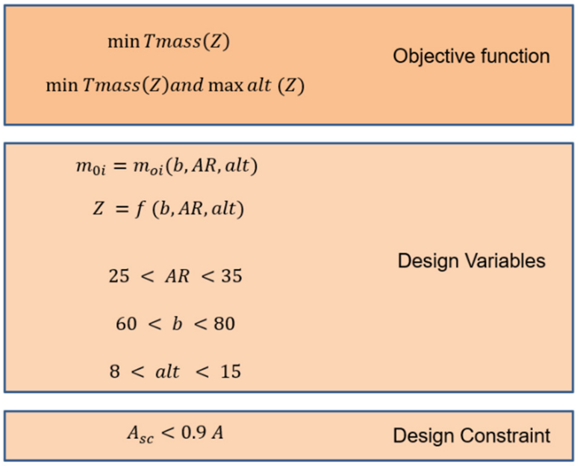

Fig. 6. Optimization problem formulation

Optimization problem formulation is presented in Figure 6. Objective function is to minimize the total mass of the UAV using the design variables of aspect ratio, wingspan and altitude with a constraint stating area of solar cells should be 90% of area of wing.Table 4 provides the optimized results of the conceptual design.

Table 4
Optimized results

Abbv	Name	Units	Value	Abbv	Name	Units	Value
AR	Aspect ratio		30.1	b	Wingspan	m	73
alt	Altitude	km	9.4	T_{day}	Duration of day		Full daylight
$T\ mass$	Total mass	kg	1254	T_{night}	Duration of night		Full night
M_{av}	Avionics mass	kg	20	M_{pld}	Payload mass	kg	150
Maf	Airframe mass	kg	590	$Plevel$	Power required for level flight	W	5696
$Mbat$	Battery mass	kg	415.5	$Pelectot$	Total electric power (propulsion + payload + avionics)	W	8096
Msc	Mass of solar cells	kg	60.4	Psc	Max solar cells power output	W	25800
$Mmppt$	Mass of MPPT	kg	10.11	V	Level flight velocity	m/s	16
$Mprop$	Mass of propulsion system	kg	8	D	Drag	N	352.4
Asc	Area of solar cells	m^2	115.8	A	Wing surface area	m^2	177

5. Initial Configuration

5.1 Inputs for Geometric Sizing

The optimized results define the geometrical values of the UAV on generating a stable normal configuration for conceptual design part.
Geometric characteristics for the final configuration are:

Wing: $b = 73\,m; c_{root} = 2.8\,m; c_{tip} = 2.8\,m; S = 177\,m^2; AR = 30.1;$

Horizontal tail: $b = 16\,m; c_{root} = 2\,m; c_{tip} = 2\,m; S = 32.6\,m^2; AR = 8;$

Vertical tail: $b = 3\,m; c_{root} = 4\,m; c_{tip} = 2\,m; S = 17.47\,m^2; AR = 1;$

5.2 Modelling

Three view and isometric view of the normal configuration of UAV were made using openvsp which is presented in figure 4. Stability analysis is carried out on XFLR5 and VSPaero.

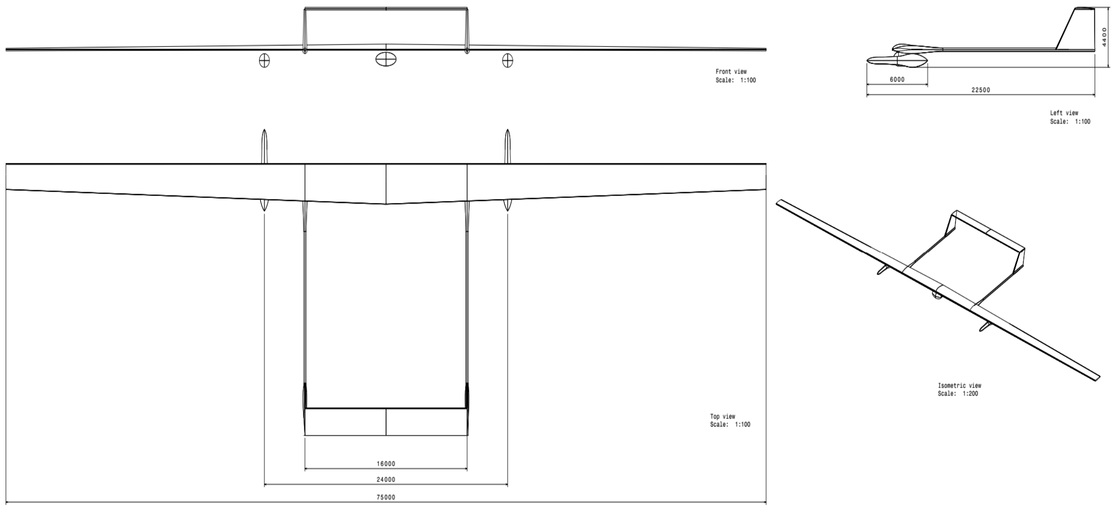

Fig. 8. Three view diagram and isometric view

6. Conclusion

The Solar HALE UAV was designed from preliminary model to conceptual design based on classical methods. An MDO framework was made using optimization method, MDF and optimizer algorithm, GA with various disciplines of aerodynamics, propulsion, mass estimation and geometric sizing. Longitudinal and lateral stability was checked using XFLR5 and achieved inside desired static margin. Current model has a payload capacity of 150kg, cruise velocity of about 20 m/s at an altitude of 9000m with a maximum endurance of one day and night coverage. Although with some changes like carrying some fuel or extending the solar panel to full wing and empennage can restart the solar energy cycle for next day which is the future part of the project.

Fidelity of the optimization problem could be increased by incorporating more disciplines like structures and trajectory which will be the future part of the research.

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