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OPTIMAL SIZING OF SOLAR POWERED UNMANNED AERIAL VEHICLE SYSTEM FOR CONTINUOUS FLIGHT BASED ON MULTI OBJECTIVE GENETIC ALGORITHM

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Abstract. *This paper presents an optimal sizing method for unmanned aerial vehicle (UAV) which is aimed to fly continuously for 24 hours using only solar energy. Multi objective genetic algorithm is used to solve the optimum solution of the UAV's wing area, cruise speed, drag, lift coefficient, and aspect ratio. Payload, solar panel characteristic, and flight location are taken into consideration. After the power balance of the model is analyzed, the result shows that the solar cell and battery are able to supply the energy required by the UAV for 24 hours under a certain irradiation level with a maximum payload of 3 kg. In addition, the effect of the irradiation level change, payload variation, and photovoltaic efficiency are also analyzed and shown in the result.*

Keywords: Unmanned aerial vehicle, Photovoltaic, Optimal sizing, Multi objective genetic algorithm, Solar powered aircraft

1. **Introduction.** UAV has been implemented in many fields such as telecommunication, long range surveillance, and disaster management. Designed with relatively small size, the UAV can perform many tasks which cannot be done with conventional aircraft. Nowadays, interdisciplinary research is performed to improve its flight duration, payload capability, and efficiency [1,2].

The utilization of solar power source for powering the UAV makes it possible to fly for a long time without landing to recharge the battery. During daylight solar energy is stored in battery and supplies the UAV electric and control system. At night, the entire system depends only on battery [3-5]. However, the integration of photovoltaic (PV) in UAV creates problems due to the fact that each element on the UAV contributes to the total weight and dimension. The solar cell as power source installed on the wing span must also be considered as it also affects the drag and lift coefficient. Because of consisting of complex problem solution, optimal sizing method based on multi objective optimization is required to find the optimal power with lower load. As input variables, the method uses payload, solar panel characteristic, and flight location.

This paper proposes multi objective genetic algorithm to solve complex problem in designing of solar powered UAV. The organization of this paper is started with modeling of UAV components, optimization procedure using multi objective optimization, results and analysis and finally closed by conclusions.

2. **Modeling the Parameters for Optimal Sizing of Solar Powered UAV.** The electrical system on the UAV consists of solar cell, battery, maximum power point tracking (MPPT), DC-DC converter, and electronic control system. Battery acts as a storage

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where the energy gathered from the solar cell is stored during the day. Therefore, an MPPT and a charge controller also present to improve the efficiency. The electrical schematic of the system is shown in Figure 1. Electronic control system is a DC-DC converter which controls the brushless DC (BLDC) motor.

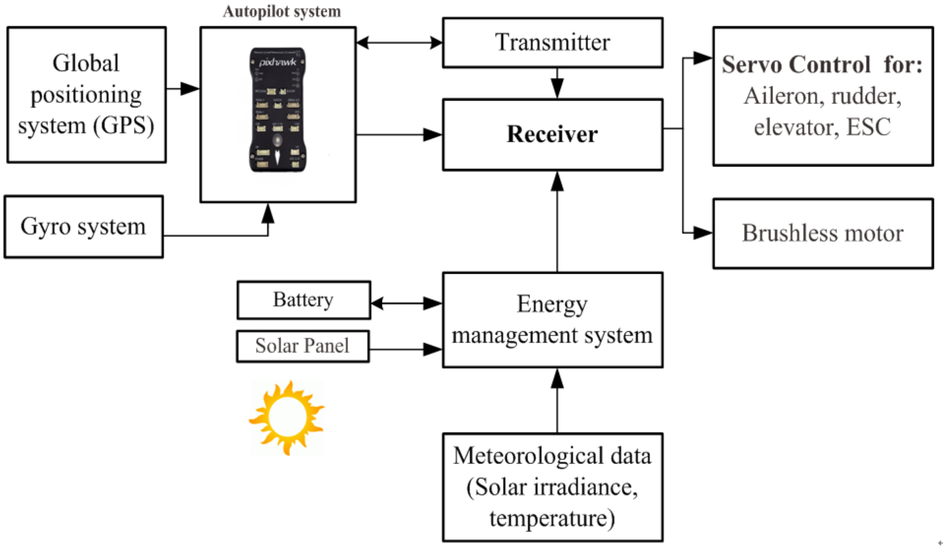

FIGURE 1. Overall control system in solar powered UAV

2.1. **UAV aerodynamics.** The optimal aerodynamic design of UAV is based on the optimal solution of wing area (S_{ref}), cruising speed (v), drag coefficient (C_D), lift coefficient (C_L) and aspect ratio (AR) under a certain aerodynamic condition and power required. Optimization must also consider the aircraft wing aspect ratio [3]. The movement of aircraft wing also affects its performance [4]. However, in this paper, wind effect is neglected because of its complexity in its direction. The optimal solution is suitable only on straight line maneuver. Several best assumed parameters will be used for initial value as shown in Table 1.

TABLE 1. Initial value for optimal sizing

Variable	Value	Variable	Value
η_{mppt}	0.95	f_{DOD}	1.2
$\eta_{converter}$	0.7	η_{motor}	0.8
K_{mppt}	0.00047	K_{panel}	0.9
g	9.8 m/s^2	$\eta_{propeller}$	0.85
$\rho_{battery}$	196 Wh/kg	f_{safety}	1.2
$\eta_{discharge}$	0.95	e	0.9
η_{charge}	0.8	S_{sol}	0.85
η_{panel}	0.16	T_{day}	12 hours
T_{flight}	24 hours	T_{night}	12 hours

2.2. **Modeling of irradiance.** The characteristic of solar irradiance depends on geographical position, time, and solar cell orientation. In this paper, solar irradiance characteristic is modeled using Duffie & Beckman's sinusoidal. Therefore, to fly UAV in a year, it requires irradiance data in one year for calculation. In this research, the flight takes place in Surabaya with an average irradiance level at 894 W/m^2 as shown in Figure 2.

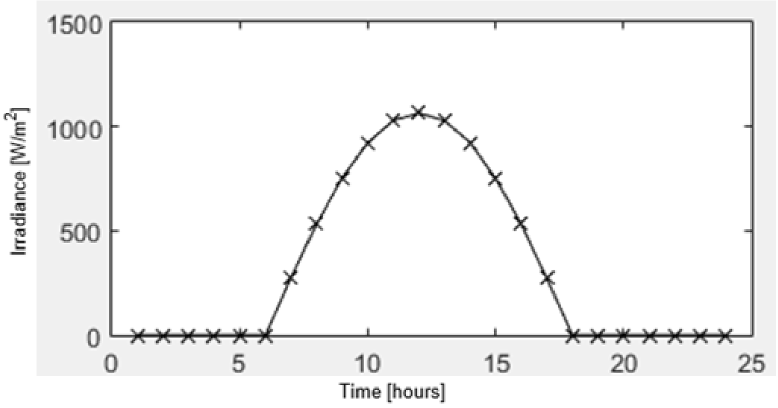

FIGURE 2. Irradiance curve estimation in Surabaya

2.3. **UAV weight estimation.** Weight estimation is required for the total power required by the UAV. The weight of every component including solar management system, battery, payload, and solar cell, is taken into calculation. The solar management consists of the solar cell, MPPT, charge controller, and electric speed controller. If the solar cell is assumed to occupy 90% of the wing area and its weight is 0.22 kg/m^2, then the total mass of the solar cell is

$$M_{panel} = 0.22 \times S_{panel} = 0.198 \times S_{ref} \tag{1}$$

Then, the MPPT weight can be calculated as

$$M_{mppt} = K_{mppt} I_{\max} \eta_{panel} \eta_{mppt} S_{panel} \tag{2}$$

where K_{mppt} is power to weight ratio of commercial product, $I_{\max}$ is maximum irradiance of 1,297 W/m^2, S_{panel} is area of solar cell and η_{panel}, η_{mppt} are the efficiency of solar cell, MPPT respectively [13]. Meanwhile, MPPT weight (M_{mppt}) is

$$M_{mppt} = 0.0834 S_{ref} \tag{3}$$

Propulsion system weight ($M_{propulsion}$) is modeled based on the linear regression of motor power to weight ratio, as follows:

$$M_{propulsion} = 0.0045 \left(\frac{1}{2} \rho_\infty v^3 S_{ref} C_D \right) \tag{4}$$

where ρ_∞ is air density, v is velocity, S_{ref} is wing area and C_D is drag coefficient. The UAV structure weight ($M_{structure}$) is the sum of its fuselage weight, which is measured 1 kg (this parameter is assumed constant for the optimization), and the wing span acquired from the calculation. The equation is as follows

$$M_{structure} = 0.9 \times S_{ref} + 1 \tag{5}$$

The battery used in the UAV has the biggest contribution to its total weight. In this research, Lithium Polymer (LiPo) battery is chosen. This type of battery has a large energy density and high charge-discharge rate [7]. Battery weight ($M_{battery}$) can be written as follows

$$M_{battery} = \left(C_{D,0} + 0.4718 AR^{-1} C_L^2 \right) 0.087 v^3 S_{ref} + 2.42 \tag{6}$$

Therefore, the total weight function including payload weight ($M_{payload}$) for the optimization is

$$M_{total} = M_{structure} + M_{battery} + M_{propulsion} + M_{panel} + M_{mppt} + M_{payload} \tag{7}$$

Hence,

$$M_{total} = \left(C_{D,0} + 0.4718 AR^{-1} C_L^2 \right) 0.092 v^3 S_{ref} + 1.1814 S_{ref} + 4.42 \text{ kg} \tag{8}$$

2.4. **Required power.** The required power is the total of remaining energy in the battery after operating for 6 hours in night and by the day for 12 hours divided by 12 hours of battery charging time [8]. The total required power ($P_{required}$) is therefore

$$P_{required} = \left(C_{D,0} + 0.4718AR^{-1}C_L^2\right) 0.24055v^3 S_{ref} - 5.525 \tag{9}$$

Solar panel will generate power $P_{generated}$ which can be calculated with following equation

$$P_{generated} = 0.9S_{ref}E_{sun}\eta_{panel} = 128.7S_{ref} \tag{10}$$

where $0.9S_{ref}$ denotes the 90% of wing area which is covered by the solar panel. E_{sun} is the average solar irradiance with a value of 894 W/m^2. Thus, the total power that must be supplied by the solar panel is

$$P_{supplied} = \frac{128.7S_{ref}}{0.8} = 160.875S_{ref} \tag{11}$$

2.5. **Genetic algorithm configuration for optimal sizing.** Multi-objective genetic algorithm begins with a set of solution candidates called population. In each iteration, the population will generate new individuals. Each individual has a property which can be mutated and altered. A better chromosome results in more offspring, which has a better chance to survive [5,12]. The algorithm moves toward the best solution by evaluating the fitness function for each individual.

1) For the optimal sizing, the algorithm begins with two sets of chromosome for each variable as initial population. Each set contains 100 chromosomes represented by 10-bit binary string as shown in Table 2. The algorithm will find the minimum optima for each variable.
2) At this stage, compatibility on each chromosome in the population is determined to be used to evaluate compatibility with the obtained solution. The fitness function is defined in the equation.

$$J(C_L, C_{D,0}, S_{ref}, v, AR) = w_1\left|L/g - M_{total}\right| + w_2|v - V_{opt}| + w_3|P_{supplied} - P_{required}| \tag{12}$$

   In this paper, the weight coefficients w_1, w_2 and w_3 are 30, 5, and 60 and some limitations must be assumed as follows:
   - $L - M_{total} \cdot g = 0$
     Lift force (L) is equal to the aircraft weight force.
   - $v = V_{opt}$
     Cruise speed is equal to the optimum speed.
   - $P_{supplied} - P_{required} \geq 0$
     The total generated power from the solar panel must be the same as required power.
   - $T_r \geq D$
     Torque must be the same as drag force.
3) After a specified condition is satisfied, the algorithm stops and reiterates.
4) The algorithm generates new population and performs crossover and mutation. Only the best 15% of the population can make it to the next iteration. Crossover can combine sub-solution from each chromosome. This can increase the algorithm tracking speed. The crossover rate is chosen by using trial and error to be 0.85. Mutation can alter the new offspring from its parent. A Gaussian operator is used for the mutation.
5) New population replaces the old ones and the algorithm starts evaluating the new population. The algorithm stops either when a maximum number of generation is reached which is 200, or when fitness function is satisfied, or when the algorithm has reached 50 s of running time.

Table 2. Chromosome representing aircraft parameters

Area S_{ref}		**Cruise Speed (v)**	
S_1	1001100010	V_1	1110110000
S_2	1101101010	V_2	1010110001
.		.	
S_3	1001001010	V_3	0010010011

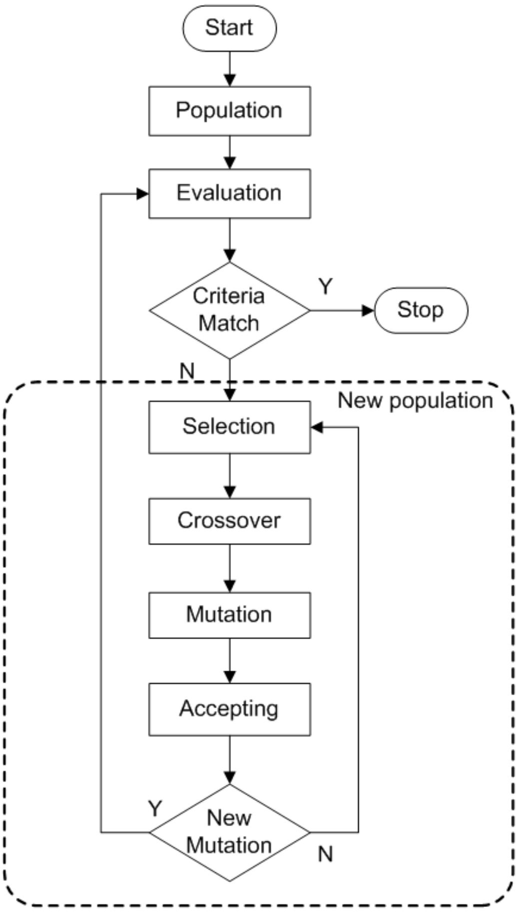

Figure 3. Optimization process using genetic algorithm

3. **Simulation Result and Analysis.** After the proposed algorithm is simulated on MATLAB Software, an optimal solution is obtained. The algorithm reaches the optimal solution in 100 iterations. As can be seen in Figure 4, the fitness function decreases in each iteration. The final fitness value is 375.69. From the algorithm result, the value for each variable can be calculated by inserting the fitness value to Equation (9). The result and aircraft specification are shown in Tables 3 and 4. From the above variables can be determined aircraft specifications as in Table 4. It can be seen that in order to fly for 24 hours a battery capacity of 1,517.53 Wh is required. The motor specification needed to be able to take off, maneuver, and downwind is 2,170 W, but to keep the plane flying straight parallel to the required power is 114.17 W. In order to lift loads the aircraft requires a wing span of 4.0728 m^2 with the ratio of the length and wings as 15, so that a wing span of 7.886 m is obtained.

3.1. **Force analysis.** From the calculation result in the previous section, the force which is applied to the aircraft can be calculated. The results are shown in Table 5 and Figure 5. From Table 5 and illustrated in Figure 5, it can be seen that the lift force is greater than

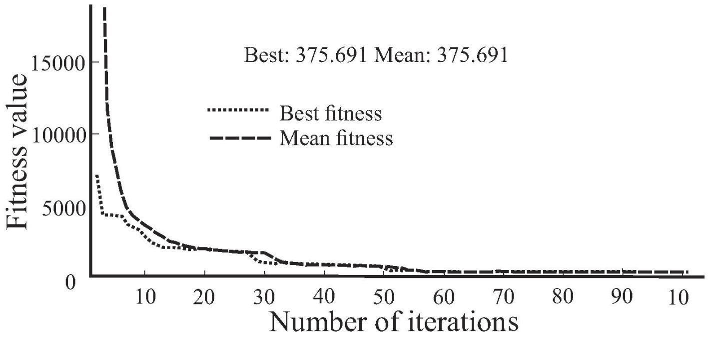

Figure 4. Fitness value of the algorithm

Table 3. Optimization result of each parameter

Variable	**Value**
ρ_∞	1.225 kg/m^3
$C_{D,0}$	0.00988
C_L	0.3121
S_{ref}	4.0728 m^2
V	12.6223 m/s
AR	15

Table 4. Calculated aircraft specification

Parameter	**Value**	**Parameter**	**Value**
Battery capacity	1,517.53 Wh	Aspect ratio	15
Battery	102.54 mAh	Wing span	7.886 m
Motor	2,170 W	Wing area	4.0728 m^2

Table 5. Force applied on aircraft

Parameter	**Value**
Lift	124.05 N.m
Weight	122.67 N.m
Drag	5.12 N.m
Torque	6.15 N.m

the weight force, which means the aircraft can fly properly. While the torque is greater than the drag force, meaning the aircraft can fly straight forward.

3.2. **Power balance analysis.** Within 24 hours an analysis of the power balance is carried out as can be seen from Figure 6. The power consumed is considered constant because it does not consider the effect of changes in air speed, changes in temperature, and power requirements for maneuvering. The power consumed is 205.95 Watts, and it can be seen in Table 6. During the night or there is no power produced by the solar panel, the power source is taken from the battery. It can be seen at night the power of the battery keeps decreasing during the night. In the morning when the active solar panel is operating at 07:00 there is incoming power from the solar panel through the photoelectric effect, at 1:00 p.m. experiencing the highest power point then continue to decrease until 7:00 p.m. and stop generating power. The power used to charge the battery is a surplus resulting from reduced power generated by solar panels with normal power consumption. At 07:00 the power that arises is smaller than the power consumed new then because the

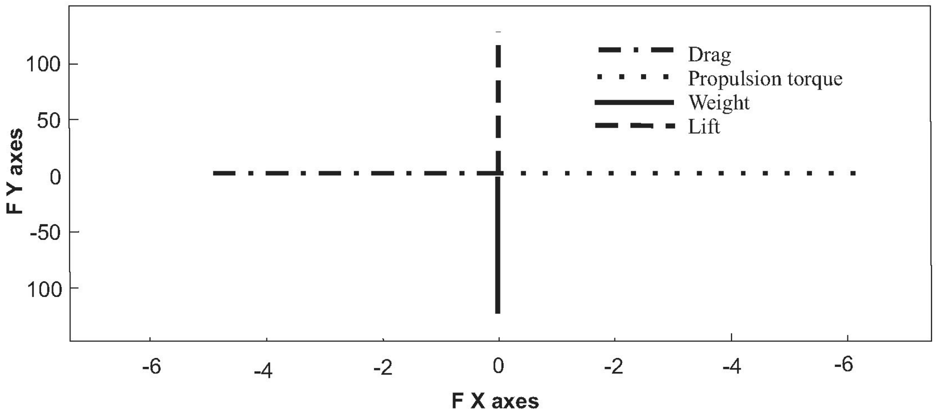

Figure 5. All forces occurring in solar UAV system

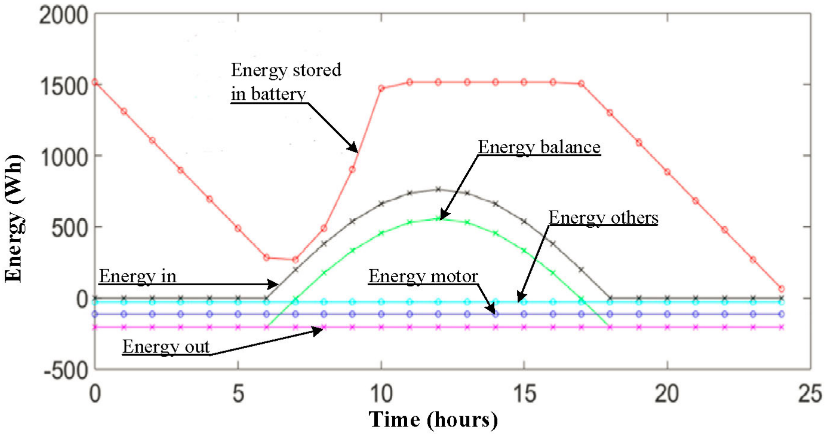

Figure 6. Power balance in the UAV system

Table 6. Energy on aircraft

Parameter	Value
Total energy charge	4,405.10 Wh
Average supplied energy	367.09 Wh
Power for propulsion	114.17 W
Consumed energy	205.95 Wh

more irradiation from the sun, the greater the power generated. It can be seen at 12:00 the battery is fully charged. Above 12:00 because the power generated is greater than that consumed the power contained in the battery is always full, until at 6:00 p.m. the remaining power in the battery will begin to decrease.

3.3. **Effect of payload.** It can be seen in Figure 7 that the change in payload weight from 1 kg to 10 kg can be seen that with the increase in payload, the gravity on the aircraft will also increase, so that a larger lift is required, to increase the lift force, an increase in cruising speed is needed. The increase in cruise speed also affects the magnitude of drag, so that the thrust force is needed as well. It can be seen to get a balanced resultant force for each change in payload in straight and parallel flight conditions, so that there is an increase in cruise speed.

3.4. **Effect of solar panel efficiency to aircraft performance.** The modeled aircraft solar panel efficiency is varied from 16% to 61% with 5% incremental step. The cruise speed is adjusted to balance the force resultant so the aircraft can still fly in straight

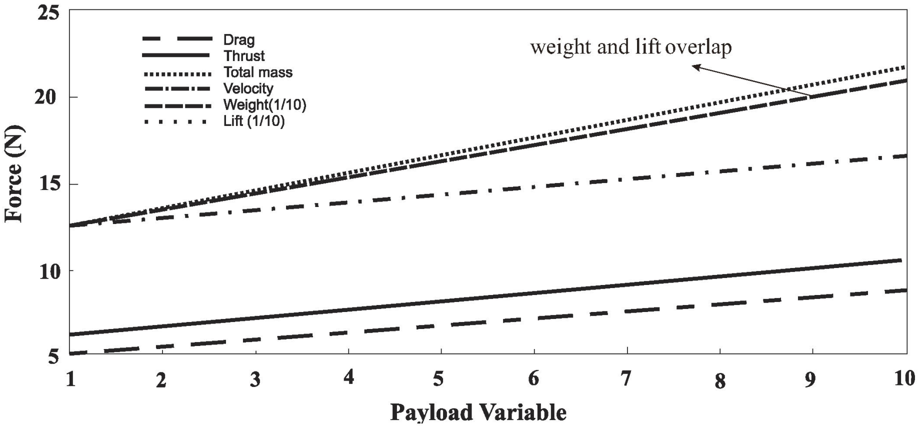

Figure 7. Effect of payload to the UAV force

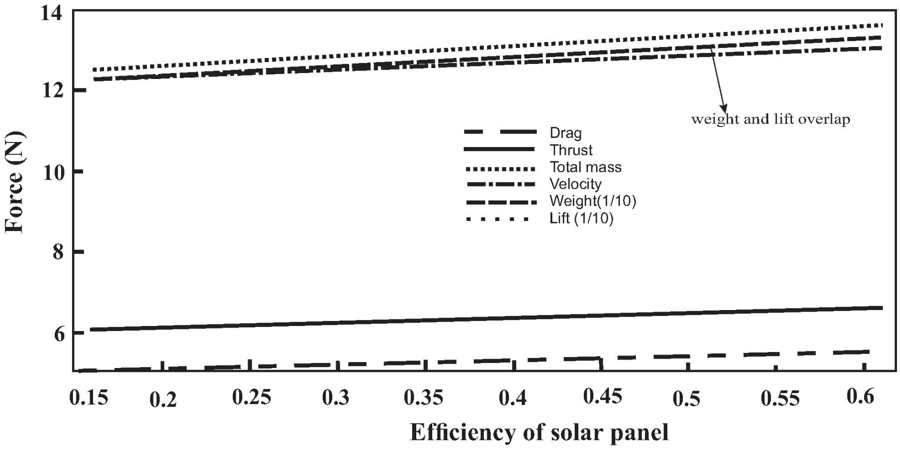

Figure 8. Variation in solar panel efficiency

line. As can be seen in Figure 8, the applied force remains constant under the change of solar panel efficiency. However, a change in efficiency must be followed by the MPPT dimension. In this case, MPPT dimension can change the total aircraft payload.

4. **Conclusion.** In an ideal condition, where the effects of wind, air pressure, and temperature are neglected, the solar powered UAV modeled from the optimal sizing can fly continuously for 24 hours. The UAV is able to fly with maximum payload of 3 kg. The UAV can fly under varying solar irradiance between 60% to 130% with initial irradiance of 843 W/m^2. The power supplied can be increased without changing the existing wing area by improving the solar panel efficiency. However, the increase of solar panel power requires a larger MPPT, which causes an increase on the aircraft total weight. A change in payload can be adjusted by changing the cruise speed. This is due to the fact that cruise speed affects the lift force. Battery contributes the most to the aircraft total weight; therefore, a further research is necessary to improve its energy density. With a bigger energy density, the aircraft will not need a large wing area in order to get an enough lift force. In the future, research will be carried out to improve in terms of changes in wind speed and direction, altitude, dynamic changes in solar irradiation and maneuvers.

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