Solar Cell to Support Perpetual Flight of High Altitude Long Endurance UAV ITB

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Abstract. Research on a High Altitude Long Endurance (HALE) Unmanned Aerial Vehicle (UAV) is currently being conducted at Bandung Institute of Technology to reach the flight duration needed and to get the solution of today’s challenges, minimizing pollution. Besides the good aerodynamic efficiency needed, energy resource is now becoming important. The energy resource must have a good endurance, easy to get, and of course, less pollution. Discussion in this paper is about the analysis of power needed by HALE UAV while takeoff and cruise flight conditions, and then determine the amount of solar cell and battery needed by the UAV.

Key Words: HALE UAV, solar cell, power consumption

Nomenclatures

| Symbol | Description |
|--------|-------------|
| T      | Thrust      |
| D      | Drag        |
| W      | Weight      |
| L      | Lift        |
| S      | Wing area   |
| ASC    | One solar cell area |
| ASCD   | All solar cell area |
| γ      | Climbing angle |
| φ      | Bank roll angle |
| Pa     | Power available |
| Pr     | Power required |
| Pe     | Excess power |
| Pau    | Avionic power |
| Ppay   | Payload power |
| Pservos| Servos (actuator) power |
| PSS    | Supporting system power |
| Pc     | Power for charge |
| Fcc    | Power for charge one cell battery |
| Psc    | Power that stored by one solar cell |
| Ptscc  | Power that stored by all solar cell |
| ρ      | Air density |
| V      | Air speed   |
| CL     | Lift coefficient |
| CD     | Drag coefficient |
| H      | Designated altitude |
| X      | Climbing distance |
| t      | Time        |
| ηmotor | Motor efficiency |
| ηESC   | Electronic Speed Controller efficiency |
| ηMPPT  | MPPT efficiency |
| ηSS    | Supporting system efficiency |
| NBT    | Amount of batteries |
| Nseries| Amount of series batteries setting |
| Nsc    | Amount of solar cell |
| Wcell  | Weight of one cell battery |
| WBT    | Weight of all batteries |

1. Introduction

Communication is one of the important things for human life. As the earthlings, a social human must have good communication skills in every way so a human can express whatever they want [1]. Especially in military aspects, communication is the most vital and important to make the command and secret data transmission transferred safely. Either long or short-range communication between earthlings, this communication activity uses satellite to widen the outreach and faster the data transmission [2]. Therefore, it’s a good thing if the satellite is owned by the military department itself.
to guarantee the secret communication. However, to make, to launch, and to operate the satellite is very expensive. In addition, if the launching is failed, the satellite couldn’t reach the orbit wanted or even broke when on a mission. The cost to fix it will be very expensive because there will be a spacecraft that needed to be launched again to fix it. So, the vehicle to substitute the satellite needed must be cheaper and easy to operate. HALE UAV is the answer for the challenge. The ability to fly high and has high endurance can be used as a repeater that can receive a signal from the earth’s surface, amplify it, and transmit it again to the earth’s surface.

To obtain a high endurance required a qualified energy source. As we know, most electric motors that used for UAVs use batteries that will eventually run out of energy. Candidate system that can overcome the limitation one of them is a solar cell. Solar cells are able to convert energy from the sun into electrical energy. Because it requires the sun, the weakness of solar cell is can not be used at night.

This paper performs a study to overcome weaknesses in the solar cell so it can produce a high enough endurance in this HALE UAV by finding the exact configuration of solar cell energy sources with batteries in which the solar cell will act as a major energy converter from the sun light into electricity and the batteries as a storage of energy from the solar cell [3]. To find out how much energy the energy source must produce is perform the calculation of the power required in some flying conditions such as take off and cruise.

2. HALE UAV Model
2.1. Model Geometry
HALE UAV use rectangular wing type with fuselage design that often used for a glider. Fuselage model designed aerodynamically to be able to minimize drag. Four brushless motors are planned to be mounted on its wing. Tail configuration uses middle HTP. All electrical components are kept inside the fuselage, except its propulsion system (motor, ESC, Battery) are kept in its own compartment. Here is it the design of the vehicle by design group of HALE UAV ITB using CATIA V5 software.

![Figure 1 HALE UAV model](image-url)
Table 1. HALE UAV Specification

| Specification          | Value          |
|------------------------|----------------|
| Wing Airfoil           | EMX-07         |
| Wing Chord (m)         | 0.42           |
| Wing Span (m)          | 16             |
| Wing Area (m²)         | 6.72           |
| MTOW (Kg)              | 20             |
| Wing Loading (Kg/m²)   | 2.976          |
| Material               | Fiberglass and carbonfiber composites |

2.2. Flight Operation

HALE UAV surveillance mission starts when approaching its cruise condition at desirable altitude and condition, as listed in the following table:

Table 2. HALE UAV flight condition

| Flight Condition      | Value          |
|-----------------------|----------------|
| Cruise Speed (m/s)    | 11             |
| Altitude (m)          | 6096           |
| Air density (kg/m³)   | 0.652694       |
| Temperature (K)       | 248.5          |
| Pressure (Pa)         | 46563.3        |

HALE UAV mission duration is expected to be twenty (20) hours.

2.3. Power Required

In order to achieve a certain amount of electrical power needed, propulsion power has to determined first. The propulsion power has to meet enough power for aircraft to take off and cruise flighting at maximum duration. Take off phase holds crucial role, due to its high power consuming because, in this stage, aircraft will climb into a certain amount of altitude. HALE UAV designed to use spring as its additional take off mechanism in order to increase its initial acceleration. Because it does not touch the runway, so the take off is only composed of a single phase that is climbing with a spiral trajectory. The vehicle continues to increase the altitude to designated altitude while turning. Actually, turning is produced by aileron with helped by rudder and elevator. So that for turning performance only seen from the lateral dimension. The cruise flight begins when the vehicle has reached the desired altitude of 6096m asl. That phase is the longest phase of the HALE UAV.

2.3.1. Take Off

Climbing phase indicated by the value of $\gamma$ is bigger than zero ($\gamma > 0$), therefore thrust has to be bigger than drag in order to produce extra power to increase its altitude. The calculation simplified by using assumptions such as aircraft is climbing with constant velocity, bank angle ($\varphi$) and climb angle ($\gamma$). Motors are mounted parallel equally within aircraft fuselage to produced $\alpha_T = 0$. The angle of attack also to be assumed as the small value [4]. First of all, longitudinal dimension needs to be analyzed to achieved conservation of power equation.
Equilibrium equations is performed on the wind coordinate order,

- X-axis:

\[ T - D - W\sin\gamma = 0 \]  
\[ \sin\gamma = \frac{T}{W} - \frac{D}{W} \]  

- Z-axis:

\[ W\cos\gamma - L = 0 \]  
\[ W\cos\gamma = L \]

Lateral dimension analysis is performed to see how bank angle affect aerodynamic forces while aircraft in turning flight condition, and its relation with longitudinal dimension,

\[ L\cos\phi = W\cos\gamma \]  
\[ L = \frac{W\cos\gamma}{\cos\phi} \]

Back to the longitudinal dimension. With multiplying equation (1) with velocity (V), we get the equilibrium equations of Power as follows,

\[ TV - DV - WVS\sin\gamma = 0 \]

TV=Pa, Power that must be provided to support certain flying condition
DV=Pr, Power that needed to against the drag
WVS\sin\gamma=Pe, Excess power that can be used to increase altitude
\[ P_a = P_r + P_e \]  \hspace{1cm} (8)

To obtain velocity, substitution equation (4) with the common aerodynamic equation of Lift.

\[ \frac{WCosy}{Cos\phi} = \frac{1}{2}\rho V^2 Sc_l \]  \hspace{1cm} (9)

\[ V = \sqrt{\frac{2WCosy}{\rho Sc_lCos\phi}} \]  \hspace{1cm} (10)

Calculation of \( Sin\gamma \) to obtain \( Pe \) reused equation (1),

\[ Sin\gamma = \frac{T}{W} - \frac{DCosy}{LCos\phi} \]  \hspace{1cm} (11)

\[ Sin\gamma = \frac{T}{W} - \frac{CDCosy}{CLCos\phi} \]  \hspace{1cm} (12)

To obtain the drag magnitude, done the comparison between lift and drag, and also substitution with equation (6),

\[ \frac{D}{L} = \frac{CD}{CL} \]  \hspace{1cm} (13)

\[ D = \frac{CDWCosy}{CLCos\phi} \]  \hspace{1cm} (14)

So,

\[ P_r = W \sqrt{\frac{2WCD^2Cos^3\gamma}{\rho Sc_l^3 Cos^3\phi}} \]  \hspace{1cm} (15)

From above equation, to obtain CL and CD required drag polar equations,

\[ CD = 0.0228 - 0.0013CL^2 + 0.0157CL^3 \] \hspace{1cm} (16)

So, need to know CL magnitude first when take-off to obtain CD magnitude with the equation above.

**Figure 4.** Climbing scheme. Reprinted from climbing angle illustration, Retrieved June 2017 from [4].

\[ tan\gamma = \frac{\Delta H}{X} \]  \hspace{1cm} (17)

In accordance with the flight operation data, HALE UAV will reach 20000ft (6096m) height directly from the ground (0 m) with a spiral path. The horizontal distance from the path is 13000m. To obtain the time from take-off to the desired height,

\[ t = \frac{X}{Cos\gamma V} \]  \hspace{1cm} (18)

While the bankroll angle limited to 30°, so \( \phi = 0.5236 \text{ rad} \).
For more conservative calculation, air density of 6096 m altitude has been used with \( \rho = 0.652694 \text{ kg/m}^3 \) (based on ISA Calculator). So, calculation becomes,

| Table 3. Take off calculation |
|-----------------------------|
| **CL (Max)** | 1.25 |
| **CD** | 0.045 |
| \( \gamma \) | 0.4385 rad |
| \( \phi \) | 0.5236 rad |
| \( V \ (g=9.8\text{m/s}^2) \) | 8.65 m/s |
| \( t \) | 1659.88 s |
| **Power Available (Pa)** | 785.43 Watt |

### 2.3.2. Cruise
Cruise is also called flat flight where the angle of attack usually small (wings parallel to local horizon plane) where the wing parallels with the local horizon. The use of power on this flight phase is very influential on the overall performance of the aircraft because of longest phase. Assumed cruise condition is stationary and analyzed on the wind coordinate order and the angle of attack is so small, so it can be ignored.

Equilibrium equations is performed on the wind coordinate order,

- **X-axis**:

\[
T - D = 0 \tag{19}
\]

\[
T = D = \frac{1}{2} V^2 S CD \tag{20}
\]

- **Z-axis**:

\[
W - L = 0 \tag{21}
\]

\[
L = W = \frac{1}{2} \rho V^2 S CL \tag{22}
\]

Cruise speed has been determined 10 m/s, the to obtain CL altitude when cruising from equation (20),

\[
CL = \frac{2W}{\rho V^2 S} \tag{23}
\]

CD calculation is done by equation (16) with entering CL value when cruise flight. Whereas to obtain power that needed when cruise flight with using equation (19) by multiplying it by \( V \).

\[
P_a = TV = DV = \frac{1}{2} V^3 S CD \tag{24}
\]
Table 4. Cruise calculation

|                      |       |
|----------------------|-------|
| \( V_{\text{cruise}} \) (\( g=9.8\text{m/s}^2 \)) | 11 m/s |
| CL                   | 0.739 |
| CD                   | 0.03  |
| \( P_{\text{Available}} \) (Pa)               | 136.1 Watt |

2.3.3. Power supporting system

In addition to calculating the power for the propulsion system, it also necessary to calculate the power for its supporting systems such as avionics system, actuator system, and payload that are carried.

\[
P_{SS} = \frac{P_{av} + P_{payload} + P_{servos}}{\eta_{SS}}
\]  
(25)

Table 5. Power supporting system

| Component | Power |
|-----------|-------|
| Avionics  | 1.71 watt |
| Payload   | 2 watt |
| Servo     | 24.48 watt |

Efisiensi is assumed to be 85%, so the total power required for supporting system is 33.16 watt.

3. Component and System Energy Source

3.1. Component

Here are some important components as parts of the energy source system whose the existence is very influential on the power required.

1. Batteries
   The batteries used are Li-ion type because it is easy to recharge and have a large capacity for the weight of only 46 grams. Each of its cell having a capacity of 3350 mAh and voltage 3.6 V. Meanwhile, recharging process of this type of battery requires the power of 6.825 watts per cell [7]. The batteries are assembled into 6S in series in order to get a voltage of 21.6 V.

2. Solar cell
   Solar cell used has a single cell size of 125 mm x 125 mm, efficiency value of 28% per cell, and the power that can be generated is 3.5 W per cell [8].

3. MPPT
   MPPT (Maximum Power Point Tracking) is a device that controls the energy flow from solar cells to both battery and another system installed in the UAV [9]. The MPPT used has an efficiency of 85%.

4. Propulsion System
   The propulsion system consists of brushless motor and Electronic Speed Controller (ESC), each having efficiency of 85%.

3.2. Energy Source

As we know, solar cells have the ability to convert solar energy into electricity at day, while at night solar cells then become useless since there’s no sunlight. Therefore, a battery is required as a storage that can be used for night operation. It will recharge its power during the day and can be used for the following night flight. The mission of this HALE UAV ITB will be for 20 hours as shown in the following scheme.
Figure 6. Flight scheme

The UAV take off at around 4:30 am with a full energy source from the battery because of the high current requirement and there is no sunlight yet. The UAV reach the cruise heights in about 27 minutes from take-off (calculation as shown in Table 3). In this phase, the UAV still use the battery as its only energy source, but with a much lower power requirement since it is now in cruise flight phase. When the sun rises up at around 6:00 am, MPPT will open a circuit to deliver energy from the solar cell to the battery charger and to the UAV’s propulsion system, disconnecting the circuit of the battery to the propulsion system. When the sunlight disappears at about 6:00 pm, MPPT will break the circuit to the battery charger and propulsion system, then reconnect the battery with the propulsion system. It is expected that at the end of the mission the UAV still has remaining energy left in the battery as an anticipation to any unwanted condition, even though the UAV is designed to landing by gliding (fly without thrust). From the above scheme, the cruise flight will be conducted for 12 hours exposed to the sun and 8 hours fly without exposure to the sun (1 hour is done early after takeoff).

3.2.1. Battery calculation

In order to get how much battery to use, it is necessary to analyze the phase of the night cruise and take off where the UAV fully use power energy from the battery. The power used is the total power that has corrected to the efficiency [10].

$$ P = \frac{P_a}{\eta_{Motor}\eta_{ESC}} + P_{SS} $$

(26)

Next, the amount of current required is obtained by dividing P with voltage,

$$ I = \frac{P}{21.6} $$

(27)

Then, to find out how much capacity is required, multiply equation (27) with the duration of the power being used.

$$ Cap. = Ixt $$

(28)

Once the amount of capacity required is known, then this amount is divided by the capacity available from the battery so that we can know the number of batteries in parallel (currents summation). Furthermore, multiplied it with the number of batteries used in series (voltage addition)

$$ N_{BTT} = \frac{\text{Needed Cap.}}{\text{Battery Cap.}} \times N_{series} $$

(29)

$$ W_{BTT} = N_{BTT} \times W_{cell} $$

(30)

Here is the table of the calculation,
Table 6. Capacity calculation

|                        |                |
|------------------------|----------------|
| \( P_{\text{cruise \_7hours}} \) | 221.5 Watt     |
| \( I_{\text{cruise \_7hours}} \)    | 10.25 A        |
| \( \text{Cap}_{\text{cruise \_7hours}} \) | 71773 mAh       |
| \( P_{\text{takeoff}} \)              | 1120.26 Watt  |
| \( I_{\text{takeoff}} \)              | 51.86 A        |
| \( \text{Cap}_{\text{takeoff}} \)      | 23913.51 mAh   |
| \( \text{Cap}_{\text{cruise \_1hours}} \) | 10253.22 mAh  |
| \( \text{Cap}_{\text{takeoff+\_cruise \_1hour}} \) | 34167 mAh |

From Table 6 above, capacity when take-off and one-hour cruise is smaller than a seven-hours cruise. By therefore the required capacity data is used from the capacity during night cruise for 7 hours. For safety reason, the multiplier factor 1.15 is used. So, the required capacity is 82538 mAh. Then equation (29) is used to obtain the required amount of battery.

\[
N_{BTT} = \frac{82538}{3350} \times 6 = 150 \text{ cell}
\]

So, it takes 150 batteries where each installed 6 pieces of series and 25 pieces of parallel.

\[
W_{BTT} = 150 \times 4.6 = 6900 \text{gr} = 6.9 \text{Kg}
\]

3.2.2. Solar Cell

To obtain how much solar cell is needed, the analysis is done on a day cruise (12 hours) where the solar cell supplies energy to charge batteries and also to the propulsion system. Power and current calculations use the same equation (26) and equation (27). To determine power that needed to recharge the batteries is as follows,

\[
P_C = P_{CC} \times N_{BTT}
\]

So, the total power required when cruising with solar cell is,

\[
P_{TSC} = \frac{P_{\text{charge}} + P_{\text{cruise \_12hours}}}{\eta_{MPPT}}
\]

Amount of solar cell is,

\[
N_{SC} = \frac{P_{TSC}}{P_{SC}}
\]

While the required area is,

\[
A_{TSC} = N_{SC} \times A_{SC}
\]

After the calculation obtained the following results,

Table 7. Solar cell calculation

| \( P_{\text{charge}} \) | 1023.75 Watt |
| \( P_{TSC} \) | 1464.96 Watt |
| \( N_{SC} \) | 419 pcs |
| \( A_{TSC} \) | 6.54 m² |

From Table 7, total area required by solar cell system is 6.54 m². The area is slightly smaller than the wing area vehicle, so it still possible to be installed in HALE UAV.
4. Results and Discussions

**Figure 7.** Climbing distance Vs Power available  
**Figure 8.** Cruise speed Vs Power available

Figure 7 above shows that climbing distance will affect to power that must be available for take off, but for cruise flight, there is no change (has no effect). Higher climbing distance with same designated altitude will give a lower climbing angle, so the power needed to take off is less but it will make the time for take off to be longer than high climbing angle. Figure 8 shows that cruise speed will affect to power that must be available for the cruise, but for the take off (climbing) flight there is no change (has no effect). Slower cruise speed will give less power for cruise. Because of cruise flight is the longest flight phase, so the cruise speed must be considered carefully. If we want to accelerate the mission, it must provide great power. But if we want a small power, cruise speed must be small as well but still higher than stall speed.

The planform area of the solar panel has to be as wide as the desired power generation. In order to generate a great amount of power, it is required a large of the solar panel too. However, the large solar panel gives result in considerable weight. Heavier weight will force the UAV to give more power. Therefore, calculation of power required is very important because it can affect the required wing area and how much the fill factor is. Fill factor is the ratio between size of solar panel area compared to wing area. The fill factor of HALE UAV ITB is 97% which means almost of the entire wing is covered with the solar panel. The stiffness of the solar panel should be a consideration since it has to fit the airfoil shape. The elastic solar panel is preferable since it has to follow the shape of the wing surface when being deflected. The 150 used batteries will be stored in a space located in the fuselage. Those batteries are connected directly to MPPT while MPPT also connects to solar panel and propulsion system. MPPT must be able to manage the power supply, when the supply should be from the solar panel and when it should be not.

5. Conclusions

HALE UAV ITB with its configuration that has fill factor 97% (6.54m² area of the solar panel) and 150 cell 3350mAH batteries still capable of doing continuous flight until 20 hours at altitude 6096 m when take off at 4.30 am and landing (with gliding descent and approach). The strategy is at the beginning of the flight battery was fully charged and drain for climbing flight (about 27 minutes) and for cruise flight (about 1 hour) until sun light appears and solar cell ready to convert and give the energy for flight. In the day, energy fully stored by the solar cell. In the night, batteries capacity will run out and that is time for landing with gliding flight which is no need external energy at 12 a.m.

For real perpetual flight (24 hours continuous flight), the configuration must be adjusted because it will need more battery capacity and solar panel area which is more weight and it must be
equal or under designed MTOW (20kg). For the next, to makes calculation close to reality, solar cell calculation must be considered the position of the vehicle, like latitude and longitude because it will affect to sun light intensity and will affect to energy that produced by the solar cell.

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