Prototype of a Solar-powered Fix-winged Unmanned Aerial Vehicle

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Abstract. The usage of solar power is a plausible and environment-friendly solution to solve the problem of limited duration of operation of current Unmanned Aerial Vehicle (UAVs) in market. Based on the state-of-the-art experiments in integrating solar power into aircraft and the basic theoretical calculations, this study investigates an attempt to construct a remote control solar-panel powered autopilot fixed-wing aircraft with technology accessible for home crafting. The aircraft is designed to recharge itself using sunlight within the duration of its operation and execute certain simple autopilot routes. The success of this model sheds light for further research and investment in making small-scale aircrafts solar-powered.

1. Introduction

The market for unmanned aerial vehicles (UAVs), or drones, currently spectates an ever-rapid boom. The maturing technologies in the aspects of radio transmission, vehicle autopilot system, photography device, robotics programming, etc. makes UAVs not only more and more accessible, but also increasingly important in humans’ industrial, social and personal activities. According to statistics of Harper [1], an estimated $11.1 billion was invested in UAVs for global military in the year of 2020, while the commercial drones’ market is expected to worth $7.13 billion by 2022, with a 18.0% growth rate [2]. However, certain obstacles still lie on the course of expansion. In particular, the power sources for commercial drones, which are mostly lithium batteries, pose a rigid limit on the duration of UAVs’ operation. For example, most of DJI’s UAV products have a maximum flight time lower than 30 minutes [3], or even shorter. Therefore, to achieve long-duration operation in the short term, it is necessary to devise a method to either recycle wasted internal energy, or obtain external energy for the batteries. On this basis, this research takes the approach of obtaining solar energy. one of the most accessible energies in the operating environment of the UAVs, in the attempt to extend the duration of the aircrafts. Most optimistically, it will allow such aircrafts to remain constantly in air. There have been several successful cases worldwide in constructing large scale solar-powered aircraft with cutting-edge technology, e.g., the Solar Impulse 2 has even completed around-the-world flights [4]. These flights are meticulously planned and employ some of the most advanced resources. Other studies, e.g., the design of the ZIU-SP-L [5], begin to focus on decreasing the scale of the aircraft for enhancing its adaptiveness and diversifying its application. This paper further investigates the feasibility to design a small scale solar-powered fixed-wing aircraft with readily accessible materials and technology for home crafting, which meets the demand of hobbyists and the general UAV market.
2. System Design:

a. Mechanical build-ups.

The overall design of the solar-powered aircraft is based on the type of design of conventional high aspect ratio gliders. Such type of design offers three advantages: the high lift to drag ratio and low lift reduction effect [6], the light-weighted airframe, and the regular rectangle surface of the airfoil compatible with the square-shaped solar cells. Nevertheless, a few modifications are applied to fully execute an entirely solar powered flight.

The most laborious redesign involves that of the airfoil. First, the structure needs to bear additional weight with the panels. Moreover, an additional circuit path is required to be constructed to connect the panels on the airfoil with the airframe. Last but not least, for the sake of mechanical simplicity and light weight, ailerons and flaps are functioned by the same part with mix control.

For simplicity, it is assumed that the cruise speed of the model is about 21.6km/h (6 m/s), the chord length is 0.29m, the Reynolds number [7] of the airfoil ranges from 100,000 to 110,000 depending on the temperature of the flight environment [8]. Considering the limited bending load of the crystalline panels [9] and the requirement of high lift coefficient (C_l) to drag coefficient (C_d) ratio, the airfoil of the model adopts the design of the FX 60 - 100 airfoil. According to Figure 1, it has a relatively low camber (max 3.6%), and at the same magnitude of Reynolds number (100,000) has a C_l to C_d ratio of around 60 at maximum. Figure 2 gives the sketch of the design.

The main material for the airfoil is 3mm Depron foam. The Heavily loaded parts such as the cross beams of the airfoils are reinforced with square-shape carbon rod of 40mm cross section area. Two 10-degree anhedral parts of the wings connect to the flat part with flexed plywood rods. The airframe is constructed with a combination of balsa wood board and round-shape cross sectional carbon fiber rods modified from fishing rods. The diameter of the carbon fiber rod in the front part of the airframe is 30mm and at the tail 20mm. Figure 3 shows the overall structure of the plane.
Figure 3. Overview of the aircraft

Figure 4. Circuit illustration

b. Electronic components.
   1) Power Unit: The power unit consists of 34 SunPower monocrystalline 125x125mm solar panels, each outputting a maximum 3.7W of power and 0.59 V of voltage, a customized maximum power point tracking system (MPPT), three 4.2V serial connected LiPo batteries, a 20A
electronic speed controller (ESC), a Futaba R7008SB signal receiver, a 2820 brushless motor and a propeller. The circuit diagram in Figure 4 illustrates the overall structure of the power unit.

All power generated by the solar cells is collected by the MPPT, which takes up multiple functions in power distribution. The MPPT prioritizes the power output to the ESC which is responsible for the motor and the receiver. Assuming a less optimal flight condition, in which the $C_L:C_D$ is minimum (about 15 according to Figure 1), the mass of the aircraft is about 1300g, and the overall mechanical efficiency is 60%, one derives the required power output from the MPPT to remain attitude is: $P_{\text{needed}} = \frac{F_{\text{drag}} \cdot V_{\text{airspeed}}}{60\%} = \frac{1}{15} \cdot F_{\text{lift}} \cdot V_{\text{airspeed}} = \frac{1}{15} \cdot 9.8kg/N \cdot 1300g \cdot 6m/s / 60\% = 8.5w$. SunPower claims the efficiency of its solar cells to be around 22% [12]. Besides, taking a lesser value, the total power generated by the 34 cells $P_{\text{offered}} = 34 \cdot 3.7w \cdot 15\% = 18.8w$. Therefore, there should be about 10w of surplus power to recharge the LiPo batteries when cruising theoretically, which is sufficient for the purpose of the design. In case of when the solar panels fail to provide adequate power for the model, the MPPT would automatically sense it and retrieve power from the LiPo batteries to the ESC.

2) Navigation Unit: The navigation of the aircraft is achieved by a dual control system. The autopilot system takes most of the responsibility cruising and executing the pre-designated route, while the manual system intervenes to take off and land or to deal with emergency. A Matek F405-Wing fixed-wing flight controller programmed with QGroundControl is connected to the channels of the R7008SB receiver, which can be remotely adjusted by the radio transmitter. The flight routes or electronic fences are set on the PC terminal of QGroundControl (Figure 5). The signal from the radio transmitter (manually controlled) is prioritized.

Figure 5. Illustration of the electronic fence

3. Final Preparation & Test:

a) Propeller: Three sizes of propellers (Diameter/Progression of each revolution) are tested. The pulling force and the power are measured and calculated in simulation of an airspeed ranging within 20~25 km/h. As shown in Table 1 below, the propeller of the 15 inches/10 inches size has the greatest pull to power ratio, i.e., it is the most efficient choice for this experiment.
Table 1. Statistics of different sizes of propellers

| Propeller Size (inch) | Pulling Force (N) | Current (A) | Voltage (V) | Power (W) | Fp/W |
|-----------------------|-------------------|-------------|-------------|-----------|------|
| 14/10                 | 1.4               | 0.9         | 11.1        | 9.6       | 0.146 |
| 14/10                 | 1.7               | 1.1         | 11.0        | 12.0      | 0.142 |
| 14/10                 | 2.0               | 1.3         | 11.0        | 14.6      | 0.137 |
| 15/10                 | 1.4               | 0.8         | 11.0        | 8.9       | 0.157 |
| 15/10                 | 1.8               | 1.0         | 11.0        | 10.8      | 0.167 |
| 16/13                 | 2.0               | 1.1         | 11.1        | 12.5      | 0.16  |
| 16/13                 | 1.8               | 1.2         | 10.9        | 13.5      | 0.133 |
| 16/13                 | 2.5               | 1.5         | 11.1        | 16.7      | 0.15  |

b) Test flight: Test flights are held out in three different afternoons of various non-raining weather and time of the day. All flights are within the same location, which’s address is Beijiang Dyke, Sanshui District, Foshan, China. The first day is for manual tests to ensure the functioning of the mechanical parts. Autopilot is used for the other two days, which is a 2D circular electronic fence of 150m or 200m radius. The altitude may vary depending on the power output of the propeller, and the lowest and highest altitude are measured and recorded every flight after takeoff and before landing. The voltage of the LiPo batteries is measured immediately before each takeoff and after landing.

4. Results & Discussion

Table 2. Flight Log

| Date      | Weather | Wind Scale | Electronic Fence Radius | Flight Altitude | Takeoff Time | Landing Time | LiPo Takeoff Voltage | LiPo Landing Voltage |
|-----------|---------|------------|--------------------------|-----------------|--------------|--------------|----------------------|----------------------|
| 12-Jun-21 | Clear   | 1~2        | / (manual test flights)   | /               | 2:15pm       | 2:30pm       | 12.4V                | 12.4V                |
| 12-Jun-21 | Clear   | 1~2        | / (manual test flights)   | 130~220m        | 2:45pm       | 3:20pm       | 12.4V                | 12.6V                |
| 12-Jun-21 | Overcast| 1~2        | 150m                     | 110~170m        | 3:45pm       | 5:00pm       | 12.6V                | 12.2V                |
| 13-Jun-21 | Overcast| 2~3        | 200m                     | 140~230m        | 4:00pm       | 5:15pm       | 12.6V                | 12.3V                |
| 13-Jun-21 | Overcast| 2~3        | 200m                     | 120~210m        | 5:45pm       | 7:15pm       | 12.6V                | 11.9V                |
| 19-Jun-21 | Clear   | 1~2        | 200m                     | 100~180m        | 3:00pm       | 5:30pm       | 12.0V                | 12.6V                |
| 19-Jun-21 | Clear   | 1~3        | 200m                     | 120~200m        | 5:45pm       | 7:40pm       | 12.6V                | 11.5V                |

5. Flight Log Analysis
A total of seven test flights are completed. Excluding the first two manual tests, most flight times exceed 1 hour, and the longest one reaches 2.5 hours. Although the state of work of both the solar cells and the LiPo batteries are not monitored during these test flights, it can be observed that the voltage difference from takeoff to landing has no direct correlation with the duration of each flight or with the wind scale. However, the data suggests the possible correlations between the discharge of the LiPo batteries and the weather and the launch time of the day. Voltage drop tends to be more evident for flights under overcast weather and during the later time of the day. Yet, more data collection is required to make a persuadable conclusion. A real time monitor and record of the charge-discharge state of the battery system and the altitude of the aircraft may be works of the immediate future tests.

6. Conclusion
In summary, this paper investigates the feasibility to construct and fly a hybrid fix-winged aircraft with civil crafting technology. According to the results, it can rely entirely on the power from onboard solar panels and recharge its LiPo batteries during most part of the flying mission. It is evident that the duration of a single flight mission of this aircraft can be far greater in magnitude compared to conventional LiPo battery powered aircrafts of the same size. Several possible improvements from the
current prototype can be prospected. First, the current aircraft only tests the possibility of flying. However, to make solar powered aircrafts applicable, many more functions are to be tested, including but not limited to aerial photography, high altitude data measurement and collection, security surveillance etc. All these functions require additional instruments mounted onboard, which may drastically affect the effectiveness of the solar cells or the aerodynamics of the aircraft and require redesigning. Second, the current prototype offers limited operation state which is the simple circular cruising. This ensures the consistency of both the power input from sunlight into the panels and the power output from the motor and the propeller. Meanwhile, a mature model would operate consistently in various states including pitching, rolling and yawing. Approaches to achieve such may be adding an automatic program to the MPPT system that offers a smarter and more dynamic use of both the solar cells and the LiPo batteries together. Third, the budget and the physical feature of the current model limits its availability in the market. The production cost of the prototype is around $250 USD, a price sufficient to directly buy a conventional RC glider from the market. The size of the model and its fixed-wing feature are also not very accessible for civil use, while the solar power would be much more difficult to utilize with a smaller model or multirotor drones. To tackle these issues, one needs to depend on the technological breakthroughs of solar energy and efficiency of UAVs in general. The upcoming tasks remain challenging, but this experiment is a strong assertion of the value and potential to continue advancing on this path.

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