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**PERFORMANCE CHARACTERIZATION OF MULTIFUNCTIONAL WINGS WITH INTEGRATED SOLAR CELLS FOR UNMANNED AIR VEHICLES**

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**ABSTRACT**

Flapping wing unmanned air vehicles (UAVs) are small lightweight vehicles that typically have short flight times due to the small size of the batteries that are used to power them. During longer missions, the batteries must be recharged. The lack of nearby electrical outlets severely limits the locations and types of missions that these UAVs can be flown in. To improve flight time and eliminate the need for electrical outlets, solar cells can be used to harvest energy and charge/power the UAV. Robo Raven III, a flapping wing UAV, was developed at the University of Maryland and consists of wings with integrated solar cells. This paper aims to investigate how the addition of solar cells affects the UAV. The changes in performance are quantified and compared using a load cell test as well as Digital Image Correlation (DIC). The UAV platform reported in this paper was the first flapping wing robotic bird that flew using energy harvested from on-board solar cells. Experimentally, the power from the solar cells was used to augment battery power and increase operational time.

**INTRODUCTION**

Unmanned Air Vehicles (UAVs) are becoming important platforms for both civilian and defense applications [1, 2]. UAVs come in various types, shapes, and sizes that allow them to be used for different applications. There are rotary, fixed-wing, and flapping wing UAVs. Flapping wing UAVs, also called ornithopters, have the potential to combine the positive aspects of both fixed-wing and rotary flight, while eliminating many of the negative aspects. Flapping wing flight is directly inspired by the flight of bats [3], birds, and insects [4, 5]. This paper focuses exclusively on bird-like flight.

The increasing interest in flapping wing UAVs has provided researchers the opportunity to investigate various aspects of flapping wing flight. There have been many studies where flapping wing UAVs have been constructed, characterized, and modeled [2-21]. For example, the Small Bird and Big Bird constructed at the University of Maryland, as well as the ornithopter constructed at the University of Delaware [22-24]. There are many similarities and differences between these three designs, but one important aspect of each design that is very similar are the wings. Each UAV’s wings are constructed using stiff lightweight rods as structural materials and a thin Mylar-based film as the wing surface/membrane.

A primary concern that arises with flapping wing UAVs is flight endurance. Typically to maintain flight, a small battery is chosen to keep the UAV as light as possible. However, the total flight time suffers because less energy can be stored in smaller batteries. Improvements in flight endurance allow for longer missions and more time between charges. To overcome this challenge, solar cells can be used to harvest energy and charge the batteries. The solar cells...
have the ability to both power the UAV and charge the UAV’s battery. This combination allows for increased flight time while decreasing the payload contribution of a large power source, thus potentially allowing for either: (1) size reduction with the same performance capability, or (2) an increase in overall payload capacity.

Most flapping wing UAVs have a small body supporting large wings, making the wings the best location for the solar cells. Integrating solar cells into the wings of a UAV turns the wings into multifunctional structures. Multifunctional structures combine multiple functional requirements into a single structural component to create better efficiency in the overall design [26]. Other UAVs with multifunctional structures have been constructed in the past. For example, an UAV constructed with MEMS technology has a membrane made of a PVDF skin, allowing it to act as a real time load sensor to directly analyze flight performance [11, 12]. Ma developed another MEMS-based insect-inspired flapping wing platform known as RoboBee uses artificial muscles to achieve novel controlled flight dynamics [27]. Thomas described the combination of structure and battery in the design of an electric-propelled UAV as an example of a multi-functional material system [26,28]. More recently at the University of Maryland, elastomeric strain gauges were placed on the wings of a flapping wing UAV [29]. These sensors captured deformations caused by flapping. The outputs from these sensors were directly correlated to thrust production which essentially made the wing into a skin-like structure.

Previously, the Advanced Manufacturing Lab at the University of Maryland developed a highly maneuverable robotic bird called Robo Raven [30, 31]. This platform features independent wing control, allowing the each wing to be programmed separately. In UAVs such as Robo Raven, flight endurance is a primary concern. Due to limitations in payload capacity, small batteries are used to power UAVs. By integrating a secondary power source, such as solar cells, flight endurance would increase. Integrating solar cells to the wings of Robo Raven would allow the UAV to harvest energy from the sun while maintaining flight.

The benefits of these multifunctional wings are clearly evident; however, the solar cells drastically change the weight and stiffness of the wings, changing the performance of the UAV. Integrating solar cells in the wings present the following two challenges. First, the multifunctional wings, with integrated solar cells, must undergo the appropriate deformation during the flapping cycle so that an adequate amount of aerodynamic lift and thrust are produced. Second, this new version of Robo Raven must produce enough aerodynamic lift and thrust to compensate for the heavier wings and maintain flight.

**OVERVIEW OF ROBO RAVEN**

In 2013, The Advanced Manufacturing Laboratory at the University of Maryland developed Robo Raven, an ornithopter with complete independent wing control. The wings are independently programmable allowing for a new degree of control and maneuverability [30, 31]. This UAV weighs 290 grams and has a wingspan of 114.3 cm. With a single servo powering each wing, new flapping frequencies, angular flapping ranges, and flapping gaits were explored. The body of Robo Raven consists of two 3D printed frames.

The first frame, located at the front of the robot, houses the two servos that manipulate/activate the wings. The second frame, located at the rear of the UAV houses a smaller servo that controls the tail. The tail is used to stabilize the UAV during flight as well as to turn the UAV by altering the heading. The two frames are supported and connected by 6 carbon fiber tubes that gives the Robo Raven a length of 0.554 m. These carbon fiber rods give the robot its body as well as a mounting location for the inside of the wings.

**Figure 1: Robo Raven**

The wings of Robo Raven were made of a thin Mylar skin supported by carbon fiber tubes and rods. The wings ability to deform provides the UAV with the necessary forces to maintain flight; therefore, the structure of the wings is a critical aspect of the UAVs design. The following figure and table clearly describe the structure of the wings.

![Figure 2: Wing Design](image)

**Figure 2: Wing Design, S is the semi-span, C is the chord, and t₆, t₃ are the diameters of carbon fiber stiffening rods**

**Table 1: Wing Design Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>605.8</td>
<td>mm</td>
</tr>
<tr>
<td>C</td>
<td>362.0</td>
<td>mm</td>
</tr>
<tr>
<td>t₁</td>
<td>3.18</td>
<td>mm</td>
</tr>
<tr>
<td>t₂</td>
<td>1.63</td>
<td>mm</td>
</tr>
<tr>
<td>t₃</td>
<td>1.63</td>
<td>mm</td>
</tr>
</tbody>
</table>
DEVELOPMENT OF ROBO RAVEN III

Expanding on Robo Raven, Robo Raven III is a new version of this ornithopter dedicated to the integration of solar cells into the wings. These new multifunctional wings allow solar energy to be harvested and converted into electrical energy for the UAV to utilize. A new technique for producing solar cell wings was developed. Powerfilm's® MPT6-75 solar cell modules were integrated into each wing. These flexible 7.3 x 11.4 cm solar cells run at 6 V and produce 50 mA of current. Six solar cells were attached together to make one solar panel. Each set of panels on each wing added a total of 10.1 g to the weight of the wing, which represents a 60% increase in mass for the wing. Each wing is capable of producing 300 mA of current at 6V totaling a maximum current output of 600 mA.

<table>
<thead>
<tr>
<th><strong>t</strong></th>
<th><strong>1.63</strong></th>
<th><strong>mm</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>θ₀</strong></td>
<td><strong>0.358</strong></td>
<td><strong>rad</strong></td>
</tr>
<tr>
<td><strong>θ₂</strong></td>
<td><strong>0.750</strong></td>
<td><strong>rad</strong></td>
</tr>
</tbody>
</table>

https://www.youtube.com/watch?v=mjOWpwbmnTw

Robo Raven is powered by a two cell Lithium Polymer (LiPo) battery rated at 25 C. The battery runs at 7.4 V and discharged at 370 mA. All two cell LiPo batteries are considered fully charged when their combined voltage reads 8.4 V. Under full load the battery can be depleted in 2.4 minutes. However, Robo Raven does not continuously run at full load and depletes the battery in 4.75 minutes using an average current draw of 4.67 A.

For Robo Raven to fly indefinitely, the UAV would have to produce 4.67 A from the solar cells. Currently, the 12 cell UAV can only produce 0.60 A. Therefore, Robo Raven III cannot fly indefinitely; however, these new wings can extend the flight time of the UAV as well as recharge the battery without the use of an electrical outlet.

To test how much more flight time the solar cells provide the vehicle, a simple flapping test was conducted outdoors on a clear sunny day. The solar cells were directly connected to the main power circuit of the UAV. This way, all of the electricity produced by the solar cells directly assisted in powering the vehicle during operation. The solar cells were able to extend the operational time of the vehicle to 5.48 minutes. This represents a 15.3% increase in operation time.

Robo Raven III currently lacks a switching mechanism to control whether the solar cells are either directly powering the motors or charging the batteries. Since the solar cells can only extend the flight time by 15.3%, the best permanent use currently of the solar cells is to recharge the bird in between flights. The battery is currently charged by connecting the solar cells through a circuit to the battery’s balancing plug. Figure 5 shows the charging circuit for the UAV.

Figure 3: Fabrication of Solar Cell Wings

These new wings ultimately changed the stiffness and thickness of the most forward section of each wing. This changed how the wings deform during the flapping cycle, thus altering the overall performance of the wings.
The solar cells are expected to produce 6.0 V at 300 mA for each wing at a solar flux of 100 mW/cm², and are depicted in Figure 15 as V1 and V2, referring to the left and the right wing. A zener diode with a breakdown voltage of 4.3 V is used as a voltage regulator. This value is necessary as the charging voltage of the Lithium Polymer battery is limited to 4.2 V per cell. The resistor in the circuit is placed to dissipate power so a 1.3 W zener diode can be used instead of a higher wattage. This circuit is designed under the assumption that the solar panel acts primarily as a current source at constant voltage. Pins are attached at the Black, Blue, and Red nodes in Figure 5 to connect into the corresponding wires of the balancing plug.

The balancing plug has a ground, blue, and red wire. The blue wire is typically a voltage reference to charge each cell at 4.2 V, and the red wire typically acts as an 8.4 V reference. The current design of the circuit provides 4.3 V at the blue node and 8.6 V at the red node due to the zener diodes. Since a voltage excess of 1 V is still considered a safe charging voltage, these values should operate without danger. The battery is connected only when the D2 diode has a minimum of 4.2 V across it and D1 has a minimum of 8.4 V. Current flows from high voltage to low voltage, so the solar cells must always be higher than the voltage of the battery. The diodes are capable of reaching the minimum voltage even on a partly cloudy day. It is expected that on an overcast day the diodes would not give enough solar power to reach the required voltage.

The charging rate of the solar cells was tested. A depleted battery was connected to the circuit and the wings were allowed to charge the battery to 8.0 V.

The wings were able to recharge the battery to 8.0 V in 93 minutes. This is twice as long as it takes to charge the battery using an electrical outlet; however, this is free energy that can be harvested anywhere there is sunlight. This allows the UAV to recharge without human intervention and can lead to very long mission with intermittent recharges. Currently, the circuit is slightly limiting the amount of current that can go to the battery through the choice of the resistor. By allowing more current through a lower resistance, more power can be harvested faster. However, this can have a negative effect on the overall life of the battery.

PERFORMANCE CHARACTERIZATION

To determine the affect the integration of solar cells has on the aerodynamic forces the wings can produce, three tests were conducted. First, a load cell was used to determine the forces generated by each wing. Next, Digital Image Correlation (DIC) was used to determine how the deformation of each wings differ because of the integration of solar cells. Last, an actual flight test was performed to determine if the UAV can fly with each set of wings.

For the load cell test, a new test stand was developed to hold the UAV and load cell inside of a wind tunnel.
This stand differs from the stand that was previously used because the load cell is now always horizontal and various angles of attacks can be tested for the UAV. The UAV can be tested anywhere from completely horizontal to an incline of 20 degrees and the load cell always measure true vertical lift and forward thrust. The base of the test stand is a 12x12 inch aluminum plate. The vertical support used to elevate the UAV so that the wings do not hit the ground while flapping is made of wood. The Small platform on top of the load cell is also made of wood, and the fittings for the UAV to attach to the test stand are custom laser-cut Delrin fittings. The load cell used was an ATI Mini40 force transducer. This six degree of freedom load cell is capable of measuring up to 40 N of force with a resolution of 0.01 N in the thrust direction and 120 N of force with a resolution of 0.02 N in the lift direction. With incoming air, aerodynamic lift and thrust are measured. The signal from the Mini40 is sent directly to a National Instruments PXI Data Acquisition Box. The raw signal is saved in National Instrument’s Signal Express software. The data is then exported to Microsoft Excel for post-processing.

The UAV has historically successfully maintained flight with a 20 degree angle of attack. To replicate the conditions the UAV experiences in the air, the UAV is set to an incline of 20 degrees on the test stand. Once the UAV is placed on the test stand and in the wind tunnel, bias data is recorded to tare the load cell. Once the bias data is collected, the wind tunnel is turned on and the UAV allowed to flap. The UAV flaps at a frequency of 4 Hz and an angular range of 60 degrees. The results are time dependent lift and residual thrust values through the flapping cycle.

Some trends are evident from looking at Figure 9 & Figure 10. As more solar cells are added to the UAV’s wings, the residual thrust that the wings can generate increases. As for the lift of the wings, the Solar Cell UAV provided the most amount of lift. This is great for the vehicle because there is the added weight of the solar cells the vehicle must overcome. By taking the average aerodynamic loads generated by the wings during the flapping cycle it is easier to quantify the differences in loads.

<table>
<thead>
<tr>
<th>Wing</th>
<th>Residual Thrust (grams)</th>
<th>Lift (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>113</td>
<td>240</td>
</tr>
<tr>
<td>12 Cell</td>
<td>118</td>
<td>251</td>
</tr>
</tbody>
</table>

This data provides information on the performance that each wing is capable of; however, it does not help solve why the integration of solar cells affects the performance in this way. To further investigate how the integration of solar cells affects performance, DIC was used to observe the deformation of the wings. Knowing the deformation, different strains can be calculated during the flapping cycle. The differences in each wing’s strain will explain how compliance plays a role in wing performance.
In 3D DIC, two digital cameras are used to record a deforming surface. The deforming surface has a speckle pattern allowing the image to be broken up into many different points. Using VIC-3D Software from Correlated Solutions, the points’ positions are tracked in relationship with each other and a 3D representation of the deforming surface is provided.

Figure 11: Example DIC Data of a Wing deforming Top: Original Image, Left: Out of Plane Deformation, Right ε_{yy} Data on Wing’s Surface

For these wings, two Flea3 FL3-FW-03S1M cameras were used to acquire the high speed images of the wing flapping. These cameras have the ability to record up to 120 frames per second (fps). However, at 120 fps, the cameras can easily become unsynchronized. To prevent this issue, the deforming wings were observed at a speed of 80 fps. Flapping at 4 Hz, this allows for 20 pictures to be taken per flapping cycle.

Our previous studies on compliant wing structures have shown that there is a direct correlation between spar deformations and thrust [32, 33]. In these studies, analytical models of the wing shape and aerodynamic forces generated \( \mathcal{F}_L \) and \( \mathcal{F}_T \) have been employed to understand the relationship as follows:

\[
\mathcal{F}_L = \int C_D \rho v^2 \cos(\theta) \, dA \tag{1}
\]

\[
\mathcal{F}_T = \int C_D \rho v^2 \sin(\theta) \, dA \tag{2}
\]

Where \( C_D \) is the drag coefficient of the wing through the air, \( \rho \) is the density of the air, \( v \) is the velocity of each point of the wing through the air (controlled with flapping frequency), and \( \theta \) is the flapping angle. In addition empirical terms have been employed for the thrust to account for the compliance of the wing on the blowback effect as follows:

\[
\Delta F_D = (kf)\sin\left(\frac{\pi(\theta - \theta_f)}{\theta_f - \theta_i}\right) \tag{3}
\]

\[
v = \left(1 - \frac{\partial f}{\partial \theta_i}\right) v_o \tag{4}
\]

where \( \Delta F_D \) is the change in total drag force, \( k \) is an empirical constant of proportionality, \( f \) is the flapping frequency, \( \theta_i \) is the angle of the wing during the flapping cycle, \( D_f \) is the level of the drag force above the point at which the deformation transitions from global to local during blowback, \( c \) is the global compliance of the wing, \( \delta \) is the displacement of the mid-chord of the semi-span of the wing if it were infinitely rigid, and \( v_o \) is the velocity if the wing were infinitely rigid.

With 3D DIC, we could obtain strain information over the entire wing instead of just the spar, where \( x \) was in the direction of the front spar and \( y \) was in the direction normal to it. Thus, it provides a more direct measure of the shape effects on the aerodynamic loads acting on the wings.

Table 3: 3D DIC Strain Results Obtained for each Wing Averaged over the Wing and over one Flapping Cycle with the Corresponding Thrust

<table>
<thead>
<tr>
<th>Wing type</th>
<th>Lift (g)</th>
<th>Thrust (g)</th>
<th>( \varepsilon_{xx} )</th>
<th>( \varepsilon_{yy} )</th>
<th>( \varepsilon_{xy} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>240</td>
<td>113</td>
<td>0.0355</td>
<td>0.0225</td>
<td>0.0042</td>
</tr>
<tr>
<td>Solar Cell</td>
<td>251</td>
<td>118</td>
<td>0.0417</td>
<td>0.0236</td>
<td>0.0092</td>
</tr>
</tbody>
</table>

Therefore, the analytical models for the thrust and lift force generation can be used to understand the relationship to these wing deformations. From the experiments, it was determined that the absolute lift correlated most directly with the biaxial strain, while the shear strain was found to provide the best correlation with the thrust data collected by the load cell. This is not unreasonable given that the biaxial strain is related to the “ballooning” effect of the wings that governs the negative lift through the change in the drag coefficient, while the shear strain is related to the distortions of the wing that generate thrust by blowing air out of the back of the wing. These distortions are expressed through the compliance in the empirical correction factors for thrust. Thus, it was concluded that the levels of biaxial and shear strains can be direct indicators of the effects of adding solar cells to the lift and thrust loads acting on the compliant wings.

Figure 12: Direct Comparison of Time-resolved Measured Biaxial Strain Obtained using 3D DIC Averaged over the entire Wing with the Lift Measured on the Test Stand for the Regular Wings
The lift and thrust compared to the biaxial strain and the shear strain as a function of flapping angle can be seen in Figure 16 for the regular wings and Figure 17 for the solar cell wings. A direct comparison of the lift and thrust profiles for the regular and solar cell wings can be seen in Figure 18, and the biaxial strain and shear strain in Figure 19.

As with the time-resolved measurements, the lift and thrust loads versus the DIC strains show very similar profiles with flapping angle, which further corroborates the correlation between these quantities. Thus, it appears the deformation directly controls the aerodynamic loads acting on the flapping wings, and that the greater deformation generated by the solar cell wings results in more air being captured and ejected out the back of the wing to generate thrust (the 3% increase in Table 4 that resulted from a 118% increase in shear strain for multifunctional wings with solar cells) and lift (a 5% increase for a 11% increase in the biaxial strain), it is also important for generating more aerodynamic lift. Therefore, it was concluded that both the biaxial and shear strains averaged over the wing is an important indicator of lift and thrust generation for designing multifunctional wings with solar cells. However, quantitatively the thrust is less sensitive to the increase in wing deformations than the lift was.
RESULTS AND DISCUSSION

To assess the difference in performance of the multifunctional wings compared to the regular wings, flight test were conducted comparing the two wing designs. By simply observing the UAV visually, there were slight obvious differences. The UAV with regular wings was able to climb slightly faster than the solar celled UAV. To confirm these observations, the forward velocity and climb rate of the UAV were measured.

<table>
<thead>
<tr>
<th>Table 4: Forward Velocity and Climb Rate for Regular and Solar Cell Wings</th>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Forward Velocity (m/s)</td>
</tr>
<tr>
<td>Climb Rate (m/s)</td>
</tr>
</tbody>
</table>

Although there was a slight decrease in climb rate, the solar cell UAV was still able to maintain flight. A video of Robo Raven III flying can be seen at the following link:

https://www.youtube.com/watch?v=t1_mPe8Y0V4

Integrating solar cells is a great solution for increasing flight time. Being able to produce as much power that is needed, an UAV could theoretically fly for as long as there is sunlight. However, producing that much energy with a limited area is difficult. Still, increasing flight time length is still a great benefit that solar cells wings provide for flapping wing UAVs. There is also the added benefit of not needing an
electrical outlet to recharge the UAV. Adding enough solar cells to produce enough energy to fly indefinitely may seem like the solution to this problem, but adding more solar cells has an effect on performance. Apparently by adding solar cells to the front most part of the wing actually helps generate more aerodynamic force. However, a total of 20.2 grams were added to the original vehicle and only an additional 11 grams of lift were generated. This shows we have a total decrease in performance since the payload capacity of the UAV actually decreased.

A wings ability to capture air underneath the wing is important for flight. The wing must be able to deform to capture the air then proceed to push the captured air back propelling the UAV forward. Adding solar cells to the front most part of the wing increases the amount of thrust that can be produced by 5 grams or 4.4%. Likewise the lift increased by 4.5%. If we were just comparing performance of the wings, it is clear that the solar celled wings outperform the regular wings. However, the solar cells increase the weight of the UAV by 20.2 grams or 6.9% of the original wings. It is clear that as more solar cells are added the amount of force produced will not be able to overcome the amount of weight that will be added.

CONCLUSIONS

The ability to harvest energy is an improvement in the design of UAVs. Historically small vehicles use a small battery to stay as light as possible. This prohibits long flights and missions because the UAV will quickly deplete the small battery and run out of energy. Adding solar cells to the wings of flapping winged UAVs allows the UAV to stay aloft for a longer period of time. Also the UAV can be recharged without the use of an electrical outlet allowing longer missions. However, integrating solar cells into the wing affects the performance of the UAV.

Robo Raven was used as a platform MAV to integrate solar cells into the wings. This new MAV with functional solar cells was called Robo Raven III. Twelve solar cells were attached to the front of the wings. This MAV was capable of a 15% longer flight and could recharge a depleted battery to 8.0 V in 93 minutes.

The benefits of solar cell integration are clear, but they have a negative effect on performance. By adding solar cells to the front part of the wing, the wing actually deforms in a favorable manor and an increase in aerodynamic forces is seen. However, the increase in aerodynamic forces does not compensate for the increase in mass to the MAV. The additional 11 grams of lift produced are nullified for the 20.2 grams of weight added to the MAV. There is a threshold where adding a certain amount of solar cells will not allow the MAV to maintain flight; however, adding 12 solar cells the MAV does not meet that threshold and the MAV is still able to maintain flight.

ACKNOWLEDGMENTS

This work was sponsored by AFOSR grant FA9550-12-10158 with Dr. Byung-Lip “Les” Lee as program manager. Dr. S.K. Gupta’s participation in this research was supported by National Science Foundation’s Independent Research and Development program. Opinions expressed are those of the authors and do not necessarily reflect opinions of the sponsors.

REFERENCES


