

ENERGY HARVESTING FOR UNMANNED AERIAL VEHICLES

Steven R. Anton

Faculty Advisor: Daniel J. Inman

Center for Intelligent Material Systems and Structures
Virginia Polytechnic Institute and State University, Blacksburg, VA 24060

Abstract

Unmanned aerial vehicles (UAVs) are a critical component of many military operations. Over the last few decades, the evolution of UAVs has given rise to increasingly smaller aircraft. Along with the development of smaller UAVs, termed mini UAVs, has come issues involving the endurance of the aircraft. Endurance in mini UAVs is problematic because of the limited size of the fuel systems that can be incorporated into the aircraft. A large portion of the total mass of many electric powered mini UAVs, for example, is the rechargeable battery power source. Energy harvesting is an attractive technology for mini UAVs because it offers the potential to increase their endurance without adding significant mass or the need to increase the size of the fuel system. This paper investigates the possibility of harvesting vibration and solar energy in a mini UAV. Experimentation has been carried out on a remote controlled (RC) glider aircraft with a 1.8 m wing span. This aircraft was chosen to replicate the current electric mini UAVs used by the military today. The RC glider was modified to include two piezoelectric patches placed at the roots of the wings and a cantilevered piezoelectric beam installed in the fuselage to harvest energy from wing vibrations and rigid body motions of the aircraft, as well as two thin film photovoltaic panels attached to the top of the wings to harvest energy from sunlight. Flight testing has been performed and the power output of the piezoelectric and photovoltaic devices has been examined.

Keywords: energy harvesting, unmanned aerial vehicle, piezoelectric, photovoltaic, solar energy

Introduction

The development of unmanned aerial vehicles (UAVs) has been of interest for military applications for several decades. Most recently, focus has been placed on creating small UAVs, termed mini UAVs, which can be small enough to be carried and deployed by soldiers in

the field. These vehicles are primarily used for surveillance and reconnaissance, however, they can be designed to perform other tasks as well. One limitation of currently available mini UAVs is their endurance or maximum flight time. Mini UAVs are small and lightweight, therefore, they cannot carry large fuel payloads. Specifically in electric powered mini UAVs, the rechargeable batteries used to power the aircraft often compose a large amount of the overall aircraft mass, so increasing the battery size to improve endurance is not practical. In an effort to improve the endurance of mini UAVs without adding a significant amount of weight, the concept of vibration and solar energy harvesting using smart materials is considered. It is proposed that piezoelectric vibration harvesters and photovoltaic solar harvesters be incorporated into the design of the aircraft in order to actively harvest vibration and solar energy. This research will focus on quantifying the energy available for harvesting from both aircraft vibrations and ambient sunlight.

The concept of using harvested energy to power an unmanned aircraft is not new. In fact, the first completely solar powered flight took place on November 4, 1974 when the Sunrise I unmanned aircraft flew over Camp Irwin, California, powered only by the solar cells attached to its wings¹. Since the Sunrise I flew in 1974, many other solar powered aircraft have flown in various skies around the world. Over the past few decades, advances in photovoltaic cell technology have given rise to lighter and thinner solar cells. With these advances has come ongoing research in the field of solar powered aircraft, including the possibility of including light weight solar modules in UAVs²⁻⁴. Traditional solar panels contain crystalline silicon, which is the active material in solar cells, encapsulated into individual cells that are housed in a metal frame and protected with a glass cover. These traditional solar panels are rigid and heavy. Today, thin film solar cell technology exists in which amorphous silicon can be painted or rolled onto a very thin substrate to achieve light weight, flexible solar cells. A relatively new thin film solar module is considered in

this study and its performance related to UAVs is investigated.

Energy harvesting with piezoelectric materials has received much attention in the research community throughout the past decade. Much of the literature focuses on the design and optimization of cantilevered piezoelectric beams for energy harvesting, the development of efficient energy transfer and storage circuits, and the creation of self-powered sensors⁵. Although photovoltaic energy harvesting has been employed in UAVs for over thirty years, piezoelectric energy harvesting in the field of unmanned aircraft is a novel concept. The development of piezoelectric fiber based transducers has been a developing area of research that is of particular importance to piezoelectric harvesting in UAVs. Several fiber-based piezoelectric devices have been developed and tested in the literature^{6,7}. Some of the most notable commercially available piezoelectric fiber sensors include the Macro-fiber composite (MFC), which was developed at the NASA Langley Research Center and is available from Smart Material Corporation, and the Piezoelectric Fiber Composite (PFC) manufactured by Advanced Cerametrics, Inc. The MFC, in particular, has been studied and tested by both Sodano et al.^{8,9} and Schönecker et al.¹⁰ Piezoelectric fiber transducers are made up of small piezoelectric fibers that are aligned and embedded into an epoxy matrix. The fibers give the device increased flexibility over conventional monolithic piezoceramic. This increased flexibility is important to UAV applications because the devices can be incorporated into the aircraft in locations of high strain without brittle fracture being a design concern. Both the MFC from Smart Material Corporation and the PFC from Advanced Cerametrics, Inc. are used in this study and their ability to harvest energy from vibrations in a UAV is explored.

The goal of this research is to perform an experimental proof of concept study on piezoelectric energy harvesting in UAV applications. Additionally, the performance of cutting edge thin-film solar cell energy harvesting in UAVs will be investigated and used as a means of evaluating the feasibility of piezoelectric harvesting for UAVs. Experimentation has been carried out on a remote controlled (RC) hobbyist glider airplane. Modifications to the RC aircraft have been performed in order to include MFC and PFC patches at the roots of the wings, a PFC cantilevered beam in the fuselage of the aircraft, two thin film solar panels on the top surface of the wings, and onboard data acquisition hardware. Both bench testing and flight testing has been performed on the aircraft. The power output of

each energy harvesting device has been investigated as well as the ability of the devices to be used to charge energy storage devices.

RC Aircraft Setup

A remote controlled hobbyist aircraft was chosen as the test bed for this study because the aircraft is inexpensive and easy to assemble, spare parts are readily available, and the aircraft is on the same length and weight scale as some existing military UAVs. The aircraft used in this study is an EasyGlider Electric ARF sailplane by Multiplex. The EasyGlider is a completely foam aircraft with an electric propulsion system composed of an electric motor and an 11.1 V, 2100 mAh Lithium Polymer battery. It has a wing span of 1.8 m, a length of 1.1 m, and a flying weight of 0.9 kg out of the box. This particular plane was selected primarily because of its long wing span and flexible foam wings, which provide a good environment for piezoelectric vibration harvesting using wing deflections. A photograph of the fully assembled aircraft including all modifications is shown below in Figure 1.



Figure 1. Fully assembled EasyGlider RC aircraft with modifications.

Fiberglass wing spar

Several modifications were performed on the original aircraft in order to include the piezoelectric and photovoltaic energy harvesting devices and the onboard data acquisition devices. First, the original carbon fiber wing spar rod which came with the plane was replaced by a rectangular fiberglass foam spar. The purpose of replacing the original round spar was to create a flat spar that would facilitate mounting of the MFC and PFC patches. The stiffness of the wing spar is an important factor in the design and performance of the aircraft, therefore, the stiffness of the fiberglass spar was designed to closely match the stiffness of the original carbon fiber spar. Prior to creating the final fiberglass spar, several quarter-scale models were

created and their stiffnesses were tested. The spars were created by cutting pieces out of a 12.7 mm thick sheet of foam and wrapping each piece in fiberglass cloth soaked in epoxy. The epoxy was allowed to set overnight in a vacuum bag. Each of the quarter-scale models had either a different type of fiberglass cloth or a different number of layers of cloth. Once the stiffness was matched, the full scale spar was created. First, the round channels in the underside of the aircraft wings were cut out to accept a rectangular spar. Next, a foam piece was cut and shaped with a hot wire cutter to fit in the modified channel. Lastly, two layers of fiberglass cloth were applied to the foam piece. Once the fiberglass spar was created, a MFC patch and a PFC patch were attached to the spar with epoxy under vacuum at locations near the roots of the wings. The MFC patch used, which can be seen in Figure 2, is a M8507-P1 patch with a length of 10.2 cm, width of 1.6 cm, thickness of 0.3 mm, and a mass of 3 g. The PFC patch, shown in Figure 3, has a length of 14.5 cm, a width of 1.5 cm, a thickness of 0.3 mm, and a mass of 2 g. Quick disconnect cables were attached to the leads of the piezoelectric patches to allow easy assembly and disassembly of the wings. The original foam covers for the carbon fiber spar could not fit over the fiberglass spar, so two fiberglass covers were molded to the underside surface of the wings and attached with superglue to hold the spar in place. Figure 4 shows a photograph of the fiberglass spar with attached patches inserted into the wing of the aircraft prior to the fiberglass covers being installed.



Figure 2. MFC patch



Figure 3. PFC patch

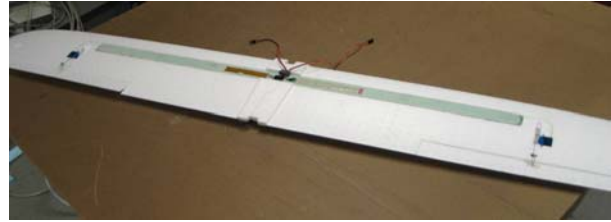


Figure 4. Fiberglass wing spar installed in underside of wing

Cantilever PFC harvester

The next modification involved installing the cantilevered PFC beam into the fuselage of the aircraft in order to harvest energy from the rigid body motions of the aircraft in the vertical direction. First, the section of fuselage directly behind the wings was selected as the mounting location of the cantilever harvester. This location was selected because it is the closest viable location to the center of gravity of the aircraft, which is approximately 7 cm behind the leading edge of the wing. The cantilever should be mounted close to the center of gravity of the aircraft because it is desired that the excitation source be from rigid body motions in the vertical direction, not from rotations of the aircraft. Once the location of the cantilever was selected, a channel was cut out of each half of the aircraft fuselage to house the beam. With the channel cut, bench tests were performed on the cantilever to select the appropriate tip mass to match the deflection of the beam with the height of the channel. After bench testing several configurations, a bimorph consisting of two PFC patches attached to either side of a metal substrate was selected for the cantilever beam. A bimorph configuration was selected because of its increased stiffness. Additionally, the power output of a bimorph is increased over a unimorph configuration because of the increased volume of piezoelectric material. The PFC bimorph selected has a length of 14.5 cm, a width of 1.5 cm, a thickness of 0.8 mm, and a mass of 5 g. Bench tests were also performed to determine the weight of the tip mass to be included with the cantilever. The beam was placed on a shaker and excited with impulses at an acceleration of approximately ± 1 g to simulate rigid body motions during flight. The weight of the tip mass was varied until an appropriate deflection was obtained when excited by the impulse. A 6 g tip mass was selected and glued to the tip of the cantilever beam. Next, a polycarbonate base was fabricated. The base is used to clamp the fixed end of the cantilever beam and to provide a rigid connection to the fuselage of the aircraft. The cantilever beam was clamped into the base and the base was attached to the inner fuselage

walls with superglue and epoxy. A photograph of the cantilever and base assembly glued to one half of the fuselage is shown below in Figure 5.



Figure 5. PFC cantilever beam installed in fuselage of aircraft

Solar Panels

Next, two thin film solar panels were installed on the top surfaces of the wings. The solar panels used are PowerFilm RC7.2-75 PSA panels with a length of 27 cm, a width of 9 cm, a thickness of 0.2 mm, and a mass of 5.9 g. The RC series of solar panels from PowerFilm are designed for RC aircraft and include an edge seal for extra weatherproofing. The solar panels were attached to the top surfaces of the wings on either side of the fuselage with a peel and stick pressure sensitive adhesive that was included with the panels. Additional duct tape was applied along the leading edge of each panel to help secure them during flight and also to secure the output wires running into the fuselage of the aircraft. The solar panels can be seen in the photograph shown in Figure 6.



Figure 6. PowerFilm solar panels installed on top surface of aircraft wings

Data Acquisition Systems

The final modifications to the aircraft involved creating two fiberglass canopies to house the data acquisition hardware used to take measurements during flight testing. Two data acquisition units were used on the aircraft. An XR5-SE-M-50mv eight channel data logger from Pace Scientific was used to measure several channels of voltage, and a UA-004-64 Pendant G 3-axis accelerometer data logger from Onset Computer Corporation was used to measure the aircraft accelerations. Each data logger is battery powered and stores data on internal memory. The XR5-SE-M-50mv logger can store up to 260,200 data points, and the UA-004-64 can store 21,800 combined x-, y-, and z-axis readings. Each data logger has an adjustable number of channels to sample and a variable sampling rate, which are adjusted in software. The XR5-SE-M-50mv has adjustable sampling rates from once every 12 hours up to 1000 Hz. The UA-004-64 can sample at rates from once every 18 hours up to 100 Hz. It was determined that the best mounting location for the XR5-SE-M-50mv, which is 12.4 cm long, 5.6 cm wide, 3.3 cm tall, and weighs 120 grams, was in the cockpit area of the aircraft. A photograph of the data logger mounted in the cockpit of the aircraft can be seen in Figure 7. The original cockpit canopy was a solid piece of foam and would not allow the data logger to be placed onboard during flight, therefore, a hollow fiberglass canopy cover was molded to fit the shape of the original canopy. The fiberglass canopy cover can be seen in Figure 6. Because the data logger added 120 grams to the front of the aircraft, an additional steel mass was added at the tail of the aircraft inside the fuselage to maintain the proper center of gravity of the aircraft.

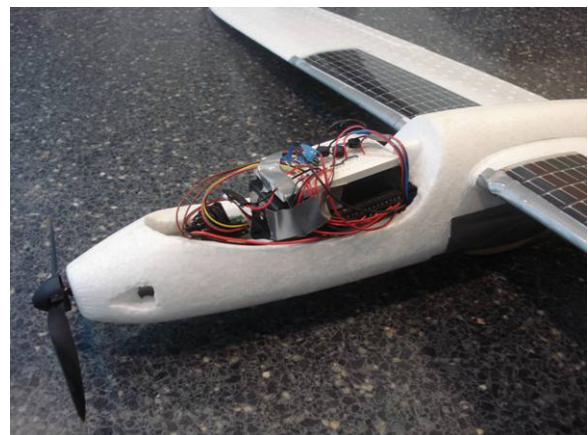


Figure 7. Pace Scientific XR5 data logger installed in cockpit of aircraft

In order to measure the rigid body accelerations in the vertical direction, the UA-004-64 accelerometer data logger, which is 3.7 cm long, 2.5 cm wide, 0.7 cm tall, and weighs 8 g, was mounted on the underside of the aircraft at the center of gravity. Figure 8 shows a photograph of the UA-004-64 data logger positioned on the underside of the aircraft. To protect the data logger, an aerodynamic fiberglass canopy was created to attach to the underside of the aircraft and cover the logger. Additionally, a polycarbonate case was created in which the data logger could be inserted to further protect it. To create the fiberglass canopy, the polycarbonate case was placed at the center of gravity on the underside of the aircraft and modeling clay was used to build an aerodynamic mold over the case and the fiberglass cover was formed over the clay. A small piece of foam was glued inside the canopy to press the polycarbonate case against the aircraft when the canopy is installed. The accelerometer canopy is similar to the cockpit canopy shown in Figure 6. Both fiberglass canopies were secured to the aircraft using duct tape around the canopy edges.

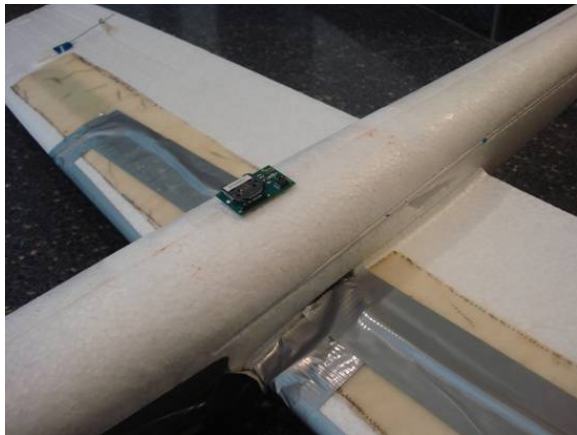


Figure 8. Onset accelerometer data logger installed on underside of aircraft

Theory of Operation

Two types of energy harvesting devices are included in the RC aircraft used in this study. Piezoelectric devices are included in the wing spar and inside the fuselage, and photovoltaic panels are attached to the wings. The three piezoelectric patches in the aircraft will harvest energy from aircraft vibrations through the direct piezoelectric effect. The piezoelectric effect describes the coupling between the electrical and mechanical domains found in piezoelectric material. The direct piezoelectric effect states that as strain is induced in a piezoelectric material, electric charge will be created

and a voltage potential will be produced across the electrodes of the material. The converse piezoelectric effect, on the other hand, states that strain will be induced in the material when a voltage potential is applied across the materials electrodes and charge is allowed to flow through the material. Detailed explanations of the piezoelectric theory can be found in reference 11. During flight, the aerodynamic loading on the wings of the aircraft will cause the wings to vibrate. As the wings deflect, the piezoelectric patches mounted on the wing spar will be strained and thus create energy. The cantilever PFC inside the fuselage of the aircraft will harvest energy when the plane moves rigidly in the vertical direction. Such motions are typical in a small UAV aircraft as the wings are loaded aerodynamically and as the plane flies through non homogenous air pockets. When the plane moves up and down, the effects of inertia on the tip mass will cause the beam to oscillate. The oscillations will cause strain in the beam and thus generate energy. Oscillatory motion of all three piezoelectric devices when excited will cause an alternating voltage output.

The two PowerFilm solar panels installed on the wings of the aircraft will generate power from sunlight through the photovoltaic effect. The photovoltaic effect states that when a photovoltaic material is exposed to sunlight, electrical energy is created in the material due to protons in the sunlight being absorbed by the semiconductor in the photovoltaic material. Typically the semiconductor found in solar cells is silicon, as is the case with the PowerFilm solar panels used in this study. Further information regarding the photovoltaic effect can be found in reference 12. The power output of the solar panels will be directly correlated to the available sunlight. Although they will generate the most energy when exposed to direct sunlight, the solar panels will also generate some energy on a cloudy day. If the aircraft were to fly at night, however, no energy would be created by the solar panels.

Flight Testing Results

Two flight tests were performed on the aircraft in which voltage and acceleration data were recorded using the data loggers. The first flight took place on August 8, 2007 and included testing of only the piezoelectric devices as the solar panels had not yet been installed. The voltage data logger was setup to record the voltage output of each piezoelectric patch through a matched load resistance in order to calculate the power output of each device. Prior to flight testing, experimentation was performed in the lab to find the matched load resistance that provided optimal power transfer for each

patch. The optimal load resistance was found to be 330 kOhms for all three patches. A small energy harvesting circuit, which can be seen in Figure 7, was built and attached to the top of the data logger. The circuit contained a full bridge diode rectifier for each piezoelectric patch and a 330 kOhm resistor attached across the output of the bridge. The diode rectifier is necessary to convert all of the negative voltage to positive voltage, which is important for energy harvesting purposes. The load resistance is used to calculate the power output of the piezoelectric patches as the open circuit voltage would not give an indication of the current output. The data logger was setup to record three channels of voltage at an acquisition speed of 200 Hz. This acquisition speed was selected because it allowed for approximately 6 minutes of data acquisition time before the logger's memory would be filled. The accelerometer data logger was setup to record accelerations in all three axes at a sampling frequency of 50 Hz, which was selected to allow for approximately 7 minutes of acquisition time. During the first flight test, the aircraft flew for about 6 minutes on a sunny day with winds approximately 11-16 km/h. The aircraft was hand launched, as it has no landing gear, and a simple wide circle pattern was flown. An airspeed of approximately 45 km/h at an altitude of around 30 m was achieved. Once the plane landed, the data loggers were stopped and the data was uploaded. The voltage output data recorded during flight can be seen in Figure 9. The XR5-SE-M-50mv data logger has an input voltage cutoff of 5 V, and from Figure 9, it is clear that each patch exceeds the 5 V cutoff several times during flight. Additionally, it should be noted that the data logger was turned on approximately 60 seconds before the plane was launched. The average power output of each patch was calculated using Matlab. This was accomplished by finding the instantaneous power at each point by squaring the voltage and dividing by the 330 kOhm load resistance, and then taking an average of the instantaneous power values. The average power output of the cantilever PFC, the MFC attached to the wing spar, and the PFC attached to the wing spar was found to be 24.0 μ W, 11.3 μ W, and 10.1 μ W, respectively. The exact power output values are expected to be much higher than these averages because of the effects of the voltage cutoff of the data logger. It is expected that the cantilever PFC output more power than the wing harvesters because of the bimorph configuration of the cantilever beam. It follows that the power output be about twice that of the wing harvesters.

The acceleration data recorded during the first flight test can be seen in Figure 10.

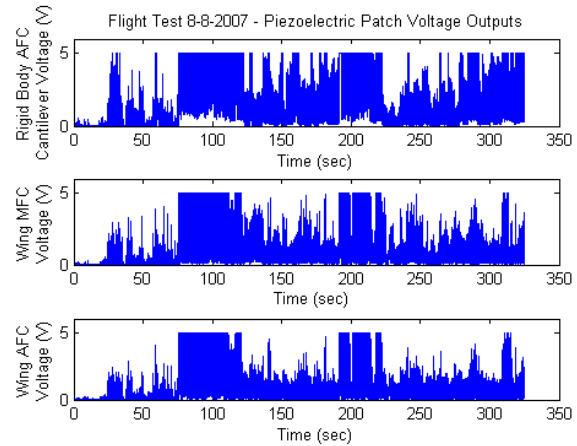


Figure 9. Voltage output data recorded during flight on August 8, 2007

From the data it can be estimated that the average acceleration in the x- and y- axis, which corresponds to the horizontal directions from propeller to tail and from wing tip to wing tip, respectively, is about ± 1.5 g, and the average acceleration in the z-axis is about ± 1 g. The constant reading of -1g on the z-axis data is due to the effects of gravity. By comparing the acceleration and voltage plots, there does not appear to be a significant correlation between acceleration and voltage. Further bench testing after the flight test revealed that the majority of the recorded vibrations are induced by the propeller and not by wind loading or rigid body motion. Additionally, it was found that the polycarbonate case created to house the accelerometer did not provide a secure connection and the accelerometer was allowed to vibrate inside the case, which was a source for some of the readings.

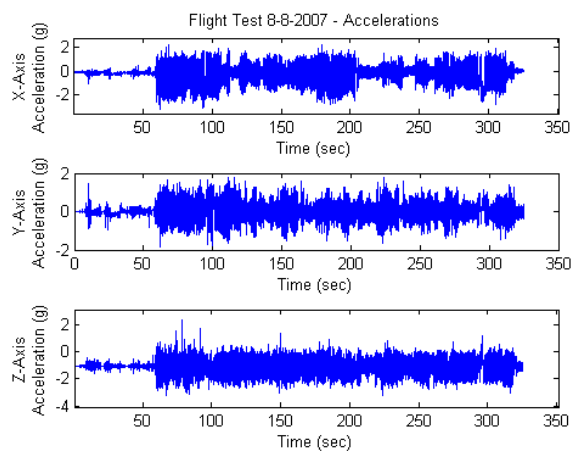


Figure 10. Acceleration measurements recorded during flight on August 8, 2007

The second flight test flight took place on February 8, 2008 and included testing of the piezoelectric and photovoltaic devices. The measurements taken during this flight focused on testing the ability of the piezoelectric patches and solar panels to charge up energy storage devices. Prior to flying, several bench tests were performed to determine the best energy storage device to be used with each type of harvester. Originally, the outputs of all five energy harvesting devices were going to be wired together to charge a single device, however, it was decided that the piezoelectric patches and solar panels would be kept separate in order to compare their performances. Bench testing involved charging various capacitors, supercapacitors, rechargeable batteries, and two energy harvesting chips. It was decided that the outputs of the three piezoelectric patches would be wired together in parallel, in order to increase the current output, and connected to the input of an EH300 energy harvesting chip from Advanced Linear Devices, Inc. The EH300 chip, which can be seen in Figure 11, is a small energy harvesting module with a length of 5.0 cm, width of 1.4 cm, height of 1.8 cm, and mass of 14 g, that is designed to harvest and store energy from various low power sources including solar panels, piezoelectric patches, and small thermoelectric harvesters. It operates by capturing energy and storing it in an internal storage capacitor with a capacity of 4.6 mJ. As the device captures energy, the voltage of the internal capacitor is increased until it reaches 3.6 V, upon which the capacitor is allowed to discharge down to 1.8 V through the EH300 output terminals. Once the capacitor is discharged, the output terminals are disengaged and the capacitor is allowed to charge up again. This device was selected for use with the piezoelectric patches because bench testing revealed that the patches could not effectively charge rechargeable batteries or supercapacitors, and the self discharge phenomenon of conventional capacitors made them undesirable.

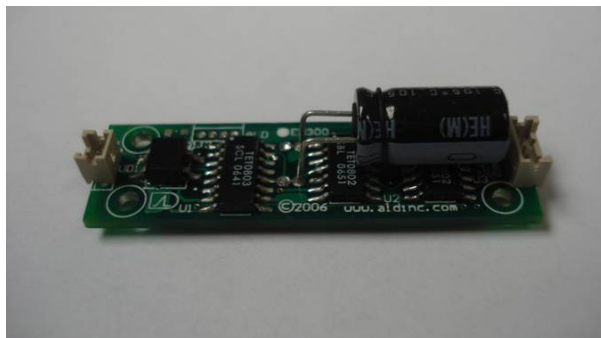


Figure 11. EH300 energy harvesting chip from Advanced Linear Devices, Inc.

During bench testing, it was also determined that the outputs of the two solar panels would be wired together in parallel, again to increase current output, and used to charge a 170 mAh, 3.7 V rechargeable Lithium Polymer battery from Powerizer, which can be seen in Figure 12. The solar panel outputs were connected through a blocking diode to a 5 V voltage regulator and the output of the voltage regulator was connected to the rechargeable battery. The blocking diode was used to prevent backflow of current from the battery into the solar panels, and the voltage regulator was used to prevent overcharging of the Lithium Polymer battery, which could cause permanent damage to the battery.



Figure 12. Powerizer 3.7 V, 170 mAh Lithium Polymer rechargeable battery

During flight, the XR5-SE-M-50mv data logger was setup to measure five voltage channels including the voltage input to the EH300 chip from the piezoelectric patches, the voltage on the EH300 internal capacitor, the voltage output of the EH300 across a 1 kOhm load, the voltage input to the 5 V regulator from the solar panels, and the voltage of the 170 mAh rechargeable battery. The data logger was set to sample at a rate of 25 Hz which allowed about 29 minutes of data logging. The UA-004-64 accelerometer data logger was configured to measure y- and z-axis accelerations at a sampling rate of 25 Hz, which was chosen to allow approximately 21 minutes of data acquisition before filling the logger's memory. The x-axis channel was not sampled because that channel was damaged sometime between the first flight test and the second flight test, therefore, it could not be used. Because the polycarbonate accelerometer case was found to introduce noise into the acceleration measurements, the accelerometer was attached directly to the underside of the aircraft with duct tape. The fiberglass canopy was still used to protect the logger. During the second flight test, the aircraft flew for about 13 minutes on a mostly sunny day with constant winds of around 11 km/h with

gusts up to 25 km/h. The aircraft was hand launched and once at elevation, the plane was flown for one hundred to two hundred meters directly into the wind, turned around 180 degrees, flown one hundred to two hundred meters with the wind, and repeated. This flight pattern was used due to the high winds in order to keep the plane stable during flight. Airspeeds varying from approximately 30 km/h into the wind and 60 km/h with the wind were achieved at an altitude of about 30 m. Once the aircraft landed, the data loggers were stopped and the data was uploaded. The voltage measurements for the piezoelectric energy harvesting can be seen in Figure 13. From the figure, it can be seen that as the plane flew, the piezoelectric patches were able to supply energy to the EH300 chip and increase the voltage of the internal capacitor from 0.3 V to 2.5 V. It can also be seen, however, that the voltage output of the EH300 chip remained zero for the entire 13 minute flight as the piezoelectric patches were unable to charge the internal capacitor to 3.6 V. Knowing that the capacity of the internal capacitor is 4.6 mJ, and that it was charged to 2.5 V, the amount of energy harvested in Joules can be estimated by taking the ratio of 2.5 V to 3.6 V and multiplying by 4.6 mJ. Carrying out the calculation, approximately 3.2 mJ of energy was harvested during flight.

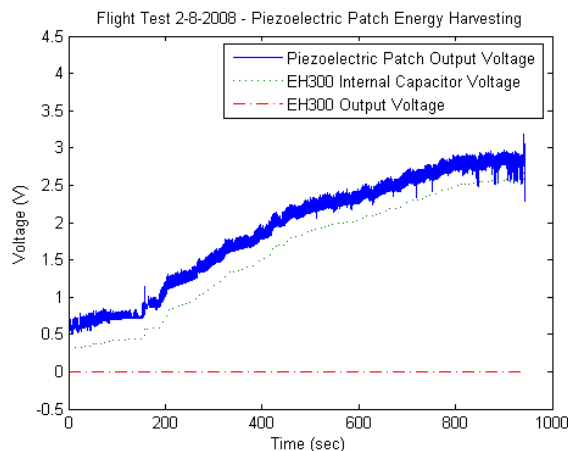


Figure 13. Voltage data for piezoelectric energy harvesting recorded during flight on February 8, 2008

Voltage data recorded during flight for photovoltaic energy harvesting can be seen in Figure 14. It should be noted that for about a minute after the data acquisition hardware was turned on, the aircraft was located inside a building at the edge of the flight field. This explains the sudden jump in solar panel voltage at around 60 seconds when the aircraft was brought outside for the flight. From the figure it can be observed that the solar panels supplied above 5 V to the

rechargeable battery for almost the entire flight. Additionally, the voltage of the rechargeable battery was increased from below 3 V to around 3.7 V. The voltage of a battery, however, is not a good indication of its charge state, so in order to determine how much energy was stored in the battery during flight, it was connected to a charger/discharger designed for Lithium Polymer batteries. The charger/discharger is capable of discharging a battery to determine how much capacity is remaining in the battery. When connected to the discharger, the 170 mAh battery was discharged and found to have 24 mAh of stored capacity. This was enough capacity to drain the battery at its rated 0.17 A for almost 9 minutes. The amount of stored energy can be converted to Joules by multiplying the 24 mAh capacity by the average voltage output of the battery during discharge of 3.6 V, and converting the result to watts and seconds. Carrying out the calculation, approximately 311 J of energy was stored in the battery.

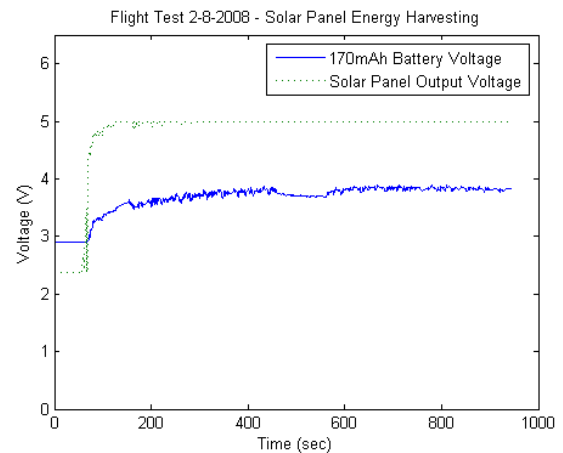


Figure 14. Voltage data for photovoltaic energy harvesting recorded during flight on February 8, 2008

The y- and z-axis acceleration data recorded during flight can be seen in Figure 15. Again, the data acquisition was started while the aircraft was inside and after about 60 seconds it was brought outside into the sunlight and after about 200 seconds it was launched. This is clear when examining the solar energy harvesting data in Figure 14 and the acceleration data in Figure 15. Upon investigating the acceleration data, a clear beating pattern can be seen. This pattern is a result of the aircraft flying back and fourth into the wind and with the wind. The average acceleration during flight in both the y- and z-axis can be estimated at ± 1 g. Also, it is observed that the z-axis acceleration is centered around 1 g. This is due to gravity applying a constant downward acceleration to the logger. The large acceleration spike near 180

seconds can be attributed to the first take off attempt where the aircraft quickly fell to the ground. The aircraft was successfully launched on the second attempt at around 200 seconds. The acceleration spike at the end of the data is a result of the aircraft landing. A photograph of the aircraft in flight just before landing can be seen in Figure 16.

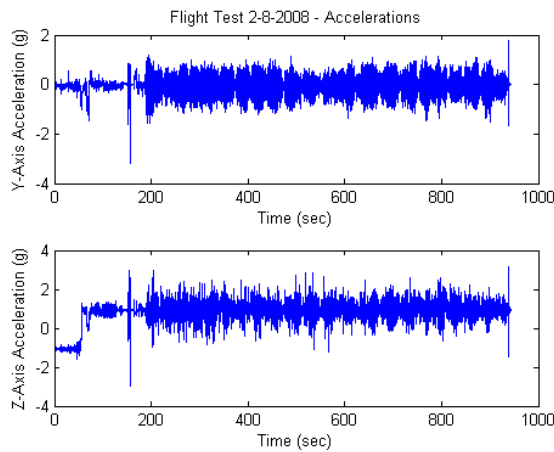


Figure 15. Acceleration measurements recorded during flight on February 8, 2008



Figure 16. Photograph of RC aircraft in flight on February 8, 2008

Conclusions

The purpose of this research is to perform a proof of concept study on piezoelectric energy harvesting in UAV applications through flight testing of an RC aircraft, and also to compare the performance of piezoelectric harvesting to photovoltaic harvesting in UAVs. Based on the two flight tests that have been performed, it can be concluded that both the piezoelectric and solar energy harvesting devices have the capability of charging energy storage devices. Preliminary tests show that during a 13 minute flight, the solar panels could charge a 170 mAh battery to 14%

capacity and the piezoelectric patches could charge the EH300 4.6 mJ internal capacitor to 70% capacity. These results show promise for the ability to use energy harvesting in UAV applications to supply energy to low-power subsystems. Taking into consideration the total area of the harvesting devices, the volumetric energy harvested during flight can be calculated as 0.011 J/cm^3 for the piezoelectric patches and 32.0 J/cm^3 for the solar panels. The volumetric energy harvested by the piezoelectric patches is orders of magnitude less than that of the solar panels, however, the piezoelectric patches are less dependent on the environmental conditions when compared to the solar panels. Anytime the aircraft is in flight, the piezoelectric patches will harvest energy, however, the solar panels will only harvest energy when exposed to light. This gives piezoelectric harvesting an advantage when flying at night or in cloudy conditions. In order to attempt to closer match the power output of the solar panels with piezoelectric devices, it is proposed that future work include increasing the volume of piezoelectric material in the aircraft to enhance the power supplied to the EH300 chip. The fiberglass wing spar can be redesigned to include several layers of piezoelectric material that span the entire length of the spar. Such an increase in volume of piezoelectric material will increase the feasibility of harvesting enough energy to fully charge a capacitor or small battery. Additional plans for future work include the installation of a small onboard camera that can take photographs during flight. The camera is to be powered from only harvested energy to prove the ability of energy harvesting devices in powering low-power subsystems in UAVs.

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