Electrical Power Generation From Insect Flight

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ABSTRACT

This article presents an implementation of a miniature energy harvester (weighing 0.292 grams) on an insect (hawkmoth *Manduca sexta*) in un-tethered flight. The harvester utilizes a piezoelectric transducer which converts the vibratory motion induced by the insect's flight into electrical power (generating up to 59 μW_{RMS}). By attaching a low-power management circuit (weighing 0.200 grams) to the energy harvester and accumulating the converted energy onboard the flying insect, we are able to visually demonstrate pulsed power delivery (averaging 196 mW) by intermittently flashing a light emitting diode. This self-recharging system offers biologists a new means for powering onboard electronics used to study small flying animals. Using this approach, the lifetime of the electronics would be limited only by the lifetime of the individuals, a vast improvement over current methods.

Keywords: Power harvesting, energy harvesting, piezoelectric, animal tracking, wildlife tracking, insect, flight, self recharging

1. INTRODUCTION

The development of lightweight transmitters for small flying animals has allowed biologists to study their populations, gain valuable insights into their behaviors, and assess the environmental factors that drive their migrations[1]. Improvements in animal tracking technology and the decreasing size of micro-electronics have resulted in transmitters (tags) weighing as little as 0.2 grams, permitting the investigation of ever-smaller species[2, 3]. Many of the same technological advances, when combined with advances in bio-electronic interfaces, have allowed for the creation and control of cybernetic insects[4, 5]. However, researchers in both areas of study have been primarily limited by the low payload capabilities of their target animal. With the majority of the electronic payload consumed by the battery, researchers are forced to compromise between functionality and lifetime, as in the case of ultra lightweight tags which last only a few weeks[3,6,**].

Following Moore's law, the size of microelectronics have greatly decreased, but their power requirements and the energy density of batteries have not kept pace. These differing rates of technology development form the underlying cause of the endurance limitations. Researchers would benefit greatly if the lifetimes of these onboard electronics could be significantly extended without increasing the mass of the system. Ideally, the lifetime of any animal tag would equal the lifetime of the animal on which it is placed. To address this issue we look to the emerging field of energy harvesting. Energy harvesting is the process of converting energy from ambient sources into electrical energy for use by electronics[7]. Thus by using energy harvesting, the power system remains fixed in mass but is now self-recharging, resulting in the electrical energy being no longer finite.

Previous energy harvesting research conducted with humans describes several techniques for wearable devices. The first reported design was a shoe generator, which harvested energy from each heel strike motion, generating up to 0.8 W [8,9]. Subsequent devices made significant power improvements by allowing for greater relative motion, in order to

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[**] Although a lighter weight class of animal electronic systems exist called passive tags, they are limited by modest range and require high equipment costs [6]. Therefore, our focus is on improving the technology associated with the more functional active tags onboard flying animals.

increase the mechanical energy available for harvesting. Such devices include an energy harvester attached to the knee, producing 5 W [10], and in the form of a backpack, producing 7 W [11]. In all three cases, the energy harvesters exploited the cyclic walking motion.

Table 1. Basic power estimates for electronics onboard flying animals. The power management circuitry is presumed needed to stay on at all times, while the sensors and communications are turned on intermittently.

System	Description	Electrical requirements	Manufacturer, Model or Source
Traditional Power Management	Ultra-low power micrcontroller, timekeeping only	3 V, 3 μA: 9 μW	Texas Instruments, MSP 430 (*Ref 14*)
Sensors	1 byte of data read per minute for 1 ms	3 V, 200 μA: 600 μW	(*Ref 14*)
Communications	RF data transmission at 10 kbps	3 V, 20 mA: 60 mW	(*Ref 14*)

In the focus group of flying animals, wingbeats produce a similar cyclic motion, in the form of a body vibration, and a large source of ambient energy from which to harvest. However, the scale difference between humans and flying animals negates the possibility of directly adapting any of these previous designs. Even micro-system energy harvesters are not applicable, since they are only effective at vibration frequencies in the hundreds of Hertz, well above the typical wingbeat frequencies of the single to tens of Hertz[7, 12,13]. In order to generate sufficient power from the animals' body vibration in flight, enough to perform basic electronic functions[14], see Table 1, we were required to develop a new energy harvester design. The result was a piezoelectric backpack (Fig. 1) that weighs 0.292 grams, generates a maximum power of 59 μW$_{RMS}$, and can be conditioned to generate 196 mW pulses. All measurements were acquired from low-mass data logging tools onboard an insect, the hawkmoth *Manduca sexta* (*M. sexta*), under free flight conditions in an unbounded volume of space. These tools allowed us to assess the insects' flight behaviors with payloads, measure their maximum payload capabilities, and evaluate the power generated by the vibration energy harvester. The use of these tools for the same assessments on other flying species may be widely applied given their low masses.
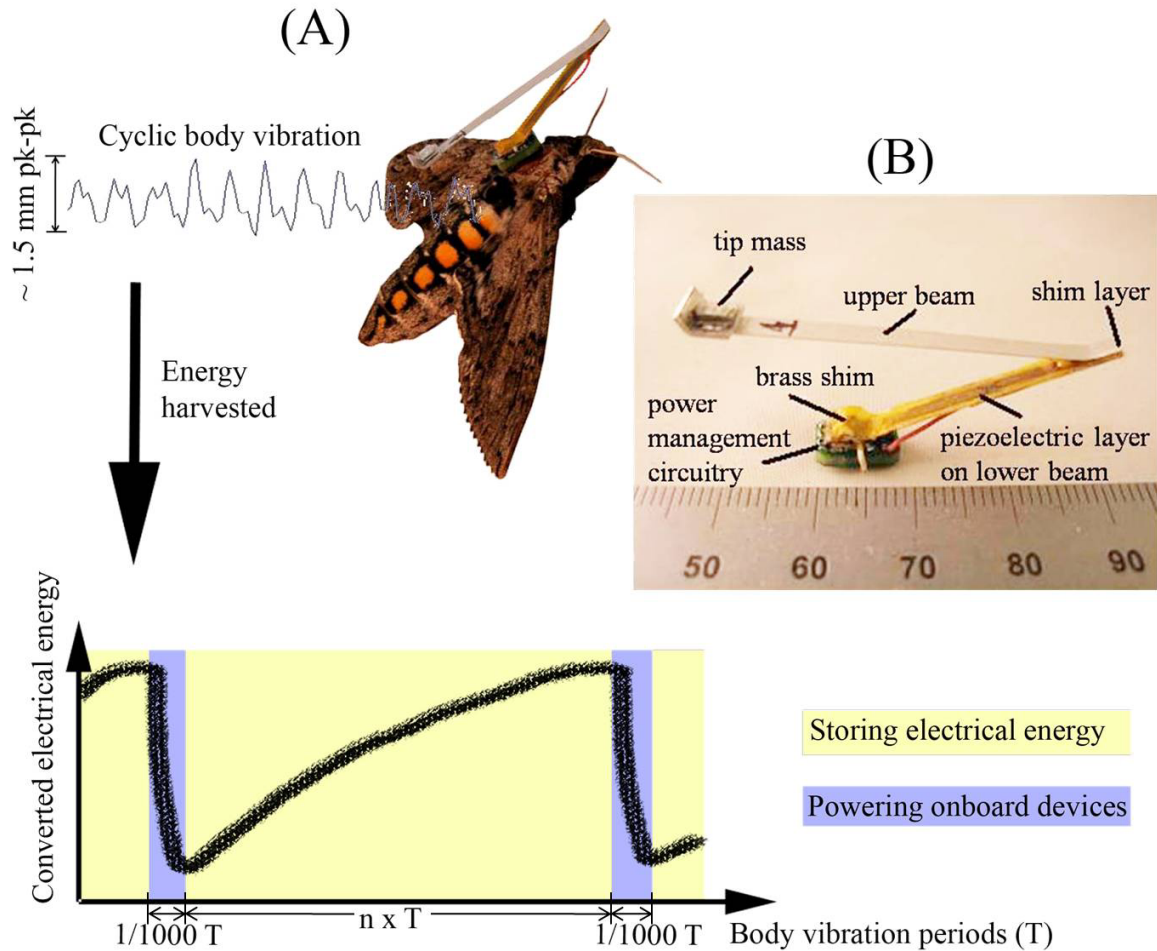
Figure 1. Flying animals have an oscillating body motion, or vibration, induced by the flapping of their wings. Attaching our miniature energy harvester to the dorsal thorax of a hawkmoth *Manduca sexta*, we harness the body vibration to generate electricity, which is then stored by our power management circuitry in order to intermittently power onboard electronics. (A) Displays the schematic of this energy harvesting process. (B) Shows the energy harvester system.

2. Determining Flight Motion with an Electronic Payload

We selected the *M. sexta* as our flying animal model, due to the numerous studies on its flight mechanics and its capacity to carry additional mass, or payload. The test specimens used have a measured body mass of 2.43 ±0.38 grams and an approximate flight muscle mass of 0.47 ±0.11 grams (mean ± standard deviation, n = 47 specimens). The loaded cyclic body motion of this species is assumed to be very close to their un-loaded free-flight flapping frequency of 24 to 26 Hz [13]. With this frequency, we can predict the cyclic excitation which drives the power generation of the energy harvester. The maximum payload ability of this species has previously been determined to be proportional to the flight muscle mass, with a maximum lifting force of 63.2 N kg^{-1} of flight muscle mass [15]. For our specimens this indicates an upper payload limit for liftoff at 0.61 ±0.60 grams. However, this value has a high variability and is unusable as a statistical estimate for this species' payload capability due to the variances that exist in the unladen muscle mass ratio, defined as the flight muscle mass divided by body mass, between individual specimens. In comparison, tag researchers widely use 5% of the flying animal's body mass as a heuristic for a generalized payload value [16]. Using this relationship, our energy harvester would be limited to a mass of 0.12 ±0.02 grams. With such a large discrepancy from the maximum payload for liftoff, the need for a new method to provide researchers with appropriate, species-specific payload limitations for flight seemed vital. To achieve this, we created a lightweight data logging tag that can directly record the body accelerations of animals in free-flight, thereby investigating the effects of various payloads. This approach offers a far less expensive

option, versus conventional high-speed camera systems, and adds the advantage of not requiring the animal be confined to a test chamber during flight.

The payload study tag consisted of a tri-axial accelerometer (Bosch, BMA 150) and a microcontroller (Texas Instruments, MSP430), which measured the flight motion onto the available memory of the unit. The attachment location, alongside the dorsal thorax, allowed for firm adhesion between the exoskeleton and the electronics. Located near the insect's center-of-mass (COM), approximately one centimeter posterior to the thorax, the unit induced a minimal pitching moment on the insect body, allowing it to maintain flight. The flight motion measurements were recorded with a sensitivity of ± 0.6 m s^{-2} and a sampling rate of 200 Hz.

We tested 47 specimens (18 males and 29 females), each starting from the ground and flying un-tethered with a payload for 50 seconds. The initial payload consisted of only the payload study's tag, weighing 0.359 grams, and increased up to a maximum of 1.460 grams with the addition of calibrated weights. Each specimen was repeatedly tested until it was no longer able to fly, with the results for specimens able to fly at a given payload illustrated in Figure 2. The top plot shows that for the *M. sexta* specimens capable of flying, body accelerations and frequencies are regulated regardless of the payload present. The frequencies under payload are on average lower than the free flight frequencies, a result also observed in a payload study conducted with tethered fruit flies[17]. Additionally, a similar study using carpenter bees showed the same relatively flat slope or constant frequencies while in loaded flight[18]. While these correlations to the frequency responses of other flying animals under payload indicate the likely generalization of the results, our acceleration results provide even more detail to the understanding of the energetic effect on the animals. Although payload increments increased the specimens' mean mass by 60%, the corresponding decrease of only 24% in body accelerations implied that the *M. sexta* were able to exert greater flapping forces in order to regulate their body motion. Observing Figure 2's bottom plot, a clear cutoff at approximately 0.8 grams existed for the percentage of our specimens that were able to fly. At this payload level, the corresponding standard deviation of the frequencies diverges considerably, indicating a statistical loss of the ability of *M. sexta* to regulate their flight motion. Beyond 0.8 grams, each subsequent payload increment was met with further reduction in the number of specimens able to fly and an increased unladen muscle mass ratio in order to sustain flight. We hypothesize that a similar cutoff exists in many flying species, at which a statistically significant divergence in body frequencies will be observed and which designates the true species-specific maximum for allowable electronic payloads with regulated flight[19,20,***].

*** In research involving electronics on flying animals, there exists added concern that the extra energy required from the animal may limit the maximum flight range or alter flight behaviors, which has been suggested by endurance studies performed with birds carrying electrical transmitters[19,20]. Thus, we regard our species-specific maximum payload as referring strictly to the affect on the regulation of flight mechanics and not its affects on energy homeostasis, wear and tear on muscles and joints, or other aspects that could be affected by chronic loading.
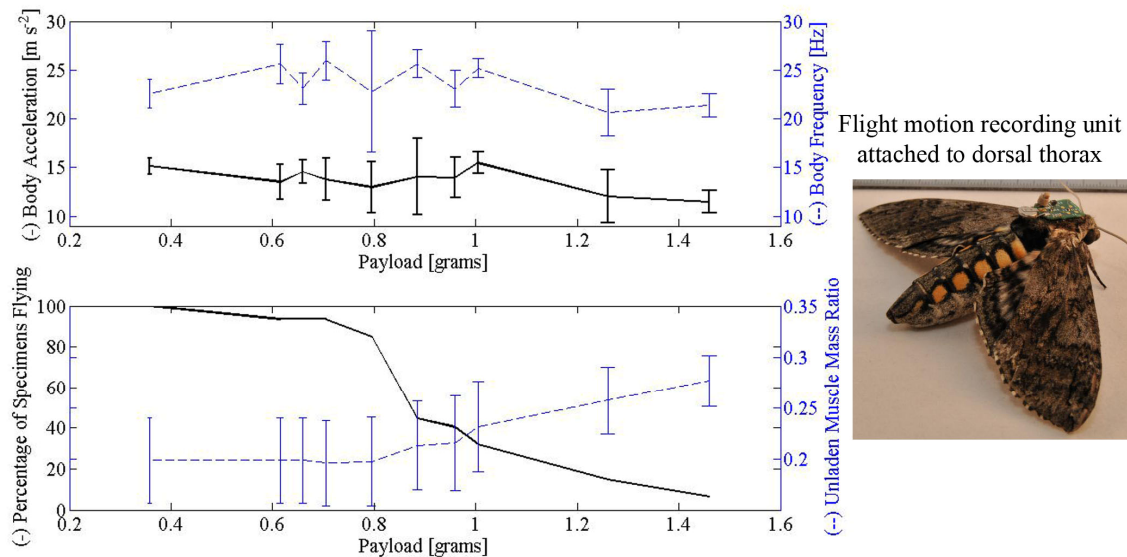
Figure 2. Top plot: In-flight body accelerations and frequencies for increasing payloads on *M. sexta*. Bottom plot: Percentage of tested specimens that were able to fly at each payload along with their unladen muscle mass ratios.

3. Energy Harvester System

Utilizing the body acceleration data, we defined the vibration energy harvester's design with three criteria. The first was to have a resonant frequency near the exhibited body frequency of the total payload mass, obtained from the payload study. The second was to have a mass that lied within the statistical payload cutoff for flight, which was specified as below 0.8 grams for our specimen pool. The third was the energy harvesting device must have a compact form, with a center-of-mass located near that of the insect's COM, to remain minimally intrusive.

We selected a piezoelectric material as the transducer of the energy harvester due to its characteristically high voltage output and demonstrated ability to be fabricated at small dimensions[21]. A piezoelectric energy harvester converts the ambient motion, in this case the cyclic body vibration of a flying animal, into electrical energy by inducing a relative motion and stress in the piezoelectric material. The axial deformation of the material's dielectric crystals causes a cyclic electric potential, and when applied to a resistive load, results in electrical power. Presently, piezoelectric designs utilize long, single-element cantilevers or large tip masses to lower resonant frequencies, but given the total mass and COM limitations, using this approach would only result in unacceptably long lengths or in micro-systems with mismatched resonances in the hundreds of Hertz[7,22]. To resolve all three design criteria, we developed a "zigzag" configuration at the centimeter length scale, which was composed of two linked elements connected to the dorsal thorax of the insect (Fig. 1B). The multiple element structure increased the effective length and decreased the resonant frequency to 22.3 Hz, without the addition of a large tip mass or a large shift in the animal's COM.

The energy harvester, weighing 0.292 grams, was custom-fabricated, consisting of two beams adhered together using Cyanoacrylate (CA) adhesive at their ends with an aluminum shim in between. The shim allowed a small separation to be created between the two beams, and resulted in the relative motion occurring without the beams striking each other at the junction. The lower beam consisted of an aluminum layer bonded in the center to a custom cut piezoelectric layer (Piezo Systems, T105-H4E-602) using a thin coating of silver conducting epoxy. A layer of shim brass was adhered to the opposite end of the lower beam from the square aluminum shim using the same layer of conductive epoxy. The brass shim allowed for a stronger solder connection over the aluminum layer for a wire lead to be placed. Two 36 AWG wires were soldered to the piezoelectric layer and brass layer to allow flexible lead connections to the energy harvester's circuit. A protective insulator layer was placed over top of the entire lower beam to prevent physical contact of the top beam with the two leads, which would otherwise cause a short circuit and result in no power

generation. The top beam was composed of a single aluminum layer and a 0.060 gram mass CA glued to the free end. The beams were bent at angles to create a separation distance greater than the maximum calculated relative motion amplitude of the free end with respect to the base. The energy harvester was then attached to another lightweight logging device, weighing 0.315 grams. The system measured the instantaneous voltage output of the vibration energy harvester across a fixed resistive load (649 kΩ), which was chosen to maximize the electrical power conversion.

The voltage readings were then post-processed to obtain the instantaneous electrical power generation, defined as the voltage^2/resistance. Given the total system mass of 0.607 grams, we used the acceleration results from the payload study to estimate the relative motion of the energy harvester as approximately 6 millimeters in amplitude. To sustain this motion, the *M. sexta* must contribute an estimated 361 μW to replenish the energy lost to damping of the relative motion and to electrical energy conversion. This power represents only 0.6% of the total mechanical power output by the flight muscles of this species, estimated at 100 W kg^{-1} of flight muscle mass. This low percentage insinuates that the weight of the unit, rather than the energy required to sustain the vibration, is responsible for the changes in flight performance[23].

4. Energy Harvested from Un-Tethered Flight

4.1 Instantaneous Power

The energy harvester testing was conducted using a subset of the same specimens as the payload tests (5 males and 4 females) under the same conditions as the electronic payload experiments. The base of the recording unit was attached to the dorsal thorax, and the energy harvester was attached to the upper side of the recording unit. Each specimen was placed on the floor just prior to recording and then allowed to fly un-tethered for 75 seconds. Figure 3 shows the frequency analysis of the cyclic body vibration and the electrical output of the energy harvester while in flight. In this trial, the primary frequency of the energy harvester's motion was 21.7 Hz (top plot). The middle plot displays the alternating polarity and the magnitudes of the voltage output of the energy harvester due to the cyclic body motion. The bottom plot presents the calculated instantaneous power generation, with a root-mean-squared (RMS) value of 35 μW.
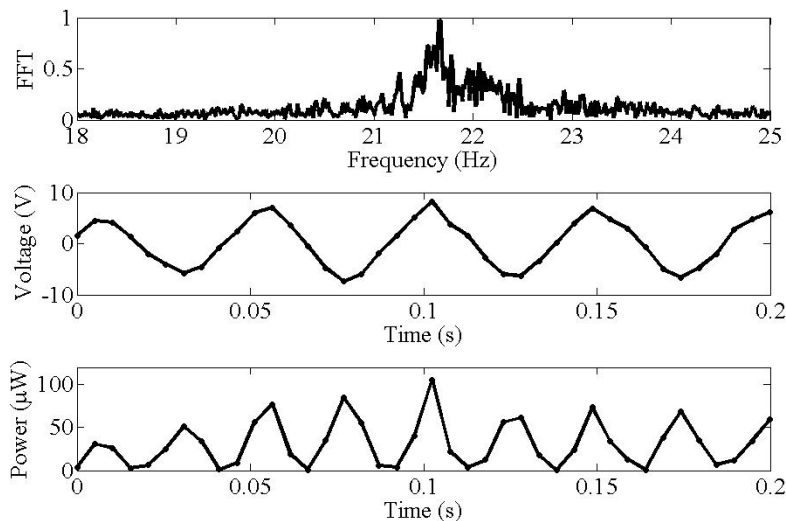

Figure 3. Top plot: Frequency analysis using the Fast-Fourier-Transform (FFT) of the generated voltage's frequency. The primary frequency of the motion is located at the peak. Middle plot: The generated voltage output across a 649 kΩ resistor. Bottom plot: The generated electrical power output during flight.

The maximum power output obtained in flight was 59 μW$_{RMS}$, equating to an efficiency of 15.8% [24]. The average power across all specimens while in flight was 30.1 ±14.6 μW$_{RMS}$. The large standard deviation in the results can be attributed to the range of exhibited frequencies and the selective sensitivity of the energy harvester to its specific

resonant frequency, or high Q-factor. This emphasizes the importance of tuning the energy harvester's resonance as close to the exhibited frequency as possible for maximum power generation (Fig. 4).
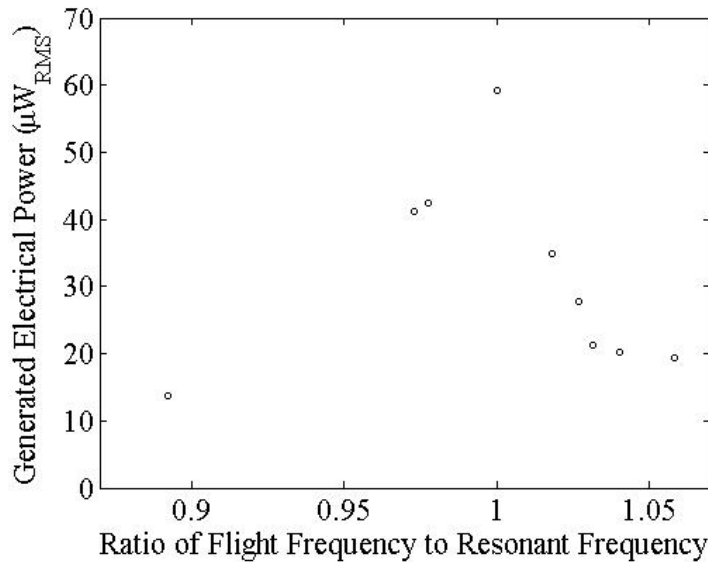

Figure 4. The electrical power output as a function of the ratio of the tuning of the vibration energy harvester's resonant frequency to the exhibited flight frequency.

4.2 Self-Recharging System

To demonstrate the operation of our energy harvester, we built a 0.200 gram power management circuit and connected it to the energy harvester. The total system, weighing 0.492 grams, blinked a LED while attached to a *M. sexta* in free flight to visually demonstrate the harvested energy. The circuit, which is self-starting and does not require a battery, works by accumulating the harvested energy into a storage capacitor, and intermittently releasing the stored electrical energy into a LED, causing it to blink. The charging time between LED blinks is dependent on the activity level of the insect, with constant wing beats decreasing the time to approximately every 2 seconds (Fig. 1A). The average power dissipation through the LED during each blink is 196 mW for 29 micro-seconds, where the power and duration are dictated by the circuit design. The power losses in the circuit are approximately 5% for rectification[11] and 1.7 μW for the rest of the circuit.
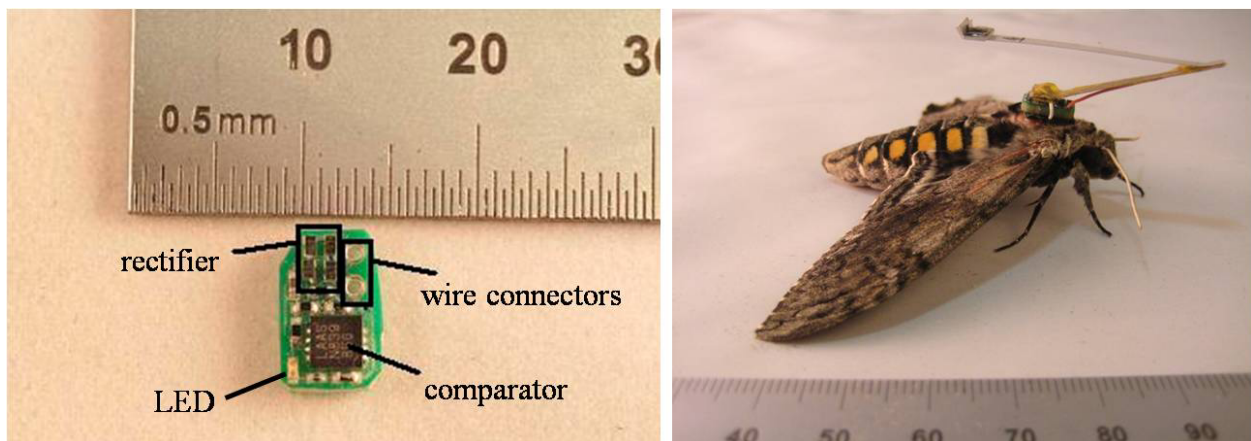

Figure 5. Left: Custom power management circuit. Rectifies and stores the converted electrical energy into a capacitor. The energy is then released when the capacitor's voltage reaches a threshold determined by the comparator. The result is a blink of the onboard LED. The bottom side (not shown) contains only one resistor. Right: Energy harvester connected to the power management circuit and attached to the *M. sexta*'s dorsal thorax.

This demonstrated level of power discharge is therefore sufficient to power many of the common intermittent applications onboard flying animals, such as sensor readings and radio transmissions, see Table 1.

7. CONCLUSIONS

In summary, two criteria must be met for an energy harvester to be a viable power source for the electronics on flying animals. First, the generated electrical power must exceed the requirements of the applications, in order to allow for losses in the power management circuitry which rectifies and regulates the harvested energy. Second, the energy harvester, power management circuitry, and other electronic devices must be able to be carried by the flying animal without causing a loss in flapping frequency control or adversely affecting flight behavior. Presently, our energy harvester system meets these criteria for the testing performed onboard *M. sexta*. Although implemented using an insect, the design allows for adaptation to other flying animals by changing the tip mass and beam geometry to match a range of wing beat frequencies.

By applying our procedure for determining free flight responses under payload, we expect researchers to be able to evaluate payload limits that are statistically relevant to the abilities of the target species. The success of our miniature piezoelectric backpack under free flight testing conditions demonstrates that the use of such devices is viable and may just provide a much sought after solution for biologists to significantly improve electronics lifetime and extend the impact of this important class of wildlife monitoring tools.

ACKNOWLEDGMENTS

REFERENCES

[1] Bookhout, T., "Research and Management Techniques for Wildlife and Habitats," *The Wildlife Society*, Bethesda MD (1994)

[2] Holden, C. "Tracking Mini-Fauna," *Science*, **310**, p.773 (2005)

[3] Naef-Daenzer,B., Fruh, D., Stalder, M., Wetli, P., Weise, E., "Miniaturization (0.2 g) and evaluation of attachment techniques of telemetry transmitters," *Journal of Experimental Biology*, **208**, p. 4063-4068 (2005)

[4] Sato, H., Berry, C.W., Peeri, Y., Baghoomian, E., Casey, B.E., Lavella, G., VandenBrooks, J.M., Harrison, J.F., Maharbiz, M.M., "Remote radio control of insect flight," *Frontiers in Integrative Neuroscience*, **3**, 24 (2009)

[5] Bozkurt, A., Gilmour Jr., R.F., Lal, A., "Balloon-Assisted Flight of Radio-Controlled Insect Biobots," *IEEE Transactions on Biomedical Engineering*, **56**, 9, p. 2304-2307 (2009)

[6] Niitepold, K., Smith, A.D., Osborne, J.L., Reynolds, D.R., Carreck, N.L., Martin, A.P., Marden, J.H., Ovaskainen, O., Hanski, I., "Flight metabolic rate and Pgi genotype influence butterfly dispersal rate in the field," *Ecology*, **90**, p. 2223-2232 (2009)

[7] Hudak, N.S., Amatucci, G.G., "Small-scale Energy Harvesting Through Thermoelectric, Vibration, and Radiofrequency Power Conversion," *Journal of Applied Physics*, **103**, 101301 (2008)

[8] Kymissis, J., Kendall, C., Paradiso, J., Gershenfeld, N., "Parasitic Power Harvesting in Shoes," *Proceedings of IEEE Conference on Wearable Computing*, p. 1-8 (1998)

[9] Paradiso, J.A., Starner, T., "Energy Scavenging for Mobile and Wireless Electronics," *IEEE Pervasive Computing*, **4**, 18 (2005)

[10] Donelan, J.M., Li, Q., Naing, V., Hoffer, J.A., Weber, D.J., Kuo, A.D., "Biomechanical Energy Harvesting: Generating Electricity During Walking with Minimal User Effort," *Science*, **319**, p. 807-810 (2008)

[11] Rome, L.C., Flynn, L., Goldman, E.M., Yoo, T.D., "Generating Electricity While Walking With Loads," *Science*, **309**, p. 1725-1728 (2005)

[12] Pennycuick, C.J.,, "Wingbeat Frequency of Birds in Steady Cruising Flight: New Data and Improved Predictions," *Journal of Experimental Biology*, **199**, p. 1613-1618 (1996)

[13] Wilmott, A.P., Ellington, C.P., "The Mechanics of Flight in the Hawkmoth Manduca Sexta," *Journal of Experimental Biology*, **200**, p. 2705-2722 (1997)

[14] MacCurdy, R.B., Reissman, T., Garcia, E., "A Methodology for Applying Energy Harvesting to Extend Wildlife Tag Lifetime," *In Proceedings of ASME International Mechanical Engineering Congress and Exposition*, 68082 (2008)

[15] Marden, J.H., "Maximum Lift Production During Takeoff in Flying Animals," *Journal of Experimental Biology*, **130**, p. 235-258 (1987)

[16] Cochran, W.W., "Long Distance Tracking of Birds," *Animal orientation and navigation*, **NASA SP-262**, p. 39-59 (1972)

[17] Lehmann, W., Dickinson, M.H., "The Changes in Power Requirements and Muscle Efficiency During Elevated Force Production in the Fruit Fly Drosophila Melanogaster," *Journal of Experimental Biology*, **200**, p. 1133-1143 (1997)

[18] Roberts, S.P., Harrison, J.F., Dudley, R., "Allometry of Kinematics and Energetics in Carpenter Bees (Xylocopa varipuncta) Hovering in Variable-Denisty Gases," *Journal of Experimental Biology*, **207**, p. 993-1004 (2004)

[19] Pennycuick, C.J., Fuller, M.R., "Considerations of Effects of Radio-Transmitters on Bird Flight," *Biotelemetry*, **IX**, p. 327-330 (1987)

[20] Powell, L.A., Krementz, D.A., Lang, J.D., Conroy, M.J., "Effects of radio Transmitters on Migrating Wood Thrushes," *Journal of Field Ornithology*, **69**, 2, p. 306-315 (1998)

[21] Roundy, S., Wright, P., Rabaey, J., "Energy Scavenging for Wireless Sensor Networks: With Special Focus on Vibrations," *Kluwer Academic*, Boston MA (2004)

[22] Elfrink, R., Kamel, T.M., Goedbloed, M., Matova, S., Hohlfeld, D., van Andel, Y., van Schaijk, R., "Vibration energy harvesting with aluminum nitride-based piezoelectric devices" *Journal of Micromechanics and Microengineering*, **19**, 9, 094005 (2009).

[23] Stevenson, R.D., Josephson, R.K., "Effects of operating frequency and temperature on mechanical power output from moth flight muscle," *Journal of Experimental Biology*, **149**, p. 61-78 (1990)

[24] Liao, Y., Sodano, H.A., "On Structural Effects and Energy Conversion Efficiency of Power Harvesting," *Journal of Intelligent Material Systems and Structures*, **20**, p. 505-514 (2009)