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AN ULTRA-LIGHTWEIGHT MULTI-SOURCE POWER HARVESTING SYSTEM FOR INSECT CYBORG SENTINELS

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ABSTRACT
The overall purpose of this study was to analyze multi-source energy harvesters for creation of a rechargeable onboard power system, capable of supplying 5-50mW of intermittent power at a system mass of less than one gram, to be placed on a cyborg MAV (CMAV). To recharge the system, three sources of available ambient energy with respect to the application were explored, solar, thermal, and kinetic. Evaluations were performed based on magnitudes of available energy from each source, mass, dimension, and biocompatible constraints for each of the transducers, and specific power output of each energy harvester. Conclusions of this research show the magnitudes of the performance for photo-voltaic, thermo-electric, piezoelectric, and electromagnetic transducers weighing less than one gram. In addition, issues related to combining these multi-sourced energy harvesters into a collective power system are discussed.

INTRODUCTION
The focus of this work is to develop sub-one gram, or ultra-lightweight, renewable power systems using the described energy harvesting techniques. The research in this paper deals explicitly with an investigation of the multiple forms of energy harvesting available and their effectiveness given an ultra-lightweight mass, or sizing, restriction. In addition, this work explores the issues involved in combining multi-source energy harvesting techniques for the creation of a rechargeable collective power source. The motivation behind this energy harvesting research is the application of using insects, as hosts with implanted electronic platforms, for development of cyborg MAVs (CMAVs), useful as autonomous surveillance and reconnaissance vehicles [1-2]. The flight "platform" is an adult flying insect, specifically in this research the *Manduca sexta* Hawkmoth. These moths have approximate physical properties consisting of a wingspan of up to 10cm, a body mass of 1.9 grams, and an allowable payload upwards of one half their mass, making them excellent candidates as insect cyborgs [3]. The premise is to embed the electronics, which include controls and power systems, within the moth to create a flight vehicle that is alive, yet manipulative in its actions. By utilizing multi-component fabrication methods, MEMS, nano-fluidic, CMOS, and meso-scale devices are integrated onto a single silicon device. This device is then surgically inserted into the moth using biocompatible implantation techniques during the pupa stage of its metamorphosis, just before it emerges as an adult moth [4-7].

With the power requirements for a cyborg MAV, CMAV [2], including items such as the sensor suite, controls, and communication systems, estimated to vary from 5mW to at times 50mW, a battery approach would appear to be a logical starting point. The issue with this approach is that CMAV endurance cannot be resolved. The *Manduca sexta* moth for instance can live up to 2-3 weeks as an adult. With multiple transmissions between the communication systems and multiple flight course corrections using the control systems, a single charge, or primary battery, system would be insufficient at the sub-one gram scale [8]. Our solution is to implement multi-source, ultra-lightweight transducers and recharge the onboard power system for increased rate of availability of sensory, control, and communication electronics. Ambient energy sources investigated within this study include solar, thermal, and kinetic forms.

NOMENCLATURE
A: Cross-sectional area
E: Energy
L: Length
R: Material resistance
R_L: Load resistance
T: Temperature
V: Voltage
c: Speed of light, 3e+8m/s
h: Planck's constant, 4.14e-15eV/s
α: Material's Seebeck coefficient