Integrating Multiple Energy Harvesting Systems for Department of Defense Applications

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Abstract- **As modern warfare has grown increasingly reliant on mission-critical electronics over the past two decades, the United States warfighter has had to carry an increasingly heavy burden of equipment, armor, and batteries. In this study, we review the properties and potential efficacy of energy harvesting technologies across several modalities: solar, radio frequency/electromagnetic, thermal, and piezo/tribo-electric. Finally, we discuss how a hybrid energy harvesting system could combine multiple modalities and extend the life of Soldier-worn batteries by 40 to 60 percent over the course of a 72-hour patrol.**

Keywords- **energy harvesting, battery charging, power integration, hybrid system**

I. Introduction

A top research and development priority for the U.S. Department of Defense (DoD) is to reduce the total weight of supplies and equipment that the warfighter must carry into combat. In May 2017, the federal Government Accountability Office found that the average load for Army and Marine Corps dismounted ground combat personnel totaled 120 pounds [1]. Such a heavy load hinders warfighter mobility and maneuverability in combat, and may result in musculoskeletal injury [2].

DoD has highlighted rising battery weight totals as a key domain where engineering research and development can significantly aid the warfighter. Concurrent to reducing battery weights is the goal of increasing the amount of mobile power/electricity available per pound to those deployed in the field. Whether that solution is a more efficient battery, or the provision of novel technologies that harvest or scavenge energy mid-mission—as this paper discusses—an improvement in power supply increases operational mobility and reduces reliance on forward operating bases and costly logistics requirements. As a recent U.S. Army report noted, “every time we deliver fuel or batteries on the battlefield, we put Soldiers at risk [3].”

Energy harvesting (EH) systems have the potential to solve the challenge of powering the warfighter in the field. An individual EH system draws from one of two types of low-intensity energy sources freely present in the environment: ambient power sources (e.g., solar radiation, or Radio Frequency/Electromagnetic [RF/EM] waves) or metabolic energy sources (e.g., thermal power, piezoelectric, or triboelectric electricity) (see Figure 1). Advancements in textile manufacturing, three-dimensional (or additive) printing techniques, and flexible circuitry have made the concept of an energy-self-sufficient combat uniform/kit that hosts multiple EH systems seem feasible. Such a multimodal, or hybrid EH system may be capable of providing a substantial amount of power to a soldier’s rechargeable battery.

This study surveys the operating principles of each harvesting method, based on research performed by the Homeland Defense and Security Information Analysis Center (HDIAC), and discusses recent research performed by engineers at the Georgia Institute of Technology (Georgia Tech) and other institutions. Georgia Tech addressed a combined RF/solar energy harvester device and a hybrid triboelectric/solar woven structured textile. This study concludes with a discussion on how these advancements in EH research point toward the feasibility of a fieldable hybrid EH system.

II. Modes of Energy Harvesting

Each ambient energy source exhibits distinct characteristics that bear upon its potential use in a hybrid EH system (see Table I). The power density per square meter of many ambient energy sources is small, often in the range of microWatts (μW) [4]. Operating alone, each energy source falls below the mark for providing a viable, consistent electricity flow useful for trickle charging a high energy density battery built into a combat suit. For instance, to generate useful amounts of power, solar cells can operate only during the day and must be oriented toward the sun, while thermoelectric devices require a temperature differential between two ends of a material. Other limitations, such as output variability and low energy-to-electricity conversion efficiency apply across the board, making sole-source exploitation of these sources unfeasible for harnessing useful amounts of electricity.

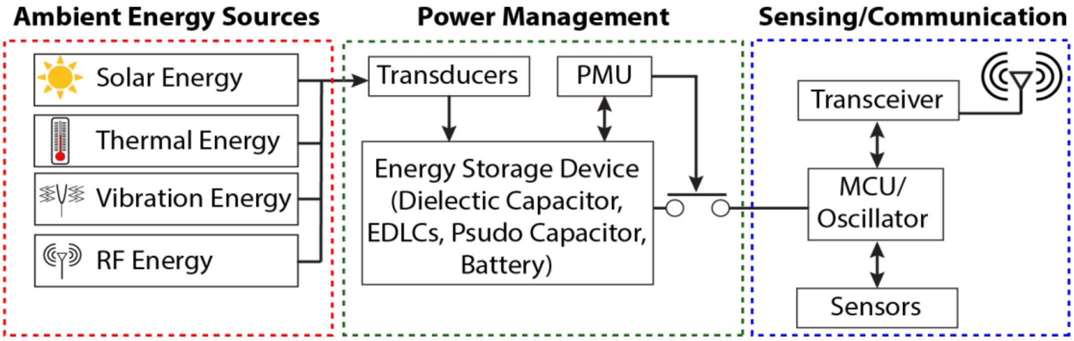

Fig. 1. Block diagram of a typical multiform, energy harvesting-enabled autonomous sensor device. Adapted from [4].

A. Solar

Solar energy has high power availability [4], making it a promising source of energy to integrate into a multimodal/hybrid EH system. It has a high power density of 100 mW/cm^2 during the daytime and 100 µW/cm^2 in an indoor environment, with a maximum conversion efficiency of more than 45 percent [5]. In a wearable context, the most promising solution for solar EH is through the utilization of polymer-based photovoltaic fibers and/or low-cost ink-jet printed solar cells.

1) Radio Frequency/Electromagnetic: RF/EM energy has a relatively low power density compared to other ambient energy sources [6]. The implementation of a high gain antenna into the EH system, however, greatly increases the amount of energy generated [6]. The energy levels available for collection heavily rely on the strength of the transmission and the distance between the RF harvester and the source [6]. In terms of energy conversion efficiency, rectifiers for ultrahigh frequency band have achieved more than 80 percent of conversion efficiency, with an optimal load and input RF power above 20 decibel-milliwatts (dBm) [7]. This is much higher than the other energy transducers for ambient EH – the highest conversion efficiency of a solar cell does not exceed 50 percent. Since the available ambient RF energy density in the far-field is very low (below 1 mW), diodes with a low threshold voltage and fast switching speed are preferable for ambient EH. From this perspective, Schottky diodes have been mainly used for RF EH.

B. Thermal

Thermal energy is readily available for use through wearable EH systems. Thermoelectric devices generate energy in the presence of a temperature gradient along the transducer itself [8]. Energy is available as long as a temperature gradient exists, but efficiently converting this energy relies on the degree of the differential as heat flows from a warmer area to a colder one [6]. In general, when a human body is a heat source, a thermoelectric generator produces an energy density of 20 to 60 µW/cm^2, yielding an approximate 18 to 25°C temperature difference between room temperature. Thermoelectric devices can continuously operate as long as the temperature gradient is maintained, but the energy conversion efficiency is low if the difference in temperature between the human body and the ambient environment is minimal. Typically, the conversion efficiency is below 1 percent when a human body is the heat source and the ambient environment is temperate. However, when thermoelectric EH is employed in desert environments (which offer extreme heat in the day and extreme cold at night-providing substantial temperature gradient with a human body), a higher energy conversion efficiency may be achieved.

C. Piezo- or tribo-electric

Vibration energy harvesters harness mechanical energy of a lower quality and at a lower frequency than traditional electromagnetic generators [9]. Nanogenerators that harvest mechanical energy use triboelectricity (energy generated from physical friction) and piezoelectricity (energy generated from compression). Triboelectric nanogenerators are a possible power source for wearable electronics, as they utilize common materials to convert almost all forms of mechanical energy, such as airflow, raindrops, rotations, and more into electricity [10]. Piezoelectric materials generate electricity when placed under physical stress or deformation and are also applicable in wearable platforms.

TABLE I
AMBIENT ENERGY SOURCES FOR ENERGY HARVESTING [4].

	Solar Energy	Thermal Energy	RF/EM Energy	Piezoelectric Energy	
				Vibration	*Compression*
Available Time	Daytime (4~8 Hrs)	Continuous	Continuous	Activity Dependent	Activity Dependent
Pros	•Large amount of energy •Well-developed technology	• Always available	•Antenna can be integrated into frame •Widely available source	•Lightweight •Well-developed technology	•Lightweight •Well-developed technology •Small volume
Cons	•Needs large area •Noncontinuous •Relies heavily on orientation	•Needs large area •Low power •Rigid & brittle	•Distance dependent •Reliant on available RF	•Need large area •Highly variable output	•Low conversion efficiency (high volt/low amps) •Highly variable output

D. Hybrid Triboelectric/ Solar System

Other research and development work has shown the promise of hybrid systems that use a different combination of EH sources. In 2016, a collaboration between engineers from Chongqing University, the Beijing Institute of Nanoenergy and Nanosystems, and Georgia Tech demonstrated the feasibility of developing a lightweight and fully flexible textile that integrated triboelectric and solar EH systems. This device, like the RF/solar discussed above, could harvest energy from one of the systems independently (i.e., from the triboelectric system, while the textile was indoors) or in a combined manner. The study was successful in producing a thin, highly deformable, breathable textile able to generate usable amounts of electricity.

The study also compared the fabric's performance through three different "electrical connection strategies": in series, in parallel, and when regulated by unidirectional blocking diodes [11]. Interestingly, a connection in series caused the triboelectric system to overwhelm the solar power circuit, reducing the system's total electrical output. A connection in parallel resulted in the opposite outcome, making the triboelectric system "ineffective" for EH [11]. Once a diode was introduced as an inter-component connection, the two energy sources were combined in an optimized manner that produced the most power (see Fig. 2).

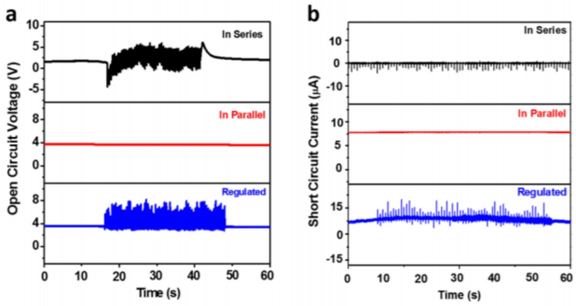

Figure 2. Power output of the triboelectric/solar hybrid textile, under different electrical connections [12].

E. Hybrid Radio Frequency/Solar System

Earlier this year, a student team from the School of Electric and Computer Engineering at Georgia Tech designed a novel hybrid EH and communication system, combining solar and radio frequency EH systems [12]. This research focused on a potential application for a stationary sensor, which would combine the ever-present but low-power RF energy with the strong but variable solar power input. The system is mainly composed of a 2.4 GHz custom dual-port antenna, an RF rectifier, a solar cell, a bq25504 Power Management Unity (PMU), a MSP430 Microcontroller (MCU), and a cc2500 transceiver. The hybrid RF/solar harvester receives -12.6 dBm of RF input power and achieves a 40% reduction in capacitor charging time when compared to the power generated from the solar cell alone.

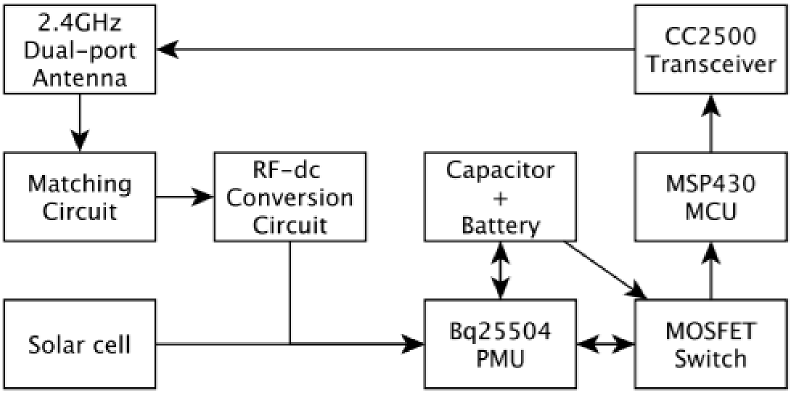

Fig. 3. Block diagram of a hybrid RF solar powered autonomous mote [11].

This work significantly improved upon previous efforts to combine an RF energy harvester with a solar cell, achieving a higher sensitivity of the hybrid system. Moreover, the study confirmed that the two EH systems together produced more usable electricity when combined into a hybrid system than when operating independently [12].

III. Multimodal/Hybrid Energy Harvesting System for Remote Battery Charging

The aforementioned research articles from Georgia Tech and its collaborating universities highlight a proof-of-concept: a hybrid EH system capable of generating usable amounts of power for small-scale electronics. Furthermore, this concept also demonstrates a promising method for charging high-energy-density batteries in remote environments.

The BB-3525 is a military-grade standard high-energy-density battery commonly used in dismounted warfighter operations [13]. Because the average patrol duration is approximately 72 hours, a dismounted warfighter will consume around 48 Whr before the first battery is drained and must be switched out with a new one.

In a hybrid EH system, the majority of the power available to charge a BB-3525 will be solar power, since its energy density is higher than the rest of the proposed energy sources (RF, thermal electric generator [TEG], and piezoelectric generator). Solar power will be obtained from a 12 cm x 12 cm flexible solar panel mounted on a helmet and operating at 18 percent efficiency. Energy from an RF device will be collected from a harvester attached to a typical two-way talk radio commonly used in operational scenarios. A typical radio outputs 36 dBm, of which 20 dBm can be recycled back into charging the BB-3525 battery without compromising the integrity of the communication link [14]. A TEG will be placed close to the body in order to establish a temperature gradient with the ambient environment—which, particularly in a desert climate, can easily reach a temperature gradient of 15° to 20°C, especially at night. Piezoelectric transducers placed on both feet can generate 59mW each, continuously, as long as the warfighter remains in motion [15].

This model of a proposed hybrid EH assumes a mission in which the warfighter conducted the patrol for at least 3 hours a day in the sun, moved/walked for 6 hours a day, and used the two-way talk function on the radio for 2 hours a day. This study also assumes an ambient temperature either higher or lower than the warfighter's body temperature by at least 15°C—a differential typical for desert climates. Table 2 further describes the proposed process for a multimodal/hybrid EH system.

TABLE II
ESTIMATED TOTAL ENERGY GENERATED OVER A 72-HOUR PATROL MISSION [16].

Energy source	**Power (W) per sq. cm**	**Area on Soldier sq. cm**	**Watts Generated (Including Efficiency)**	**Time Harvesting (hours)**	**Watt-hour Generated**
Solar	0.1	144	2.59	9	23.33
RF (Two-way talk radio) [14]	N/A	68.75	0.06	6	0.37
TEG	0.00019	232	0.04	72	3.17
Piezoelectric Generator [15]	0.00181	18.75	0.12	18	2.12
Total Energy					**29.0**

Based on the data presented in Table 2, it is estimated that the life of a soldier-worn BB-3525 battery can be extended by approximately 60 percent (from 48 Whrs to 77 Whrs) over the period of an average patrol. Such an increase in battery life could result in a drastic reduction in the number of batteries warfighters carry during dismounted operations.

IV. CONCLUSION

Recently, the use of wearable EH technologies for low-power electronics has become well established. However, ability to deliver usable energy at greater quantities is being realized. The RF/solar and triboelectric/solar systems demonstrate how multiple EH systems can be combined in close quarters with minimal to no interference, reducing energy loss. Finally, our proposed EH method for the remote charging of a high-energy density battery demonstrates a potential efficacy for multimodal/hybrid systems to meet larger energy demands.

Efficiently merging energy flows from multiple sources (or transducers) is not an easy endeavor. As has been discussed elsewhere, finding the right electrical architecture for how multiple EH sources combine within a hybrid system is a critical facet of applications, like a combat suit-integrated EH system [17]. For example, components like power management units run more efficiently with higher power or, as anticipated, when drawing from multiple EH sources. Multispectrum, unified hybrid EH systems may attain optimal performance depending on how they are wired.

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