A Survey of Multi-Source Energy Harvesting Systems

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***Abstract*—Energy harvesting allows low-power embedded devices to be powered from naturally-ocurring or unwanted environmental energy (e.g. light, vibration, or temperature difference). While a number of systems incorporating energy harvesters are now available commercially, they are specific to certain types of energy source. Energy availability can be a temporal as well as spatial effect. To address this issue, 'hybrid' energy harvesting systems combine multiple harvesters on the same platform, but the design of these systems is not straightforward. This paper surveys their design, including trade-offs affecting their efficiency, applicability, and ease of deployment. This survey, and the taxonomy of multi-source energy harvesting systems that it presents, will be of benefit to designers of future systems. Furthermore, we identify and comment upon the current and future research directions in this field.**

I. Introduction

Energy harvesting has become a commercial reality, with many deployed embedded devices being powered from naturally-occuring or unwanted energy in their environment. Electrical energy can be harvested from light, wind, vibration, or temperature difference and used to power embedded devices. The increasing popularity of these systems has been driven by a convergence between the increasing power output from harvesters and the decreasing energy demand of electronic devices. While batteries have conventionally been used to power such devices, they have a finite capacity and must be replaced or recharged when depleted. For this reason, energy harvesting is an attractive power source as it potentially offers a perpetual source of energy, provided there is sufficient and appropriate energy in the deployment environment. A drawback of many existing systems is that they only support one energy harvester type and may only be used where that type of energy source is present; changing the energy harvester requires changes to the system's hardware and software.

The design trade-offs for single-source energy harvesting systems have been extensively considered [1], [2]. To increase the availability of energy, and address the drawbacks of existing single-harvester systems, a number of reported works have proposed the simultaneous use of several energy harvesters [3]–[6]. By using a small wind turbine [7] and a solar cell, for example, more energy can potentially be generated (and for a longer period per day) than if a single harvester is used. Furthermore, the size of the energy buffer (e.g. a supercapacitor or rechargeable battery) can potentially be reduced as there may be a shorter period where energy is not generated. While the use of multiple energy harvesters is a simple concept, their selection and integration into a complete system involves choices which impact on factors including efficiency and ease of deployment.

This paper aids the effective design of multi-source energy harvesters by surveying the design of existing systems. It explores the many interrelated trade-offs and design choices that are essential for effective design of efficient and easily-deployable multi-source energy harvesting systems. A taxonomy for these systems is introduced with the aid of two example architectures developed by the authors of this paper (Sec. II), and subsequently used to classify the design of existing systems (Sec. III). The paper concludes (Sec. IV) with a discussion on the open research challenges and likely direction of future developments.

II. System Design Taxonomy

Illustrative examples of two multi-source energy harvesting systems, developed by the authors of this paper, are shown in figures 1 (the 'Smart Power Unit' [6], hereafter referred to as 'System A') and 2 (the 'Plug-and-Play Architecture' [5], 'System B'). In these examples, energy harvesters and storage devices are connected via a power unit to an embedded device (wireless sensor). System A is intended for outdoor operation, harvesting energy from wind and light and also using a fuel cell as energy backup; its power budget is of the order of a few milliwatts. Conversely, System B is intended for indoor use, harvesting energy opportunistically from a selection of modules as appropriate to the available energy in the deployment environment; its power budget is <1mW. This section considers options for system architectures, of particular interest when noting the differences between the two example systems. It looks at methods for connecting devices, and options for intelligent management and power processing.

1) Power Conditioning Functionality: Most energy harvesting devices produce power intermittently, so it is necessary to buffer the energy they produce. This allows the bursty loads of embedded devices such as wireless sensor nodes to be accommodated. As a minimum, an input power conditioning circuit is required to go between the harvester and the storage

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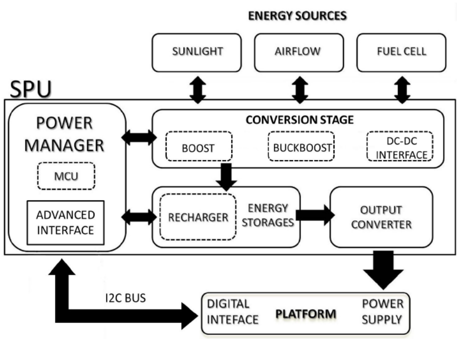

Fig. 1. Smart Power Unit Architecture (reproduced from Magno *et al.* [6])

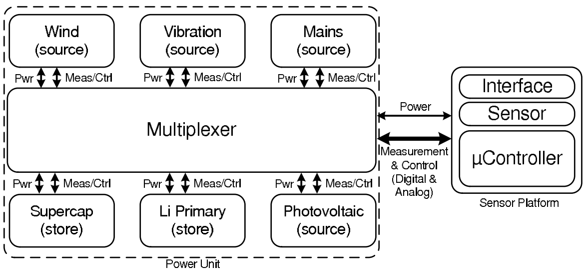

Fig. 2. Plug-and-Play Architecture (adapted from Weddell *et al.* [5])

device – to prevent the backflow of energy to the harvester, and in many cases to rectify and regulate its output.

The amount of power harvested depends on the environment, the harvester, and its match with the power conditioning circuit. There is a trade-off between the efficiency and the complexity/quiescent power consumption of the power conditioning circuit. System A uses a maximum power point tracking (MPPT) arrangement that works to ensure that the energy harvesters operate at their optimal point. In addition System A uses a hydrogen fuel cell which has a high energy density comparated with traditional battery and which starts to work when the stored energy coming from the environmental sources is running out. Conversely, System B has devolved this functionality to the individual modules, but the demonstration modules produced operate at a fixed point which offers a compromise between efficiency and quiescent current draw.

Most devices also have an output conditioning circuit between the storage device and the load, to supply a suitable voltage to the embedded device. In the case of System A, a Buck-Boost converter is used. System B uses a low quiescent current linear regulator, which again is a compromise between its conversion efficiency and quiescent current draw.

2) Exchangeable Hardware: In contrast with early single-source systems like Prometheus [2], which are designed for fixed energy devices, some reported systems provide the facility to connect a range of different energy devices. However, there are several levels of functionality for this:

- *Swappable energy harvesters.* The most basic systems allow energy harvesters to be exchanged, but options are limited by the input power conditioning.
- *Swappable energy harvesters and storage.* More complex systems allow the harvesters and energy storage devices to be exchanged, with similar constraints. In particular different storage technologies offer different characteristics well known in literature [9], [10].
- *Completely flexible.* The most flexible system architecture permits the harvesters and energy storage devices to be exchanged, but each harvester/storage device has to have its own interface circuitry.

Providing the facility to change the energy device for one of a different type means that additional power conditioning circuitry is likely to be required to interface between the storage device and the rest of the system. In other words, functionality and flexibility must be traded off against system complexity. Some systems have the energy devices soldered directly to their circuit board. For System A, which is designed to be used outdoors, the natural choice is to use wind and light energy harvesters, so these are assumed by the system design. Conversely, for System B which is designed for industrial monitoring indoors, a range of energy harvesting techniques are applicable and would only be decided by the properties of the deployment location. For this reason, System A assumes certain energy hardware (although the device size is changeable within certain bounds), while System B can accommodate any device provided that it has an appropriate interface circuit.

3) Energy Monitoring/Control Capability: Intelligent features allow the system to monitor its energy status so that it can respond by, for example, adjusting its duty cycle to conserve energy when resources are limited, or selecting auxiliary storage such as the fuel cell. At their most basic, energy-aware systems may provide an analog line to allow the microcontroller to monitor the store voltage; complex systems allow the amount of energy stored and the power being generated to be monitored (and perhaps controlled).

For systems with a fixed input power conditioning architecture, they may only allow the microcontroller to observe the input current and stored energy level. More complex devices which allow the energy storage device to be exchanged may offer the facility for this monitoring to take account of hardware changes. The means of communication with devices may be analog or digital. They may also be two-way, allowing the microcontroller to impose changes on the power conditioning circuitry (e.g. to adjust its supply voltage or to move energy between storage devices). Here, the main trade-off is between the complexity and loss of efficiency by adding the extra functionality, and the advantages gained by the improved energy-awareness of the system.

System A is a particularly capable example, as it has an embedded microcontroller on the SPU which communicates via an I^2C bus, allowing the energy status to be monitored and controlled. The provision of the facility to exchange the energy hardware normally means that energy awareness will be sacrificed. System B is a notable exception, as it has an electronic datasheet on each energy module which may be individually interrogated to determine their properties. They communicate via a digital interface to the embedded system.

TABLE I
CATEGORIZATION OF MULTI-SOURCE ENERGY HARVESTING SYSTEMS

Device	**A** Smart Power Unit [6]	**B** Plug-and- Play [5]	**C** AmbiMax [3]	**D** MPWiNode [4]	**E** Maxim MAX17710 Eval [11]	**F** Cymbet EVAL-09 [12]	**G** Microstrain EH-Link [13]
No. Harvesters/Stores	3/3	6 (shared)	3/2	3/1	2/1	4/2	3/1
Swappable Sensor Node	Yes	Yes	Yes	No	Yes	Yes	No
Swappable Storage	No	Yes, ≤ 6	Yes, battery	Yes, battery	No	Yes, battery	Yes
Swappable Harvesters	No	Yes, ≤ 6	Yes, 3	Yes	Yes, 1 of 2	Yes, 4	Yes, 3
Energy Monitoring	Yes	Yes	No	Limited	No	Yes	No
Digital Interface	Yes	No	No	No	No	Yes	No
Quiescent Current Draw	5μA	7μA	$< 5\mu$A	75μA	$< 1\mu$A	20μA	$< 32\mu$A
Harvesters	Light, Wind	Light, Wind, Thermal, Vibration	Light, Wind	Light, Wind, Water Flow	Piezo/Mech, Light, Radio	Light, Radio, Thermal, Vibration	Piezo, Inductive, Radio, General AC/DC > 5 V
Storage	Fuel cell, Li-ion rech. batt., Supercap.	Supercap, NiMH rech. batt., Li non-rech. batt.	Supercaps, Li-ion/poly, 2xAA rech. batts.	AA rech. batts.	Thin-film battery	Thin-film batt., optional ext. Li batt.	Aux: supercap/ thin-film
Commercial Product	No	No	No	No	Yes	Yes	Yes

4) Location of Interfacing/Energy Awareness: There are several options for where to locate the 'intelligence' of the energy hardware (i.e. the part that calculates the amount of incoming power or stored energy). These may be:

- *On the embedded device*. This uses information it can obtain from the energy hardware (e.g. store voltage) to estimate the energy status of the system. The advantage of this is that only one processor is needed by the system (reducing overall cost and complexity). The main drawback is that the embedded software now needs to manage its energy resources.
- *On the power unit*. This is separate from the embedded device microcontroller. It may communicate using a digital protocol with the embedded microcontroller, reducing the complexity of the interface between the embedded device and its energy hardware. The main advantage of this architecture is that the application microcontroller does not need to know any details about the energy hardware, and can treat it as another peripheral.
- *On the energy devices*. This is the most devolved type of intelligence, requiring that each of the energy harvesters (and storage devices) has its own power conditioning circuitry and a microcontroller that can monitor performance and communicate directly with the application microcontroller. This allows any complex models related to the performance of the energy hardware to be incorporated into these distributed processors.

The main consideration here is of what level of energy awareness the embedded device will have and whether it has the capacity to accommodate the additional software to manage its energy hardware. By hosting the energy-awareness on a dedicated microcontroller (e.g. System A), the interface between the embedded device and the power unit is simplified. Conversely, System B utilizes the embedded device's microcontroller. If the intelligence were to be devolved to the energy devices themselves, the system would become more flexible as each harvester could manage itself.

III. CLASSIFICATION OF EXISTING ARCHITECTURES

Seven prominent systems that have been reported in the literature or released as commercial demonstrators are detailed in Table I. This table lists the relevant features of each device including the types of energy resource it supports and its energy monitoring capabilities. Please note that, where the storage or EH hardware are listed as 'swappable', this means that the devices are not soldered onto the board and may be connected to the terminals. It is important to ensure that the alternative EH device has similar characteristics to the original, and that it does not violate the requirements of the input power conditioning circuitry. System B is the only one that is not sensitive to this, because each energy harvester/storage device has an interface circuit that brings its characteristics into line with those required by the power unit. The most commonly-used harvester types are photovoltaic (PV) cells, wind turbines, and vibration energy harvesters [6], [5], [8]. This section reviews the capabilities of the existing technologies.

1) Power Conditioning Functionality: Many of the reported systems focus on the efficiency of conversion, using MPPT algorithms to achieve optimal performance, rather than on adaptability, energy-awareness, or their ease of application to a range of scenarios. All the listed systems (apart from B) have their power conditioning circuits on the power unit. Additionally, systems D and G have the sensor node on the power unit, which means that the system topology is inflexible. System B has a power conditioning board for each energy harvester/storage device; these boards act as interfaces between the energy devices and the power unit, meaning that voltages can be converted and devices can be swapped easily (provided that they have the required interface).

2) Exchangeable Hardware: The only system discussed in this paper which allows all sources and stores to be swapped dynamically without impacting on the software's energy-awareness is System B. While some of the other systems have a fixed energy storage device, or maybe a single energy harvester soldered to their power unit, most of them allow the energy harvesting or storage devices to be changed by attaching an alternative device to the terminals of the power unit. However, given that these devices are designed for specific types of harvester, their requirements can be very restrictive (e.g. for System F, certain inputs must be below 4.06 V, while others must be between 4.06 V and 20 V). For the devices that perform energy monitoring, the connection of an alternative device (especially storage device) will typically affect measurements as the software will not automatically be able to recognise any change in capacity.

3) Energy Monitoring/Control Capability: Perhaps the most developed scheme is System A, which has a dedicated microcontroller on the power unit which is able to manage the system autonomously, or provide visibility and control facilities to the sensor node. System B allows the system to monitor incoming power and stored energy and can accommodate changes in the energy devices without requiring any changes to the power unit circuit board or software. System D only allows the store voltage to be monitored, and System F allows the system to see which devices are active.

4) Location of Interfacing/Energy Awareness: Systems A and F have dedicated controllers that carry out the energy-awareness tasks and interface with the sensor node. System B has no on-board microcontroller, and relies on the sensor node's microcontroller having appropriate software to be able to interface with the energy hardware. The rest of the systems have no 'intelligence' on board.

IV. Discussion and Conclusions

The features of the prominent multi-source energy harvesting systems, and their designs, have been explored. The architectures of systems A and B were described in detail while introducing the taxonomy. Systems A and F are the only ones to provide an explicit digital interface to the embedded system to allow it to determine the status of its energy hardware. System B allows up to six energy devices to be connected, and is agnostic about whether these are storage or harvesting devices. The drawback of this architecture, however, is that each device must have a suitable interface circuit and energy-awareness puts an additional demand on the embedded device. Many of the systems implement some form of MPPT, which is important providing that the overhead of implementing it does not exceed the delivered benefits. Often this is deployment-specific, which underlines the importance of considering the deployment environment when choosing energy hardware.

A limitation of the existing collection of energy harvesting systems is that they either mandate that certain types of energy harvester should be used (systems A, C-G), or require that devices have a certain interface circuit (System B). While all the described systems support multiple energy devices, most are not energy-aware and only one allows changes in the connected hardware to be automatically recognized so that the system can remain energy-aware. In view of the fact that energy harvesting autonomous systems are deployed in a wide range of environments, the capability of changing the energy hardware is extremely important. Similarly, as energy generation rates are highly variable, the requirement for the embedded device to adapt its activity to its energy status is essential. Therefore, the ability to exchange energy devices and for them to be recognised by the system is important.

It looks likely that, owing to the variable nature of deployment environments and available environmental energy, future commercial systems will require high levels of efficiency, reconfigurability, and energy awareness. Given these needs, there are definite drawbacks to all the analyzed systems. An open research challenge which would address many of these drawbacks is the development of a 'smart harvester' scheme. This would require each energy harvester and storage device to be energy-aware, operating with a common hardware interface and incorporating a low-power microprocessor to interface with each other and the embedded device.

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