

Research Article

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A Design Methodology for Energy Harvesting: With a Case Study on the Structured Development of a System to Power a Condition Monitoring Unit

Abstract: A design methodology is proposed for electronic systems powered by energy harvesting. The methodology first considers the operating environment. It then evaluates the *supply-side* (the attributes of the harvester), the *demand-side* (the engineering application or load which receives and uses the converted power), and the *power conditioning* needed between supply and demand. A test case is presented in which the vibrations of an electromagnetic device are harvested, converted, and used to power a wireless sensor node. Such a node is being used for the *condition based monitoring* of manufacturing equipment.

Keywords: energy harvesting, energy scavenging, self-powered, low power, design methodology, power conditioning, condition based monitoring of manufacturing equipment

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Introduction: a design methodology for energy harvesting

Figure 1 proposes a design framework for determining whether energy harvesting will support an engineering

application that is being evaluated. The procedure is divided into three main areas: the “supply-side” of environment being considered, the “demand-side” of the desired application, and the power conditioning between supply and demand. This systematic design approach is based on standard works by Pahl and Beitz and Suh. In general, the desired operating performance (demand) of an engineering system is specified in detail, and then various electromechanical elements are supplied and combined to create simulations, physical prototypes, and products that fulfill the performance. Design iterations take place to decide among many options within constraints such as cost, long-term performance, and time to market (Hazelrigg). The power-conditioning and power-transfer issues in the design of energy harvesting systems play a similar role, since there are costs and efficiencies involved when designing harvesting systems.

The environment of the supply-side

Step S1

The design methodology first considers the specific *environment* in which the final system will operate. Parameters such as the shape of the surrounding machinery or environment and the maximum volume available for the harvesting device need to be considered. The various harvesting methods – photovoltaic, vibration, thermal, and fluid flow then need to be evaluated in terms of their possible supply of energy (these are described elsewhere in the Journal and see Pillatsch et al. 2013; Williams and Yates 1996; Miller et al. 2011; Strasser et al. 2002; Rowe 2012; Seeman, Sanders, and Rabaey 2008; Chee et al. 2008; Chee, Niknejad, and Rabaey 2006; Reilly et al. 2011; Weinstein et al. 2012; Edamoto et al. 2009; Waterbury 2011; Inman 1994; Warneke et al. 2001; Vyas, Lakafosis, and Tentzeris 2010; Ruhle et al. 2012; Carli

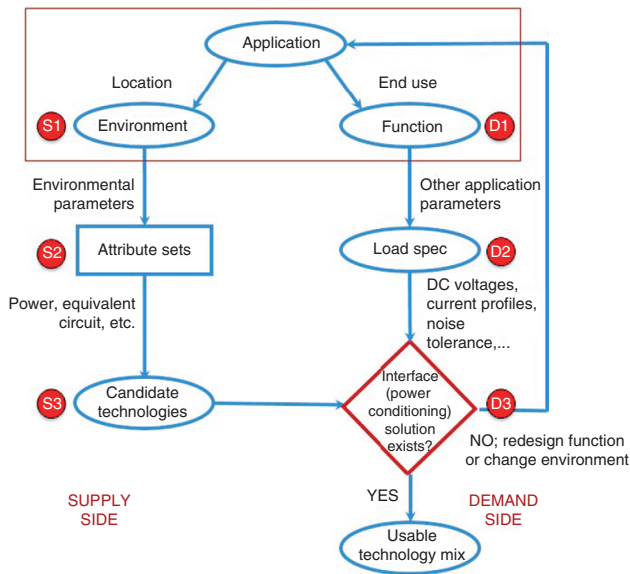


Figure 1 Design methodology

et al. 2010; Bansal, Howey, and Holmes 2009; Priya 2005; Sanchez-Sanz, Fernandez, and Velazquez 2009; Venkatasubramanian et al. 2007; Dalola et al. 2009; Jovanovic 2006; Moghe et al. 2009; Paprotny et al. 2010; Paprotny et al. 2012; Roundy 2003). Characterizing the likely intermittency associated with each harvesting source is also critical. As indicated in Figure 1, the “supply” and the “demand” sides can be investigated somewhat independently, but it is important to maintain feedback between them to avoid divergence.

Step S2

Second, the methodology considers the *attributes* of energy harvesting technologies that might provide a desired solution. Attributes are properties of a harvesting technology – or outputs of a harvester (scavenger) in a specific environment. Attributes also include estimated power over the operating range, equivalent circuit models, and basic form factor. These can be used as a first-order basis for evaluation. Attributes can also be seen as codified expert knowledge that is available for any design task. In Table 1, for example, the authors and colleagues collected data from various vibration sources. In that work, a specific resonant frequency often occurred from a source such as electric sander. Such cases easily led to piezoelectric cantilever designs tuned to that excitation (Roundy 2003). However, in other examples, such as the lathe, the frequency spectrum was broader, less distinct, and dependent on the varying operating conditions of

Table 1 The environment’s attributes

	Frequency (Hz)	Acceleration (g’s)	Characterization
Washing Machine	85.0	0.314	s
Rockwell Sander	59.3	0.121	s
Monarch Lathe Chassis	284.0	0.144	bb
Delta Drill Press	41.3	0.407	s/bb
HVAC on Roof	184.5	0.252	bb
Running	1.5	2.045	s/lf
	5.1	0.762	s/lf
Walking	1.0	0.430	s/bb/lf
	3.7	0.305	s/bb/lf

Notes: s (single frequency), bb (broadband), and lf (low frequency).

machining. The vibrations from operating industrial machines (machine tools, motors, pumps, etc.) obviously vary in frequency and magnitude for different systems. Such practical considerations have prompted the development of the electromagnetic harvester presented later in the case study (Sections “Using the methodology” and “Experimental results”) and ongoing analyses by the authors (Pillatsch et al. 2013).

Step S3

Third, the methodology narrows down the *candidate technologies*. This is done by mapping the attribute data collected in step S2 onto the environment analysis in step S1 (where the constraints of the environment and the characterization of its energy source were considered). This can be done algorithmically or through table lookup. In some cases, it will be clear by inspection that a particular harvesting technology will be unsuitable given poor light, low vibrations, or the absence of temperature gradients. The results from step S3 become a set of performance parameters that describe how much energy or power can be delivered by the harvester(s) to the load on the demand-side.

The engineering system on the demand-side

Step D1

On the demand-side, the methodology first needs to consider the *function* of the electronic system that will be

powered, its sub-components and desired outputs. In the majority of energy harvesting applications, some kind of wireless sensor is created. Therefore, the designer will be considering the energy draw (demand) of one or more sensors, the need for on-node sensor averaging, etc., the characteristics of the radio transmission, and the likely duty cycle for sending out sensed data to a wider network of nodes and/or a base-station. In general, the load operating profile will include periods of very low to zero energy consumption. This can take the form of a deep sleep mode or gating of the power rails. Duty cycles of less than 1% are common, and for many sensor applications in condition based monitoring this is entirely adequate.

Step D2

Second, the design methodology must consider the specific *load* parameters for each sub-component. These include the necessary DC voltages, current profiles, and the noise tolerance of the sensors, microprocessor, and radio.

Step D3

Third, at this point, the amount and nature of the power required by the demand-side load and the power

available from the supply-side harvester should be known. Using steps S3 and D2 as input, an interface solution – a *power-conditioning* system – that matches the harvester to the load must be designed as the final step. (Note that many publications on harvesting (scavenging) technologies often express the available power (S3) as measured across an ideal resistive load (in D2.) This can be a valid metric for comparing energy harvesting transducers among each other as stand-alone harvesters. However, it is not as useful for evaluating energy harvesting *systems*, because no realistic load will be an ideal resistor, and many harvesters need rectification and adjustments for the appropriate load-voltage.

Power conditioning to match the supply-side and demand-side

Power conditioning converts the energy obtained from the energy harvester into the energy that is used by the application (Figure 2). Power conditioning usually contains a storage element, such as a capacitor or a battery to support the peak demand (usually radio transmission) of the applications.

One characteristic of electronic systems powered by harvesting (scavenging) is that the generated energy is

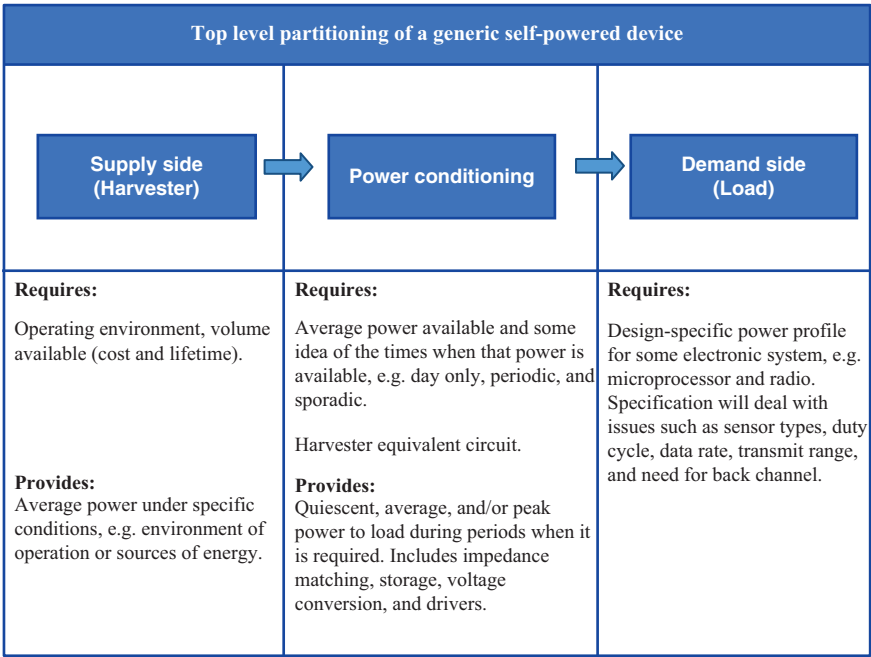


Figure 2 The three components of a system: energy harvester, the power-conditioning circuit, and the load

not directly usable by the load's typical device electronics. The reasons for this include:

- The harvester output voltage is rarely at or near common V_{dd} levels. Contributing to this is the nearly universal requirement to operate oscillating vibrational harvesters in resonance. Voltage and power drop off dramatically when operating away from resonance.
- The impedance from a harvester tends to be high relative to standard battery characteristics.
- For some harvesting technologies, output voltage will be low, sometimes less than 1 V. Although supply voltages for low-power electronics have been reducing over time, unless a custom integrated solution is available it may prove difficult to locate off-the-shelf components that can manage the low voltages generated by energy harvesting technologies.

Although it is desirable to create a harvesting source that can be useful in a wide range of applications, the notion of

a one-size-fits-all “battery replacement” energy harvester and power conditioner is unrealistic. Every application operates in a unique environment, and each environment draws on different sources of energy. Consequently, in most cases, both the energy harvester and its power-conditioning circuit must be uniquely optimized. Certain classes of circuits, or blocks, may be shared across applications. For instance, almost all harvesting systems contain storage of some kind, typically a rechargeable battery or a capacitor. Most will have voltage conversion or regulation blocks that, if sufficiently parameterized, can be used in various applications.

Figure 3 decomposes several simple prototype energy harvesting systems implemented in various research projects by the authors (Seeman, Sanders, and Rabaey 2008; Chee et al. 2008; Chee, Niknejad, and Rabaey 2006; Reilly et al. 2011; Weinstein et al. 2012), including the implementation covered later in the paper. All these examples were built using commercial off-the-shelf (COTS) components. The designs share some similar blocks, but note that no two are identical. Although the examples are

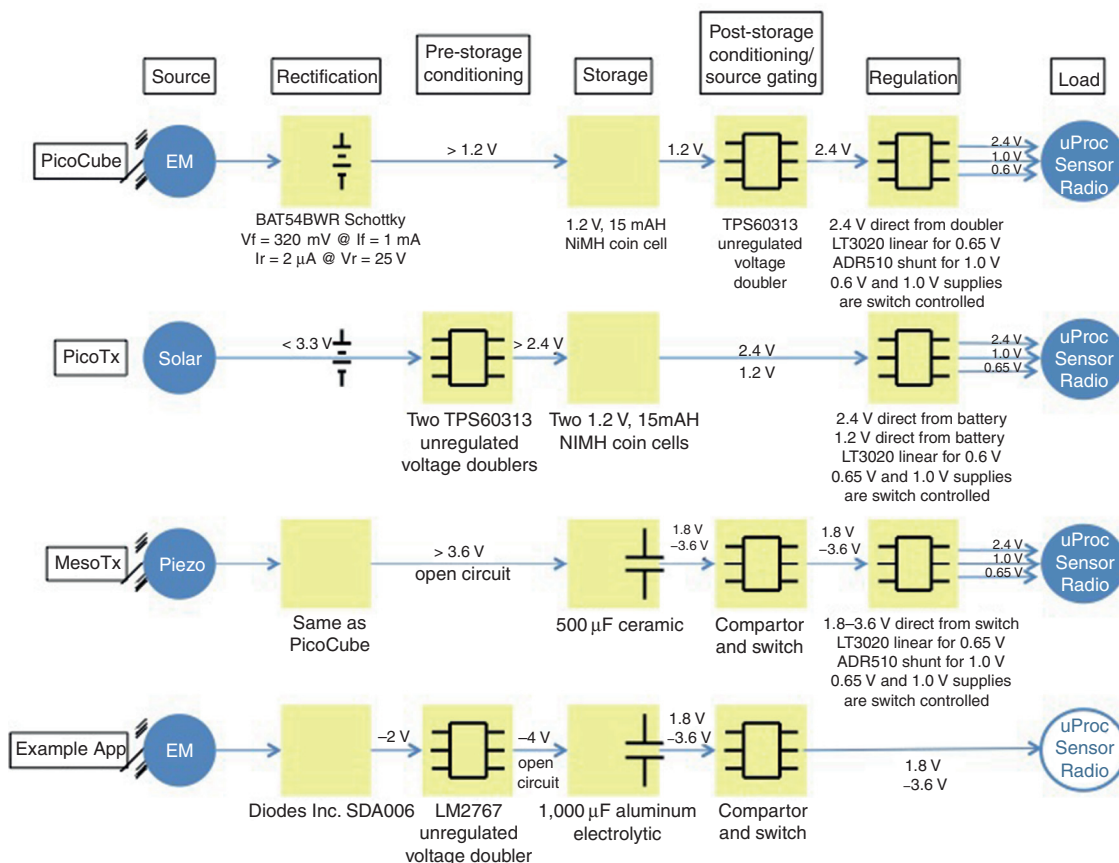


Figure 3 Decomposition of simple power management blocks for several existing research prototypes

sufficient for simple demonstration circuits or prototypes, power management is moving from PCB-based circuits (employing simple regulator ICs and discrete passive devices) to on-chip blocks custom designed specifically for the electronics on a particular chip with some external passive elements such as large capacitances. However, the general decomposition should not change a great deal. In Seeman, Sanders, and Rabaey (2008), an efficient regulator IC targeted specifically to the “PicoCube” (Chee et al. 2008) is an integrated solution employing switched-capacitor DC–DC converters. This research device was implemented as a stand-alone IC, but the intent was that it be used as a building block (core) in future integrated designs. Using a COTS system, a new device from Linear Technologies, the LTC3588, was used to integrate a rectifier, comparator, switch, and regulator for a piezoelectric harvester.

Using the methodology

This section illustrates the proposed methodology. A test case is presented in which the vibrations of an electromagnetic harvester are used to power a wireless sensor node for the condition based monitoring of expensive manufacturing equipment. First the harvester is tested on a laboratory-bench “shaker.” Next, the harvester is integrated with a radio, microprocessor, and a MEMS-scale vibration sensor to monitor the manufacturing equipment.

Environment characterization (step S1)

The goal is to design a condition based monitoring system for an expensive water pump, integral to the semi-industrial infrastructure of a large micro-fabrication laboratory. The sensor node, including everything necessary for operation, must be small in mass with respect to the water pump so that the inherent vibration spectrum from the pump remains unaltered. A single sensor reading is desired about once per second. The device must not require maintenance such as battery replacement. It will be transmit-only, so a receiver is not necessary. Given this general background, the design goal is to answer: How much power is desirable to support the monitoring system?

The sources of energy in the manufacturing space included light, vibration, waste heat, fluid flow, and energized conductors. An informal audit quickly showed that the space has no windows, so photonic energy was only present when the room lights were on, which was seldom since the room was usually unoccupied. For this reason,

light was not a good candidate. Fluid flow was a possibility since water flows through the pumps and associated pipes. However, a drawback to water flow would have been the need to penetrate the pipe or pump housing to insert the harvesting device. The nearby HVAC ductwork was another potential source, yet the HVAC airflow was not co-located near the pump, so issues of energy transfer between the source and sink would have arisen. Each pump has AC power supplied to the motor, but the wiring was encased in galvanized steel conduit. Thus, the magnetic fields of the conductors were shielded and unavailable to harvesters. Appropriately, designed harvesters could be installed in the junction box at the pump, but installation would have required a skilled electrician and taking the pump out of service for safety.

Waste heat (Strasser et al. 2002; Rowe, 2012) and vibrations (Pillatsch et al. 2013; Williams and Yates, 1996; Miller et al. 2011) emerged as the two most favorable harvesting sources. For waste heat, in the most favorable situation, the motor surfaces were $\sim 5^\circ\text{C}$ hotter than the ambient air. An off-the-shelf TEG device (Ferrotec 9500/127/120B) was considered for harvesting. Calculations showed a $40\ \mu\text{W}$ power output for an $\sim 5^\circ\text{C}$ temperature difference or an $\sim 14\ \mu\text{W}/\text{cm}^2$ power density. With appropriate power conditioning such levels might reach satisfactory power levels and ongoing research is in progress: but, in summary, vibration emerged as the most attractive option for powering the system. In addition, the vibrational energy was available whenever the pump was operating and hence whenever measurements were desired. Figure 4 characterizes the vibration associated with the pump motor. There are several spectral peaks that are candidates for harvesting. Input acceleration magnitudes are very small and generally below $0.2g$.

Attributes of possible harvesting technologies (step S2)

From step S1, it is apparent that the general case of vibrational energy harvesting is a desirable candidate for powering the sensor node. This could involve piezoelectric cantilevers, capacitance designs, or electromagnetic designs.

Candidate harvesting technology (step S3) and characterization on a “shaker table”

A particular vibration energy harvester was selected that utilized electromagnetic transduction and had

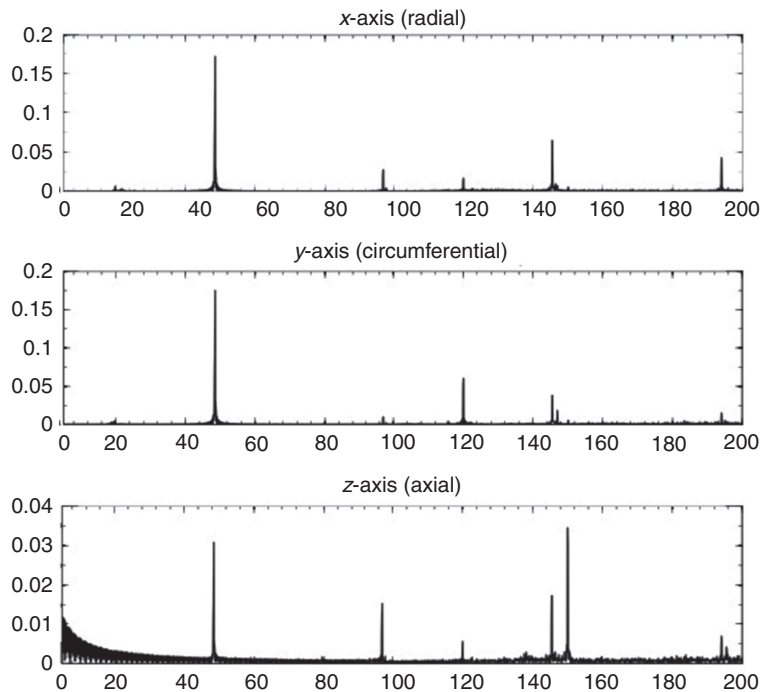


Figure 4 Acceleration (y axis) versus frequency (x axis) spectra for a 15 kW process cooling-water pump motor (three axes of a vibration sensor)

interchangeable springs for manual adaptation to a target frequency. The relatively small size, adaptable resonant frequency, and relatively high power output of the selected prototype made it well suited to the application environment where harvestable vibration peaks vary in frequency and magnitude for every piece of equipment.

The prototype, shown in Figure 5, employed a magnetic circuit similar to a coreless axial flux motor containing a Halbach array. Six block magnets created a flux loop entirely through permanent magnetic material to develop a large gap flux density of 0.9–1.0 T over a

relatively long air gap of 2.5 mm where coils are wound. The high gap flux density and large gap length resulted in a great deal of induced voltage for the small input accelerations associated with ambient industrial sources. For an input acceleration of 0.05g at 95.9 Hz, the prototype harvester generated 0.81 mW at 2.2 VRMS for a coil with 510 turns and an optimum load resistance of 6 k Ω . Power versus frequency and load graphs are shown in Figure 6. The shape of the frequency curve illustrates the high sensitivity to resonance typical of vibrational energy harvesters. Basic performance parameters for the device included an RMS output voltage, expected average power at resonance (@ 0.05g) of approximately 800 μ W, and an optimal load impedance of 6 k Ω at resonance.

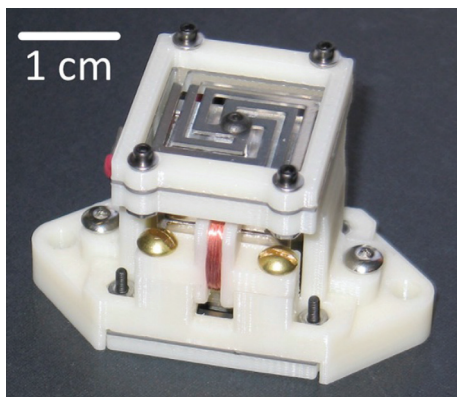


Figure 5 Electromagnetic harvester

Engineering system and load architecture (step D1)

The application specified one sample every second, operating wirelessly from harvested energy with an appropriate energy buffer. A common platform for this class of functions consists of a sensor (or sensors), a microcontroller, and a radio.

Figure 7 shows a block diagram of a typical load. The microcontroller transferred data samples from the sensor

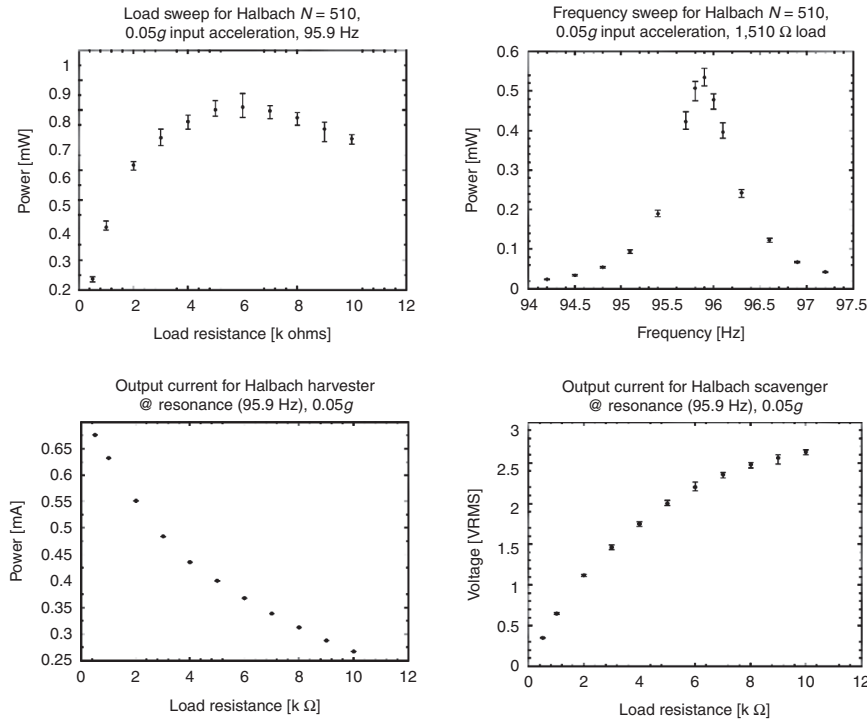


Figure 6 Frequency and load sweeps for selected harvester, from the harvester characterization (part of its attribute set)

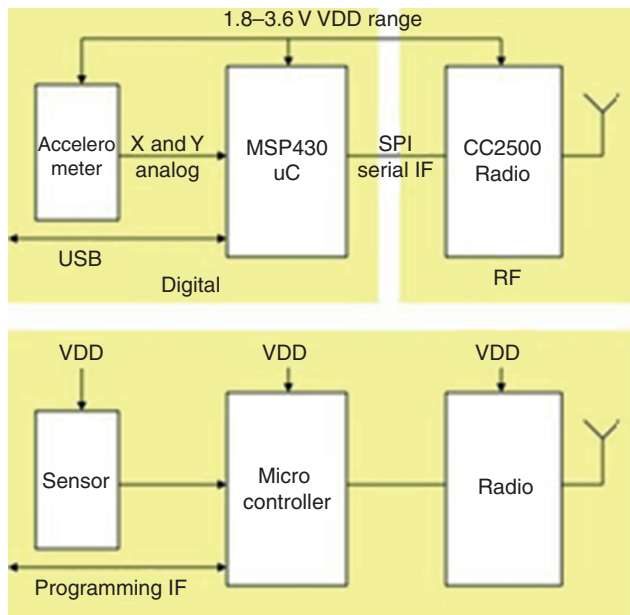


Figure 7 Block diagram of a sensor system

to the radio for transmission. The sensor issued interrupts to the microcontroller at specified intervals. Even if the controller were continuously powered, it would spend most of the time in a low-power sleep mode. In the event that the sleep mode power demand exceeded the

harvester capability, power could be completely disconnected by means of a solid-state switch until enough charge accumulated in the storage element. The radio(s) considered ranged from a simple transmit front-end (upconversion, modulation, and amplification) to a highly configurable mixed-signal transceiver with conformance to standards such as 802.11.4 (Zigbee).

Load specification (step D2) for the complete system

The Texas Instruments (TI) MSP430 processor and the companion CC2500 radio were considered to match the architecture attributes of step D1. Both have been commonly used in sensors designs, have attractive power profiles, and are relatively inexpensive. This platform was available as a development kit (eZ430-RF2000) and was used as a first-order estimate for a load specification. The development platform contained a MSP430F2274 microcontroller and the CC2500 radio operating in the 2.4 GHz ISM band. The kit included software for Texas Instruments SimpliciTI network protocol. From the data-sheets, a set of performance attributes were compiled:

- Approximately one packet per second (minimum from the application specification), processor “on”

time estimated at 5 ms, with a resultant duty cycle of 0.5%

- Supply voltage range 1.8–3.6 V
- Sleep mode power of $\sim 1 \mu\text{W}$
- Microcontroller maximum active power of about 8.5 mW @ 3 V, radio and sensor off or asleep (negligible power)
- Radio transmit power between 33.3 and 65.5 mW @ 3 V, depending on transmit power level.
- Expected ratio of transmit time/total node active time = $\sim 2 \text{ ms} / 5 \text{ ms} = 0.4$ so about half of the time the node will be consuming 8.5 mW and half of the time 50 mW typical, so transmit power is dominant. On a first order, ignoring sleep mode, average power will be approximately $(50 \text{ mW} * 2 \text{ ms}) + (8.5 \text{ mW} * 3 \text{ ms}) / 1,000 \text{ ms} = 125 \mu\text{W}$ at the load. This did not take into consideration losses in the power management circuit or sleep mode power if the device was continuously powered (potentially $< 1 \mu\text{W}$).

The estimate indicated that the energy source needed to cope with a relatively large burst of current once per second. Also the average power provided should meet the quiescent power needs as well as the surplus power for the sensing and transmitting period. Energy

should be presented to the load at a voltage between the supply voltage limits. Finally, there needed to be two power steps: one when the circuit became active and one during transmission. Bench tests using a profile similar to that specified yielded the numbers shown in Table 2.

Power conditioning

When the harvester shown in Figure 5 was mounted on the pump, the accelerations created 1 mA at $\sim 2 \text{ VRMS}$. However, the harvester power cannot be applied directly to the sensor-node electronics, because individual components have specific requirements for voltage, noise, and regulation. For example, low-power radios best operate with clean, regulated voltages and bursts of current for transmission; and so 1 mA at $\sim 2 \text{ V}$ was able to sustain the operation of the node in the “sleep mode” but not to provide such a regulated voltage and burst-current for radio transmission (Figure 8). Following full-wave rectification, a buffering capacitor was therefore added for storage (Figure 9).

Further, since the RMS voltage from the harvester was only $\sim 2 \text{ V}$, a charge-pump voltage doubler was

Table 2 eZ430-RF2500 measured performance

Power consumption		
Operating mode		Power (mW)
Running	Radio asleep, board initialized	9.6
	Radio awake, rx/tx off	14.7
	Transmitting sample	57.6
	Low-power mode 3	0.0012
Sleeping	Low-power mode 4	0.0003
Timing (μs)		
Overall cycle time		1,080,000
Overall awake time		2,650
Boot (power applied to first timing I/O transition)		60
Initialize		2
Take sample		342
Build payload		21
Wake up radio		364
Send packet		1,896
Put radio to sleep		25
Duty cycle		0.25%
Average power		110 μW
Conditions: Vdd = 3.04 V, using DCOCLK at 8 MHz, transmit power 0 dBm		

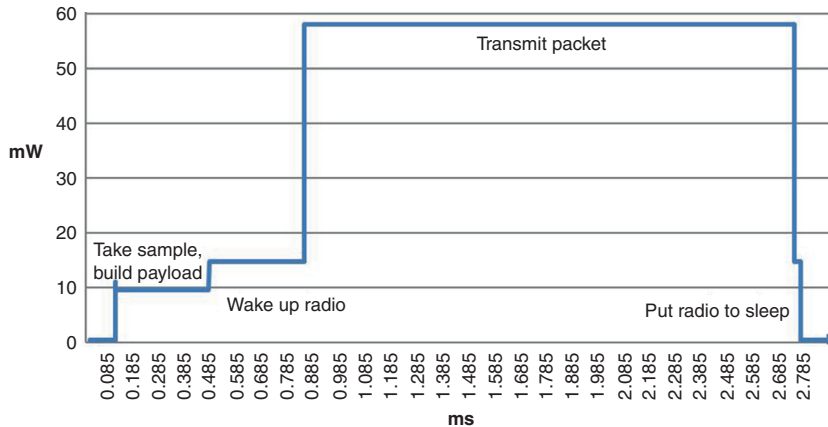


Figure 8 Power profile. The transmitter, both in magnitude and in time, dominates the power draw

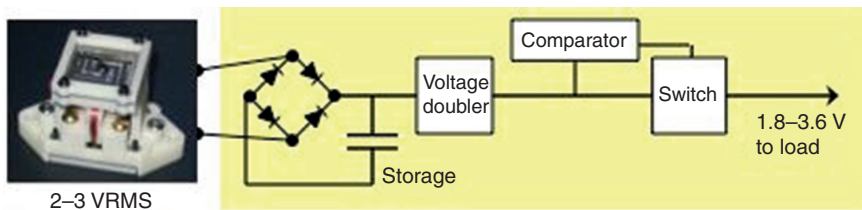


Figure 9 Block diagram of the power-conditioning circuit

added to provide 3.6 V. A comparator sampled this voltage doubler output, and when that voltage approached the maximum input voltage of the system's controller, the power switch in Figure 9 was closed: then later re-opened when the doubler voltage dropped below the minimum required operating voltage.

Experimental results

Vibration table

The circuit was first evaluated using a vibration table to excite the harvester. The acceleration was increased until the device was operating as intended: 0.08g at 95.7 Hz. The harvester charged 1,000 μF of capacitance. The duty cycle was ~ 1 s set by the microcontroller timer, and one full packet was generated each cycle. Figure 10 shows voltage and power profiles for the two primary modes of operation: charging and transmitting. The high and low voltage difference from the doubler was ~ 900 mV (3.3–2.4 V), illustrating that the harvester was more than

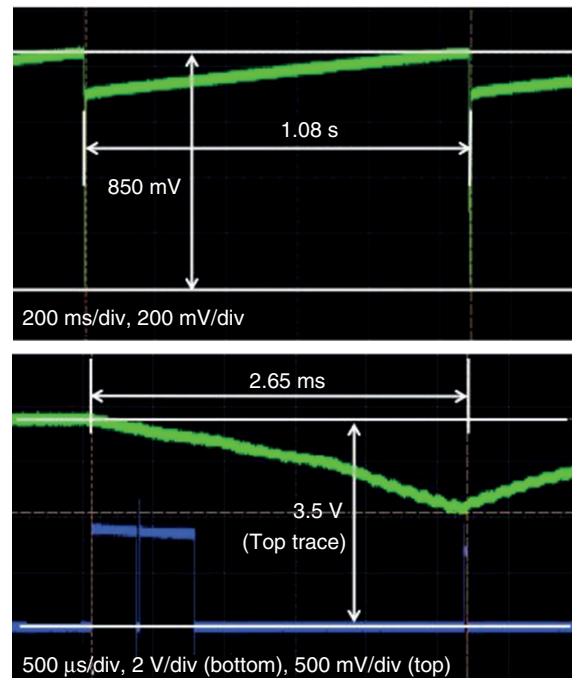


Figure 10 Top: One full cycle of charge/transmit, 1.08 s. Bottom: Transmit sequence, $y_{\min} V = 0$. Blue trace is a marker where transitions indicate phases of operation, e.g. init, take sample, packetize sample, turn on radio, transmit, and turn off radio

capable of maintaining load operation within specifications.

Since the duty cycle was very small, the harvester was almost always charging the capacitor between 2.7 and 3.5 V. Using $P = (0.5 * C * dV^2)/T$, where dV is the change in voltage, yield that about 100 μW was required to charge the capacitor over one cycle. The average load power consumption was about 110 μW , and the load appeared to be consuming all of the power available at its supply terminals.

The roughly 100 μW consumed by the electronics of the load during evaluation highlights the difference in power levels realized for a practical implementation of an electrical load and the simple resistive load commonly used to characterize a harvester as in section “Candidate harvesting technology (step S3) – and characterization on a ‘shaker table’”. The roughly 800 μW produced during characterization represents an ideal situation where the load impedance is static and matched to the parameters of the harvester. Implementing a passive rectification design, capacitive energy buffer, and dynamic load results in harvester performance that deviates significantly from the conditions of a characterization using a purely resistive load. The non-ideal diodes of a bridge rectifier result in voltage drop. Matching the ideal impedance of the harvester becomes challenging. For the selected power-conditioning architecture, the impedance downstream

of the harvester was roughly 4 $\text{k}\Omega$ rather than the optimal 6 $\text{k}\Omega$. Additionally, operating components such as the charge-pump voltage doubler at lower than the 1.8 V rated input caused a significant loss. In static bench testing, as much as 1 mW can be drawn when operating the doubler below the rated input voltage. From experience with commercial electronics, it was expected that the doubler could be “pushed” somewhat on the low side, and although it does produce the needed voltages the operating power was excessive given the extremely low-power budget.

Using the complete system on a water pump in the machine room of a micro-fabrication facility

Figure 11 shows a photograph of the complete system magnetically mounted on the water pump. The system harvested the 51 Hz y -axis vibration peak shown in Figure 4. Figure 12 shows that seven packets could be sent from one discharge of the capacitor before recharging was needed. A MEMS accelerometer from Analog Devices (ADXL345) was used to monitor the pump vibrations over time. Base line vibration characteristics of a new pump were compared with data over time in order to make sure that the pump was operating well without need for maintenance.

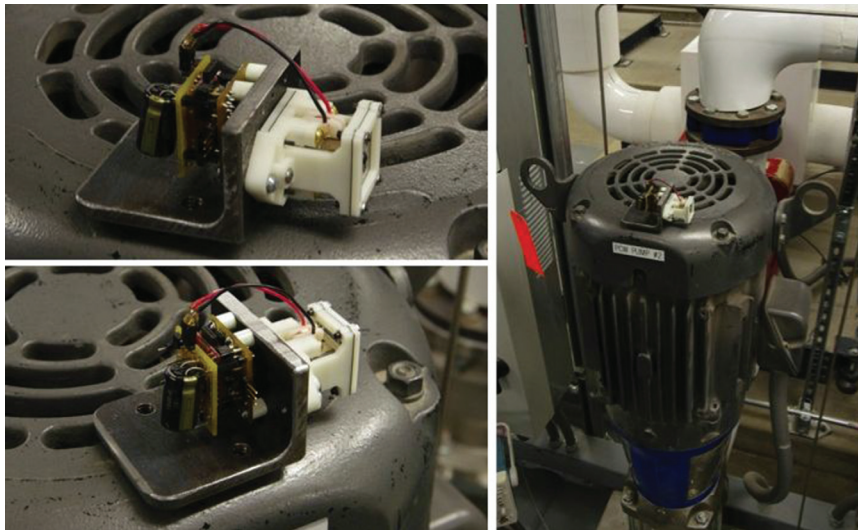


Figure 11 Complete system mounted on the water pump

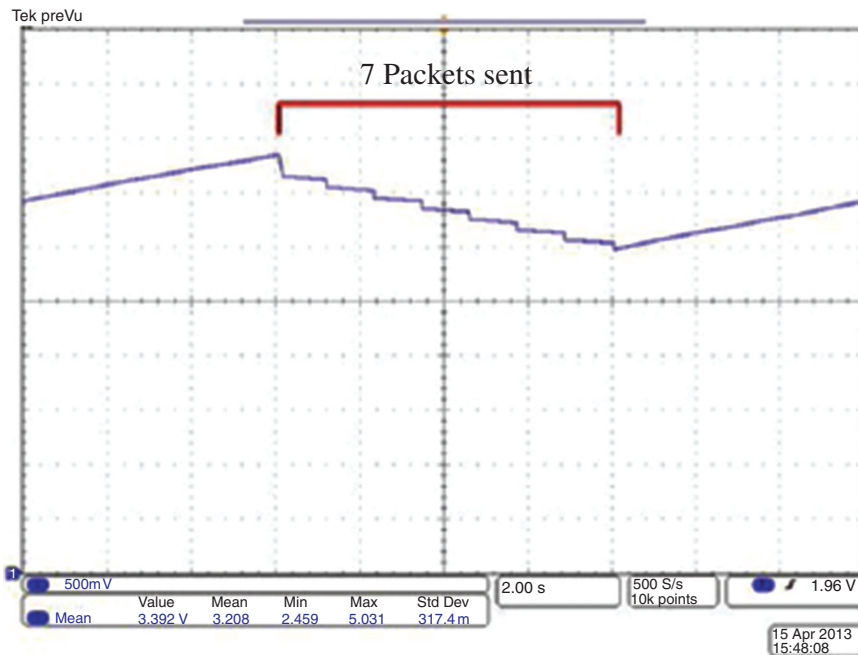


Figure 12 Seven packets being discharged from capacitor on single charge

Conclusions

1. Energy harvesting (scavenging) is a satisfactory power generation option for electronic systems in many scenarios, including inaccessible locations, high-density deployments, and long-term applications with no battery replacements. We presented an overview of these considerations, with a proposed methodology for system design (Figure 1).
2. The role of the overall environment was emphasized in any design for energy harvesting. The need for advanced circuit design for power conditioning was also emphasized.

3. A test case was presented in which an electromagnetic harvester powered a wireless sensor node for monitoring the condition of a water pump in a micro-fabrication facility.

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