White Paper

Energy Harvesting Powered Wireless Sensor Node and Asset Tracking Solutions in Random Vibration Environments

by

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Executive Summary

AdaptivEnergy has developed a line of Joule-Thief™ DC power solutions capable of harvesting energy from a wide variety of ambient vibration sources, converting mechanical energy to usable electrical energy. The applications range from wireless switches and data loggers to beacons and asset tracking using active RFID and GPS/SATCOM. The *JTRA-e5mini* "Random Vibration" energy harvesting module is designed for vehicular applications and can harvest useful energy from vibration experienced in automobiles, trucks, and trains. In addition to providing the highest power density over competing piezo-based energy harvesters, the AdaptivEnergy Joule-Thief™ offers significant advantages in size, reliability and cost over other energy harvesters. The flexibility and robustness of this technology, coupled with Energy Key™ electronics, results in a complete standalone product for energy harvesting solutions. This paper presents an overview of AdaptivEnergy's *JTRA-e5mini* Random Vibration Module. In addition, a brief discussion on the random vibration demonstration kit is provided for the user to evaluate AdaptivEnergy's Joule-Thief™ technology in any customer specific application.

What is available to power?

Ambient energy harvesting as a power solution has steadily gained momentum in recent years, especially with significant progress in the functionality of low power embedded electronics. While many potential avenues exist for Energy Harvesting (EH) enabled solutions, Wireless Sensor Network (WSN) applications present an ideal match between the available energy from harvesting and the power requirements for embedded systems. Wireless sensor networks typically include spatially distributed devices with sensors that remotely transmit and receive data over a network. The relayed information is used to monitor both physical and environmental conditions such as temperature, location, and pressure.

Wireless sensor nodes, active RFID tags, and wireless switches can be powered by a variety of methods, of which the most prevalent method is batteries. Batteries are a cost effective, ubiquitous, commonly known, and well understood powering technology. However, they present specific drawbacks that include finite useful life, replacement cost, and disposal concerns. Although they are an ideal solution for many applications, there are many other applications where batteries fail to fit application requirements: for example, the asset is not available to replace the batteries, the cost of battery replacement is too expensive over the life of the product, the device is in a hazardous environment, or the device is embedded and a continuous power supply is required. Applications with these needs provide a good fit for receiving power via ambient energy harvesting.

Although significant work in energy harvesting has resulted in demonstrated successful complete system solutions, the industry has yet to adopt energy harvesting as a widely adopted technology. Many challenges that prevent early adoption among customers include cost, safety, lifetime, form factor, and ease of use. Overcoming these challenges from a customer perspective is critical to enable energy harvesting as an effective solution power WSN applications. Therefore, it is imperative to understand the customer requirements and design a suitable energy harvesting product that fits their application with minimal redesign and development.

A comprehensive market survey was recently conducted on wireless sensor networks and their predicted growth in a variety of markets. Figure 1 displays some plots on the rising demand for WSNs and the power sources for these nodes. As seen in the figure, battery and/or EH powered WSNs are expected to generate a significant momentum in the market and generate an opportunity for energy harvesting enabled power solutions.

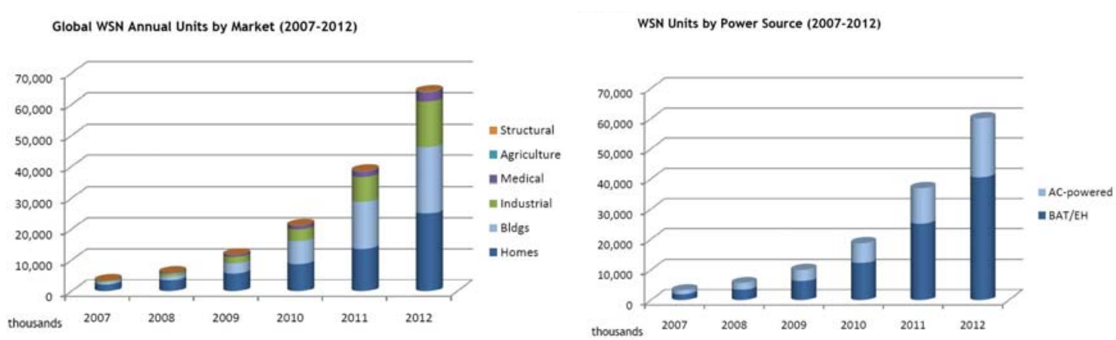

Figure 1. Market survey data on the potential of wireless sensor networks and their associated power supplies. *Source: On World, 2008*

What information do we need?

AdaptivEnergy's Joule Thief™ DC power solutions are designed to harvest mechanical strain energy by using low and moderate level vibrations from surrounding environments. A prime opportunity for energy harvesting solutions is to serve as "perpetual" power sources for microelectronics in a wide array of applications that include structural health monitoring, wireless sensors, condition monitoring, active RFID, GPS, and medical implants. These products can also supplement battery storage devices in applications to prolong their life. A schematic of an energy harvesting enabled power solution for wireless applications is shown in Figure 2.

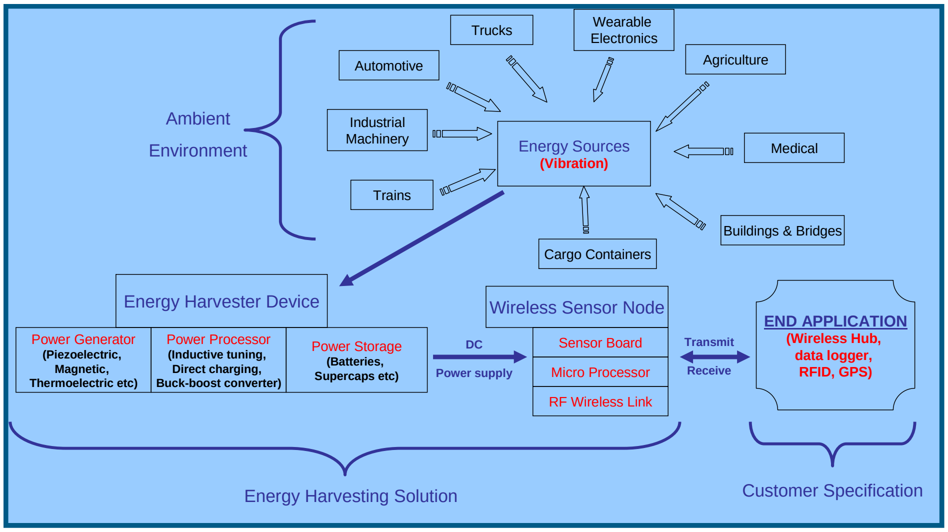

Figure 2. Schematic of an energy harvesting enabled power solution for wireless applications.

The first customer requirement in designing an energy harvesting product is typically the power needed for the application. A typical wireless sensor node performs three main functions: (1) the sensor array that detects any event and obtains relevant environmental information; (2) the microprocessor CPU performs in-node processing of the acquired data; (3) the transmitter/radio interfaces data via wireless transmission with neighboring nodes or a remote monitor.

An overall low power solution is optimized when the ultra low power micro-processor, sensors, and RF transceivers are all integrated onto a single chip. Power consumption can further be minimized by turning these components on and off as required, or by entering them into various sleep modes. For example: the microprocessor is switched into a very low power mode and whenever an event occurs it wakes up the system to perform its necessary function. Efficient power management is controlled via the firmware within the microprocessor.

Another key requirement in designing an energy harvesting powered solution is to understand the ambient environment of the application and the various “free” energy sources available. Quantifying the amount of energy available in a customer application becomes a more difficult task if prior knowledge about the energy content in the environment does not exist. Furthermore, in many cases, the ambient energy environment is dynamic and constantly changing. Although some vibration can be characterized as periodic, most ambient vibration is random in nature. For example, vehicular vibration is mostly random in nature, with numerous applications in asset tracking for trains, tractor trailers and automobiles. The vibration spectra generated with these vehicles contains varying amplitudes around a myriad of frequencies. Furthermore, vibration produced on a vehicle depends on the type of vehicle, driving speed, road conditions, and position of the harvester on the vehicle.

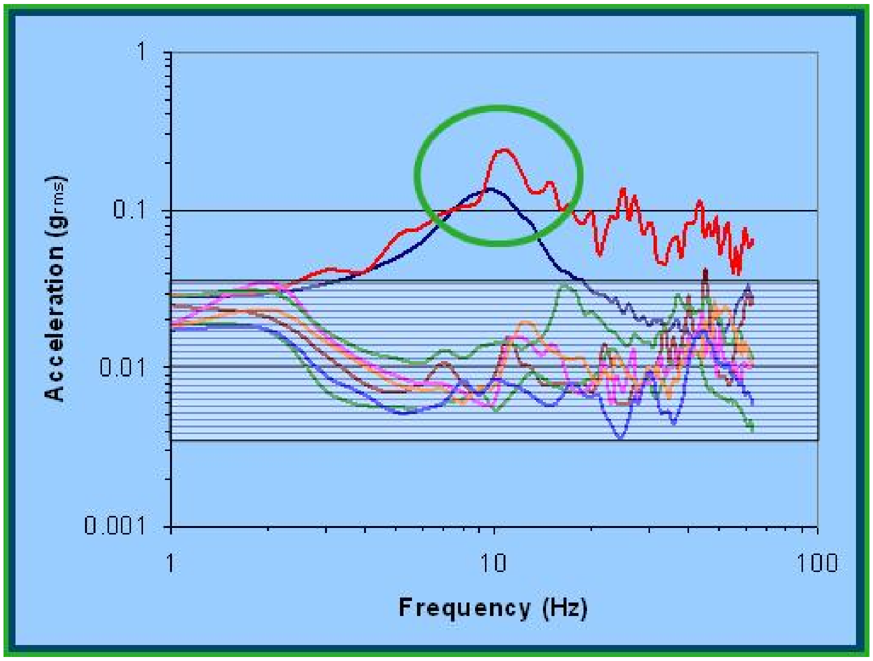

Figure 3. Interior and exterior vehicle vibration data on automobiles, trucks and minivans.

In Figure 3 above, real vibration data collected from various automobiles such as cars, minivans and light trucks has been summarized as a function of frequency. Data collected in the interior of these vehicles exhibited a general random vibration with content across all frequencies and amplitudes less than 0.020 - 0.025 grms. However, when data was collected from the exterior of these vehicles, significant increase in vertical vibration was observed, with common frequency content in the 10 - 15 Hz range. An example obtained from light trucks is indicated in the figure. Although the overall vibration appears random, some common underlying sources exist, such as vibration related to suspension and tires. It is particularly difficult to design resonant devices when both the frequency and vibration amplitude change with time.

AdaptivEnergy's Solutions

The AdaptivEnergy Joule-Thief™ energy harvester has been designed to deliver electrical power at a high density (power per unit harvester volume). The core piezo material within a typical Joule-Thief™ (the Ruggedized Laminated Piezo or RLP®) allows for higher strain rates than other piezo technologies, extending the power output available while also significantly elongating lifetime of the harvester solution. The resulting device is a robust product that excels in performance and reliability even when subjected to harsh environments (high temperature, humidity, caustic areas, etc.) for extended periods of time. This unique feature of AdaptivEnergy Joule-Thief™ products provides a great advantage over competing technologies in similar applications.

AdaptivEnerg's Joule-Thief™ power solutions have demonstrated functionality in wireless sensor node applications using a variety of ambient vibration sources. AdaptivEnergy's Joule-Thief™ product line is currently produced by two ISO 9001 manufacturing partners. This provides an opportunity to design and produce Joule-Thief™ devices with higher reliability and superior performance in large quantities.

A standard energy harvesting product now available is the Random Vibration Joule-Thief™ module, *JTRA-e5mini*, which effectively converts random vibration and impulse events to generate usable power. The JTRA-e5mini module is particularly suited for vehicular applications and effectively converts the random vibration experienced within the cabin of standard automobiles, light trucks, minivans and SUVs to power a variety of wireless sensor network devices. This module has successfully demonstrated functionality in powering remote wireless transmissions of real-time sensor data from different locations on multiple vehicles driven on different road conditions.

Vehicular applications range from simple wireless switches for windows, lights and latches to condition monitoring of machine critical components. Since wireless sensor nodes need to be deployed in hard-to-access areas in a vehicle to relay sensor data such as pressure, temperature, and vibration, energy harvesting solutions achieve a unique "plug-in-and-forget" functionality that possesses significant advantage over other solutions. Such wireless sensor nodes lead an array of applications that include active RFID tags, data loggers, component sensors, and Global Positioning Systems (GPS). These solutions when implemented can be extended to a variety of vehicles from automobiles, trucks, trains to rotary wing aircrafts and factory warehousing transporters.

For typically non-vehicular, periodic vibration sources aimed at machinery condition monitoring applications, Joule-Thief™ 60 Hz and 120 Hz modules are available that have demonstrated timed wireless transmissions from various sensors to a remote location.

Inside the Joule-Thief™ Random Vibe Module (JTRA-e5mini)

A picture of the Joule-Thief™ Energy Harvesting Module is shown in Figure 4. The module contains the RLP® Joule-Thief™ piezo-based smart material and the Energy Key™ electronics, which converts the electrical signal from the piezo material into a useful regulated DC voltage. The AdaptivEnergy energy harvesting circuit is designed to function as an interface between the Joule-Thief™ piezo material and any form of storage, such as a capacitor, supercapacitor, thin-film battery, or rechargeable lithium polymer battery. The circuit is designed to address issues such as avoiding over-charging and discharging beyond the allowable limits of the battery, while also preventing battery leakage when the module is not in use. This circuit achieves high efficiencies in the regulated voltage ranges when low-to-moderate vibrations are experienced. The JTRA-e5mini device in its present form will output higher power with higher vibration levels, but the efficiency of conversion does decrease at higher power levels. Several improvements to the circuit are currently in progress and will be included in future versions of the energy harvesting circuit in order to improve efficiencies across the entire performance band.

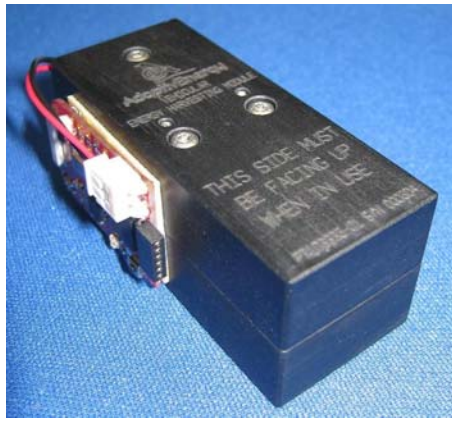

Figure 4. AdaptivEnergy Joule-Thief™ Random Vibration Energy Harvesting Module.

Inside the Joule-Thief™ Random Vibration Kit (K1-JTRA-e5mini)

The AdaptivEnergy Joule-Thief™ Random Vibration Energy Harvesting Demonstration Kits are available for customer evaluation in a candidate wireless sensor application. The demonstration kit comes with the JTRA-e5mini module, Energy Key™ electronics with onboard capacitive storage, and a custom sensor board. The sensor board is equipped with multiple sensors (temperature, light, battery voltage). The wireless radio performs 2.4 GHz transmits utilizing the Texas Instruments EZ430-RF2500 Wireless Development Tool (MSP 430 microprocessor with Chipcon CC2500 radio). Energy harvested from the vibration is utilized to power the sensor array and transmit data real-time to a remote wireless receiver for processing. This kit demonstrates a completely stand alone turn-key energy harvesting solution in the area of wireless sensor networks.

Figure 5 shows the contents of the demonstration kit that is currently shipped by AdaptivEnergy, along with a screenshot of the associated display software. The Joule-Thief™ Demonstration Kit does not ship with a vibration source. The wireless application software and the user interface software are provided with the kit. Although the JTRA-e5mini is particularly suitable for vehicular applications, the user is encouraged to evaluate the module in a variety of random vibration environments. AdaptivEnergy will engage the customer and provide necessary engineering support if required to implement the kits and/or standard modules in their applications. If required, alternate sensor boards can be implemented with other sensors, microprocessors and radios for customer specific applications. Suitable energy storage such as batteries and super capacitors are also available for these applications.

Figure 5. Joule-Thief™ Random Vibration Energy Harvesting Demonstration Kit

While there is no standard performance metric for energy harvesting devices, the following was captured as a benchmark for device performance and evaluation by the customer. Figure 6 summarizes the power output of the JTRA-e5mini module as a function of vibration levels and frequencies. Data has been listed for power levels obtained in real vehicle environments. However, the power outputs are provided as a base guideline and will vary depending on the vehicle, road/drive conditions and location of the module. The user should contact AdaptivEnergy for assistance regarding the selection of the right module for the specific environment.

Freq (Hz)	Acceleration (Grms)	JTRA-e5mini AVG Power (mW)
2.5	1.00	0.095
3.5	1.00	0.102
5	0.50	0.028
10	0.40	0.077
15	0.20	0.036
15	0.40	0.129
Random White Noise	0.15	0.010
Random White Noise	0.25	0.030
Luxury Car Interior	0.03	0.012
Light Truck Interior	0.04	0.014
Light Truck Exterior	0.10	0.070

Figure 6. Average power output of JTRA-e5mini Random Vibration Modules under various vibration conditions.

It is important to note that AdaptivEnergy reports *actual* power output from the energy harvesting module rather than *optimum* outputs - this means that the energy/power figures reported are all usable by the end application.

Contact Information

For additional technical information about the AdaptivEnergy Joule-Thief™ energy harvesters, readers are referred to the product datasheets available online. All related documents and product information can be downloaded from AdaptivEnergy's website, www.AdaptivEnergy.com.

For information and technical support regarding this document, contact Anurag Kasyap at (757) 320-4121 (AKasyap@AdaptivEnergy.com).