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Energy Harvesting Techniques for Sustainable Embedded Systems: Design and Applications

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Abstract

The realm of embedded systems is undergoing a radically different transformation with the common emerging technologies of energy harvesting. With the growing demand for self sustaining, lasting devices, engineers and designers are looking to inventive ways to power these systems without relying on traditional energy sources. This paradigm shift is enabling applications in the remote sensing, wearable technology as well as Internet of Things (IoT) devices. Basically, you take energy from around you and convert it into electrical energy. This is not only an environmentally friendly and economically viable approach to lengthen the operational lifespan of embedded system but also to reduce the cost of battery replacement and maintenance. Look forward to us delving further into this exciting and interesting space as we explore the many techniques, design considerations and real world applications playing a part in creating this sustainable embedded systems future.

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Introduction

The diversity and continuous expanding range of energy harvesting methods include solar cells that harness the energy of sunlight to piezoelectric materials that convert mechanical vibrations into electricity. In system design and implementation, each technique has advantages and disadvantages, and careful consideration must be made in the use of the respective technique. Knowing these nuances will aid developers in designing more efficient and resilient embedded systems that work alone for long periods of time.

In this complete guide, we'll look at the different energy harvesting technologies by their principles, talk about major aspects of power management and storage, and emphasize about designing for perpetual operation. And we'll discuss the trade offs of various energy storage solutions and look at their boundaries in emerging trends that are enabling energy autonomous embedded systems. We are about to travel to a world where energy harvesting for embedded systems is not only making devices different standing alone on their own, but is also inspiring sustainability and even opening application domains that were deemed impossible a short time ago. In this blog post we're going to dive into the world of self powered embedded systems to discover what's possible when we utilize this game changing type of technology.[1-4]

Fundamentals of Energy Harvesting

Energy harvesting is the generating of small amounts of energy from one or more naturally occurring energy sources within the environment. One common application of energy harvesting is powering smart watches. It is then converted into electrical energy that is used to power small, low input energy electronic devices (which includes mobile phones, lap tops and the like), or stored for later use. Energy Harvesting is not new, but Advances in low power electronics and energy conversion efficiency have made it increasingly viable for powering those systems. The primary energy harvesting goal in embedded systems is effective perpetual operation, where the device would operate indefinitely without the requirement for battery replacement or external power supply availability. applications of this mechanism are particularly useful in the case where regular maintenance is difficult, costly, or unfeasible, such as in remote environmental monitoring stations or implantable medical devices.

Energy harvesting systems typically consist of three main components: It consists of the energy harvester, which extracts ambient energy; the power management circuit, which conditions and controls the harvested energy; and the energy storage element that stores surplus energy for use when the ambient source is unavailable or insufficient. For the specific application, environmental conditions, and power requirements of the embedded system, each component's choice depends on the specified application. Ambient energy variability and unpredictability are amongst the key challenges in designing energy harvesting systems. For instance solar energy varies according to hour of daylight hours and the weather conditions while vibration base harvesters may only harvest power when a mechanical force is experienced. Because of these variable conditions, reliable operation requires careful system design.

The power density of various energy harvesting techniques is a further important consideration. In ideal conditions some ways such as photovoltaic cells can generate power at high powers, while others like thermoelectric generators are normally of low power densities. Being able to understand these differences is key to making the proper choice of energy harvesting method given a certain application. Let's say that energy harvesting techniques can be broadly categorized according to the type ambient energy they exploit. Suggested common sources include: Solar energy (photovoltaic); thermal energy (thermoelectric); mechanical energy (piezoelectric, electromagnetic); and radio frequency (RF) energy. These sources are unique in at least one, and sometimes several, ways and have their own unique characteristics that lend to different types of applications and environments. In the following sections, as we go dive deeper into each energy harvesting technique, we will discuss their principles, advantages, limitations and how they are used. Understanding these fundamentals in full allows us to make informed decisions about how energy harvesting can be integrated in embedded system designs to reshape more sustainable, and autonomous devices.

Solar Energy Harvesting: Harnessing the Power of Light

Photovoltaic (PV) energy harvesting, or solar energy harvesting, is one of the most widely used, and best established, techniques for powering embedded systems. Semantic materials, commonly silicon based, using this method convert light energy directly to electrical energy. This technology is based on the first observation of the photovoltaic effect, first observed by Alexandre Edmond Becquerel in 1839. Modern solar cells are based on many layers of semiconductor materials, often Si (silicon) crystalline. If sunlight up there hits the solar cell, the photons will hit the solar cell and excite electrons in the semiconductor material for an electron hole pair. These charges can then separate through the cell's structure, which contains this built in electric field, forming an electric current that can be used to drive electronic devices or charge energy storage components.

The relatively high power density of solar energy harvesting is one of the primary advantages of ambient energy harvesting. Commercial solar panels can reach efficiencies of up to 20 – 22% under optimal conditions, and in laboratory settings we can get even higher efficiency out of advanced multi-junction cells. Indeed, solar energy harvesting is particularly suitable for outdoor applications as the direct sunlight is readily available (Figure 1).

In practice however, solar cell performance depends on many environmental parameters such as

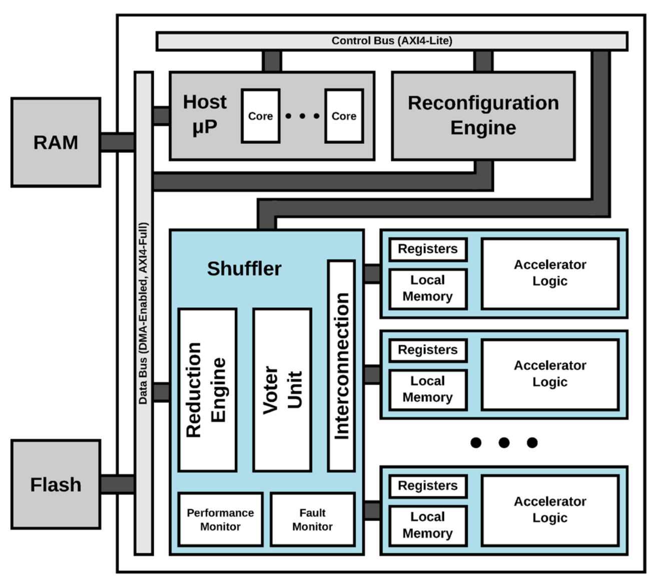

Fig. 1: Solar Energy Harvesting: Harnessing the Power of Light

incident sunlight intensity, angle of incidence, and temperature. But cloud cover, shading and seasonal variations can greatly vary the amount of energy that can be harvested. To avoid these problems, designers usually insert Maximum Power Point Tracking (MPPT) algorithms into their systems. The continuously adjusting operating point of solar cell under varying conditions increases the power extracted from the solar cell, increasing the energy yield. Because the light intensity is much lower for indoor applications, specialized low-light solar cells have been developed for such use. By optimizing these cells to run under artificial lighting, the resulting system is optimized for powering indoor sensors and internet of things (IoT) devices. Indoor solar cells, while their power output is less than its outdoor counterpart, can still offer a fair amount of power to low power embedded systems in many indoor conditions. Solar energy harvesting is a technology of importance and it needs to be integrated carefully with other embedded systems. Arguments that become smaller as the system requires more power, arguments from available space and arguments from the size and efficiency of the solar panel. Moreover, in fixed installations, the orientation and placement of the solar panel are very important regarding performance.

Another important facet of solar powered embedded systems is energy storage. However, solar energy is not constant (e.g., at sundown or on cloudy days), so most systems couple the storage of excess energy in rechargeable batteries or supercapacitors for use at times of low light. For a given energy capacity, charge and discharge rate, and anticipated operating life of the system, the choice between batteries and supercapacitors depends on the balence between many factors such as, along with others, the active material, the electrolyte, and operating temperature. New possibilities have emerged for integrating solar energy harvesting into embedded systems with recent advancements in solar cell technology — thin film solar cells and organic photovoltaics. By being flexible and lightweight, these solar cells could be included in wearable devices, curved surfaces, and even transparent materials, vastly expanding the range of solar powered embedded systems. As we continue to push the limits of solar energy harvesting, we can expect that more and more efficient solutions continue to evolve. Solar energy harvesting has been demonstrated to enable the development of sustainable embedded systems featuring energy autonomous electronics or self powered environmental sensors for unlimited operation in the absence of external sources of power or battery replacement.[5-9]

Thermal Energy Harvesting: Converting Power to Temperature Difference

In thermal energy harvesting, an interesting technique is used to extract the electrical power, from temperature differences, for embedded systems. Thomas Johann Seebeck discovered a principle of thermoelectric effect in 1821, which this method is based on. Direct conversion of temperature differences into electrical voltage and conversely is thermoelectric effect. Thermoelectric generators (TEGs; also referred to as Seebeck generators) are at the core of thermal energy harvesting. These solid state devices consist of series or parallel assembled multiple thermocouples. Each thermocouple consists of two dissimilar semiconductor materials, e.g., n type and p type semiconductor, joined at two junctions. A voltage is generated across the device caused by movement of charge carriers from a hot to a cold junction where one specific junction is exposed to a higher temperature than the other.

As a result, the thermoelectric generator efficiency is primarily dependent on the temperature difference between the hot and cold sides as well as thermoelectric material properties. TEGs often use bismuth telluride (Bi2Te3), lead telluride (PbTe) or silicon-germanium (SiGe) alloyed materials as common materials. Each material also has an optimum operating temperature at which the TEC or TEG performs best in a given application. Continuous operation requires no moving parts, and the ability to power continuously in the presence of a temperature gradient is one of the primary advantages of thermal energy harvesting. Because applications with a constant source of waste heat exist (industrial processes, automotive systems, etc.), it is particularly well suited. In fact, wearable devices can use body heat to power low energy sensors and communication modules. Although however, thermal energy harvesting often results in lower power densities than several other energy harvesting schemes. More power is generated, the larger the TEG and the larger the temperature difference. The power output can be impractical in many real world applications due to the small number of available temperature gradients. To deal with this problem researchers work constantly on optimizing thermoelectric designs and making more efficient thermoelectric materials.

To integrate thermal energy harvesting into embedded systems, thermal management is needed. Therefore, the design has to guarantee good thermal contact between the TEG and the heat source, as well as effective heat disspation on the cold side, to maintain the temperature gradient. Maximum temperature difference across the TEG is obtained using heat sinks, thermal interfaces, and sometimes active cooling mechanisms.

Thermal energy harvesting systems also require power management. As the output voltage of TEGs is usually low (mV), V(∈) step up converters are usually needed to increase the voltage to a usable level for the embedded system. Maximum power point tracking (MPPT) techniques may also be used to increase the power extracted from the TEG at different temperatures. To stabilize the supply to a thermal energy harvesting system with a fluctuating temperature gradient, energy storage solutions, such as rechargeable batteries or supercapacitors, are commonly combined with the thermal energy harvesting system. It achieves continuous operation of the embedded system, which facilitates energy accumulation during time periods of high thermal energy availability. New possibilities for thermal energy harvesting are currently opening due to recent advancements in the fields of nanotechnology and material science. For instance, nanostructured materials and quantum dots are being tested for increasing thermoelectrical properties of materials and then more efficient TEGs could be achieved. Moreover, flexible and stretchable thermoelectric materials are also being developed so that they enable new applications in wearable technology and conformal electronics (Table 1).

Thermal energy harvesting holds promise as a valuable alternative power source for solid state embedded systems that waste having to generate electrical power using resources such as their own processor. Thermal energy harvesting is providing energy for wireless sensor networks in industrial settings and powering self powered health monitoring devices, for example, to add energy autonomy and reduce the need for batteries in new embedded system designs. With continuous research and development in thisfield we can expect more and more new applications of thermal energy harvesting in the near future.

Mechanical Energy Harvesting: Recording Vibrations and Their Motion Mechanical energy harvesting is a diverse technique of harvesting electrical energy from vibrations, motion or pressure. Since mechanical energy is frequently abundant (i.e. in industrial machinery, transportation, as well as the human body), this method is especially attractive for powering embedded systems. Different approaches of mechanical energy harvesting have been created, piezoelectric, electromagnetic and electrostatic are among the more popular.

The piezoelectric effect discovered by Jacques and Pierre Curie in 1880 is an offshoot of piezoelectric energy harvesting. Such effect arises in some materials that develop an electric charge in response to mechanical stress or strain. Lead Zirconate Titanate (PZT), polyvinylidene fluoride (PVDF), and other piezoelectric ceramics are common piezoelectric materials. These materials can generate a small electrical current, which can be used to power embedded systems, when they are deformed by mechanical vibrations of pressure. Usually piezoelectric harvesters are designed as a cantilever

Table 1: Energy Harvesting Techniques for Embedded Systems

Technique	Process
Solar Power	Solar power harvesting uses photovoltaic cells to convert sunlight into electrical energy, suitable for outdoor embedded systems.
Thermoelectric Generation	Thermoelectric generation converts temperature differences into electrical energy, commonly used for systems with varying thermal gradients.
Vibration Harvesting	Vibration harvesting captures mechanical energy from vibrations and converts it into electrical energy, ideal for low-power systems in dynamic environments.
RF Energy Harvesting	RF energy harvesting collects energy from ambient radio-frequency signals and converts it into usable electrical energy for small devices.
Piezoelectric Harvesting	Piezoelectric harvesting captures energy from mechanical stress or movement, often used in wearable or motion-based embedded systems.
Wind Power	Wind power harvesting uses wind turbines to generate electrical energy, which can be used to power remote embedded systems or sensor nodes.

beam, diaphragm, or stack to match the frequency and amplitude of the vibration source. Regarding harvester design, the resonant frequency of the harvester is a critical parameter, as maximum power output is achieved when the natural frequency of the harvester corresponds with ambient vibrations. These broadband and adaptive piezoelectric harvesters seek to harvest efficiently across varying vibration frequencies, which are ubiquitous in real world applications.

Faraday's law of electromagnetic induction is, however, the basis of electromagnetic energy harvesting. Usually, this method involves a coil and a magnet as respectively the current source and the current seeking field, usually by having a magnet moving relative to a coil, inducing a current in the coil. Linear or rotational electromagnetic harvesters are designed depending upon the nature of the mechanical energy source. Electromagnetic harvesters may produce higher power outputs than piezoelectric devices, but come at the expense of being bulkier and requiring more complex mechanical designs. In electrostatic energy harvesting, we use the change in capacitance of a variable capacitor as its plates move relative to each other because of external vibrations. They, however, require an initial voltage on the capacitor, which can be supplied by an electret material, or an active charging mechanism. Because electrostatic harvesters are compatible with semiconductor fabrication processes, they are a particularly suitable implementation within MEMS (Micro-Electro-Mechanical Systems).

An important problem with mechanical energy harvesting is dealing with the variability and unpredictability of vibration sources. The power out put of the harvester is also subject to ambient vibrations whose frequency and amplitude may change in time. This has to be addressed by researchers developing adaptive harvesting systems that can change their resonant frequency or harvesting mechanism to compensate for changing environmental conditions. The conversion of the harvested energy into an usable form for the embedded system requires another important consideration involving power conditioning circuitry. Mechanical energy harvesters produce output that is typically AC (Alternating Current) at varying frequency and amplitude. Since DC power is necessary, rectification, voltage regulation and sometimes frequency conversion is necessary to allow for a stable DC power source for the embedded system. Often a hybrid of compact mechanical energy harvester and energy storage is used to smooth out the power fluctuations and provide continuous supply of energy. For this purpose, rechargeable batteries or supercapacitors commonly used, and the choice may be determined by, for example, energy capacity, charge/discharge rates and lifetime of the supposed operating conditions of the system.

Since the advent of mechanical energy harvesters, hybrid systems combining multiple harvesting mechanisms have been developed to improve efficiency and robustness. Piezoelectric-electromagnetic hybrid harvesters use both strain and electromagnetic induction to produce power, which can increase the energy harvest and operating range of the system. A wide range of embedded systems are using mechanical energy harvesting. It can power wireless sensor networks for condition monitoring of machinery in industrial environments, providing a platform that eliminates the need to change batteries in hard to reach locations. Vibration energy generated from vehicles is available in transportation that can be harvested to power sensors and communication modules. Human motion can be used to power health monitoring devices and even smart textiles in wearable technology. Future development in integrated mechanical energy harvesting promises to become more and more important as we develop new materials, designs, and techniques for integration with autonomous embedded systems. This technology is going towards the creation of more sustainable, maintenance free embedded systems in multiple industries from self powered IoT devices to energy harvesting smart infrastructure (Figure 2).

Radio Frequency (RF) energy harvesting is a recently emerged technique to harvest the electromagnetic energy emanating in the ambient radio waves and transform the same into electrical power useful for the embedded systems. It's particularly intriguing as it makes use of the ever-present electromagnetic fields produced by wireless communcation systems, including Wi-Fi, cellular networks and broadcast transmitters. We on the other hand are living in a world with more and more interconnected pieces, giving way to more and more energy sources from which RF sources still remain untapped. The basis of rf energy harvesting is the wireless power transfer technique first introduced by Nikola Tesla around the turn of the century. In modern RF energy harvesting systems, an antenna is used to receive the electromagnetic waves, a rectifying circuit (or 'rectenna') to convert the AC signal to DC

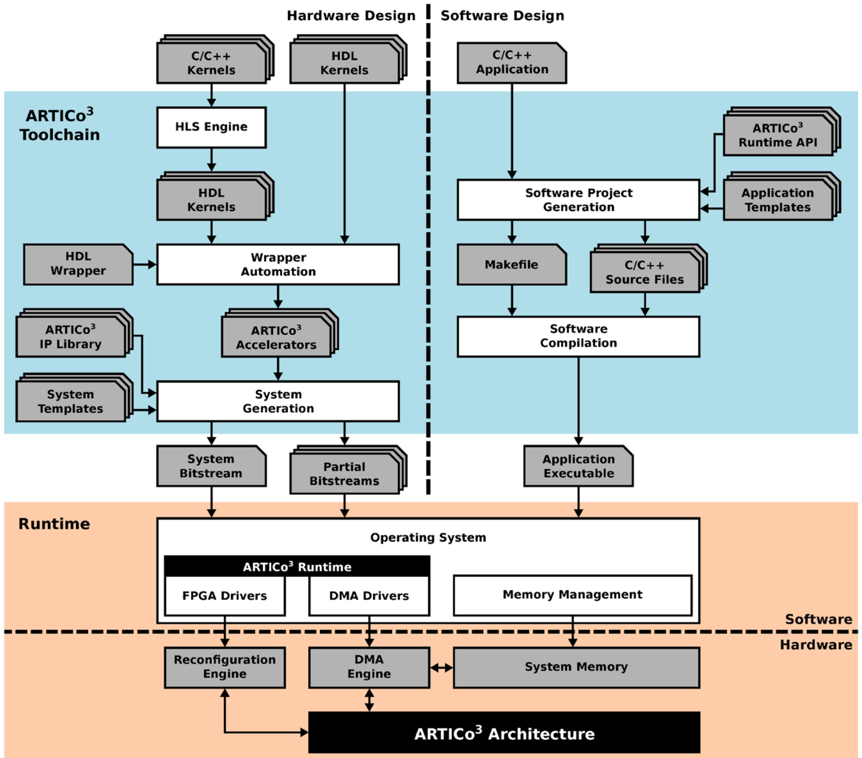

Fig. 2: Thermal Energy Harvesting: Converting Power to Temperature Difference

power, and power management circuitry to condition the harvested energy to be used by the embedded system. Perhaps one of the most attractive features about RF energy harvesting is that it can continuously and quietly supply power, if there is sufficient RF energy density present. It is particularly well suited to energizing urban area or close to strong RF sources low energy devices. RF energy harvesting could be used for powering wireless sensor nodes within smart cities by reducing or eliminating the need for battery replacements and operational maintenance costs.

But also, RF energy harvesting has some drawbacks to be solved for practical use. The high power density limit of ambient RF signals is a principal limitation, leading typically to very little harvested energy. In other words, the power delivered by RF harvesting relies on many factors, including that relative to the RF source, frequency of the electromagnetic waves, presence of interfering obstacles on the signal path. In turn, RF energy harvesting is most suited for ultra low power embedded systems or as a secondary power source in hybrid energy harvesting systems. Research is directed at maximization of the efficiency of RF energy harvesting in several key areas. Another approach is to create wideband and multi band antennas that would capture this energy from a wider spectrum simultaneously. The system can extract energy from multiple RF sources, which could increase the total harvested power. The second area of research is the optimization of rectifying circuits for RF to DC conversion efficiency improvement. However, low power levels are not effectively utilized by traditional diode based rectifiers due to a high voltage threshold. We explore advanced rectifier designs using zero threshold transistors or spintronic devices to overcome this limitation and harvest more efficient energy from weak RF signals.

In RF energy harvesting systems, the harvested energy in the intermittent and low power regime is highly dependent on power management. To make efficient utilization of the harvested energy, sophisticated power management circuits are being developed. For example, these circuits typically use maximum power point tracking (MPPT) techniques to extract energy, and cold start capabilities to start without any power source. RF energy harvesting systems can include energy storage solutions which allow storing or accumulating energy over some period of time in order to be used later. The frequent charge-discharge cycles and the long operational lifetimes make supercapacitors often a preferable choice over batteries in these applications. The choice between supercapacitor and battery, however, is based upon the details of the embedded system, and the characteristics of the RF energy source. RF energy harvesting has potential applications in many domains as the Internet of Things (IoT) expands. RF energy harvesting could be used to power low energy sensors and actuators in smart homes and offices, without the requirement for wired power connections, or frequent battery replacements. It could enable self powered wearable devices for continuous health monitoring in healthcare. RF energy harvesting could be used to power wireless sensor networks of equipments for monitoring, e.g. in areas where conventional power sources are impractical.

Harvesting RF energy has rapidly advanced in recent times with the development of hybrid systems that are capable of using RF harvesting in conjuction with other energy harvesting mechanisms. For instance, one advantage of RF harvesting is that it can be integrated with other harvesting devices such as solar cells or thermoelectric generators to give a more robust and reliable power source for embedded systems. In the future it appears that the rollout of 5G networks and the high density of wireless communication infrastructure will present new opportunities for RF energy harvesting. But while first generation 5G signals will be restricted to shorter range, potentially higher power density 5G signals may arrive at a higher frequency. In addition, the possibility of wireless power transfer by means of dedicated RF sources for the charging of electronic devices over short distances is being studied as an alternative to ambient RF energy harvesting in some applications. As electronics and energy efficient design push further and further, RF energy harvesting has promise to provide a sustainalble power source for the next generation of embedded systems. Although work towards both improved efficiency and greater harvesting power remains, recent research and development efforts in the field will eventually make it possible to extract and effectively harness ambient RF energy to power the electronic devices around us.[8-12]

Power Management and Storage Solutions

A design of energy harvesting systems for embedded applications must incorporate effective power management and energy storage. These elements are the guarantees that the harvested energy will be used efficiently and banked in a way that guarantees the system can operate faithfully when the ambient source of energy cannot provide it often or enough. In this journey, we will explore through different strategies and technologies to enhance power management and storage in energy harvesting systems. Power management in energy harvesting systems involves a very complex tradeoff of hardware and software solution to achieve maximum energy efficiency of the system and highest system performance. But at the core of these systems are specialized microcontroller chips — or what are known Power Management Integrated Circuits (PMICs) — that handle everything from voltage regulation, battery charging, to power sequencing.

Energy harvesting systems present one of the key challenges in power management when dealing with variable_name of variability and often unpredictability of harvested energy. To overcome this issue, PMICs tend to include Maximum Power Point Tracking (MPPT) algorithms. MPPT always nudges the operating point of the energy harvester to get as much power as possible even under varying conditions. The importance of this technique is especially true for solar and thermoelectric energy harvesters, where the power output varies significantly with environmental variations. Voltage regulation is another key principle of power management. Energy harvesters have output voltages that can be wide ranging, dependent upon the harvester method and environmental conditions. This is because voltage regulators or PMICs are used to provide a stable and desired voltage level to power an embedded system using a variety of type of voltage regulators such as Low Dropout Regulators (LDO) and various types of switching regulators such as buck, boost, and buck boost converters. The decision of using linear or switching regulators is mainly dictated by the need for high efficiency, noise sensitivity and the input to output voltage relation (Table 2).

Furthermore, energy aware power management techniques are applied to minimize energy consumption and provide the optimal system performance. Techniques such as dynamic voltage and frequency scaling (DVFS), in which the processor's clock speed and voltage are adapted, on the fly, as a function of the workload and available energy. Another means to attenuate the power consumption during low activity existence is power gating, in which certain portions of the system are selectively killed off. On the software

Table 2: Considerations for Energy Harvesting in Embedded Systems

Consideration	Factor
Energy Storage	Energy storage systems, such as batteries or supercapacitors, are necessary to store harvested energy for later use in embedded systems.
Efficiency Optimization	Efficiency optimization ensures that the maximum possible energy is harvested, considering environmental factors and system requirements.
Cost Effectiveness	Cost effectiveness is an important factor in selecting energy harvesting technologies, as they should provide sufficient energy at a reasonable cost.
Environmental Conditions	Environmental conditions, such as temperature, humidity, and light exposure, directly influence the effectiveness of certain harvesting techniques.
Size and Integration	Size and integration considerations ensure that energy harvesting components can be incorporated into embedded systems without impacting their form factor or functionality.
Power Management	Power management techniques regulate and optimize the flow of harvested energy, ensuring that energy is efficiently distributed across the embedded system's components.

side, we need to plan system resources as power aware, for example, with power aware scheduling algorithms. These algorithms schedule and prioritize tasks given the energy requirements of tasks compared to the available harvested energy, to maintain the critical tasks while non critical tasks are deferred when supply of energy is too low. Even in the case of some advanced systems, these energy prediction algorithms forecast future availability of energy as a function of historical data and environmental considerations, thus facilitating more proactive power management strategies.

Energy storage is another important component of energy harvesting systems, which serves the role of buffering fluctuations in harvested energy and for functioning in low ambient energy source availability. Different factors such as the energy capacity required, the charge/discharge rate, cycle life and environmental conditions determine the choice of energy storage technology. Because of their high energy density and established technology, rechargeable batteries are often selected as the energy storage elements in energy harvesting systems. Especially Lithium-ion batteries are favored because of high energy density, low self discharge rate and not having memory effect. But cycle life and performance at extreme temperatures are limited. Specialized thin film batteries for very long operating lifetimes are sometimes used for applications that require long operational lifetimes. With each passing year, supercapacitors, also referred to as ultracapacitors or electric double layer capacitors (EDLCs), are being integrated more and more into energy harvesting systems. Because they provide high power density, fast charge discharge capabilities and very long cycle life (often greater than 1 million cycles), they are many advantages over batteries. Because of their ability to withstand frequent charge/discharge cycles and the high burst power they can provide, supercapacitors are well suited for use in applications with short (high burst) power demands. While they provide lower energy density than battery cells, the ability to limit their use in applications where long term energy storage is required.

Energy harvesting systems are starting to use hybrid energy storage solutions combining batteries and supercapacitors. The hybrid systems utilize the high energy density of batteries for their long term storage function, and the high power density of supercapacitors for high power demand and frequent charge/discharge cycles. The combination can enhance the life of the whole energy storage system and extend its working life across a broad range of operating parameters. Methods for advanced energy storage management are also being developed to improve storage performance and durability. They include sophisticated battery management systems (BMS) that monitor and balance individual cells in multcell battery packs, and adaptive charging algorithms that switch between different charging parameters according to the primary states of health of the battery and associated environment. Future energy storage technologies will continue to improve the performance of energy harvesting systems, as we look to the future. Examples of such solid state batteries include higher energy density, greater safety and faster charging than traditional lithium ion batteries. Hybrid supercapacitors and pseudocapacitors are also advancing the state of the art for supercapacitors, utilizing advanced supercapacitor technologies to bridge the gap between supercapacitor power density and battery energy density. The ability to realize the full potential of energy harvesting in embedded systems depends on the ability to manage and store the energy harvested effectively. We carefully integrate advanced PMICs, intelligent power management algorithms, and proper energy storage solutions to build up robust, efficient energy harvesting systems that work through the whole range of environments. With ongoing evolution of technology, we can expect to see even more refined and enhanced power management and storage capabilities to enhance the ways in which energy autonomous embedded systems function.[13-14]

Energy Harvesting Embedded Systems: Design Considerations

Embedding energy harvesting in embedded systems necessitates an integrated, holistic design given the energy harvesting mechanism, the overall system architecture, power requirements, and operational environment. In this section, we present key design considerations and best practices for making efficient and reliable energy harvesting embedded systems. Careful matching of energy supply and demand is one of the major issues in designing energy harvesting systems. It entails a detailed analysis of the power consumption profile of the embedded system and an estimation of the harvesting apparatus energy yield. Power requirements have to be considered both average and peak, and duty cycle of various system components has to be analysed by designers. Energy profiling and power budgeting are tools that can be used in this analysis to help designers optimize system architecture for energy efficiency. In energy harvesting design, however, choosing the microcontroller or processor is crucial. They are often preferred because they are ultra low power microcontrollers with advanced power management features. Most commonly these MCUs provide multiple low power modes, enabling some subsystems of the system to be powered down independently of the others. Other important impacting features include fast wake up time and energy efficient peripherals, which greatly reduce the overall energy consumption. In particular, some advanced MCUs can incorporate specialized hardware accelerators for typical tasks to alleviate the need for energy intensive data processing.

The system energy efficiency is also fraught with peripheral selection and interface design both. When possible, low power sensors and communication modules should be used. For instance, we design interfaces between components to minimize the energy consumption, using low power serial interfaces or burst mode data transfers that reduce active time. Creating energy-efficient systems also requires software design. However, energy aware programming techniques like event driven architectures and sleep mode efficient usage can drastically reduce power consumption. Algorithm and data structures can be optimized carefully to reduce processing time and decrease memory usage which in turn reduces energy requirements. Built in power management features and energy aware task scheduling offered by some embedded operating systems and software frameworks designed for energy harvesting application exist. Energy harvesting systems must be robust and reliable, especially for energy harvesting applications such as a remote or inaccessible environment. The harvested energy variation and the potential periods of energy scarcity need to be handled by the system. In general this often means gracefully degrading operations by turning off non essential functions in a way that preserves as much critical functions as possible as the energy is depleted.

Energy harvesting designs call for special care in the initial power on and cold start behavior of the system. The harvester only provides energy, and the system must be able to bootstrap itself from a completely discharged state. This typically entails carefully arranging power up procedures and the use of ultra low power supervisory circuits to control the first charge accumulation and the startup of the system. The design of energy harvesting systems is highly dependent on environmental factors. The performance of the energy harvester can be affected as well as the overall system by these environmental conditions namely temperature, humidity, vibration, etc. These factors need to be taken into account by designers to select components and to design enclosures. Weatherproofing and protection to high environmental conditions are required for outdoor applications. Energy harvesting systems share a few important design principles: scalabilty and modularity. An extension of the controller design can be easily customized and adapted to different energy harvesting sources or application requirements through a modular approach. As an example, a system could incorporate interchangeable energy harvesting modules enabling the system to be modified for solar, thermal or vibration energy harvesting according to the deployment environment. Energy harvesting system design has to be often constrained with size and form factor. The challenges and opportunities afforded by miniaturization of energy harvesters and storage devices are substantial. Functions of the system can be maintained through advanced packaging techniques such as system in package (SiP) or 3D integration that can reduce overall system size. Energy harvesting systems are no different than other embedded system design, and always cost considerations play an important role. Energy harvesting can drastically reduce or relieve the battery replacement costs over the long haul, but the up front costs for energy harvesting components may be higher. The upfront vs. the benefits over the long term value and the total cost of ownership is something that designers have to rate tactfully.

Because the harvested energy is variable, energy harvesting systems present unique challenges when tested and validated. They are critical to the comprehensive testing under a wide swath of environmental conditions and energy availability scenarios. Because laboratory experimental efforts are usually inflexible, it may be necessary to use specialized test equipment and methodologies to accurately simulate a wide range of energy harvesting conditions and verify system performance. As energy harvesting technology continues to improve, new design challenges are emerging. For instance, artificial intelligence and machine learning algorithms are already integrated into energy harvesting systems, allowing for more adaptative and intelligent power management. Real time energy harvesting and utilization can be optimized using these advanced algorithms that can learn from usage patterns and environmental conditions. Finally, to design effective energy harvesting embedded systems, energy harvesting, power management, system architecture, software design, and environmental factors should be taken into account multidosily. This work focuses on how to address these design considerations, and how to leverage the latest technologies and methodologies to create robust, efficient and long lasting energy harvesting systems that help to boundarize the limitations of autonomous embedded systems. As the field evolves, we will see increasingly more sophisticated and innovative energy harvesting embedded systems that enable new applications and move us closer to a less energy intensive technological future.[14-17]

Applications and Case Studies

From environmental monitoring to wearable tech, energy harvesting embedded systems are being used in varied industry and use cases. This section will look into some of the most innovative and impactful applications of energy harvesting in embedded systems, as well as case studies which major real world benefits and challenges. Energy harvesting has made possible the deployment of long term, maintenance free sensor networks in remote or inaccessible locations in the field of environmental monitoring. For example, researchers at the University of Washington have built a solar powered sensor network to monitor glacial movement in the Alps. In operation, these sensors, which have GPS and communication modules, harvest energy from sunlight to power themselves and report data back to researchers. As autonomous sensors, these sensors have the energy harvesting capability to operate for years, without needing to replace batteries frequently in challenging alpine environments, and provide valuable data on the impacts of climate change. Another area where energy harvesting is gaining huge ground is wearable technology. This article explores a notable case study — the PowerWalk Kinetic Energy Harvester developed by Bionic Power. The natural motion of walking can be used as a source of energy again to create electrical power to charge batteries or to power other devices, and this wearable device harvests that energy. This technology was developed for military use to decrease the electrical load carried by soldiers, and has presented interest for application in civilian use in outdoor recreation and healthcare. Through the PowerWalk we visualize how mechanical energy harvesting can be integrated into wearable form factors effectively, enabling for the first time self powered mobile devices.

Energy harvesting is a source of interest for use in powering various sensors and electronic systems in vehicles to offload some of the main electrical system and save fuel. A thermoelectric generator system that generates on vehicle waste heat to power auxiliary electrical systems has been developed and tested by researchers at the University of Warwick. In conventional vehicles, this technology could reduce fuel consumption up to 5 percent, and in electric vehicles it could increase range.

Perhaps one of the most promising energy harvesting applications on the Internet of Things (IoT). In this domain, the EnOcean wireless standard is a compelling case study of adoption. Energy harvesting from motion, light, or temperature differences is used to power wireless sensors and switches in EnOcean based devices, making such devices batteryless and not requiring wired power. Several large commercial buildings have successfully utilized this technology, eliminating the costs associated with installation and reducing maintenance requirements in order to improve energy efficiency. Energy harvesting in the healthcare sector now enables possibilities for new implantable and wearable medical devices. A wearable energy harvesting device generated by human skin friction was developed by researchers at the University of Wisconsin-Madison. With battery capability, such a triboelectric nanogenerator could supply power for wearable health monitors or drug delivery systems. Implantable medical devices, which can harvest energy from heat or movement, are being developed that will allow for longer operating lifetimes and less frequent required invasive battery replacement surgeries. Energy harvesting technologies are also useful in other sectors of research including agriculture. The example of Plantect system developed by Fujitsu is also worth mentioning. The solar-powered sensors used in this system that monitor environmental conditions in greenhouses – temperatures, relative humidity and Co2 levels –. These sensors can be easily deployed without the requirement for power cables or the daily replacements of batteries, which provides the energy harvesting capability, allowing this to more easily be implemented by farmers for precision agriculture and optimisation of crop yields. Energy harvesting is now allowing long term, autonomous monitoring of bridges, buildings, and other infrastructure in the field of structural health monitoring. Vibration energy harvesting is demonstrated on the Oakland Bay Bridge in a case study from the University of California, San Diego, while powering wireless sensors. They measure the bridge's structural health continuously — without the need for battery replacements or wired power connections — using sensors that harvest energy from the vibrations caused by traffic.

Conclusion

Energy harvesting is currently under investigation by the aerospace industry for specific applications. Thermoelectric generators that harvest waste heat from spacecraft engines to power onboard systems are just one example of what NASA has been developing: This tech could cut the bulk and burden of spacecraft power systems, freeing up more cargo room or extending mission run time. Energy harvesting technologies have been widely made use of in consumer electronics. For example, solar cells built into a smartwatches' displays are increasingly being used to supplement battery life. One of the better examples of this trend is the Garmin Fenix 6 Pro Solar, which packs a transparent solar charging lens over its watch face for harvesting sunlight and ambient lighting for longer than normal between charges for industrial wireless sensor network is the focus 0f the field.

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