

MICRO ENERGY HARVESTING AS A CORE TECHNOLOGY FOR ENERGY-AUTONOMOUS EMBEDDED SYSTEMS

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Abstract: Within the last decade micro energy harvesting has shown all characteristics of an emerging research area. In this pioneering phase the aspect of exploring a novel technology has been the main driver. Also research has mostly been focused on microgenerators for mechanical, thermal, optical and chemical energy harvesting, leaving research on energy storage, electronic power management and energy-autonomous embedded systems lacking behind until today. Now, a second research phase begins to use the gained knowledge to work on the original motivation of micro energy harvesting, i.e. the practical realization of energy-autonomous embedded systems. This publication will discuss the requirements of such an application-oriented scope and will display several examples of actual research on energy-autonomous embedded systems.

Keywords: Micro energy harvesting, piezoelectric generators, thermoelectric generators, energy storage, power management, energy-autonomous embedded systems

INTRODUCTION

Today, wireless sensor networks (WSNs) are called as the premier application for micro energy harvesting from several reasons:

In general, distributed and embedded systems, often using MEMS, have penetrated almost every area of our daily living, although this might not be obvious for their users in many cases. We find a widespread application in cars, building automation and industrial fabrication, medical care and, more recently, as MEMS-RFID tags in transport and logistics. This is, in essence, the result of a long research history on smart sensors [2,3], starting with first examples of low-power sensor systems in the 1970s [1]. Wireless communication is the premier benefit and add-on of the actual WSN concept to the well-known - and commercially successful - idea of smart sensor networks. This feature promises a high level of mobility, flexibility and efficiency concerning the deployment of sensor nodes or their integration into an existing network. It does therefore not seem sensible to define a WSN where data transfer is happening by wireless communication while the energy supply to the nodes still happens through a power grid, that has to be deployed, extended and maintenance separately. The large and wide-spread power grid required for a large WSN may even provide a general bottle neck for the further application and spread-out of this technology. As an example, a modern mid-size passenger car uses 20 to 30 electronic control units (ECUs) with approximately 3 km of connecting wires for their power supply and data communication. In high class cars even 50 or more ECUs are in use [4][5]. The corresponding power and data grid is complex and error-prone, fabricated and installed by hand, not easily maintained and provides, over all, a substantial cost and environmental factor for the production, operation and servicing of cars. Similar problem

scenarios can be set up for any other public transportation system as well as for many stationary power and data grids.

Batteries and other exhaustible energy sources are used as an alternative and have to be used for truly mobile systems. In general, this power supply concept is restricted to low power embedded systems that are easily accessible for battery service or recharge. Moreover, environmental concerns arise from the growing numbers of batteries in use. For example, in 2006 the largest German battery recollection system has counted a total sale of approximately 1.4 billion of batteries in Germany alone [5][6]. Only one third has been recollected to be recycled or disposed environmentally friendly, leaving 22000 tons of undiscovered waste for the same year.

Aside from these well-known and often-cited arguments, the application of micro energy harvesting for the supply of a low-power sensor node in a WSN becomes more and more realistic, as the usually low harvested power levels converge with a shrinking power demand of modern microelectronics. The actual trend towards a reduction of transistor size, supply voltage and power consumption is mostly driven by the widespread application of mobile, battery-operated IT hardware. However, this trend also is an extremely helpful commercial driver for the delivery of suitable, i.e. low-voltage and ultra low-power analog and digital electronics for WSNs.

REQUIREMENTS FOR AN APPLICATION-SPECIFIC ENERGY HARVESTING

In a synthesis of the arguments given above, micro energy harvesting, i.e. the conversion of ambient energy into an embedded system's electrical power supply, would provide an utmost flexibility for the deployment, extension and servicing of a WSN, as it would make the nodes fully autonomous and avoid the problems described above. Corresponding research on

energy harvesting has started around 2000, driven by this vision of energy autonomy and, hence, the perspective of an almost unlimited range of application for wireless embedded systems. This first exploratory phase has mainly tackled the aspect of energy harvesting itself with research on suitable generators. The results are, in the meantime, presented in a large number of global and specific review publications on microgenerators (see e.g. [7][11][12]) with only few later contributions including energy storage [8]. In comparison to that, system aspects like e.g. energy-efficiency in wireless communication [9] are rarely found until today. Also electronic power management, although indispensable, has made a late entry into energy harvesting research.

Nevertheless, energy-autonomous embedded systems are no longer to be considered as a vision, but as an upcoming reality. However, their application is significantly different from the often-cited analogy of “renewable energies on a small scale”. Usually the application site will set severe constraints concerning the size of microgenerators and complete systems and, consequently, the level of available electrical power. Also, the delivery of ambient energy to the generator may happen with high - and in part unpredictable - fluctuations, concerning e.g. the amplitude and frequency spectrum of vibrations, the time-dependent variation of temperature gradients or the power spectrum and power level of optical irradiation. This calls for microgenerators with a high efficiency and a size and functionality compatible to the respective application site. The varying availability of ambient energy may require an efficient intermediate storage to bridge phases of low supply. An efficient energy management has to transfer the electrical energy between all subsystems in an optimal way. Finally, the energy consumption of the embedded system itself, and, as a consequence, its operation profile, has to be optimized to a high extent by appropriate design and system control measures.

While the latter aspect will benefit from the ongoing development of low-power microelectronics, the design of application-specific generators and their optimal adaptation to the application site is definitely an issue for the up-coming second phase of energy harvesting research. This will be discussed in the following with examples in the field of vibration and thermal energy harvesting. Also, a few remarks on energy storage will be given, being aware that this field is by far extending the scope of this publication. Examples of successfully implemented energy-autonomous embedded systems will conclude this paper.

APPLICATION-ADAPTED VIBRATION ENERGY HARVESTING

Vibration energy harvesting is one of the oldest and best-studied concepts of micro energy harvesting [7][8]. This may be attributed to the fact that at least

three different conversion principles - piezoelectric, electromagnetic and electrostatic - can be combined with a simple mechanical oscillator to harvest electrical energy from the mechanical energy of ambient vibrations. Also, the inertial forces acting as transduction mechanism do not require a complex and specifically tailored interface between the generator and a vibrating host, but merely a solid mechanical connection.

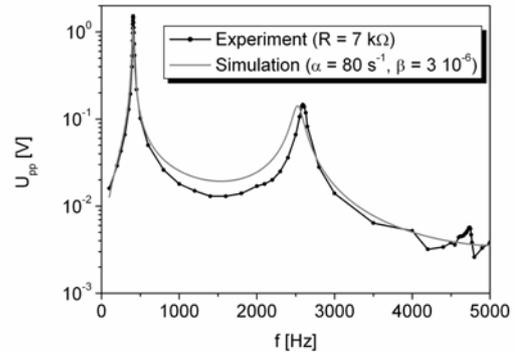


Fig. 1: Output voltage of a cantilever-type piezoelectric generator as a function of the ambient frequency [10] with resonance peaks at 407 Hz and 2593 Hz.

A general problem for the application of most vibration energy harvesters is their mono-resonant behavior. As shown in an example in Fig. 1 the mechanical oscillator will transfer a maximum of mechanical into electrical energy at its resonance frequency only, with a steep descent of the output power as soon as this optimal frequency is left. Therefore, this conversion principle will be best suited for host vibrations with a constant frequency, as this may be the case for electrical motors running synchronous with the AC mains frequency. However, even in these applications temperature variations or ageing effects can move the resonance frequency of the generator away from the host’s constant vibration frequency, with the detrimental effect described above. All other conceivable applications provide vibrations with fluctuations of their amplitude and frequency spectrum and do thus provide the challenge of harvesting from non-constant or even highly variable vibrations.

In the meantime, a large variety of concepts and ideas for an energy harvesting from broadband vibrations are studied [11][12]. While this strategy is addressing the problem of a variable input frequency, the problem of variable input amplitudes remains unaddressed or becomes even worse when choosing a certain concept of broadband harvesting. A few examples shall be discussed in the following.

Plucking-type generators

The function principle of this - relatively novel - generator is best explained with the plucking of a guitar string. The guitar string, representing a mono-resonant vibration harvester, is triggered sequentially by mechanical plucking from the guitar player

representing a host with a variable vibration spectrum. This operation does perform a frequency up-conversion and frequency filtering: Once deflected and released, the mechanical oscillator will start to oscillate at its resonance frequency with a decay time dictated by its total damping. Therefore, all plucking operations with input frequencies lower than the oscillator's resonance frequency can be used for energy harvesting, taking into account the decay time of the mechanical oscillator's resonance as a minimal time interval between two plucking events. The energy gained per event depends on the initial excitation and the internal damping while the output power depends on the excitation level and the plucking frequency.

Only few theoretical and experimental studies on plucking-type generators have been presented until now. One example is a bistable plucking generator [13] using two stacked electromagnetic vibration harvesters that are agitated sequentially through a vibrating magnetic plucking mass mounted on a spring in between. A more recent publication demonstrates a piezoelectric plucking generator [14]. The device concept is similar to historic music and noise instruments, like rattles or musical clocks: A central rotor is carrying four radially oriented cantilever bimorph piezogenerators. The inner side of a co-axial stator is equipped with a number of plectra, giving it an appearance similar to an internal ring gear. A rotation of the rotor with respect to the stator will initiate a sequential plucking of each piezogenerator via the line-up of plectra travelling by.

Both concepts do successfully demonstrate a frequency up-conversion and, hence, broadband energy harvesting from vibrations. However, plucking generators will always require a minimum amount of input energy to overcome the energy barrier of the excitation principle. They are therefore not suited for the acceptance of vibration over a large dynamic range as they provide a cut-off for low input energy. On the other hand the concept converts several drawbacks of vibration energy harvesters into benefits concerning their application. Due to their small seismic masses microminiaturized vibration harvesters exhibit high resonance frequencies up to the kHz-range [15] that are not present in most natural or technical environments. From that reason they cannot be applied for a direct, resonance-driven application. Frequency up-conversion via plucking might take a benefit from generators with such high resonance frequencies, as the repetition rate and thus the usable excitation bandwidth can both be increased, while the minimum excitation energy may even go down.

Duffing-type generators

The so-called Duffing oscillator uses a nonlinear spring in a mass-spring-damper system for a broadband excitability of oscillations. This concept has attracted considerable attention in the last years [16] [17][18]. A typical curve for the oscillation amplitude

and the output voltage of a piezoelectric Duffing oscillator [18] is given in Fig. 2 and depicts also the general problem of this broadband oscillator.

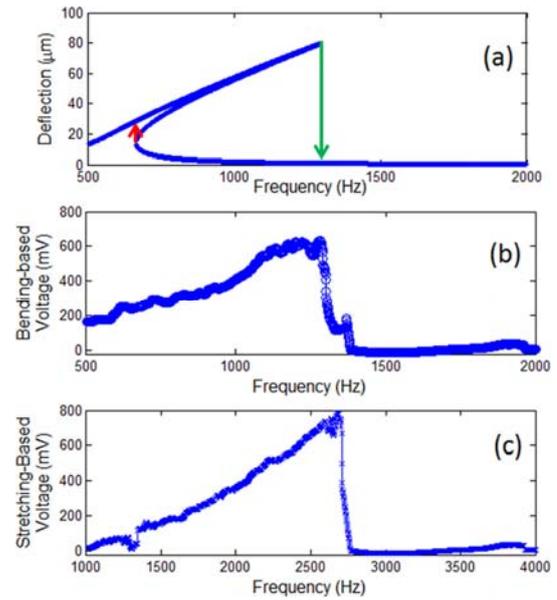


Fig. 2: Deflection (a) and output voltages (b,c) of a piezoelectric Duffing-type generator as a function of the excitation frequency [18]

The Duffing oscillator is essentially a bistable system that falls into an unfavorable low power mode as soon as the excitation frequency passes over the upper limit of the broadband excitation range. The oscillator can only be relinquished from this low-power mode by a reduction of the input frequency to much lower values. Nevertheless, the concept is promising, as it leaves a wide space for optimization and does also match the excitation patterns of several applications. For instance, the acceleration of a gear-shifted car is usually accompanied with an increase of the engine's vibrations within one gear stage and a fallback into lower frequencies after an up-shift of the gear setting.

Frequency-tunable generators

Following the analogy of a guitar string frequency-tunability would mean that the guitar player is continuously re-adjusting the resonance frequency of the string to follow the frequency of an external vibration. For such an active tuning device it is mandatory to reduce the amount of energy required for the tuning operation as much as possible. In general, the frequency tuning of a mechanical oscillator can happen through several parameters determining its resonance frequency. Literature gives examples of changing the spring constant, the internal strain of the spring or the seismic mass. An early example of an active frequency tuning mechanism in a closed loop configuration was given in [19]: Here, the magnetic attraction of a tuning magnet changes the internal strain of a cantilever-type spring to influence the resonance frequency of the oscillator's spring-mass

system. The magnetic tuning force is modified by varying the relative position of the tuning magnet with a linear stepper motor. The system is operated in closed-loop intermittent self-tuning, however suffers from the high power demand of the linear stepper motor. Only long tuning intervals of up to 1 hour can be realized as enough energy has to be harvested in between for the next tuning operation.

The problem of a high tuning power has been addressed with the device shown in Fig. 3, which has been developed over several design versions [20][21]. The ends of two double-cantilever piezo bimorphs are connected via a central piezoactuator. Longitudinal strain in the piezoactuator generates a restoring moment for the oscillations of the cantilevers thus changing the resonance frequency of the whole set-up. As a substantial benefit for low-power operation, the pre-charged piezoactuator will keep its internal strain over an extended period of time. Therefore, tuning energy is only required for an intermittent compensation of leakage currents and for readjustments of the actuator charge.

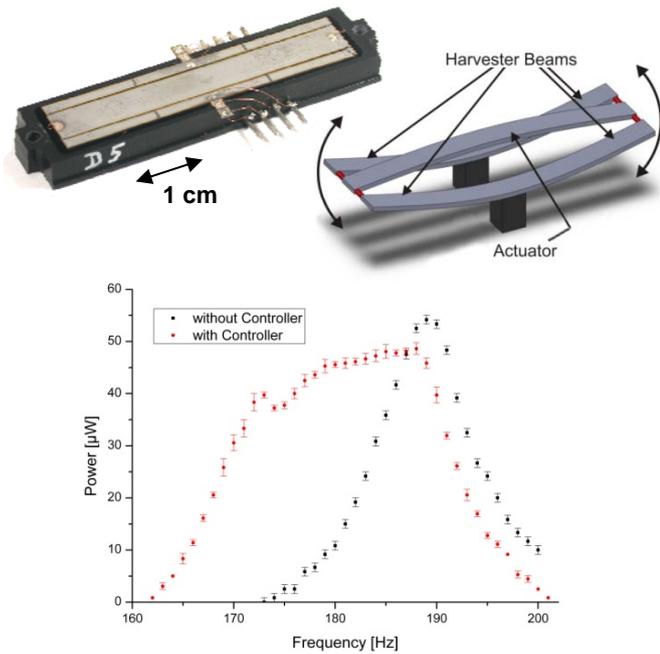


Figure 3: *Frequency-tunable piezogenerator [21]: schematic (top right), photograph (top left), output power of the frequency-adaptive energy harvesting system with and without active tuning (sinusoidal excitation, amplitude: 0.6 G, tuning interval: 20 s)*

In combination with a low-power microcontroller, a self-sufficient frequency-tunable energy harvester system has been obtained [21]. The microcontroller measures the actual ambient frequency in regular time interval and adjusts the actuator voltage in such a way that the generator's resonance frequency falls together with the host's vibration frequency. The power for the microcontroller and all associated electronics is harvested from these ambient vibrations. Active tuning generates a nearly constant output power over a frequency range approximately 4 times wider than the

power bandwidth of the un-tuned generator (Fig. 3). Due to the consumption of tuning power the available net power is 5 to 25 μW lower than the peak power of the un-tuned oscillator. A similar system has been presented using a piezoelectric resonance-tuning of an electromagnetic harvester [22]. Within this study it could again be demonstrated that piezoactuators, once charged to a fixed voltage level, retain their strain, even under vibration, for a certain period of time. Therefore, it is sufficient - and power-efficient - to activate the control system in intermittent time intervals only.

APPLICATION-ADAPTED THERMO-ELECTRIC ENERGY HARVESTING

As outlined before the problem of a variable input frequency for a vibration energy harvester is addressed in the meantime with several novel concepts. It turns out that also other generators may suffer from the same problem. Thermoelectric energy conversion is among those candidates, although this aspect is not well recognized until today. However, rapid variations of temperature occur in many technical applications, with significant consequences for the amount of finally harvested energy. In these cases the dynamic response of the whole generator has again to be taken into account and optimized, if required. This is shown in [23] for a thermoelectric generator that harvests from temperature gradients between a tunnel wall and the air inside a road tunnel. While the tunnel wall can at least be regarded as a slowly reacting thermal mass with an almost constant temperature T_{wall} the air temperature T_{air} shows a highly dynamic behavior depending on traffic density, weather conditions, seasons and daytime. Also the total temperature difference $T_{\text{air}} - T_{\text{wall}}$ between air and tunnel wall can be small, with typical values around a few Kelvin only.

Usually a thermoelectric generator system for this scenario comprises of a heat sink protruding into the tunnel, the thermoelectric generator (TEG) itself and a thermal interface to the tunnel wall. This set-up and its electrical equivalence circuit are shown in Fig. 4.

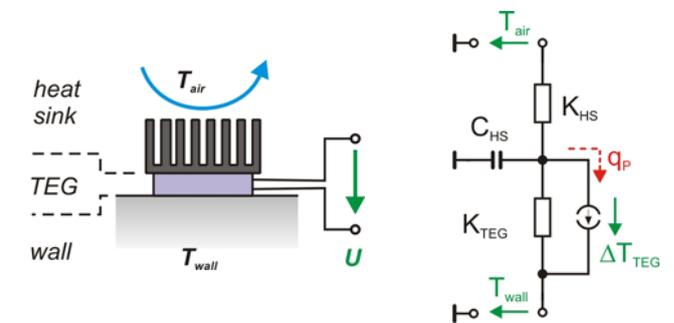
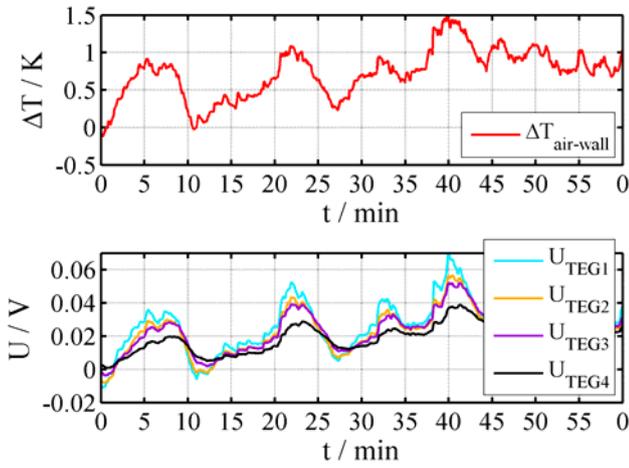


Figure 4: *Schematic set-up and electrical equivalence circuit of a wall-air TEG system as used in [23]*

In the equivalence circuit K_{HS} and K_{TEG} describe the thermal resistances of the heat sink and the TEG, respectively, C_{HS} the thermal capacitance of the heat sink and q_P the Peltier effect occurring inside the TEG.

The thermal capacitance of the TEG is neglected as well as all thermal contact resistances. More details on this model have been published recently and will be presented in a separate publication in the near future [24]. For a static or quasi-static operation from large temperature reservoirs the thermal resistance K_{HS} has to be reduced as much as possible to maximize ΔT_{TEG} over the thermoelectric generator. Surprisingly this is not the best optimization strategy for a dynamic temperature profile. In this case the RC lowpass given by the heat sink will define the ability of the TEG system to follow rapid transients of the air temperature. Especially for small temperature differences $T_{air}-T_{wall}$ all efforts have to be taken to reduce C_{HS} and K_{HS} as much as possible. This is an inherent design conflict as a smaller thermal resistance K_{HS} of the heat sink is usually achieved via larger cross sections and surfaces and, hence, larger masses with a higher thermal capacitance C_{HS} .



no.	heat sink		air-wall TEG with heat sink	
	$\tau_{HS} = K_{HS} C_{HS}$ [s]	K_{HS} [K/W]	P_{mean} in $[\mu W]$ for $R_L = R_{TEG} = 9.7 \Omega$	E/day [J/day]
1	239	8.3	20.1	1.74
2	374	8.5	15.3	1.32
3	402	2.8	10.1	0.87
4	416	4.9	7.9	0.68

Figure 5: Top: temperature difference $\Delta T = T_{air}-T_{wall}$ and open circuit voltage U of four with different heat sinks in a road tunnel, bottom: measured thermal resistances K and time constants τ and calculated average power and average energy/day for these four TEG air-wall systems [23]

The measurement data given in Fig. 5 demonstrate that this effort is worth to be undertaken: The combination of TEG and heat sink 1 with the shortest thermal time constant τ_{HS} allows for the most efficient energy harvesting from rapid transients of the small temperature differences ΔT . In comparison to heat sink 4 with the longest time constant the calculated output power with optimal load matching would be 2.5 times higher. The higher thermal resistance K_{HS} of heat sink 1 will at the same time even reduce the temperature difference over the TEG, which has a similar thermal

resistance K_{TEG} of 2.44K/W. However, this is obviously not the dominant influence parameter on the output power in a highly dynamic thermal situation.

Fig. 5 reveals another problem occurring with energy harvesting from low-temperature gradients. Conventional mesoscale Bi_2Te_3 -TEGs offer Seebeck coefficients in the range of 10...100 mV/K. The TEG used in [23] exhibits a Seebeck coefficient of 95 mV/K with a size of 40 x 40 x 3.9 mm³. Even this relatively large TEG delivers no-load voltages of several 10 mV only when operated at low temperature differences of one to several Kelvin. This calls for electronic step-up converters with a low start-up voltage and a sufficient efficiency to transform these low input voltages into a usable output voltage. Experimental [25] and commercial [26][27] devices, either as hybrid designs or as integrated circuits are available with start-up voltages down to 20 mV and typical best efficiencies around 35%. Their common circuit concept is a self-resonating step-up converter based on a Meissner oscillator [28][29]. For the application scenario shown in Fig. 4 any further decrease of the start-up voltage would be beneficial: With highly transient and low temperature differences a TEG will deliver low output voltages with significant fluctuations. Therefore, the start-up voltage of the Step-up converter will provide an intermittent cut-off and limit the amount of usable electrical energy.

ENERGY STORAGE

Taking fluctuations of the ambient energy into account almost every energy-autonomous embedded system requires internal energy storage, either to buffer the system power over short periods of time or to keep the system active over longer brown-out periods. Today's solutions are almost completely electric and use either electric capacitors or rechargeable batteries. In general, literature on an application of storage concepts for energy harvesting is rare. A few global aspects of electric energy storage have been discussed by the author in a recent publication [5] and shall not be repeated here in detail. In sum it turns out that lifetime and leakage effects of rechargeable batteries and capacitors that are negligible in conventional electronic systems will become dominant in a low-power system powered by energy harvesting. As a consequence, all elements used for electric power storage have to be chosen and operated carefully, with a close look onto the power required by the embedded system and the power available from the generator.

Depending on the application site and application scenario alternatives to electric energy storage may provide a substantial benefit. This idea has always stimulated imagination: In one of his science fiction novels the author Stanislaw Lem describes an extra-terrestrial space satellite using pre-stressed piezoelectric material as a "mechanical battery" [30]. He may have been inspired by similar concepts found over almost 100 years on earth in every automatic

match where a spring system is wound up by the movements of a pendulum.

Another, more promising candidate for such a “non-electric battery” would be thermal energy storage in combination with thermoelectric energy harvesting. A corresponding case study has been performed in our lab, using the combination of a TEG and a thermal battery. For this purpose the TEG was mounted at the outlet of a 1 liter dewar vessel filled with water as a thermal storage medium. A heat sink was mounted on top of the TEG as a thermal contact to the ambient air and as a thermal solar panel. During the day solar irradiation and energy from the increased air temperature is harvested while heat is transferred through the TEG into the colder thermobattery. During night the thermal energy stored in the dewar vessel is dissipated through the TEG into the cold ambient. Therefore, the TEG will deliver energy both during the charge and discharge phase of the thermobattery. In summer 2010 this non-optimized system was capable to deliver no-load output voltages between -62 mV and + 80 mV under mixed weather conditions. Taking into account the efficiency (25%) and start-up voltage (20 mV) of an optimized step-up converter, the maximum energy harvested per day was 0.67 Ws. This is sufficient to run an embedded system with a power consumption of 50 μ W, similar to the devices described in [36][37], for almost one hour.

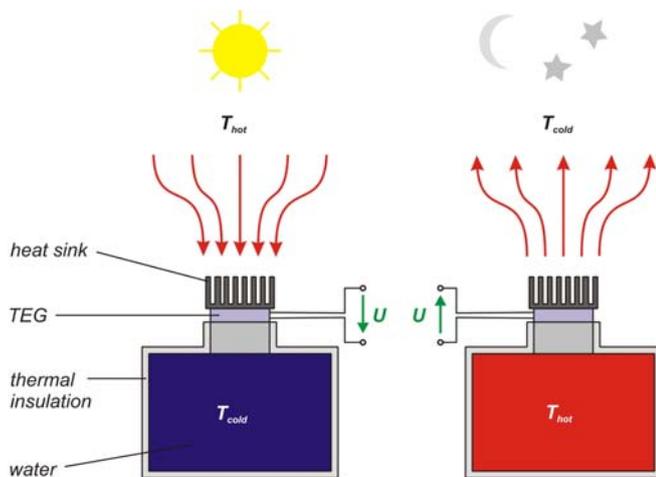


Figure 6: TEG in combination with a thermobattery: Schematic depiction of the charge and discharge phase

ENERGY-AUTONOMOUS EMBEDDED SYSTEMS

In comparison to the comprehensive literature available on micro power generators, complete energy-autonomous embedded systems show only up in few cases. High-lighted examples of commercial products [31][32][33] are found in several selected application areas. This shows one of the up-coming problems for energy harvesting and energy-autonomous embedded systems today which is the search for suitable application areas, corresponding business concepts and, finally, the struggle with existing and competitive

technical solutions and products. Nevertheless, the first examples of realistic application scenarios appear in literature and shall be discussed with two examples.

Monitoring of critical states and transient events

A thermobattery module similar to the one discussed before has been presented recently for an aircraft application, using a phase-change material as a thermal storage medium [34]. Although this is not a complete system it demonstrates an interesting application scenario for energy-harvesting. Here, the large temperature differences occurring during take-off and landing are exploited with the idea to supply sensor nodes for a structural health monitoring during the same critical flight phases. Therefore, the energy-autonomous system will begin its operation in a quasi-automatic fashion as soon as a critical state to be monitored is entered.

This concept could be driven further with specific microgenerators that start their operation or increase their output power level upon the on-set of a critical or a transient condition to be detected. Such a so-called “sensor-generator” would therefore be triggered by e.g. undesired vibrations of an engine and deliver at the same time the energy required for a wireless alarm signal. Energy-autonomous light switches being triggered and supplied from the energy deployed while pressing the light switch are a prominent commercial example of this concept [31]. A most recent publication describes an energy-autonomous train passage detector that is triggered and supplied from vibrations occurring in the rail sleeper during the passage of a train [35]. For this purpose an array of piezoelectric generators with different resonance frequencies has been developed to harvest from broadband vibrations present at the rail. An ultra-low-power wake-up and power-down system will trigger the wireless signaling of the train passage and will set the system back into a zero power sleep as soon as the train has passed over the sensor node.

Quasi-continuous engine condition monitoring

These WSN nodes are built with the intention to monitor critical operational parameters of technical equipment like, e.g., temperatures or vibration levels. As these data are not required during equipment off-times, the energy-autonomous sensor system is allowed to fall into a low-power deep sleep or even a power-dead state as soon as the monitored equipment is turned off. Therefore, an internal rechargeable battery may not be required at all. This is beneficial for the operational lifetime of the WNS node.

Two similar case studies for engine condition monitoring have been published describing almost identical problems encountered for this application scenario. In [36] an electromagnetic vibration harvester is used to power a wireless temperature sensor system for condition monitoring of a vibrating engine. Ref. [37] uses an impact-type piezogenerator

that harvests energy from the vibration dampers of a compressor pump, again to monitor its motor temperature. In both cases small generators have been developed and deployed to harvest energy in the range of 100 μ W on a small host. This is sufficient to supply a temperature sensor with its associated digital signal processing electronics and a wireless transmitter in the ISM band, with typical transmission rates of 1/s.

While the regular operation of these systems is feasible without any problem especially their start-up has to be controlled by a specific electronic power management. The situation is similar in the system described in [35]. In the start-up phase the internal capacitors are uncharged thus providing a low-impedance load for the generator. While the system voltage slowly rises also the system's CMOS electronics may drain an increased current in its sub-threshold voltage range. Both effects together can overload the generator which is not capable to deliver enough power as it is operated still far away from its optimal load point. The logical solution for this problem is the insertion of a voltage monitor with a load switch between the system electronics and the generator. This sub-system will monitor the rise of the generator's output voltage and connect the system only when a sufficient voltage level is achieved. For this purpose low voltage devices with a low power consumption and a defined start-up behavior have been selected or developed, either as suitable integrated circuits from commercial suppliers [36] or as specifically designed electronic modules [35][37].

CONCLUSIONS AND OUTLOOK

After one decade of basic research micro energy harvesting has reached a strategic turning point towards application. In the first pioneering phase the exploration of a novel technology in its foundations and capabilities has been the main driver. As a result comprehensive knowledge is available on the function principle and design of microgenerators which have been in the primary focus from the beginning. Recently, more and more attention is directed towards energy storage and power management as the other two indispensable sub-systems of an energy-autonomous system. With this broad scientific and technological basis a more intensified research on and development of energy-autonomous embedded systems will - and should be - the additional focus of future research. For the further progress into this direction it should not be underestimated that micro energy harvesting and energy-autonomous embedded systems have reached a certain level of maturity that starts to be competitive with well-known "conventional" techniques. Consequently, potential business cases have to be developed together with system design and application-specific research that use the full benefit of energy-autonomous embedded systems, i.e. a simple and cost-efficient deployment, a completely maintenance-free operation, cost

reductions in the full value chain and, last but not least, novel functionalities and application areas that cannot be covered by common, established systems.

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