Energy Harvesting for Autonomous Microsystems

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Today, we are surrounded by a high diversity of distributed and decentralized systems. Pilot applications are easily identified with mobile phone, notebook and PDA. However, distributed systems – often based on MEMS devices – have meanwhile penetrated not only the IT sector but almost every area of our daily living. Examples are the steadily growing application of MEMS devices in cars, distributed sensor and actuator systems in buildings and industrial fabrication, distributed MEMS devices in medical care and, recently, MEMS-RFID tags in transport and logistics.
While RF communication may serve for a flexible data transmission in a distributed system, the energy is still supplied by wire or batteries today. This requires a complicated and error-prone power grid that is usually installed by hand, not easily maintained and, above all, does constitute a substantial cost factor. The use of batteries and other exhaustible energy sources is restricted to low power systems that are easily accessible for service and thus not a real alternative in many cases.

Micro Energy Harvesting, i.e. the conversion of ambient energy into a microsystem node's supply, promises a much better approach for operating a distributed system, as it would make the nodes energy-autonomous. We do this in the macro world by employing wind, solar or water power as "renewable" forms of energy, with all associated problems like

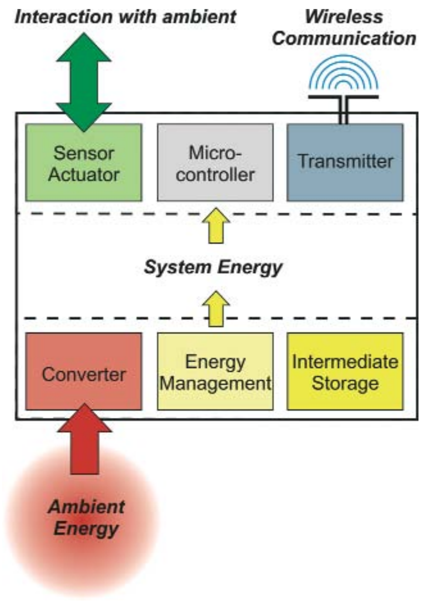

Figure 1: Microsystem with integrated micro-energy harvesting [1]

varying energy supply, the need to bridge power-down phases and the environmentally friendly design of the power stations. These challenges do multiply if we tackle the field of "micro energy harvesting". A simple replacement of the battery or the supply cord by a "micro power plant" will not solve the task. In contrast, micro energy harvesting relies on a thorough design of the whole system (Figure 1). Converters have to be provided with a size and function compatible to the respective application site. The varying availability of ambient energy will require an efficient intermediate storage to bridge phases of low supply, as the back-up power grid is not available. A dedicated energy management has to transfer the electrical energy between all subsystems in an optimal way. And, finally, the energy consumption of the system node itself has to be minimized to a high extent by design and control measures.
Full compatibility with the main system functions and the ambient conditions is the prominent requirement for all energy harvesting methods. This is mostly accomplished by choosing the appropriate **conversion principle**. It is, for instance, not practical to employ a disturbing thermoelectric converter when the systems main task is temperature sensing. It is also impossible to use a large generator when the microsystem has to operate in a small environment, e.g. as a medical implant. This calls for conversion principles with a sufficiently high degree of miniaturization, high conversion efficiency and the capability of easy system integration. Several promising candidates for mechanical, thermal, optical and chemical energy harvesting are discussed in the following.

Piezoelectric converters
Mechanical stress in a piezoelectric material, like PZT ceramics or PVDF polymer, generates an electrical charge that is extracted by metallic electrodes located on its surfaces. A dynamic mechanical load, e.g. from ambient vibration or sound, will result in an AC current. Miniaturized piezoelectric converters can deliver high electrical voltages (up to several volts) with currents in the microampere range. They do, however, require a careful mechanical design to provide a homo-geneous mechanical stress distribution in the piezoelectric material. Otherwise, the electrodes will short electrical charge from highly stressed regions with charge from low-stress regions. This internal short circuit will considerably reduce the conversion efficiency. A stress-homogenized geometric design of the converter can provide a homogeneous stress distribution and therefore maximum conversion efficiency [1].

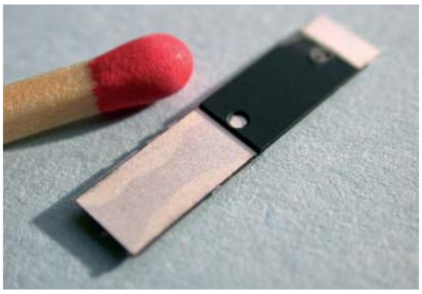
Figure 2: Piezo-polymer composite [3]

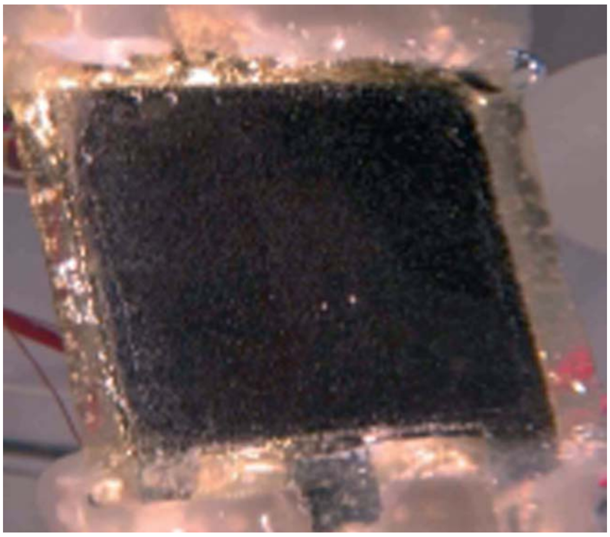

Figure 3: Polymer electrolyte glucose direct fuel cell: membrane unit with polymer coating (size approx. 30 x 30 mm²)

Today, autonomous RF power switches are available based on piezoelectric converters [2]. For these as for other applications (e.g. tire pressure sensing), a flexible and low-cost fabrication and integration concept is a premier demand. We have developed a piezo-polymer composite technology that integrates PZT ceramics into an almost deliberately shaped polymeric structure [3]. Although primarily developed for Microactuators, this concept is usable for an easy integration of piezogenerators, e.g. to make energy-delivering push buttons in polymeric electronic encasements or vibration converters in moulded IC housings.

Thermoelectric converters (TEGs) are based on the Seebeck effect, i.e. the generation of an electrical voltage in a thermocouple located in a temperature gradient. Suitable thermoelectric materials exhibit a high thermoelectric coefficient, low electrical resistivity and low thermal conductivity, such as bismuth-telluride alloys, polysilicon or silicon-germanium. If properly designed, a chip-based micro-TEG exhibits a typical power density of 0.6 μW/mm². This is sufficient for low power electronics, e.g. in wristwatches. However, the low voltage level (around 100 mV) has usually to be boosted by electronic means.

Nanocomposite Solar Cells
Photovoltaic energy conversion is among the oldest principles of energy harvesting. Especially flexible solar cells can be integrated in challenging application sites (e.g. in smart textiles) to supply energy-autonomous systems [4]. We have worked on flexible solar cells that use Cd-Te-nanocrystals embedded in a polymer semiconductor matrix [5]. These solar cells can be fabricated by spin coating technologies and are therefore much cheaper than silicon-based devices. When compared to pure polymeric concepts, their long-term stability should be higher. Also, the absorption spectrum can be tailored by applying appropriate nanocrystals.

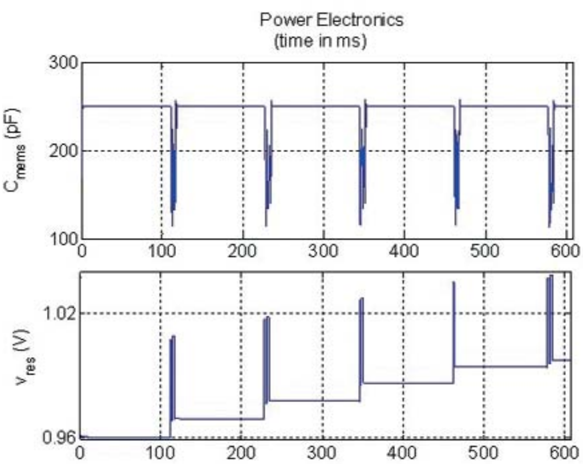

Figure 4: Simulated input signal (top) and output voltage (bottom) for an adaptive DC-DC converter with a capacitive converter.

Biofuel Cells
The sustainable power supply is a special problem for implantable microsystems. Currently such devices use secondary power cells that need surgical replacement at the end of their lifetime. Within the framework of the European "Healthy Aims" project [6] we investigate implantable energy harvesting devices to convert sustainable body energy into electrical energy. For this, biofuel cells are superior to other technologies in terms of continuous power output, longevity, minimal invasive implantability and biocompatibility. However, not all types of fuel cells show the same advantages. Enzymatic fuel cells have a high reactant specificity, allowing a simple one-compartment design. They do, however, lack longevity and amenability to steam sterilization.

Due to their self-regenerating capability, microbial fuel cells have shown superior longevity. Until now, they have not been considered as implantable due to the infective nature of most known microorganisms. A third option, direct glucose fuel cells, is the focus of our current research due to their longevity, amenability to sterilization, and biocompatibility. A basic manufacturing protocol has already been established and tested, as shown in Figure 3. Typical energy densities of such biofuel cells are in the range of 0.1 to 100 μW/cm².

Energy and System Management
Most ambient power sources will only deliver a low level of usable energy. An energy management system will therefore have to seek ways to maximize the effectiveness of the power converter. Solar cells, for example, require an adaptive operating point in order to deliver their maximum power. This will be also true for all other sources. This adaptive control has to be intelligent enough to find the optimum set point without requiring too large amounts of energy itself. Of course, also the rest of the system needs to follow low-power concepts and must include extensive power management mechanisms.

So diverse the energy sources are, even more wide-ranging are the conversion principles that can be applied to convert the available energy to electrical power. For example, vibration energy can be converted through piezoelectrical means as described before, but also by electromagnetic or capacitive principles. And, although the energy source is one and the same, these conversion principles will require a different circuit technique. One can - at least - identify two groups of transducers which have similar properties at their output and can be covered by similar circuit concepts. The first group includes all mechanisms that deliver high output voltages but small currents, like piezoelectric converters. The second group is constituted by converters with low output voltages but high currents, like capacitive, thermoelectric or electromagnetic generators.

In both cases the major requirement for efficient energy extraction is a proper impedance matching between transducer and conversion circuit in order to compensate for changes in the parameters of the generator or the energy source. Adaptive DC-DC converters are especially needed for piezoelectric transducers. Capacitive converters do require an even more complicated circuit structure with a synchronous switching to the energy source (figure 4). Naturally, the conversion circuit itself should be low power. It should be capable of estimating the amount of energy extractable from the ambient. It should cease conversion as soon as the energy input is below its own requirements in order not to waste power.

Many systems will not be able to rely on just one power source, either because of the amount of energy required or due to fluctuations of the ambient energies. Thus, hybrid systems will be required with different microgenerators, distinct conversion electronics and an even more demanding power management.

The development of micro energy harvesting is a challenge for science and engineering and still in its beginning. However, the vision of self-supplying networking microsystems that can be operated at remote sites and without service is an efficient commercial driver for progress in this pioneering area.

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