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Autonomous wireless sensors for process instrumentation - Autonome drahtlose Sensorik für die Prozessindustrie

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1 Introduction: Wireless devices and energy harvesting

Wireless devices have received increasing attention in the process industry over the last years. After wireless technology has dramatically changed the way we live our lives and do business, the next logical step is to introduce this technology into production processes, as well.

As the primary means of collecting information about the process, field instruments are vital to the operation of plants in the process industry. Generally, communication and power supply of such sensors are done by hard wiring, which can be very complex and laborious. In particular, sensors in remote locations, on rotating parts, and sensors added to an already-operating plant instead of during commissioning could benefit the most from a wireless solution. Since a plant can only be operational if all necessary assets are functioning correctly, demands on reliability in the process industry are far more stringent than for consumer devices.

Although specialized wireless solutions exist in the process industry since the 1960s, until now, they have been successful only in specialized markets or products. From the experience with fieldbus technology, it is clear that any wireless protocol that aims at achieving critical mass requires an industry standard with many device manufacturers adapting it. Such a standard is now established as wirelessHART, which combines state-of-the-art wireless technology with the ease of use of the HART protocol.

Plants in process automation usually have a projected lifetime of about twenty years and longer. In order to maximize the return on investment, plant utilization should be as high as possible over the lifetime of the plant, thus unscheduled downtimes must be minimized. Asset monitoring is a new trend targeting to detect possible defects in equipment before they cause breakdown and to allow the root cause to be eliminated in a scheduled manner. In order to do so, additional sensor information is required, which further increases the number of sensors installed. For any sensor, total cost should be as low as possible in order to maximize the benefit. Since wiring and installation can amount to almost 90 % of the total cost for the device, wireless is a logical option in this scenario.

Wireless devices and sensors offer more installation flexibility and reduced installation costs due to the absence of wiring effort. Although primary cells (batteries) offer an autonomous energy supply in principle, this solution suffers from strongly limited lifetime, and hence potentially high maintenance cost through battery exchange and increased risk of failure. Therefore, additional energy sources are necessary for a more efficient way of operating wireless devices.

Energy harvesting (EH) offers to improve the maintenance-free lifetime of wireless devices into the lifetime range of process plants by using autonomios power supplies which are based on the convertion of ambient energy or energy coming from the process itself into usable electrical energy. In principle, this kind of energy exists in abundance in many processes, in forms such as thermal gradients, vibrations, flow or light (see Figure 1). Using suitable generators, this energy can be used to power wireless devices, allowing for truly autonomous field devices [Nen11-1].

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Figure 1: Energy harvesting converts ambient energy or energy available in the process itself into usable electrical energy.

2 Energy harvesting technology overview

A number of different instruments, including temperature, pressure, and vibration sensors, have been realized as low-power wireless devices using a battery for power, or may be converted to low power in the future. Just as these and other low power optimized instruments would benefit from becoming energy autonomous, the range of energy sources with different properties is wide:

- **Solar radiation:** Photovoltaic cells have become a robust and established technology, and outdoor use is routine. However, while the radiation intensity outdoors can reach a power density of approximately 1.000 W/m^2, typical values for indoor applications lie only around 1 W/m^2 [Mue09]. Hence, the amount of energy that can be harvested indoors is rather limited, and special indoor solar cells should be used. In most cases, solar cells will need to be combined with some form of energy buffering to compensate for the day-night cycle.
- **Thermoelectric:** Thermoelectric generators (TEG) generate electric energy from temperature differences. They use the Seebeck-effect to convert temperature gradients (e.g. between hot or cold process media and the ambient air) into electrical power [Vin01]. The efficiency of TEGs is rather low (typically below 1 %), and a temperature difference of at least several K is required, but in the process industry, large thermal reservoirs are common, which means that sufficient power is available. Where sufficient thermal gradients are continuously available, they may be the energy harvesting system of choice, as they offer excellent robustness and reliable commercial products can be bought from different suppliers.
- **Kinetic converters:** Direct conversion of mechanical movements like vibrations into electrical energy can be done with different transducer mechanisms.
  - Electromagnetic mechanisms use a flexible mounted coil, which is moving inside a static magnetic field of a small permanent magnet. This induces a voltage according to Faraday's law.
  - Piezoelectric transducers are based on piezoelectric materials. By means of a proof mass supported by a beam of piezoelectric material, the kinetic movement results in a displacement of the mass, which induces mechanical stress on the beam, which results in a voltage.

  - Electrostatic transducers are based on a charged variable capacitor. When mechanical forces are employed, work is done against the attraction of the oppositely charged capacitor plates. As a result, a change in capacity induces a current flow in a closed circuit.

  However, all these principles are based on a mechanical resonator. In consequence, the systems only deliver a reasonable power output if the resonance frequency of the harvesting device matches the external excitation frequency.

- **Pressurized air as a source of electrical power:** In certain locations where no electrical power supply has been established, pressurized air (or other gasses) may be available as a source of power. Examples of such locations would be natural gas pipelines in remote areas or parts of the extremities of certain industrial robots. Conversion of the mechanical energy stored in the pressurized air or gas to electric energy can be achieved by expanding the gas in a controlled fashion, e.g. by releasing it to the environment through a turbine and generator.

In conclusion, none of these four power sources can be a general-purpose solution for all applications, but for each, use cases exist where it excels. Thus, a building blocks approach with a generic power management that can accept any of these, or even upcoming alternative, power sources would indeed be the most comprehensive response to the demand for autonomous wireless devices.

3 Energy harvesting concepts for process automation

3.1 System components

Energy harvesting can be a rather discontinuous process. For example, day-night-cycles will lead to unstable power sources in case of outdoor photovoltaic applications. Downtimes of plants can lead to different process temperatures which may influence the delivered energy coming from TEGs. Variable frequency drives can lead to varying power yield of vibration harvesters. In contrast, there may be periods of time where the EH system supplies more energy than needed. Additionally, the power consumption profile of typical wireless sensor nodes is also discontinuous: depending on the duty cycle and update rate of the device, peak loads may occur which have to be buffered since EH systems are not able to support these high short term currents.

In conclusion, every EH system needs an energy buffer to overcome times when the harvesting device cannot supply enough energy for the sensor node. Conventional primary cells are also a reasonable alternative in combination with EH to provide a stable and long-term buffer strategy. Although they do not allow for the storage of excessive energy coming from the EH system, they can be used to provide power at times when the EH cannot. Typical industrial primary cells offer very long shelf lives at low self-discharge rates, and thus provide a very reliable alternative backup energy source.

The variety of harvesting devices and buffers lead to the necessity of an appropriate power management (PM) for a truly autonomous power supply. The PM has to adjust the characteristic of the output voltage and current of the EH system to the input requirements of the electrical consumer. In addition, the PM has to take care about the management of the different energy source of the EH and the buffering system. It has to switch smoothly between primary cells, energy buffers like rechargeable cells and available EH sources.

Especially in process automation, the application scenarios are rather diverse. Different field devices are installed in different environments under different installation conditions. Some of them are close to temperature gradients – some are not. Some are applied in outdoor applications; other ones are only used indoors. Certain devices see strong mechanical vibrations or have access to pressurized air

– others do not. A comprehensive energy harvesting power supply concept therefore needs to be applied to these diverse application scenarios and a diverse product portfolio, which results in a list of fundamental requirements that need to be fulfilled in order to be applicable in process industry (see Figure 2).

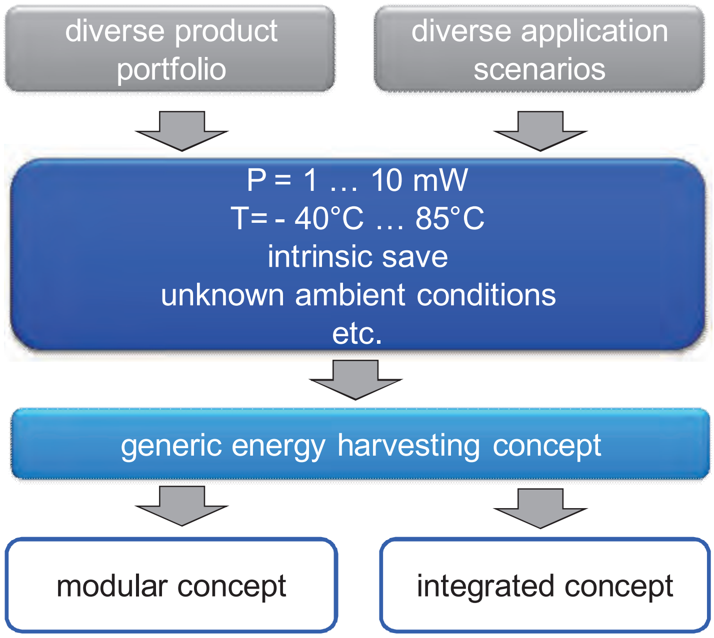

Figure 2: Requirements and constraints for energy harvesting concepts in process automation.

Obviously, it is not a practical approach to customize the EH-power supply unit for every single field device by e.g. tuning a vibration harvester to a particular resonance frequency or adapting the thermal connection to a potentially available temperature gradient. In conclusion, a generic and universal energy harvesting concept is needed to allow for broad and universal usage in the majority of wireless field devices, independent of the installation situation or the sensor type. There are two possibilities to achieve that:

- Modular concept
- Integrated concept

Both concepts will be described in the following sections.

3.2 Modular concept

In a modular EH concept, several harvesting sources can be attached to one central power management unit (see Figure 3). This power management handles the conversion and harmonization of the different input voltages (DC in case of e.g. solar, thermoelectric generators and AC in case of e.g. vibration harvesting). Excessive energy could be stored in rechargeable energy buffers (e.g. accumulators, super-capacitors). In addition primary energy sources (e.g. primary batteries) can be attached to the power management unit, which then organizes and controls the energy sources according to the energy demand. This whole unit could then be used as a universal power supply for any kind of wireless device or even a group of devices.

The advantage of this modular approach is that an arbitrary combination of harvesting sources and energy storage systems which may be attached to the central power management electronics. This allows the flexible usage in the rather diverse application scenarios of different field devices. Appropriate EH sources can be chosen according to the situation at the device installation spot.

However, depending on the number of different EH sources, the development of universal power management electronics may be rather complicated and complex since a range of different input energy sources with variable signature, voltage and current level and power range have to be controlled and converted to a common level. If rechargeable energy buffers are used, necessary internal voltage levels may be higher than the actual output voltage which needs additional voltage boosters. Hence the main challenge with respect to the development of such an universal power management will be a satisfactory overall efficiency of the electronics.

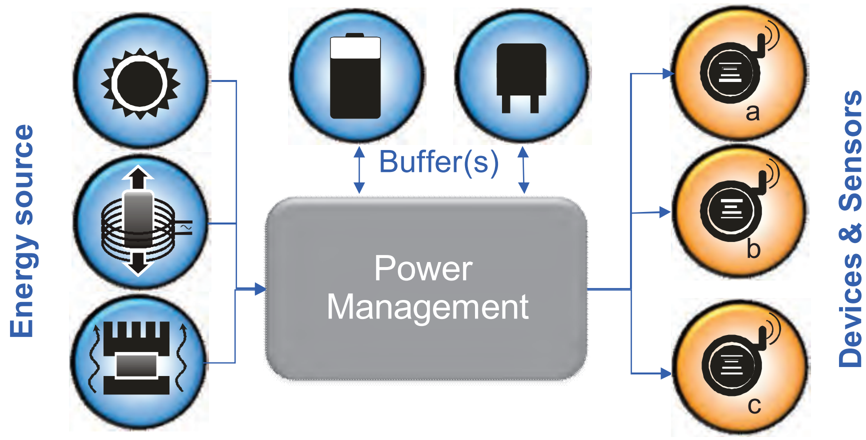

Figure 3: System architecture of a modular energy harvesting concept.

3.3 Integrated concept

With an integrated energy harvesting concept, all necessary components (energy harvester, energy buffers, and power management) are fully integrated into the wireless devices. No additional cables in order to attach EH sources or energy buffers are necessary. This has the advantage that, for the end-customer, the device has the same "look-and-feel" as a conventional purely battery powered device – but with an extended functionality.

However, a meaningful combination of EH source and sensor device needs to be identified since the harvesting technology is embedded into the measurement device. Therefore "natural partners" are needed (see Figure 4). Such combinations may be e.g.:

- Harvesting from thermal gradients and temperature measurement devices,
- Harvesting from mechanical movements and vibration monitoring devices.

If such combinations are identified, an integrated concept may also allow for a very device-specific optimizations and adjustments in order to reach optimal performance – especially of the power management electronics.

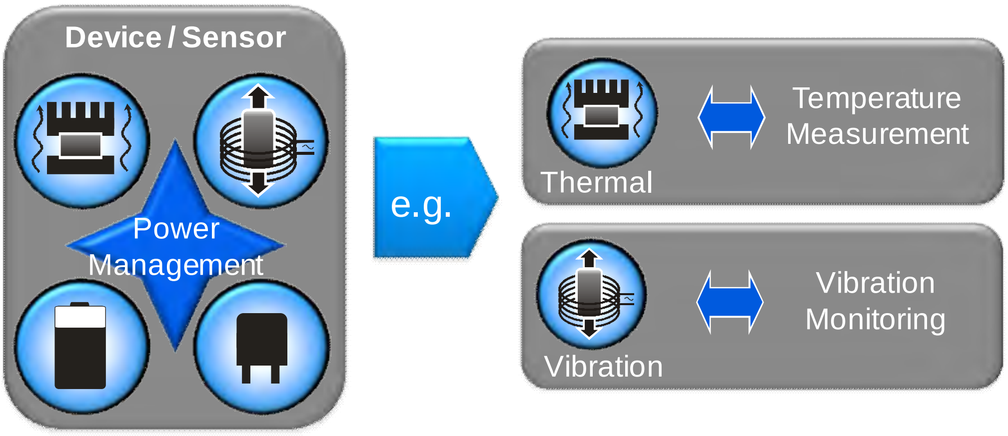

Figure 4: System architecture of an integrated energy harvesting concept.

4 Technology demonstrators

4.1 Modular concept demonstrator: energy harvesting building blocks

The energy harvsting builiding blocks (EHBB) demonstrator electronics for process instrumentation applications provides a modular concept that enables a greater variety of combinations between energy harvesters such as thermal gradient harvesters, vibration harvesters, indoor and outdoor solar cells, or pressurized air microturbines, and sensors such as wireless temperature and pressure transmitters. The conditions for successful use of these energy harvesting technologies have been examined, and a demonstrator for a modular energy harvesting power management has been built.

In many cases, power supplied by energy harvesters cannot be assumed continuously available. For example, solar power may be subject to day-night-cycles or working hours, and vibrations or thermal gradients may not be available during plant downtimes, shutdown, or startup, or be otherwise dependent on the mode of operation. The power consumption profile of typical wireless sensor nodes is also discontinuous: Depending on the duty cycle and update rate of the sensor, peak loads may occur which have to be buffered because EH systems are not able to support these high short-term currents.

Therefore, a technology demonstrator was built with a power management that provides both two low-voltage interfaces for sources such as thermoelectric generators, and two medium-voltage interfaces for sources such as vibration energy harvesters. It can also control an energy buffer based on supercapacitors or lifetime-optimized solid-state batteries .

Up to two instruments or other power consumer in the regime of some mW, can be connected. Optionally, the power management is controlled via USB from a LabView interface on a laboratory PC, which also allows monitoring input and output currents and voltages for characterizing harvesters, buffers and instruments. This approach allows the simulation of the different scenarios in real field applications, as well (variable slection of EH sources and different power load levels).

Figure 5 shows the modular concept lab-demonstrator electronics without any measurement sensor attached. The power management can be pre-configured and operated independent of external control. The prototype system fits inside the electronics compartment of a typical field instrument housing.

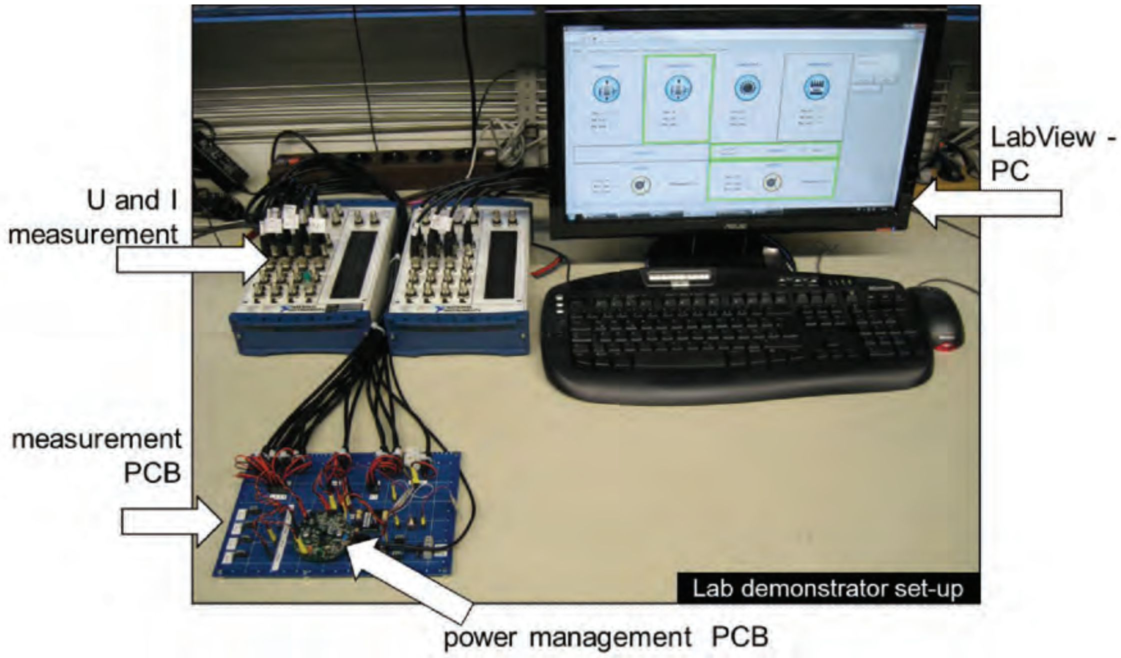

Figure 5: Modular concept demonstrator laboratory set-up.

4.2 Integrated concept demonstrator: autonomous temperature instrument for process automation

Obviously, an integrated solution is preferable in cases where a standard combination of power source and sensor is frequent, such as the case of a temperature transmitter powered by a thermal gradient harvester, which could be employed in most cases where the temperature of a hot process medium is being measured.

Within a research project, a complete autonomous temperature transmitter using a fully integrated EH system was developed [Nen11-2, Ulr11]. Thermoelectric generators have been integrated into the device in such a way that the handling, stability and form factor of the transmitter stays the same while its lifetime and functionality are considerably enhanced. The device also includes a smart energy buffer solution for occasions when the process temperature is insufficient to generate enough energy.

The overall size of the selected temperature transmitter prevented the integration of conventional TEGs, which normally have macroscopic dimensions around 10 to 20 cm^2. Instead novel micro-thermoelectric generators (micro-TEGs), produced with a wafer-based manufacturing process [Nur09], were used .

The major challenge of integrating these devices was ensuring that the stability and robustness of the transmitter was maintained. In most cases, the process is warmer than the ambient air temperature, and so the hot side of the TEGs needs to be coupled to the process with optimal thermal conductivity.

Extensive numerical simulations were carried out to maximize the heat flow through the TEGs (see Figure 6). The other (or cold) side must be cooled, and is therefore coupled to the ambient air with a heat sink. The heat sink needs to be positioned at a sufficient distance to allow for applications where the process pipe is covered with a thick insulation layer.

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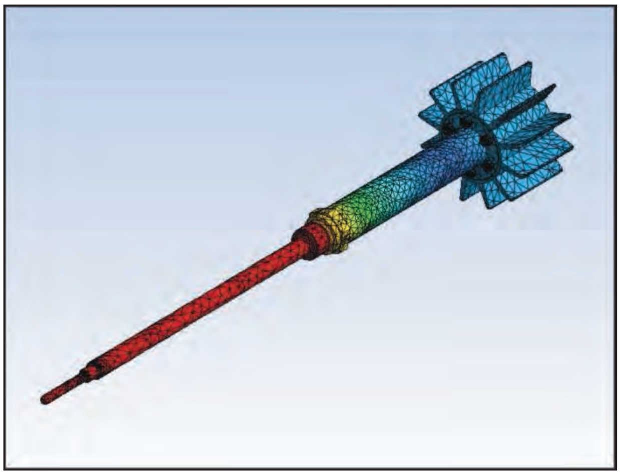

Figure 6: Numerical thermal simulations shows the outer temperature distribution at 80°C process temperature (red) and 25°C ambient temperature (blue).

With a minimum difference of about 30 K between the process and ambient temperatures, the system is able to generate sufficient energy to supply both the measurement and wireless communication electronics. At temperature gradients greater than 30 K, more energy is generated than is needed, which could be used to allow for faster update rates, for example.

Finally, the EH-powered temperature transmitter (see Figure 7) solves a central issue of wireless sensor nodes: The regular exchange of primary cells is no longer necessary, and this in turn can help reduce the total cost of ownership. While an integrated EH concept is not possible for all sensors in every circumstance, it is a viable concep for a wide range of devices.

Figure 7: Fully autonomous temperature transmitter with an integrated energy harvesting concept.

5 Summary and conclusion

This article summarizes our research and development done in the area of energy harvesting for process field instrumentation. Different energy harvesting sources were evaluated and rated with respect to their applicability for industrial process automation. Two different concepts were discussed:

The modular concept has one central and universal power management which allows the modular attachment of several EH sources and the flexible buffering with recheargeable energy storage devices. This can then be used as a generic power supply unit for any kind of wireless sensor node. The individual external energy harvesting unit are attached e.g. with short cables to the power management unit. Hence the system can be adjusted to the application environment of the corresponding device - similar to a building blocks architecture.

With an integrated concept, all necessary components are combined within the device. The advantage for the end-customer is that the system has the same look-and-feel as a regular battery powered device – but with an enhanced functionality since no regular maintenance intervalls are necessary for battery changes. In this concept, a fixed combination of measurement device and EH source is preferable, because this allows a highly optimized power management design with the best overall efficiency.

In conclusion, an EH-powered temperature transmitter was developed with fully integrated thermoelectric generators. In addition a concept demonstrator of a power management platform shows the technical feasibility of the modular concept. Both developments help to further evaluate the potentials of EH technology to enable truly autonomous devices for process automation. Since they may solve one central issue of wireless devices at the moment (battery changes), they may contribute to further establish wireless solutions in industrial field instrumentation in order to better understand and control processes and therefore make them more profitable.

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