Requirements for battery-free embedded systems

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Extended Abstract

1. Introduction

Historic and current development of Europe's information society aims to increase functionality, mobility and of availability of commercial and non-commercial services. [1] In the 1990's one of its major drivers was the evolution of mobile phones, followed by mp3 players, "gameboys" and laptops. These multi-billion dollar markets were technological drivers for the evolution from specialized to multi-function and all-in-one systems.
Another important factor is the trend to ubiquity of embedded systems. Almost everything should get a function anywhere at any time. One common example is the known automatic glass door at the entrance of shopping sites. The development in this technological area emerges from very simple systems to complex integrated services with online payment. In this example our simple glass door has evolved into an automatic entrance door e.g. at the ski lifts of a large and networked skiing site with integrated automatic taxing. And since the information within these systems should be also available everywhere there is the need to network all the single embedded devices wired or wireless.

Furthermore in many new applications the focus has shifted from the platform to the network, named "Network centric environments". And as each single embedded system of this network is part of a continuously adapting ecosystem the complexity of such environments increases a lot.

The most limiting factor for all these current and future developments is: *The available power*.

Starting with simple mobile systems followed by complex networked environments with flexible nodes there is always the need for energy that comes not from the power socket. And since the applications get more complex, should last longer and work more robust the demand for mobile energy increases day by day.

The most common solution to have mobile power is of course the battery. But the battery is one of the most laggard technologies within embedded systems. The evolution of battery technology has not been pushed by industrial development compared to processing power or disc capacity; batteries have just doubled their energy/volume ratio within a 10 year interval, processing power still raised as fast as predicted in Moore's law by factors more. [2]

So batteries have some significant drawbacks [3]:

- Limited capacity:
  Since batteries convert chemical into electric energy, their capacity is limited by the available volume for the chemistry. More and more applications are downsized and should work a long period.
  Also at some time a battery is exhausted and has to be exchanged. This is often not possible because the user has no more access to the system.

- Physical limits:
  Temperature limits and mechanic conditions (e.g. shocks) are a huge problem to batteries. Since their capacity decrease with the temperature, they have to be planned oversized a lot. This increases cost and space consumption.

- Cost/lifetime:
  Modern batteries, e.g. lithium-ion batteries, are quite expensive at a limited lifetime. For many mobile phone users it is common to buy more batteries than mobiles. But there are many applications that need very cheap hardware in a large numbers.

Other solutions for power generation besides batteries can be categorized by energy source:

- Solar, using the light of the sun
- Thermal, using thermal differences in-between e.g. 2 areas
- Mechanical, using e.g. vibrations or bending
- Etc.

or by the environment they are used in:

- Human resources, using human movement, heat, breathe etc.
- Natural resources, using environmental vibrations, heat, etc.
- Machine power harvesting, using mechanical or thermal energy produced by a machine.

The degree of functionality of an embedded system is directly dependent to the amount of available power. And lack of appropriate power is not an easy problem to solve. Therefore there is a significant number of applications that have not been realized due to this problem. Others have design tradeoffs and do not work at their best possibilities.

Within our research we have tested several battery free solutions to be integrated in an alpine ski. The aim was to determine the limits of parasitic power harvesting compared to batteries.

2. Comparison of different power sources for networked embedded systems

This chapter should give a comparison of the currently most featured power generation tools besides batteries:

Piezo Elements:

Piezoelectric elements convert mechanical energy (pressure, vibration) to electric energy. An often used method to make their power usable is to implement a rectification where a capacitor is loaded. Piezo elements are quite cheap and to get in large numbers. Disadvantages are that they are mechanical sensitive and have a poor voltage/current ratio. So for proper usability impedance matching is needed. This technology can be placed in many mechanical stressed components, e.g. shoes. [4], [5]

Thermo elements:

Thermal elements generate electrical energy, when both sides of the element have different temperature levels. Very small thermoelectric converters produce an output power of 10 to 100µW from small temperature gradients of only a few Kelvin. Proper industrial samples are rare, but available. Problem of these devices is the thermal connection and isolation of both sides. This often adds additional manufacturing costs. These devices can be placed anywhere where a large temperature difference is to be expected, e.g. human skin. [6]

Solar cells:

Solar cells converts light directly to electric energy. But direct solar energy supply is high time varying and may not always be sufficient to power the embedded system for the application. Therefore a special solar power management is needed. Solar cells need quite a lot of space compared to the other principles and are mechanical sensitive in many cases. [7]

Inductive Elements:

Electromagnetic methods for power generation make use of the typical induction principle. A mechanic system is designed in a way that with minimal mechanical effort generates a maximum change of the magnetic flow. These systems can be produced quite small, generate a good current to voltage ratio and have a long life-time. Limits are physical limits of the used magnets, e.g. maximum temperature range or shock resistance. [8]

An alpine ski has been prepared to test the different principles in practical environment. Solar cells, Piezo elements, inductive generators have been mounted on a ski and several test drives have been logged by a mobile data logger located inside a backpack of the test driver.

Figure 1: Test driver, with data logger backpack and prepared skis.

Also a small energy management unit (prototype board) has been constructed to fit to the ultra low power and environmental conditions to store the energy inside a capacitor. The voltage level of this capacitor has been monitored in order to measure its energy.

The realization and the results of these measurements are then subject to the full paper.

The following table gives a brief overview of the named power generation methods regarding their relevant properties (total energy earning, voltage and current properties, and the space consumption) and some possible applications for the respective elements:

Energy source	Energy earning under optimal conditions	Space consumption	Voltage versus current	Energy converter available	Application
Piezo element: Disc converter	medium	low	voltage: high, current: low	commercial available	Mechanical stressing: e.g. Sports, moving vehicles, etc..
Piezo element: Bend converter fixed	high	low			
Piezo element: Bend converter free running	high	medium			
Thermo element	low	very low	voltage: low, current: medium	commercial available	Thermal difference needed: e.g. motor or body heat
Solar cell	very high	high	voltage: low current medium	commercial available	Outdoor sites, daylight applications
Electromagnetic method: Induction from movement	high	high	voltage: medium current: high	Prototype developable	Mechanical stressing: e.g. Sports etc.

Table 1: Comparison of the four most important power harvesting principles

3. Applications and their possible contributions to network centric environments

In the last chapter the advantages and disadvantages of several -mostly non commercial available- power sources and their field of usage have been described. As we move our view now from the single embedded system to the complete networked environment several new challenges arise. Future networked environments will more and more integrate parts that are dependent on power harvesting energy sources.

There are several aspects that have to be considered while designing the networked centric environment with integrated power harvesting devices.
At first that there will be systems that run out of power, and subsequently parts of the network communication fails. But redundancy and robustness as countermeasures cost additional power, which could not be available.
Secondly will there always be the problem of uneven energy distribution. As some parts could have plenty of power others are tight to run out of resources. So the network will not run at optimal conditions.
The first aspect can be solved with careful and secure design of the power harvesting device and the application it feeds.
Also the status of the corresponding network nodes must be monitored as their actual condition directly depends on the environment surrounding the embedded system. So we have a direct influence of the “real world” environment into the networked environment, which must be minimized in order to guarantee fail save operation.

The second aspect can be solved with energy aware routing. It can be shown that the network lifetime can be increased up to 40% if you consider the available energy at each node [9]. But in many today’s network centric environments such solutions are not integrated. Someone can monitor the e.g. the network bandwidth or delay, but not the energy/packet value or in many cases even not the available energy at each node. For this basic values new, innovative solutions will be needed.

The following part of this chapter will show some examples of power harvesting for embedded systems. This should give some ideas how parts of new adaptive network centric environments powered by parasitic harvesting can look like.

One of the most known examples is parasitic power harvesting in shoes. The following picture shows a laboratory test system build at the MIT.

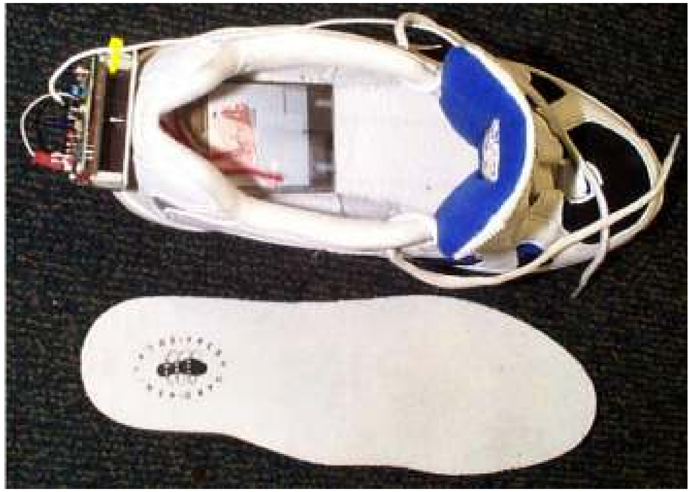

Figure 2: Shoe prepared with a piezoelectric element and electronic on the backside (Source: [10])

This wearable subsystem broadcasts an RFID code, which identifies the carrier within its environment. Within a networked environment this could be a pico-node in order to trace someone's movement. [10]

The following picture shows an alternative power harvesting device for embedded systems underwater. Under the extreme conditions most other principles would fail.

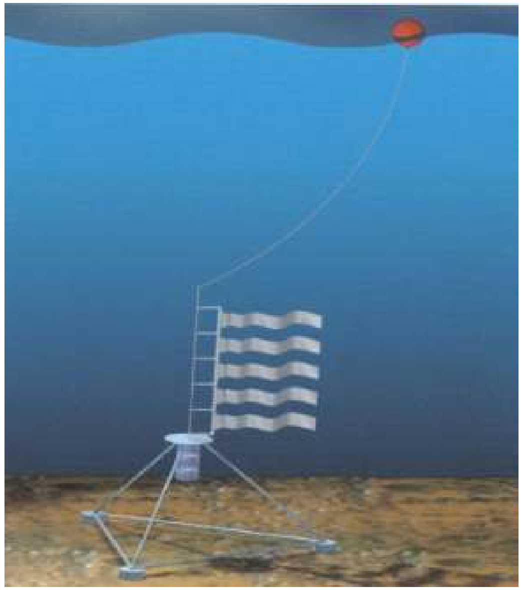

Figure 3: Hydropower harvesting device (Source: [11])

With the help of this device the kinetic energy of the flowing water is converted via piezoelectric devices into electric energy. The turbulent underwater flow bends the piezoelectric polymer material. Power density reached values up to 70W/m². An interesting application would the routing of information from connected underwater sensor node arrays. As an integrative routing part of a networked environment such devices will sooner or later be of good benefit for new applications, e.g. boat or diver detection. [12]

Figure 4: The “Camel Fridge” (photo courtesy Naps Systems)

Camels wearing solar-powered refrigeration units helped deliver vaccines to remote African villages in the 1980s. Today similar systems could be used to move larger networked embedded systems with the help of horses, e.g. to places cars can not reach. [13]

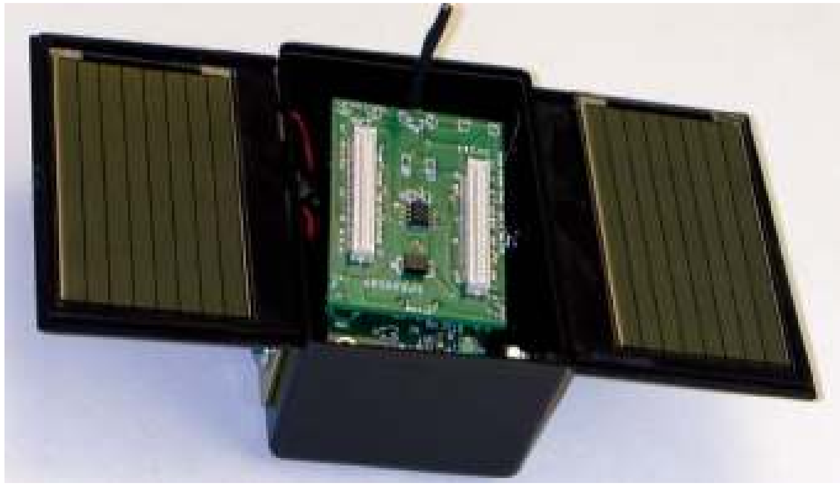

Figure 5: Heliomote, a solar harvesting sensor node (Source: [15])

The heliomote has an intelligent power management. It harvests the power over day, stores it and calculates the average available power. With this value it calculates its maximum sample rate for the integrated sensor. This includes the energy needed for wireless transmission of the measured results. While solar energy seems currently to be the outdoor energy source with the maximum output power, new solutions will catch these applications. [14]

One special application regarding the energy harvesting unit mounted on the skis has been porposed: an integrated partner search service. The functionality is as follows:

The amount of energy inside the ski corresponds to the driving behavior of the driver. This information is exchanged in between several different skis via a wireless protocol. If a driver gets close to another one at the same energy level a green led flashes up indicating that someone is near who has the same driving behavior.

4. Conclusion

In this paper, we presented several methods for parasitic power harvesting as energy generation method for embedded systems. We did show their advantages and disadvantages and some of their possible applications. The effect of this development on network centric environments has been discussed.
One special application -skiing- has been tested in practical environment in order to compare the results of different energy harvesting principles.

What has to be done in future seems also quite clear. New and effective business models for they usage of the new extended range of applications have to be developed. Also new cooperative strategies have to be developed. This has to be implemented into the network environment, especially the network protocols.

5. Sources

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