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Embedded systems with limited power resources

This paper deals with the design approach for embedded systems with limited power resources. The focus is on embedded systems powered purely by energy harvested from the surroundings. Realtime operation and power consumption are critical design aspects of these systems. A number of design problems are discussed and solutions are presented. Selected products are looked at as examples of successful implementation of the solutions.

Attila Strba, Research & Development, EnOcean GmbH

1. INTRODUCTION

Significant advances in microelectronics technology made the increasing miniaturization of embedded systems possible. This trend to miniaturization began in the late 1960s and, as stated by Moore's Law [3] that the power of microprocessors doubles about every 18 months, has held true with astonishing accuracy and consistency until the beginning of the 21st century. An announcement like that by IBM concerning the use of 29.9 nm technology to print circuits [7] indicates that this trend will continue for a number of chip generations.

The trend is leading to and will result in the development of tiny embedded systems, integrated into more and more everyday objects. And will create a world of smart devices surrounding us. For example, parents will no longer lose track of their children, even in the busiest crowds, when location sensors and communication modules are sewn into their clothes. Similar devices attached to timetables and signposts could guide blind or foreign people in unknown environments by *talking* to them [6].

Another interesting possibility offered by such technology would be the creation of intelligent homes where a refrigerator can detect old food, a washing machine can query the instructions for dirty clothes, or window and door handles indicate whether they are open or closed. This concept called ambient intelligence, where humans have computing and networking technology embedded in their surroundings, was developed by the ISTAG advisory group [4], [5], [6].

While this vision may sound utopian when you first hear about it, current technology is already at a stage where it is possible to realize it. Ambient intelligence requires that there be thousands of tiny embedded devices in the environment. Each of these devices require some source of power for it to function. While power can be sent to them through cables or batteries, neither of these possibilities offers an effective and longterm solution. The large number of these devices makes it highly desirable that they be fully self-sustaining and service-free. This can be achieved by harvesting energy from the environment.

Energy harvesting is a way of using the omnipresent sources of energy in our surroundings, like from moving objects, vibrating machine parts, temperature changes, electromagnetic waves such as light, radio or infrared [8], [9]. The idea is not new, but successful and low-cost realization in embedded systems calls for the right expertise. A specific design approach is needed for embedded systems fulfilling the concept of ambient intelligence.

2. EMBEDDED SYSTEM DESIGN WITH LIMITED POWER RESOURCES

Each system design has to begin with a specification. Focusing on devices for an ambient intelligence application, we will look at the design problems of embedded systems expected to satisfy the following requirements:

- self-sustaining and service-free
- energy harvesting from the environment
- seamless wireless communication interface
- interaction with realtime events
- unobtrusive hardware

The first step to take when designing an embedded system is to build its architecture. An architecture model of an embedded system with limited power resources is shown in Figure 1. To understand the design problems of such systems, you must first understand their functional concept.

The energy harvested from the environment – which can be a single pulse or a continuous flow from a solar cell, thermoelectric or electrodynamic energy converter – is temporarily stored and then used to power a microcontroller for a short period of about several milliseconds. During this time the controller receives data from associated sensors and transmits the data wirelessly together with an identification code. After transmission the circuit turns off completely and can be started again when energy is available. Or if there is a continuous flow of energy (for example from a solar cell or thermo energy converter) the circuit enters a sleep mode with low energy consumption [8].

There are three critical design constraints with such systems:

- energy management
- computing resources
- price aspect

All these parameters are tied together and for a successful design they must be properly balanced. Changing one of them could influence another. They are looked at below and possible solutions are pointed out.

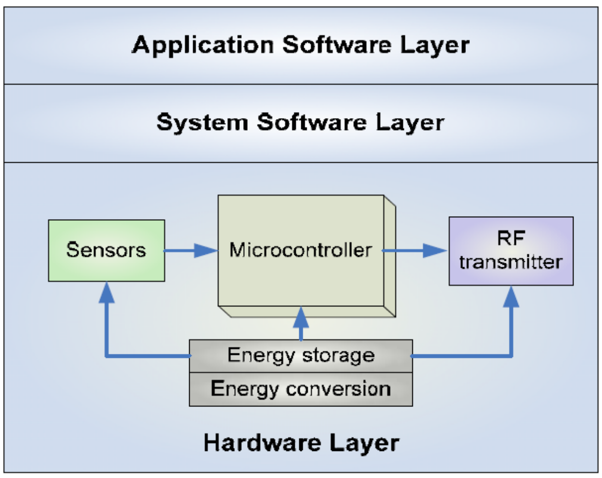

Figure 1 Architecture model of embedded system with limited power resources

2.1 Energy management

Once the requirements and architecture of the power limited system are defined, the next important part of the design process is to determine how much energy is available. This can be done through an energy budget analysis that determines energy availability and consumption during the period of time. It is essential to validate energy budget calculations with simulations, although building up a simulation model of the system is not a trivial task. There are several software tools available on the market that can help here, for example *Matlab Simulink* or *P-Spice*. All following system design steps must be based on the energy budget calculations.
Energy converters deliver a certain amount of energy in the form of voltage and current that is stored in capacitors. From the time delivery aspect you can characterize energy converters as follows:

- converters delivering energy periodically
- converters delivering short energy bursts

The first group of converters can power a system seamlessly and continuously by storing the energy when available for a longer time. In such a scenario the time for completing the tasks does not play a critical role. Examples of converters belonging to this group are solar panels, thermo converter based on a Peltier element, windmills and dynamos. The concept of efficient energy management in such systems is to switch on the circuit for as short a time and as infrequently as the application allows, and for the rest of the time the circuit should idle with very low power consumption.

With the second group of energy converters the time aspect is critical. An example of such a converter is a piezo or an electrodynamical element. The greatest energy savings in such systems can be achieved by starting a system and completing the required processing tasks within the shortest possible time.

An important requirement for a successful design is to minimize the power consumption factors. Based on the embedded system architecture shown in Figure 1, the following are domains where you can apply power saving strategies. It is important to understand that most of the optimization factors spoken of here can interact, and wrong combination can cancel the energy saving benefit.

2.1.1 Microcontroller power saving strategies

Supply voltage
In the case of a microcontroller, power consumption is proportional to the square of the supply voltage. So the lower the supply voltage of the microcontroller, the better are the power perspectives [10]. There are three types of power consumption relevant to microcontrollers and digital circuits: Internal power, switching power and leakage. Internal power and switching power are referred to as dynamic power and leakage as static power [18]. When choosing the microcontroller for a system it is important to consider these values.

Startup time
The startup time of a microcontroller also plays also a very important role. It is usually influenced by oscillator delay. Mechanical resonant devices such as crystals and ceramic resonators can take several milliseconds to stabilize. RC oscillators, by contrast, provide fast startup but generally suffer from poor accuracy over temperature and supply voltage [19]. To save time it is advisable to use a microcontroller that can start with an RC oscillator and subsequently switch to a crystal oscillator.

Power features

Microcontrollers offer several power saving features like adjustable clock frequency, voltage scaling, different sleep modes. Many embedded processors now include features such as run-time power modes that are used to scale power consumption:

- Static power management: this approach does not depend on CPU activity. An example of this style is user-activated power-down modes.
- Dynamic power management: this approach is based on CPU activity. An example of this approach is disabling functional units.

It is important to consider how much energy saving can be achieved by which features in the designed system.

Software power saving strategies

One of the ways to reduce system power consumption by software is with energy-efficient source code transformation. There are several high-level software optimization techniques of performance such as loop unrolling, procedure in-lining [20]. Better software performance reduces execution time, therefore energy is saved.

Another way of saving energy is to use operating systems that support energy-constrained RT scheduling [10] or dynamic power management (DPM) [21]. DPM strategies are strategies that attempt to make power-mode-related decisions based on information available at runtime.

Besides sophisticated software methods, much energy can be saved by sticking to few simple rules:

- More CPU activity means more power.
- The software should put the microcontroller to sleep when waiting for an event.
- One thing to consider when waking a CPU is the oscillator startup time.
- There are also power down costs. Power down costs include factors such as the time to enter and exit the mode and the energy consumed by doing this.
- Avoiding flash, EEPROM and other memory writes.
- Simplicity of software means efficiency, resulting in energy saving.

2.1.2 RF transmission power saving strategies

Most energy in an embedded system defined by the architecture shown in Figure 1 is consumed by radio communication. It is caused by the power consumption of each RF block like LNA, down-converter, synthesizer, etc. This leads to the conclusion that power limited embedded systems should use RF transmitters with a minimal number of active components. Another important fact of minimizing power drained by the RF block is to minimize the time the transmitter is turned on [22].

Saving energy during RF transmission is also possible by using an energy optimized transmission protocol with small data overhead and strategies such as not transmitting empty data (e.g. leading zeros). An important consideration during energy optimized RF design is the transmission rate and modulation type.

2.2 Computing resources

Embedded systems with limited power resources have limited functionality time given by the circumstance that all tasks must be executed during the time period while energy is available. Therefore the correctness of the computations depends not only on the logical correctness of a computation but also on the time in which the result is produced. Based on this fact all embedded systems with limited power resources are considered to be realtime.

To ensure that all required tasks are completed in time, there must be enough computing resources available. This requirement could be fulfilled by using a powerful microcontroller. On the other hand the more powerful and complex the microcontroller, the more energy is required for its functionality. What makes the design of the system even more difficult is that the time period during which enough operational energy is available varies. This is caused by the fact that the amount of energy delivered by the energy converter is not constant. It is important to calculate with the worst case time period when the least energy is available in the system.

To determine what computing resources are needed for correct functionality of the system, it must be classified from the perspective of the application. According to the timeline aspect you can classify realtime embedded systems in the following way [23], [24]:

- Hard: a late response is incorrect and implies a system failure. An example of such a system is medical equipment monitoring vital functions of a human body, where a late response would be considered a failure.

- Soft: timelines requirements are defined by using an average response time. If a single computation is late, it is not usually significant, although repeated late computation can result in system failures.

- Weakly hard: this is a combination of both hard and soft timelines requirements. A weakly hard system is one in which few late responses will not lead to a total failure, but missing more than a few may lead to complete and catastrophic failure. For example, if a smoke detector after detecting smoke starts the alarm few seconds later or earlier it is not functionally critical. But delaying the alarm by several minutes can lead to serious damage.

The second classification criteria is to determine whether the system is fail-safe or fail-operational. For example, if a temperature sensor powered by a thermo converter skips several measurement data caused by lack of energy, it is not critical. In the case of the smoke detector powered by a solar cell, such a situation is not allowed to happen.

Another important design step is to list and analyze each task that the system must perform during its function. The typical tasks of the system based on the architecture shown in Figure 1 are:

- self-test (memory, program check)
- power management (sleep mode/wake-up timing, available energy measurements)
- data processing (data acquisition from sensors and evaluation, radio protocol preparation, CRC calculation, encryption)
- data transmission (transmission timing, listen before talk, repetitive transmission, frequency hopping to assure failure safe transmission)

2.3 Price aspect

The total cost of ownership for embedded systems powered by ambient energy must compete with battery powered solutions or even with wired solutions. Ambient energy powered systems become economically feasible if the cost of the devices together with energy converters will be comparable to battery costs – for similar performance of the whole system. In this case service-free systems will ensure wide acceptance [8].

Energy source	Mechanical energy	Mechanical energy	Thermal energy	Light energy
Conversion device	Piezoelectric element	Electrodynamic element	Thermocouples	Photovoltaic solar cell
Dimensions of energy converting element	20x6x1 mm	33x22x10 mm	5x5x2 mm	10x20x2 mm
Energy input	e.g. button push 3 mm x 5 N	e.g. button push 2 mm x 5 N	Temp. difference of 5 K	Light 400 lux
Energy output	200 µWs per operation – efficiency 1%	230 µWs per operation – efficiency 60%	20 µW permanently	20 µW permanently

Table 1 Energy converters overview from the price and delivered energy aspect

The price of the energy converters is not the limiting factor. Currently electrodynamic converters and solar cells are already products in mass production, for an acceptable price. For an overview of the amount of energy a list of energy converters and their amount of delivered energy is shown in Table 1. The only possible way to achieve low-cost embedded systems is to reduce the number of components the system is composed of and to set the aim to a high level of integration [22].

3. APPLICATION EXAMPLE

Over the past decades several experiments tried to make the vision of ambient intelligence an everyday reality. Several projects and prototypes were realized but there is still a lack of such embedded systems on the market. Today, thanks to a few breakthrough companies, ambient intelligence is gradually becoming a reality. What follows is a successful implementation of an embedded system with limited power resources that is already available on the market.

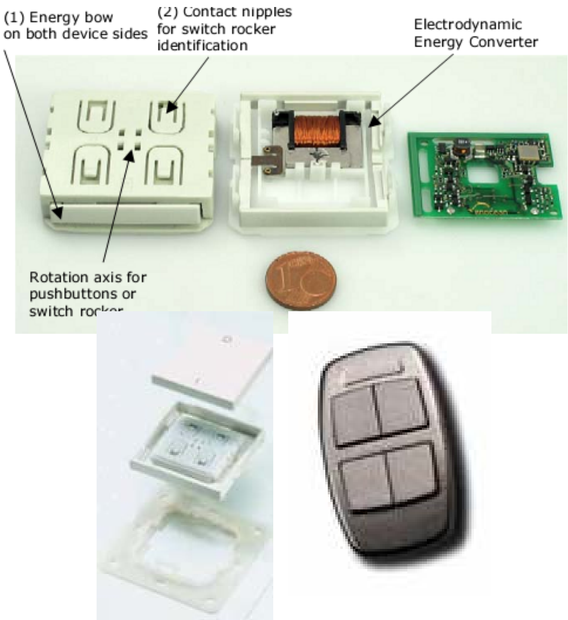

Figure 2 Electrodynamically powered radio transmitter device; the top picture shows the module construction, and in the bottom pictures two applications implemented with this module are illustrated

The product shown in Figure 2 is a transmitter device called PTM 200 from the company EnOcean that enables the implementation of wireless remote controls without batteries. Power is provided by a built-in electrodynamic energy converter. When the energy bow is pushed down, electrical energy is created that powers up a microcontroller and the RF transmitter. The microcontroller reads the status of the contact nipples and after that a radio telegram is transmitted to the air at 868 MHz in Europe or at 315 MHz in North America. The transmission range is approximately 300 meters in a free field. Key applications of this device are wall-mounted flat rocker switches as well as handheld remote controls [25].

4. CONCLUSION

There are a large number of design requirements with power limited embedded systems, making the design process a complicated procedure. The most efficient way to handle all the design problems is to develop an integrated system on chip solution in the form of an ASIC. At present there is an ongoing ASIC development that should offer an effective cost optimized solution to most of the design problems mentioned in this paper.

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