Designing Reliable Transient Applications

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ABSTRACT

State-of-the-art wireless sensor systems are typically performance-constrained, battery-based devices which can, at most, reach self-sustainability using energy harvesting and aggressive duty-cycling. In certain scenarios, however, the energy availability is such that no large scale storage device is necessary to fulfill application requirements. Transient systems, which operate in an energy proportional way, are good candidates for such applications because they can reduce both the transducer area and storage device required for functional correctness, thus minimizing the systems cost and form factor. Designing transient systems which guarantee optimal program progress and electrical efficiency requires novel hardware-software design technique to address specific challenges. By using an Energy Management Unit (EMU), designers can abstract away transducer specifics and still guarantee maximum power transfer between the source/EMU and EMU/load.

KEYWORDS

Energy Harvesting, Transient Systems, Wireless Sensor Networks.

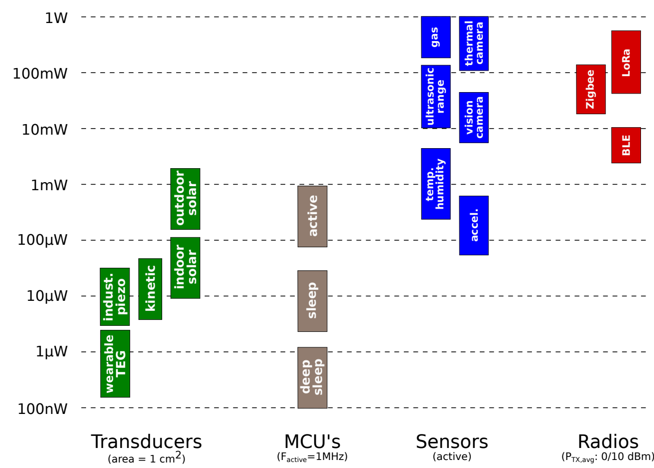

Figure 1: Power density ranges for common transducers, sensors, microcontrollers and transceivers.

1 INTRODUCTION

The advances in ultra-low power design over the past decades have significantly extended the lifetime of battery-powered devices. However, the billions of devices in the emerging Internet of Things (IoT) will demand for deploy-and-forget installations with virtually unlimited lifetimes. Battery-based designs can conceivably have long lifetimes, but they can be very expensive, bulky, energetically inefficient, and significantly hinder large scale deployments. Energy harvesting, though a mature technology, has only been successfully deployed in large scale systems where size is not a limiting factor. In many scenarios, such as wearable systems, a source's physical dimensions are just as important as the power levels [1, 8].

Transiently powered systems operate efficiently in adverse harvesting conditions, requiring only limited storage capacity and input power to reliably execute power-hungry applications. The recently-proposed Energy Management Unit (EMU) [3] allows a transient system to operate in an energy-proportional manner. As opposed to traditional duty-cycling, an EMU-based system is energy driven, meaning that as the available energy increases, so does application's execution rate. This would allow devices to operate reliably and efficiently in the wide input power range found in typical wearable sources: solar panels, thermo-electrical generators (TEG's) and piezo-electric.

Different energy sources can have widely ranging power levels depending on the environmental conditions, but they are almost always below the levels required for sensing and transmitting information, as shown in Fig. 1. Even when a transducer is large enough to directly power a load in the correct voltage and current range, there is no guarantee that it will harvest at its maximum power point [10]. If the load adjusts its operating point to extract the maximum power from the load, it will most likely not be the load's optimal operating point, which depends only on the application and the peripherals it uses, not the environmental conditions. EMU-based designs leverage decoupling to guarantee that the maximum power is harvested and the minimum power is consumed, simultaneously.

Vision sensors, which acquire and process images, are typically power-hungry devices which require substantial computational resources. For this reason it was not until recently that it became feasible to have batteryless vision sensors in a wearable form factor, thanks to new paradigms in energy harvesting systems [4, 9]. In this work we describe the design and implementation of an energy-opportunistic, wearable vision sensor node capable of executing computationally intensive tasks with temporal dependencies [5]. In particular, we consider the example of a solar-powered vision sensors for wearable applications. These transient sensor nodes have the property of guaranteed information and energy availability, since darkness does not provide neither energy nor information and light provides both.

2 EMU-BASED APPLICATION DESIGN

Transient systems must be able to tolerate highly volatile sources and still guarantee program progress. In order for these systems to operate reliably and efficiently, they have to accumulate harvested energy until enough is available for the execution of one single atomic task, also called a burst. Afterwards, the system should be shut down completely until enough energy is accumulated for the next burst execution. The time interval between two bursts depends on the instantaneous input power. This type of operation directly leads to three challenges for the design of transiently powered systems:

- Constraint (1) **Minimum Energy Guarantee** The energy harvester cannot directly power the system. To guarantee the execution of atomic tasks, the storage device should provide this *minimum energy availability*.
- Constraint (2) **Temporal Independence** There is no control over the length of the time interval between two bursts, since this only depends on the currently available input power. The application needs therefore to be split into *separate bursts with no temporal dependencies*.
- Constraint (3) **Non-Volatility** Between two bursts, the system is shut down and peripherals are powered off. Therefore, if an application cycle requires several bursts *non-volatile memory* (NVM) technologies to retain the system's state between bursts. Even if an application cycle fits in a single burst, logging data requires NVM.

Fig. 2 shows the prototype mounted in a user's glasses. The device performs three main tasks: *Image Acquisition*, *Processing* and *Storage*. To overcome *Constraint (1)*, the application-specific requirements must be used to determine the EMU's energy burst size. Since motion estimation algorithms require at least two successive images to detect pixel displacements, each burst needs to guarantee at least the energy required to acquire two pictures, thus satisfying *Constraint(2)*. The *Storage* tasks copies the estimated velocity to an external FRAM memory for logging. Thus, the simplest solution to *Constraint (3)* is to group the entire application in a single burst. Based on experimental characterizations, it was determined that the entire applications cycle consumes around 1.3 mJ, requiring only a 150 uF capacitance for the transient system to work. The prototype was then connected to a 42 cm^2 flexible solar panel, and exposed to varying light levels. The system's energy efficiency as well as the resulting execution rate can be seen in Fig. 3. The energy efficiency is defined as the ratio between the energy consumed by the application to the harvested energy.

3 CONCLUSION AND FUTURE WORK

In this work, we have argued that batteryless systems can offer all the necessary guarantees to build reliable sensor applications, even with high-power peripherals. As opposed to battery-based

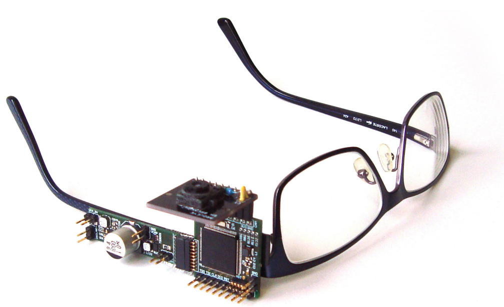

Figure 2: Wearable transient vision node [5].

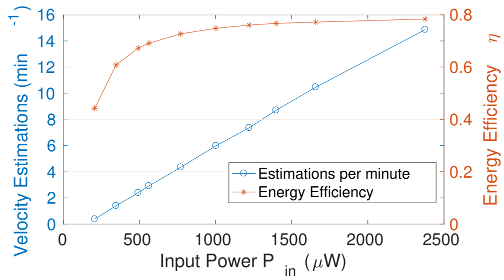

Figure 3: Measured energy efficiency and execution rate as a function of the input power [5].

devices, these systems are energy-driven and thanks to their energy-proportionality, they can operate efficiently even in very variable and adverse harvesting conditions.

Thanks to EMU-based design, we have designed an application that can reliably and efficiently acquire and process images to estimate the user's walking speed in a wide variety of harvesting scenarios. Our proposed vision sensor has an average active power consumption of 6.85 mW, but requires only 100's of μW's to begin estimating the velocity. Furthermore, it can reach up to 5.8 velocity estimations per second, and has a motion estimation error of 1.4 % of the distance traveled.

The concept of the EMU-based design is a promising approach to build reliable IoT applications with minimized energy storage and harvesting requirements. While the EMU has bridged the gap between small, volatile energy sources and power-hungry sensor nodes, there are many possibilities for improvement. In particular, cpu-based tasks have more flexibility during execution, since they can be arbitrarily paused and resumed. This approach is orthogonal to the EMU and has been explored in different works, such as [2, 6, 7] and can be used to reduce the energy required for processing.

Acknowledgements

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