

# From Sensors to Miniature Networked *SensorButtons*

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**Abstract**—Wearable computing aims to empower people by providing intelligence embedded within garments. It relies on sensors placed at different locations of the body. To foster user-acceptance sensors should be small, light, and unobtrusive. In this paper we present a wearable platform that addresses those challenges: a miniature networked *SensorButton* with the form factor of a button, so that it can be integrated in garments in an unobtrusive way. It has several sensors used in wearable computing, on-board processing power, a wireless link for sensor networking or communication with a base station, and it focuses on low power consumption. We describe its use to recognize user activity and highlight the need for further research in power-aware algorithms for wearable computing.

## I. INTRODUCTION

Wearable computing aims to empower people by providing intelligence in an intuitive way and at appropriate moments. The applications are wide-ranging, from context-based information delivery, proactive health care or health care monitoring, up to personalized sports trainer. In order to foster user-acceptance, wearable systems should thus be small, light, and unobtrusive [1].

One approach to create unobtrusive wearable systems is to integrate them within garment. For example a computer may be integrated within a belt [2]. We believe that to increase user acceptance of wearable systems, they should look and function like normal pieces of clothing. They should have long operational time to minimize maintenance work, be light (and therefore have batteries of limited capacity), and they should rely on wireless communication for sensor networking or communication with a base station. This allows distributed processing and the fusion of data from several sensors placed on the body, as well as it improves ease of use.

In this article we describe a miniature wearable platform that addresses those challenges: a networked *SensorButton*. As the name implies, its shape is similar to a button and it is designed to be integrated (sewed) in garments. It offers sensors useful for wearable computing (accelerometers, light sensor, microphone) in a compact form factor, a micro-controller, and a wireless link for communication with other sensors or a base station. Figure 1 illustrates this concept by showing the *SensorButton* next to regular buttons.

The *SensorButton* is used to study algorithms and software architectures for context recognition (i.e. recognizing user state and activities); this includes studies of feature sets and classifier algorithms suited for on-line recognition. We focus

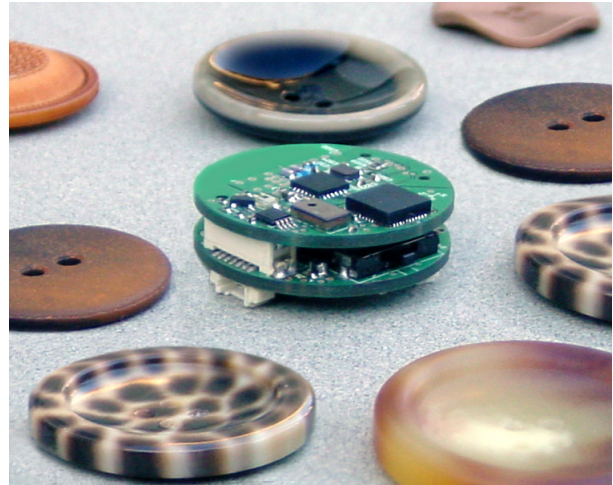


Fig. 1. The *SensorButton*: a wearable platform that has the size of conventional button on clothing (in the center: 31 mm diameter, 11 mm thick).

on algorithms minimizing energy use, and power-aware algorithms that make trade-offs between algorithm performance (e.g. percentage of correct user action classifications) and energy use depending on application needs.

Data from many *SensorButtons* at various locations may be fused using the wireless link. This platform may be used to study how computations can be distributed over devices with limited processing power. It also allows to study dynamic sensor network self-organization where the system dynamically reorganizes when devices are added (e.g. to improve user activity classification) or removed (e.g. when sensors fail).

The *SensorButton* described here is an evolution of previous prototypes that did not yet have the “button functionality” [3], [4]. This article is the first to report in detail the hardware characteristics of the button-shaped platform.

In section II we describe the hardware of the *SensorButton*. In section III we describe applications and algorithms that are implemented on the platform. In section IV we discuss the *SensorButton* in comparison to other miniature wearable systems and highlight future challenges. We conclude this paper in section V.

## II. SENSORBUTTON HARDWARE

The architecture of the *SensorButton* is illustrated in figure 2. A 16-bit low-power micro-controller (MSP430F1611 from

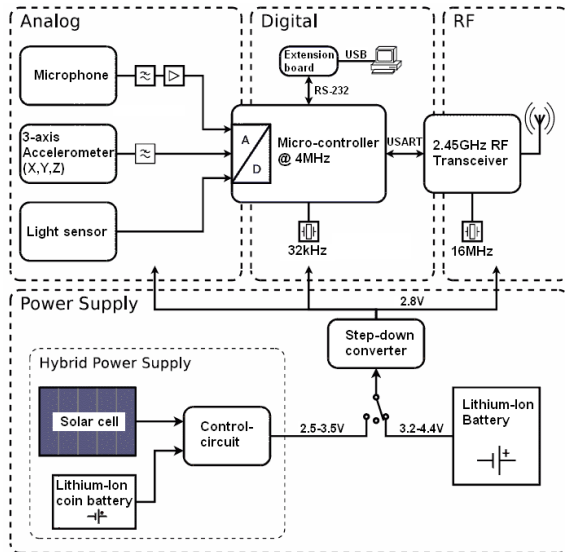


Fig. 2. The architecture of the *SensorButton* centers on a MSP micro-controller that reads and processes sensor data and communicates with other devices (or a desktop computer) over a wireless link or serial link. Analog sensors include a microphone, a 3-axis accelerometer and a light sensor. A 2.4 GHz transceiver is used for wireless communication. Power is provided by a lithium-ion battery or by a hybrid power-supply (bottom-left) where a solar cell combined with a miniature battery powers the device.

Texas Instruments) running at 4 MHz is in charge of data collection and processing (e.g. classification, compression). It includes a hardware multiplier (e.g. for efficient multiply-accumulate operations typical of digital signal processing applications) and a 12-bit ADC converter with 8-input channels used to acquire analog sensor data. The micro-controller can communicate with other *SensorButtons* or with a base station (e.g. a desktop computer), either with the wireless link or over a serial line. Programming is done via a JTAG interface.

The included sensors are: a 3-axis accelerometer (LIS3L03AQ, ST Microelectronics); a MEMS microphone (SPO1013, Knowles Acoustics); and a light sensor (SFH3410, OSRAM). All the sensors are filtered using a second order Butterworth filter and are connected to one of the analog inputs of the ADC converter of the micro-controller.

A 2.4GHz shock burst transceiver (nRF2401E, Nordic Semiconductors) with a compact patch antenna is used for wireless data transmission with others devices or a desktop computer.

The *SensorButton* is powered by a lithium-ion battery (130mAh, 3.7V, LPP402025, Varta) via a step-down converter or a linear regulator. To reduce power consumption, the power of the three sensors can be individually toggled by the micro-controller via an analog switch.

The *SensorButton* is composed of two stacked PCBs with overall diameter of 31 mm and 11 mm thickness. Weight is 12 g. Figure 1 shows the assembled *SensorButton*. The micro-controller, the battery and serial I/O line are located on the bottom PCB. The sensors and RF link are located on the top PCB. The stacked approach offers modularity since the sensors or the wireless communication device may be changed by

simply redesigning the top PCB. The connectors used to stack the boards provide a stable mechanical connection between the two boards.

### III. APPLICATIONS, ALGORITHMS AND POWER

In order to provide advanced levels of interactivity or deliver information proactively, wearable devices rely extensively on the detection of the state of the user or of the actions he performs. This process is called context recognition. Context is recognized by interpreting the information coming from sensors placed at different locations of the body. Table I lists sensors that may be used in wearable systems and the information which they may reveal about the user.

The *SensorButton* has accelerometers, a microphone and a light sensor that are useful for context-recognition. Accelerometers are commonly used for physical activity recognition such as the detection of walking patterns (e.g. walking, standing, sitting) [5], [6], [7] or of daily life human activities [8]. Ambient sounds picked up by a microphone may indicate the location of the user (different locations may have different ambient sounds) or whether he is speaking, etc. Combining data from accelerometers with a microphone may also improve the accuracy of activity recognition [9]. Light sensors may be used to detect sunshine, lamps or activities such as putting a hand inside a pocket (light occlusion).

Sensors	Observation
Accelerometers	Motion patterns of the body and limbs
Microphone	
Visible light sensor	Localization of light sources
Rotation	Body movements
Compass	Orientation of the body and the head
Pressure	Vertical motion in elevator or staircase
IR light sensor	Sunshine, localization of lamps
UV light sensor	Localization of fluorescent light tubes
Skin temperature	Health state (e.g. fever)
Environment temperature	Outdoor, indoor
Humidity	Physical activity
Strain, stress	User's breathing
Electrical potentials	Electrocardiogram (physical activity)

TABLE I

APPLICATIONS OF VARIOUS SENSORS. THE FIRST THREE SENSORS ARE AVAILABLE ON THE *SensorButton*.

The *SensorButton* placed on the wrist recognized from ambient sounds 5 activities in a wood workshop (e.g. sawing, drilling, hammering), or the use of household appliances (coffee grinder, coffee maker, hot water nozzle, microwave and watertap) [10]. In another scenario, information from acceleration and light sensors were combined to detect typical office activities [4]<sup>1</sup>.

Table II indicates the algorithms implemented on the *SensorButton* and used in these applications. Our results show that with the appropriate algorithms and optimizations, even a low-speed micro-controller can perform complex recognition tasks.

<sup>1</sup>These scenarios used an early version of the hardware with a square layout; the algorithms are however compatible with the current platform.

Category	Algorithms
Features	mean, max, min, variance zero-crossing rate, fluctuation of amplitude bandwidth, frequency centroid fluctuation of amplitude spectra
Classifiers	spectral rolloff frequency, band energy ratio naive Bayes (gaussian distribution) decision tree
Others	sorting algorithm (Bubble sort), FFT hill-climbing algorithm, matrix multiplication

TABLE II

ALGORITHMS IMPLEMENTED ON THE *SensorButton* FOR FEATURE EXTRACTION, CLASSIFICATION AND OTHER SUPPORT FUNCTIONS.

Furthermore the *SensorButton* offers battery life in excess of one day for continuous operation on these scenarios: the household appliance scenario that relies only on sound uses 10 mW and achieves an operation time of 48 hours. When the accelerometers and the microphone are used the power is 12.6 mW and the operation time is 38 hours; If the device is only doing periodic user activity recognition and spends the rest of the time in low-power “sleep” mode, the battery life of the system consequently increases (figure 3).

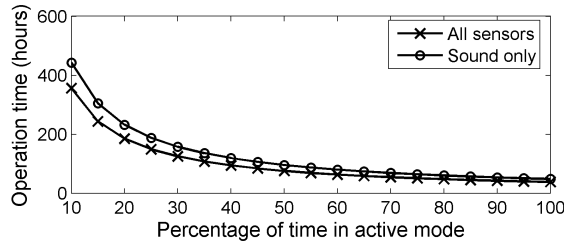


Fig. 3. Operation time of the *SensorButton* (with a 130mAh lithium-ion battery) for activity recognition in function of the percentage of time the *SensorButton* is actively recognizing user activity (the rest of the time the device is in sleep mode). Two scenarios are considered: one with only microphone (household appliance) and another with all the sensors used. With continuous activity recognition (100%) the operation time is of 48 and 38 hours for the two scenarios respectively. Operation time increases when the device spends more time in sleep mode.

To illustrate the processing capabilities of the micro-controller we implemented a 32-bit FFT optimized for real valued input. Figure 4 indicates when continuous sampling and processing of the observation window is possible by showing the maximum percentage of overlap allowed between successive observation windows for a given window length and sampling frequency  $f_s$ . An overlap value close to 100% means that for every new incoming sample the FFT can be computed. An overlap of  $-100\%$  means that only every second frame can be processed. Although continuous FFT computation may not be possible for high values of  $f_s$ , frame based recognition with non-overlapping segments is nevertheless possible [10].

An alternate hybrid power-supply (miniature battery and solar cell) was developed with an algorithm tracking the maximum output power harvested from the solar cell by controlling the duty cycle of the processor (and hence the load of the solar cell). The output power available in a well-lit

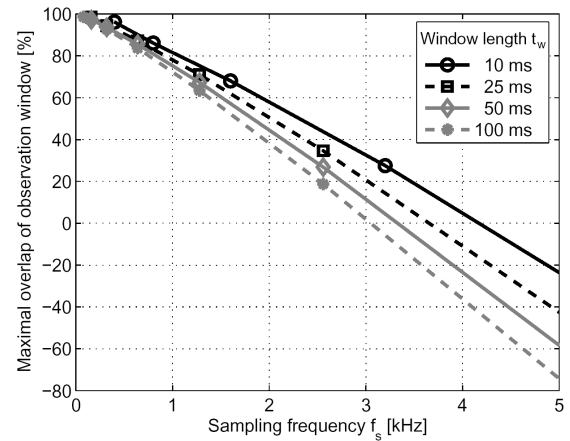


Fig. 4. Processing capability of micro-controller indicated in terms of percentage of window overlap that allows to continuously sample the input signal at a given frequency and compute a 32-bit FFT optimized for real valued inputs. An overlap value of close to 100% means that for every new incoming sample an FFT can be calculated. Overlap of  $-100\%$  means the FFT can be computed only every second frame.

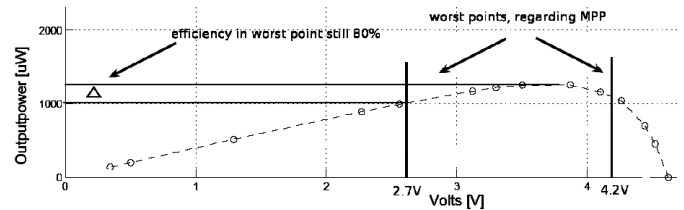


Fig. 5. The maximum power point tracking algorithm controls the load of the solar cell by varying the duty cycle of the processor. A difference of output power of about 20% may be gained by using the maximum power point tracking algorithm compared to the output power at the extremes of the voltage operating range of the system.

home or office is sufficient to power the system in low-power mode from a solar cell. When classification is performed the extra power is provided by the battery. Without power tracking, the energy efficiency is of about 80% at the extremes of the operating voltage of the system. By tracking the maximum power point, this efficiency may be improved (see figure 5) by varying the rate of user activity classification.

#### IV. DISCUSSION

Many research groups have built wearable platforms that contain one or more sensors. However, they do not emphasize on on-line activity recognition algorithms and we argue that they do not integrate within garments as well as simple “buttons” would. Examples include the Smart-It [11], Smart Badge [12], Ubisensor [13] or the TEA Device [14]. Custom hardware and improved technology process were investigated in SmartDust [15] and egrains [16] without major emphasis on algorithms for context recognition or intelligent sensing. Human++ seeks to reduce size and power consumption in inexpensive sensors in order to detect physiological parameters for medical monitoring [17]. However, this system mainly operates as a data logger and analysis is done off-line. Processor

choice for wireless sensor networks was explored in [18]. The *SensorButton* stems from our previous research on empirical study of design choices for multi-sensor context recognition systems. In particular the architectural trade-offs affecting e.g. flexibility, energy use, relative recognition performance were investigated in order to develop the platform as well as to compare it to others [19].

The strong points of the *SensorButton* are that it can be integrated in clothing. It is a versatile systems with a modular architecture that is fitted with sensors useful for wearable computing. Complete control over the system allows to optimize power at every level (hardware, data acquisition, algorithms). Furthermore its novelty lies in the on-line context-recognition algorithms implemented in the platform. The size of the *SensorButton* is however still larger than buttons commonly used in clothing and further miniaturization is needed. The limited processing power also requires optimized and power-aware algorithms in order to achieve context recognition while optimizing the battery life. Algorithms currently used in wearable systems generally seek to achieve maximum performance regardless of the energetic cost. However depending on the applications, an “optimal” performance or a guaranteed minimal performance may be sufficient. Algorithms balancing performance and energy were investigated in the context of the *SensorButton* platform [10], [3] and elsewhere [20]. This however remains an important topic of research.

In the future energy efficient multi-point wireless communication protocols will be investigated, such as the ANT protocol [21], instead of the current point-to-point communication.

## V. CONCLUSION

We showed a low-power, wearable and wirelessly networked sensor platform (a *SensorButton*) that may be used in wearable computing for context recognition. This platform has a button form factor so that it can be integrated in garments in an unobtrusive way. The size (diameter of 31mm, 11mm thickness) and weight (12g) of the system is suitable for wearable applications.

We showed that this micro-controller based system can recognize complex activities (in a wood workshop and in a household appliance scenario) continuously for more than one day on a single battery charge. In contrast to algorithms running on a desktop computer, the battery life of a wearable device is critical. Therefore we stress the importance of *power-aware* algorithms that balance the energy requirements with the precision or quality of the answer they provide. The *SensorButton* platform also allows to investigate distributed processing algorithms in sensor networks or dynamic sensor networks self-organization when devices are added to or removed from the network (e.g. in case of failure).

The characteristics of the *SensorButton* are interesting to address the growing challenges of health care related applications or ambient-assisted living, where long operation time, unobtrusiveness and near zero maintenance are critical factors. Specific sensors for health care related applications (e.g. body temperature sensor, electrocardiogram) may be easily

added to the *SensorButton* thanks to its modular architecture. The algorithms and methods investigated in the *SensorButton* (classification algorithms, feature sets, etc.) are also directly applicable to a distributed sensor network.

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