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An Autonomous Multi-Sensor Wearable Device with Human Body Harvesting

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Abstract: *Wearable technology is gaining popularity, with people wearing everything "smart" from clothing to glasses and watches. Present-day wearables are typically battery-powered, and their limited lifetime has become the most critical issue. Most devices need recharging every few days or even hours, falling short of the expectations for a truly satisfactory user experience. This work presents the design, implementation and in-field evaluation of a novel sensor-rich smart bracelet powered by energy harvesting optimized to be deployed on human body. The wearable device is equipped with an ultra-low power camera and a microphone, in addition to accelerometer and temperature sensor, which enable low power context recognition classification directly on board. Due to the low power design and aggressive power-aware policies co-design it can achieve self-sustainability using solar cells with only modest indoor light levels and thermoelectric generators (TEG's) with small temperature gradients from the body heat even performing the context recognition. Our experiments in real-world scenarios show an average of up to 550µW for photovoltaic in indoor and 98 µW for TEG with only 3 degrees temperature gradient and up to 250 µW for 5 degrees gradient.*

I. INTRODUCTION

Technology advancements in integrated circuits, wireless communications, and sensing allow the design and fabrication of lightweight, ultra-low power intelligent monitoring devices with such a small form factor that they can be worn and completely "forgotten about" by users. A fast growing class of such devices is "smart wearables", where electronics are tightly coupled with the human body [1]. In general, wearable devices – from bracelets that monitor physical activity and sleeping patterns, to clothes with built-in sensors , or to smart glasses – may mark the next big technology wave, following the transition from personal computers to smartphones and tablets [2]-[6]. . Wearable technology has gained popularity over the last few years, with people wearing everything from clothing that lights up when users receive phone calls (e.g. Bluetooth-enabled dresses) to smart glasses (e.g. Google Glass) and smart watches (e.g. Pebble, Apple Watch, Microsoft Band) [2]. Most of the leading high-tech consumer companies have either already launched wearable products, or are in the process of creating prototypes in an effort to fuel the next wave of exponential growth in the consumer market. These ubiquitous devices, also known as wireless sensors devices have been recognised as a fundamental enabling technology for a large variety of cyber-physical system applications including environmental monitoring, healthcare, security, industrial domains and, of course, the Internet of Things [8]. Wearable technology is also very important in healthcare, where electronic smart devices can continuously monitor the patients' vital signs and enable doctors to identify possible diseases earlier, helping to provide optimal treatment [9]-[11].

The major challenge which affects this vision is the autonomy of the wearable devices is the energy source. Even the latest generation of smart watches needs to periodically recharge the batteries (i.e. once a day or a few days), forcing the user to stop wearing it and thus interrupting the normal usage of the device. Lifetime extension is aggressively pursued though low power design and the development of new battery technologies. However, the ultimate goal of unbounded lifetime (wear and forget) can be achieved only if the wearable device can harvest enough energy from its environment to sustain its operation, thereby achieving energy neutrality.

Power management and harvesting energy from the environment to power equipment has been explored in numerous application scenarios[12]-[15]. Energy harvesting in a wearable context is a challenging scenario because of strict form factor constraints and usability concerns. However, steady progress is being made in this area. Traditional "time keeping only" watches can be fully harvesting powered and several mature products are available on the market. However, smart watches, sleep-tracking wristbands, smart glasses and smart badges all have one thing in common: they need much more power because of their much richer sensing capabilities and functions.

Harvesting energy to power these small, always-on devices represents an exciting challenge, which needs particular design attention. Environmental energy sources vary significantly over time and power management needs to implement methods that can opportunistically take advantage of periods of overabundant energy, and survive intervals when the system is starving for energy[7].

In this work we investigate how the most advanced HW and SW low-power design in combination with power management and energy harvesting technologies can be pushed further to enable a perpetual and endlessly wearable sensor-rich device. We integrate advanced ultra-low power and stateretentive shutdown devices with aggressive power management and high-efficiency environmental energy conversion into a single wearable system, to shape a complete new class of smart watches which outpaces the state of the art in energy autonomy. In particular, we show how to achieve a self-sustainable smart watch which allows users to really forget about recharging batteries.

The smart watch is equipped with a complete suite of useful sensors including a microphone, an accelerometer, a temperature sensor and even a camera sensor while still managing to keep the power budget within the sustainability envelope. Visual feedback is provided by an e-paper display which behaves as zero-energy image retention display.

Connectivity is always a critical feature for power consumption. Usually, when a device does not have much power, it may only be able to send a packet once every couple of seconds or only when the energy on-board is sufficient. In our case, we prefer to use NFC communication exploiting the energy transmitted from external readers. This allow us to synchronize and exchange data on user's demand with no energy expenditure on the bracelet

The contribution of this paper is twofold: i) characterization of the ultra-low power components and energy harvesting in wearable scenario, which enables the self-sustainability of our smart watch and ii) performance evaluation for several application scenarios of the self-sustainable smart watch.

The remainder of this paper is organized as follows: Section II details the proposed approach, discussing the proposed wearable system architectures. Section III describes the implemented approach, along with measurements. Section IV concludes the paper.

II. WEARBALE DEVICE ARCHITECTURE

The system consists of wearable embedded device similar to a watch able to acquire, process and transmit the sensor data via NFC radio[12]. A block diagram of hardware is shown in Fig. 1. The system, also hosts energy harvesters: solar panels and thermoelectric generator (TEG) modules deployed on a wrist band achieve perpetual operation using only indoor light and body heat. The sensors included are: a 3-axis accelerometer, an analog microphone, an analog 112×112 pixels camera, and a temperature sensor. The communication subsystem is based on a NFC radio to transmit/receive data. The developed device worn on the user's wrist and periodically and opportunistically acquires information from the sensors according to the available energy. The device is holistically designed to be ultra-low power and without any needs to replace or manually recharge the batteries. Thus, the design allows extreme power management to keep the quiescent and operative energy consumption low. The architecture is stand alone with each subsystem implemented on one board to facilitate wearability. Only the camera is left out of the main board to have a more flexible field of view choice depending of the final packaging and the application (e.g. face vs. lateral mounting). Due to the low power consumption, the device could survive for up to 5 years with only 100mAh battery in sleep mode and several months with aggressing duty cycling of the sensors. In this work, to achieve a perpetual lifetime and wake-up capabilities, it is equipped with a combined solar and thermal harvester unit to recharge the battery.

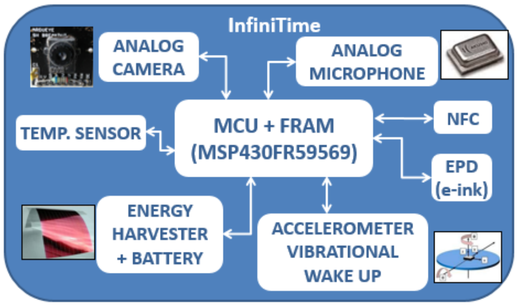


Fig. 1. *InfiniTime* prototype's block diagram

The hardware architecture is divided into five distinct subsystems:

- A microcontroller subsystem built around a Texas Instruments MSP430FR5969, which includes 64kB of non-volatile FRAM.
- A multi-sensor subsystem where a nano-power accelerometer, a temperature sensor and an analog microphone are hosted on board and the conditioning circuitry to have analog and digital signals, including an analog camera which can be connected on the main board through a connector.
- A communication module consisting of a NFC/RFID tag IC transceiver.
- An energy harvester subsystem, solar and thermal, is present directly on board and can recharge both Li-Ion battery and supercapacitors, according to the application specification.

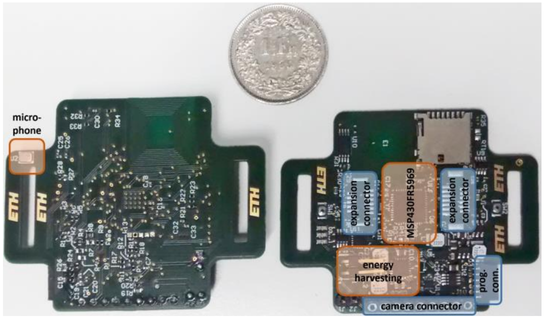


Fig. 2. The developed core board with microcontroller, sensors, peripherals connectors (top view on left) and energy harvester (bottom view on right).

III. ENERGY HARVESTING SUBSYSTEM

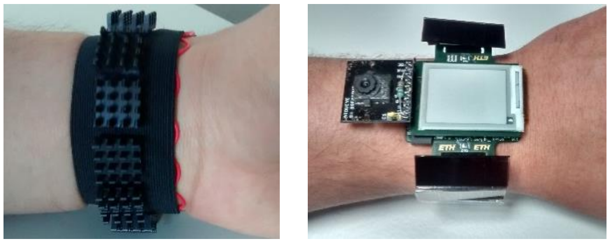
The design includes both a solar and a thermal harvester subsystem to exploit the combination for the two sources. Both are used to supply a single battery, thus it is important to manage them to do not waste important power when one of the two sources are not harvesting.

Solar Energy. The solar energy harvesting subsystem is based on the bq25570 ultra-low power IC from Texas Instruments. It exploits a high efficiency boost converter to harvest energy from sub-milliwatt low-voltage sources such as thermoelectric generators or small solar cells under indoor lighting and it can recharge all battery chemistries or supercapacitors. In addition, the bq25507 features maximum power point tracking (MPPT) capabilities and configurable protection of the storage from over-voltage and under-voltage events. Moreover, it integrates an ultra-low power buck converter with programmable output voltage and a set of control pins to indicate battery health and to enable/disable the buck converter or, depending on the application, the whole chip. The bq25570 consumes less than 500nA in active mode and about 5nA when it is switched off. The power source of the InfiniTime is the wrist strap, which embeds 8 small amorphous silicon solar cells, AM-1417CA from Sanyo Energy, connected in parallel. The bq25570 always adapts itself to work at the maximum power point (configured at 80% of the open-circuit voltage) providing a maximum power of of 550µW @ 2.1V under office light conditions (500lx) and a maximum current of 4.42mW @ 2.5V under sunlight (5000lx). The adopted storage element is a 40mAh – 3.7V lithium-polymer (LiPo) rechargeable battery.

Thermal Energy. The thermal energy harvesting subsystem is built around the LTC3108 from Linear Technology. This DC-DC converter can start conversion from only 20mV and boosts the voltage using a fly back converter with a 1:100 transformer at the input and was optimized to work with input between 20mV and 150mV. Because our TEGs should be wearable around the wrist, we are severely constrained in size. The Quick-Cool QC-32-0.6-1.2 has a size of only 8×10mm and a thickness of 2.6mm, allowing to fit them on the bottom of the wrist together with a heat sink of 14×14mm and a height of 6 mm glued on top of each of them. We found that using 7 TEGs in series was a good compromise, requiring a temperature difference of only 1.75K to obtain the required startup voltage for the step-up converter and being still wearable. The arrangement of the energy harvesters and the electronics is illustrated in **Errore. L'origine riferimento non è stata trovata.**.

IV. EXPERIMENTAL RESULTS

The smart watch has been, designed and developed (Fig. 3) to carry out experimental evaluation of directly in field in terms of power consumption, energy harvester by solar and thermal sources, power management and functionalities has been performed. Firstly, measurements of power consumption in the device and the subsystems components in different states are presented. Evaluation of the intake energy in the challenging indoor life-time of the network is investigated for different application scenarios are presented. Data acquisition and processing of the accelerometer sensor, microphone sensors and video sensor to show the flexibility and of the proposed device are presented.



Bottom view with TEGs **Top view with camera**

Fig. 3. InfiniTime prototype with thermal and solar energy harvesting.

Table I shows the current consumption in different states with 3V supply. The power consumption of a system depends on the state of its components as it is possible to verify. The quiescent current of the wearable device is only 925nA, which is ten thousand times lower than the power consumption when is acquiring an image. This is the lower quiescent current which can be obtained if the microcontroller in deep sleep (LPM4.5) all the peripherals are off and the accelerometer is in wake up mode. This is an important characteristic when performing extreme duty cycling to achieve a self-sustainable system as the device can be placed in ultra deep sleep mode to save energy (i.e. in the night when data acquisition may be not needed). The average time needed to perform the algorithm tasks is shown in Table II.

Table I InfiniTime Current Characteristics

Device Mode	**Consumption**		
	States	***Subsystems (active)***	***Current (µA)***
Ultra sleep Mode (Night)	MCU Wake on interrupts. All in sleep.	Acc. wake up mode.	1.225
Idle Mode	MCU Active + Sensors off, NFC off, EPD Off.	MCU, Acc wake up mode.	859
HW-based Image Acquisition	MCU acquisition and processing data by camera via ADC, NFC,EPD and Microphone off.	MCU LPM3, DMA, PWM, Camera.	1259
SW-based Image Acquisition	MCU acquisition and processing data by camera via ADC, NFC,EPD and Microphone off.	MCU Active, Camera.	1587
Accelerometer Acquisition	MCU digital acquisition, Camera,Microphone, NFC and EPD off.	Acc. Acquisition mode, MCU.	890
Microphone Acquisition	MCU acquisition and processing data by microphone via ADC, NFC and Camera off.	Microphone, MCU, ADC.	1211
Data Sending preparation	MCU transferring the data by I^2C	MCU, NFC.	950
Data Sending	NFC Sending data to a remote host. All subsystems can be off	Only NFC with RF power	0.442 (sleep mode)

Table II Timing and Energy Consumption

	Measured Data	
Task	**Time [s]**	**Energy [mJ]**
SW-based Image Acquisition	0,468	2,229 per image
HW-based Image Acquisition	0,047	0,177 per image
Accelerometer	60	1,60
Microphone	5	18,16
Display Update	1,192	15,298
Data Sending preparation	8,324	2,85

The device incorporates an energy harvesting unit and 8 solar panels and 7 TEG modules which have been assembled in the hardware prototype for laboratory testing and deployed on a student's wrist. After checking the smooth functionality of each sub-circuit, we carried out several tests to evaluate the real performance of the designed circuit when worn on the wrist band, to determine the effective energy available and the efficiency of the energy conversion subsystem. For the solar harvester we measured both voltage and current delivered by the energy sources the storage during four consecutive days from 10:30 AM to 6 PM. Thus, in these measurements only indoor harvested energy was evaluated. For the solar harvester the maximum power with office light (500 lx) has been measured as 502µW with around 91.2% efficiency of the conversion circuit.

Table III shows the experimental measurement of the thermally harvested energy using the setup presented in previous section for different temperature gradient across the TEG modules. The first column lists the range of the gradient across the TEG modules. This gradient is much lower that the difference between the body and the ambient temperature in our wearable setup, because of high thermal resistances between human body and TEG as well as the ambient air and TEG. This means that if there are 20 degrees Celsius of ambient temperature and the body is at 36 degrees Celsius on the two surfaces of the TEG we have only 2 K gradient.

The range of the power harvested is in the same range of the power consumed that self-suistanability can be achieved with different application scenarios [12].

Table III Measured TEG max. and harvested power for different temperature gradients relative to the body

ΔT [K]	P_m [µW]	TEG Voltage [mV]	$P_{H.}$ [µW]	*TEG EH eff. [%]*
(0.0,0.5]	14.49	0.0-15.1	0	0
(0.5,1.0]	72.45	8.9-18.3	0	0
(1.0,1.5]	188.37	16.4-23.4	0	0
(1.5,2.0]	362.25	20.3-25.7	0.274	0.08
(2.0,2.5]	594.08	24.4-28.8	3.048	0.51
(2.5,3.0]	883.88	27.1-31.9	16.743	1.89
(3.0,3.5]	1231.63	30.1-36.2	37.500	3.04
(3.5,4.0]	1637.35	36.2-41.4	89.289	5.45
(4.0,4.5]	2101.02	37.5-45.9	183.219	8.72
(4.5,5.0]	2622.66	43.4-52.1	253.674	9.67

V. CONCLUSIONS

We implemented a prototype of smart watch which caon acquire multi sensor data and process them directly on board and achieve self-sustainability. The smartwatch hosts an ultra-low power gray-scale camera, a MEMS microphone, a 3-axes accelerometer, and an analog temperature sensor. Moreover, the device is equipped with a solar harvester and rechargeable Li-Ion battery to continuously recharge the battery even in indoor scenario.

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