SHelmet: An Intelligent Self-sustaining Multi Sensors Smart Helmet for Bikers

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Abstract. This paper presents the design of a wearable system to transform a helmet into a smart, multi-sensor connected helmet (SHelmet) to improve motorcycle safety. Low power design and self-sustainability are the key for the usability of our helmet, to avoid frequent battery recharges and dangerous power losses. Hidden in the helmet structure, the designed system is equipped with a dense sensor network including accelerometer, temperature, light, and alcohol gas level, in addition, a Bluetooth low energy module interfaces the device with an on-vehicle IR camera, and eventually the user's smart phone. To keep the driver focused, the user interface consists of a small non-invasive display combined with a speech recognition system. System architecture is optimized for aggressive power management, featuring an ultra-low power wake-up radio, and fine-grained software-controlled shutdown of all sensing, communication and computing subsystems. Finally, a multi-source energy harvesting module (solar and kinetic) performs high-efficiency power recovery, improving battery management and achieving self-sustainability. SHelmet supports rich context awareness applications; breath alcohol control; real time vehicle data; sleep and fall detection; data display. Experimental results show that is possible achieve self-sustainability and demonstrate functionality of the developed node.

Keywords: Wearable device · Sensors network · Energy harvesting · Power management

1 Introduction

According to the European Commission, in 2014 almost 25,700 road fatalities were reported in Europe, most of them involved motorcycles [1]. During recent years, road safety work throughout the European Union led to a considerable decreasing trend for road accidents. In fact, considering the 2010–2014 window, the annual number of road deaths decreased by 18% [1]. This means 5700 fewer deaths in 2014 than in 2010. However, there is still major room for improvement. In Europe, distraction (27.38%), and speeding (16.34%), combined with driving while intoxicated (14.6%), are the most important causes of death. For this reason, many efforts have been dedicated to help reduce these sources of danger.

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Technology advancements in integrated circuits, smart sensors and communication, allow the fabrication and integration of small form factor, light and ultra-low power sensing "smart" devices that they can be worn and completely "forgotten about" by users. Wearables, where the whole system it tightly coupled with the human body [1] are examples of these devices rapidly gaining in popularity. Many of them, 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 well known as Internet of Things (IoT) [2–6]. Smart wireless sensors, have been recognised as a fundamental enabling technology for wide range of applications including automotive, healthcare, industrial and security [8]. With the same technologies today is it possible to design wearable devices that target the improvement of safety for drivers (i.e. integrated in helmets of glasses for bikers or other vehicles' drivers).

Sensing technologies are successfully used in biomedical and sports applications [3–7]. In fact, terms as multi sensors, sensors fusion, smart sensing, intelligent device, among others are very popular in the academic and industrial research [8]. Although wearable devices are very popular today, there is a big challenge that limits the success of these devices. This is the limited autonomy of the batteries that require too frequent recharges (every few hours or one day). Lifetime extension is aggressively pursued though low power design, the development of new battery technologies and other technologies [9–11].

Among others, harvesting energy technology achieved the right maturity to be exploited in several application scenarios to overcome the limited energy issue of batteries [12–16]. However, energy harvesting in a wearable context is still a very challenging scenario because of form factor constraints and usability concerns [17, 18]. Harvesting energy to power these small, always-on devices represents an exciting challenge, which needs particular design attention in the whole system and the combination of hardware and software.

In this paper we present SHelmet, a multi-sensor, intelligent, self-sustaining wearable helmet to increase the safety of motorcycle drivers. Every component of our SHelmet is designed to avoid fatalities and injuries on the road but also to increase awareness related to the driving experience. We analyzed the most common sources of road accidents to develop a wearable system aimed at reducing risks on the road [1]. Figure 1 shows the most common causes of road accidents and the solutions using sensors or other electronics implemented in our design to reduce the related risks.

As our smart helmet has been conceived to be worn as a normal helmet, it is designed as a self-sustainable system which the driver can always rely on, without the need for recharging. Due to the dual source (solar-kinetic) energy harvesting module, the user will be always supported by the SHelmet on the street. To achieve this goal, energy harvesting is supported also by aggressive hardware and software low power techniques to reduce the overall system power consumption. These features include a dynamic switch on the unused peripherals and wake-up radio technology embedded in the design, to increase the wireless communication energy efficiency. For example, when the helmet leaves the vehicle's area, it is forced into a deep sleep mode waiting for a radio signal from the on-board module.

Cause	Solution
Defect in vehicle	ECU data, Infrared camera, Buzzer feedback
Distractions (cellular, inputs to system)	GUI on helmet, speech recognition, bluetooth
Overspeeding	Accelerometer, Buzzer feedback
Driving under alcohol effect	Alcohol Gas Detection, Buzzer feedback
Drowsy driving	Eye Blink Detection, Buzzer feedback
Reduced visibility	Infrared Camera, Display
Lack of roadside assistance	Falls detection, auto-call via Bluetooth

Fig. 1. Causes of accidents and solution in SHelmet.

Recent literature on helmets using sensors and data processing is available especially targeting safety for workers [19–21]. In [19] the authors designed a helmet to monitor the air quality and to trigger the users in dangerous situation. In [20] other researcher developed a helmet to support mine-workers during their work while in [21] a helmet is equipped with a wireless interface (ZigBee) to enable voice communication between different workers. In [22] the authors present a helmet that continuously monitors brain and cardiac activity. This last system is designed as a helmet, however is not meant to be supplied by batteries but more as a data logger of the human parameters.

The above-presented works are all based on embedded electronics and sensors. They demonstrate the potential of use a smart helmet to give a feedback to the users and monitor human activities. In contrast with these works, in our smart helmet we focus on low power design and self-sustainability of the smart helmet in the motorbike safety application scenario. On the same application, a few examples of smart helmet were presented in literature. In [23] the authors designed a system with a camera to avoid collision. This work uses video processing to perform the classification of dangerous situations. Experimental results are based on a real helmet worn on the head. Finally in [24] the authors designed a system with GPS and ZigBee communication to geolocalize the drivers. Both works are presenting interesting implementation and in-field testing of the system, but they are not targeting low power design, multi sensing with novel sensors, Bluetooth low energy communication and especially self-sustainability as in our works.

2 System Overview

Figure 2 shows the overall architecture of the developed system that consists of two separate modules designed and developed (one for the Bike and one for the Helmet). The two modules host a microcontroller (MCU) to process sensors' data and take actions, and a Bluetooth Low Energy (BTLE) interface allows communication.

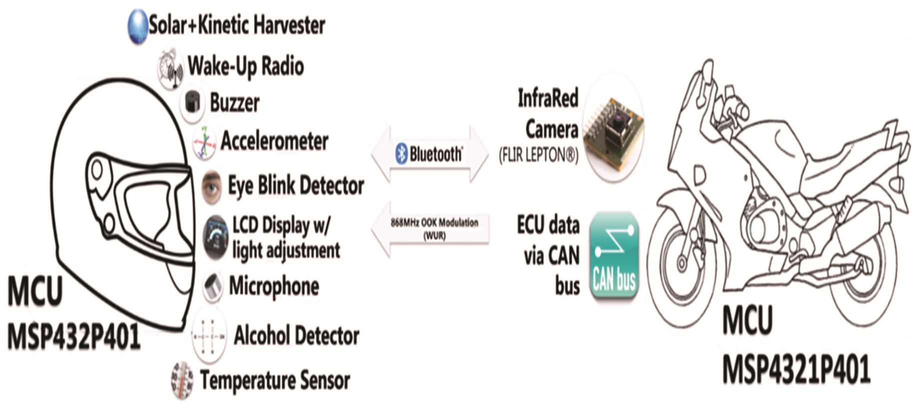

Fig. 2. System overview of the proposed solution. The system comprises of two separated wireless sensor node. The first node on the left is thought to be place into the helmet and it includes several sensors, and LCD display and a buzzer. The second node on the rights is placed on the motorbike including an infrared camera and the CAN communication. Both nodes are designed around the MSP432 microcontroller and CC2564 Bluetooth low energy module.

The microcontroller selected for both the modules is the ***MSP432P401RIPZ*** from Texas Instruments (TI). This choice has been made because the system needs both the computational performance to process on-board the data, and a low power profile to be self-sustainable. In fact, with 14-bit internal ADC, eight serial ports interface with 57 DMIPS and only 4.6 mA of power consumption were the perfect combination to achieve the goal of self-sustainability and to manage all the sensors and the embedded external peripherals (Bluetooth, LCD, etc.). For space reason only the module implemented in the smart helmet is presented and evaluated in this work in the following sections.

3 Helmet Wireless Sensor Node

Figure 3 shows the block diagram of the developed node that is mounted on the helmet. This node manages the sensor's acquisition and processing, as well as the user interface, which can be both graphical, using a LCD display and audio using a buzzer feedback and microphone. As one of main goal of the design is to have a device that does not need to recharge its batteries continuously, the node includes a dual source (solar and kinetic) energy harvesting circuit that provides continuous energy to supply the system and recharge the LiPo battery that is used as an energy buffer.

In terms of functionality the main aim of the developed node is to transform a standard motorbike helmet in a "smart helmet" to assist the driver in augmenting the probability of undertaking safe behaviour. To achieve this goal, we embedded a series of sensors (Figs. 1 and 2) to detect dangerous situations and a MCU to process the sensor data to alert the driver quickly. In the following subsections we present the sensors and the power supply subsystem that includes the dual source energy harvesting.

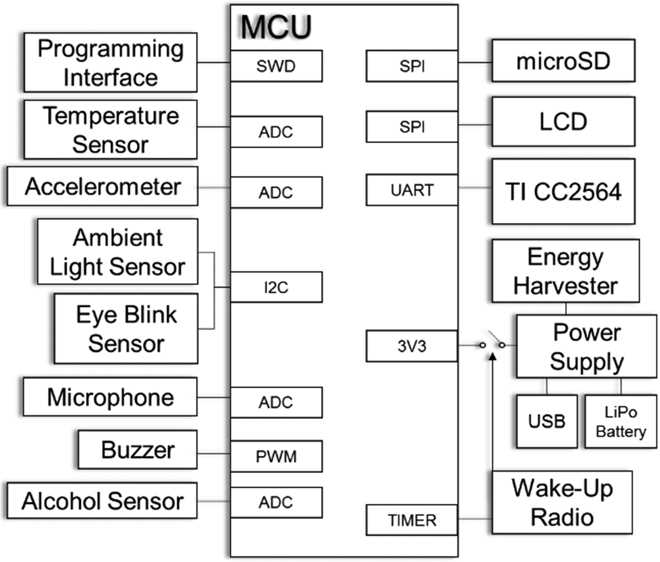

Fig. 3. Block diagram of the wireless sensor node developed to be place into the helmet. The node includes a rich set of sensors to increase the security of the driver, a Bluetooth wireless interface, an audio feedback and a power supply with battery that can be recharged by sola a kinetic energy harvesting. Finally, a wake up radio is used to reduce significantly the power consumption in sleep mode.

3.1 Accelerometer

The ***Kionix KXTC9-2050*** is a high-performance, tri-axis accelerometer with analog outputs, a factory-programmable low-pass filter and g-range from ±1.5 g to ±6 g. The sensor is directly connected with the MSP432 microcontroller through three channels of the Analog Digital Converter. This sensor provides very useful information on motion g-forces as well as fall detection, and the small packaging (3 × 3 × 0.9 mm 10-pin LGA) eases the tricky PCB layout needed for the board to fit in the helmet. Furthermore, it has low current consumption (5 μA in standby, 240 μA at full power) which is very important in terms of power management. With regards to safety, the system will wait for a user confirmation and, if that is not received, it will call ICE contacts with the phone connected via Bluetooth.

3.2 Ambient Light Sensor

The TI's ***OPT3001*** is a digital ambient light sensor (ALS) that measures the intensity of light as visible by the human eye. Its digital output is reported over an I^2C serial interface; in addition, its low power consumption and low power-supply voltage capability enhance the device's self-sustainability. The main function of this sensor is to provide information about light levels in order to modify the system behaviour. For example, the LCD backlight is continuously adjusted by PWM depending on light measurements; thereby, useful power is saved and the user is not disturbed.

3.3 Temperature Sensor

The ***MCP9700A*** is an analog temperature sensor connected via MSP430 ADC channel. It is a low-cost, low-power sensor with an accuracy of ±2 °C from 0 °C to +70 °C while consuming 6 µA (typical) of operating current. This sensor was selected for low-power consumption and the fact that it does not require an additional conditioning circuit. This sensor is useful to detect dangerous situation linked to the temperature (too hot, too cold) but also to have accurate sensor date from other sensors that have output function of the temperature (i.e. alcohol sensor).

3.4 Alcohol Detection System

In order to detect alcohol traces in the driver's breath, SHelmet includes the ***MQ-3 Gas Sensor***. This device has high sensitivity to alcohol and small sensitivity to benzene, which is not to underestimate in automotive applications. Moreover, it has a very simple drive circuit. Figure 6 shows the *MQ-3* drive circuit: a 5 V line supplies both the heating and the sensing resistance of the sensor, the latter changes its value depending on alcohol gas levels in air and determines the voltage drop on a load resistance. In the SHelmet, the MQ-3 is designed to be sampled using the 2.5 V MCU ADC internal reference both a 5 V supply line and an output de-amplification circuit were required.

Figure 4 shows the conditioning circuit for the MQ-3, including TI's ***LM2622 Step-up DC/DC Converter*** which generates the 5 V line from the 3.3 V and a TI's ***OPA344 Low Power Operational Amplifier*** used to reduce the output voltage swing from 0–5 V to 0–2 V. OPA344 (same of BOOSTXL-EDUMKII) was selected mainly for its low power consumption, compact package, and very low offset voltage. The MQ-3 acquisitions require 20 s of pre-heating time, this is necessary for the output to be stable. Then the signal rises or falls depending on alcohol concentration in air.

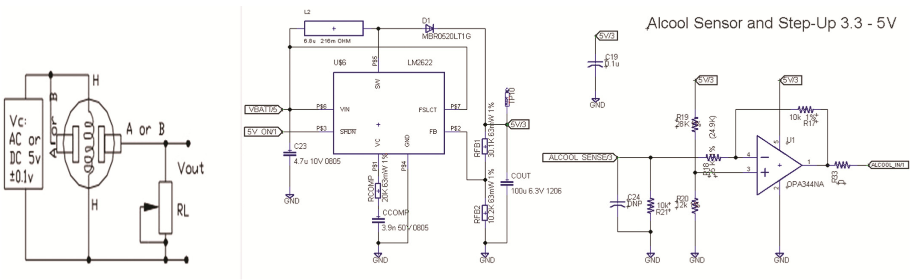

Fig. 4. Alcool sensor (left) and conditioning circuits schematics (right)

Figure 5 shows voltage trends for pre-heating (a), breath with alcohol (b) and breath with no alcohol (c). The voltage drops in (b) and (c) scenarios is due to the fact that the more you blow the more the heating resistance cools, causing its resistivity to rise. When the MCU detects a dangerous situation, an alert is sent to the motorbike module that prevents ignition of the motorbike.

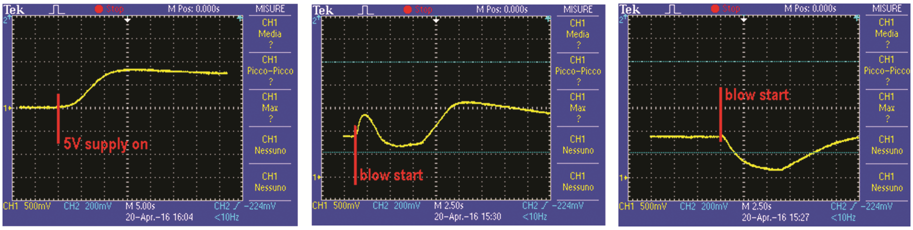

Fig. 5. MQ-3 voltage trends, in order, (a), (b) and (c)

3.5 Eye-Blink Detection

This feature has been included to avoid drowsy driving, by sending an alert to the driver when the eye is closed for too long. To enable the SHelmet with this capability, we used the **VL6180X Proximity Sensor**. This component is based on patented Flight Sense™ technology allowing absolute distance to be measured independent of target reflectance. Moreover, combining an IR emitter, a range sensor and an ambient light sensor in a three-in-one ready-to-use reflowable package, the VL6180X is easy to use as a one-dimension gesture detector. This is a digital sensor connected through I^2C directly to the MSP432. The pupil and the eyelid have different reflectance. Combining the ambient light sensor with a threshold in distance (time domain) and in amplitude (signal and noise), an algorithm that detects eye swipes is easily implemented. Figure 6 describes an eye pulse that can be processed to extract information about gesture detection (input commands to system) and driver alertness.

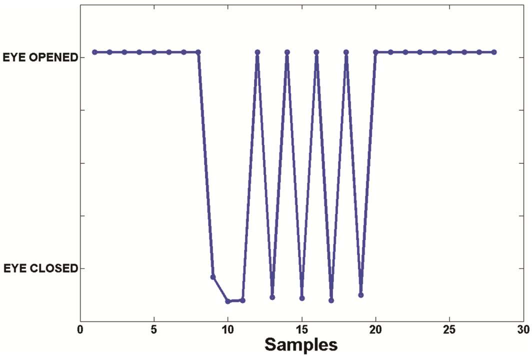

Fig. 6. Eye blink sampling

3.6 Energy Harvesting and Power Subsystem

The energy harvesting subsystem has been designed to achieve a self-sustainable system that can be fully embedded in a motorcycle helmet. This subsystem includes both a solar (or as further option thermal) and a kinetic path to exploit the combination for the two energy harvesting sources, and the recharging and power stags. The energy sources are used to recharge a single lithium-polymer (LiPo) battery that supplies the node as presented in Fig. 7. The adopted storage element is a 2000 mAh – 3.7 V LiPo re-chargeable battery. For supporting the energy harvesters, when for example the helmet is not worn for very long periods, to recharge this battery, a highly integrated Li-ion and Li-Pol linear charger device targeted at space-limited portable applications was included. The devices operate from either a USB port or AC adapter. This component is the TI's ***BQ24093***. The block diagram is presented in Fig. 7.

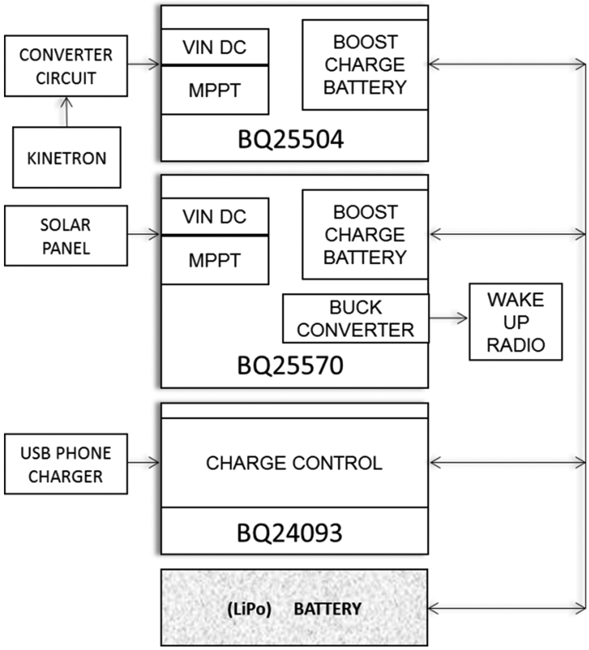

Fig. 7. Energy harvesting and battery management block diagram. In this paper the wake up radio is not presented.

Solar Energy: The solar energy harvesting is designed around the ***BQ25570*** ultra-low integrated circuit from Texas Instruments. For high efficient energy harvesting, the BQ25570 features maximum power point tracking (MPPT) capabilities. Moreover, it integrates an ultra-low power buck converter with programmable output voltage. The BQ25570 consumes less than 500 nA in active mode reducing the overall quiescent current of the whole system. The power source of our system is on the top of the helmet, which embeds four solar cells with a 40 cm^2 area. The developed systems providing a maximum power of 2mW under low room light conditions (250 lx) and 45 mW under sunlight (50000 lx).

Kinetic Energy: The kinetic harvester generator used is the Micro Generator System 26.4 (MGS26.4) produced by Kinetron [25] (shown in Fig. 8 on left); it is an electro-magnetic generator with a 26.4 mm thickness and a 4.3 mm diameter. The kinetic energy harvesting has at its core the TI ***BQ25504***. It contains a Boost Converter with an ultra-low quiescent current of 330 nA. However, the Kinetron generates an alternating waveform (AC), which is not directly accessible from the BQ25504, then a rectifier is needed. Figure 8 (right) shows the ac-dc doubler voltage converter (D3-D4-C43-C42) circuit we needed to insert before the BQ25504. The total efficiency of the whole circuit (AC-DC + BQ25504) has been measured to be 64%. We also tested the energy harvesting circuit in realistic condition when the driver is wearing the helmet and the energy acquired is reported in the following table.

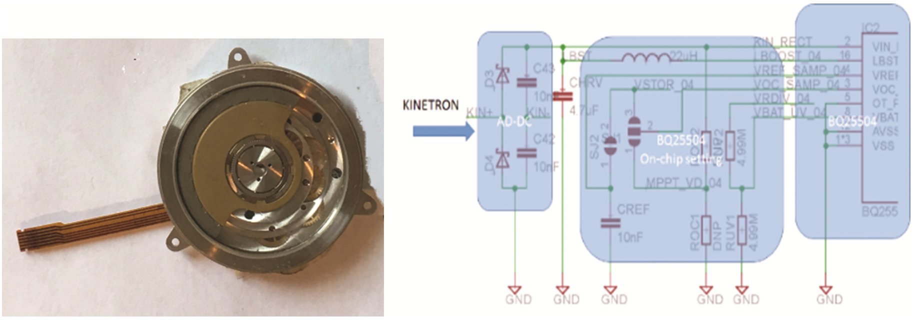

Fig. 8. Kinetic generator (on left) and kinetic energy harvesting circuits comprised by a AC-DC conversion stage connected with the DC-DC converter BQ25504.

4 Experimental Results

In order to evaluate the performance of the developed smart helmet module a prototype has been developed and test on the field (Fig. 9).

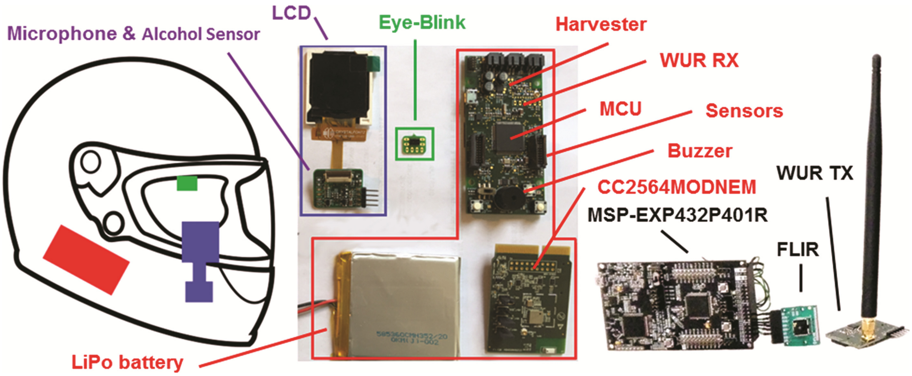

Fig. 9. Developed prototypes to test the functionalities and power performances.

All of the functions presented above have been tested, in particular: data acquisition from sensors, processing the data and testing the communication. Experimental measurements have also been conducted to evaluate the self-sustainability of the SHelmet under realistic circumstances. Figure 10 shows current consumption in the most used configurations of the device. When the system is in sleep mode with the harvester on and waiting for wake-up signal, the quiescent current consumption is ultra-low (3,7 μA). The second configuration is the standard one and only draws 17 mA current, with the context recognition sensors powered and analyzed, ensuring a fully operational user interface. It can be noticed that the alcohol sensor is a power hungry sensor consuming 270 mA@3,3 V, thus power management is important to use the sensor only when necessary (i.e. when the helmet is worn for the first time on the trip).

I_{sleep} @3.3V [μA]				
BQ24093	BQ25504	BQ25570	WUR	5 * LP5907
1	0,33	0,49	0,88	1
TOT		3,70		
$I_{MCU+MULTI-SENSOR+LCD+LED+BUZZER}$ @3.3V [mA]				
		17		
$I_{MCU+MULTI-SENSOR+LCD+LED+BUZZER+BLUETOOTH}$ @3.3V [mA]				
		58,2		
$I_{MCU+MULTI-SENSOR+LCD+ALCOHOL}$ @3.3V [mA]				
		270		

Fig. 10. Current consumption of the developed wireless sensor node to be place on the helmet.

To evaluate the self-sustainability of the solution the power generated form the energy harvesting has been measured during 2 days of use of the developed prototype. To evaluate the lifetime and the self-sustainability of the system, we did some assumption on the application scenario, in particular. The Bluetooth module is on when the system requires infrared camera thermal images and that only happens in low light environments. And alcohol sensor acquisition is required a couple of times a day at most. All the other sensor and system are always active during the use to have a reactive system for the dangerous situation. Figure 11 show the lifetime for nighttime and daytime use. In particular, the Fig. 11 (up) is referred to an under-daylight application scenario supposing the infrared camera working for a third of the time the device is used and an alcohol acquisition per day. Green bars go to infinite on the "days" axis in scenarios where the SHelmet is self-sustaining. Figure 11 (down) demonstrate still a very long lifetime but as the energy archived in the night is limited has been not possible achieve self-suitability.

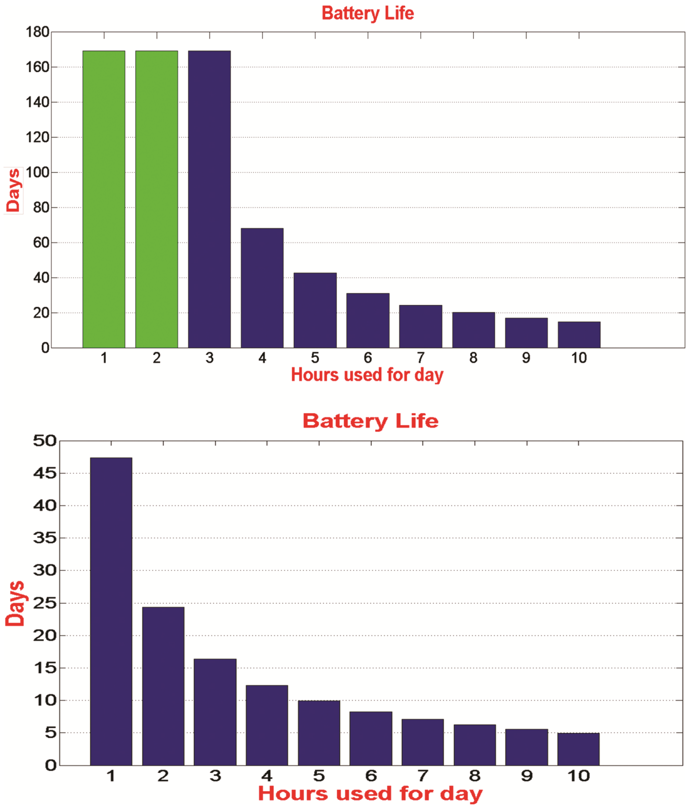

Fig. 11. Battery life during day light (up) and night (down). (Color figure online)

5 Conclusions

We presented SHelmet a smart helmet that results as a life-saving, self-sustainable, wearable device, which the user can always rely on during the driving experience. Context-aware sensors, in addiction to infrared camera, eye-blink detection, alcohol detection, on-board processing, and non-invasive user interface empower the driver to avoid dangerous situations. The wearable device has been thought with low power in mind and to be never recharged. To achieve this goal, it includes dual-source energy harvesting (solar and kinetic) to guarantee self-sustainability in the application scenario. Wireless communication trough Bluetooth Low Energy enables communication between vehicle and user guarantying fast alerts and flexibility of the solution. Experimental results on the developed prototype demonstrated both the functionality of the system and the self-sustainability when the helmet is worn on the motorbikes' head. Future work will focus in make a more accurate evaluation on the algorithms to detect dangerous situations and a long term in-field evaluation of the lifetime.

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