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Towards a modular IoT device design and prototyping for the Sports domain

Evripidis Chondromatidis, Emmanouil Tsardoulias, Konstantinos Panayiotou, and Andreas Symeonidis
School of Electrical and Computer Engineering, AUTH, Thessaloniki, Greece
evrichon@auth.gr, etsardou@ece.auth.gr, klpanagi@ece.auth.gr, symeonid@ece.auth.gr

Abstract

As the ever-growing demand of Internet of Things (IoT) devices continues, so does the necessity for rapid and systematic ways of designing their hardware and software. The above-mentioned issue becomes aggravated when the final requirements of a system cannot be determined a priori, especially when the system is expected to scale up in the future.

This work proposes a modular architecture. We discuss our approach in context of a device targeted in the Fitness vertical. Subsequently, we proceed by instilling these principles into a working prototype solution in the direction of evaluating its practical usage.

1 Introduction

The unprecedented collection and exchange of data that our Information Age offers, is largely driven by the emergence of compact and cost-effective devices, the so-called Edge & Internet of Things Devices. The total number of such devices is expected to triple from 9.7 billion in 2020 to more than 29 billion IoT devices in 2030 [1]. This undoubtedly shows that the industry already has and will continue to heavily invest in the direction of IoT devices, reaching USD 3,352.96 billions by 2030 [2].

Following the existing trend, many Sports Organizations employ IoT in order to tackle three fundamental objectives [3]: a) Player Development, b) Player Safety and, c) Fan Engagement. IoT devices can provide an abundance of data which when combined with advanced analytics can provide to Coaches suitable metrics in order to assess the performance and efficiency of their athletes in a much more accurate and unbiased manner. Moreover athletes are able to recover faster from injuries as well as improve their overall health conditions, as Sports Physicians and Team Doctors can continuously monitor their biometrics.

Despite the undisputed advantages that IoT technologies bring to the Sports domain, currently their large scale impact is hindered by a number of reasons. Most of the commercial IoT sport devices are quite expensive with regard to their hardware. Moreover, this issue is further enlarged by the fact that these solutions are closed-source. Licensing imposes restrictions on the number of users who can use the software on such devices. As a result, sports organizations are unable to adapt the products to their specific needs due to the special permissions required to do so. Furthermore existing IoT SportS devices are dedicated to execute specific tasks. This means that small modifications in the training protocol may demand new functionality, rendering existing devices obsolete. These reasons allow only a limited percentage of the Sports Community to embrace these new technologies and magnify the skill gap in the

Sports industry.

In the current work, the methodology of design, implementation and deployment of a modular IoT device is presented, with the aim of tackling all the aforementioned issues, dedicated to the sports domain. Our solution encapsulates not only the hardware design and assembly process, but also the software implementation using the powerful open source Riot-OS [7].

2 State of the Art

Currently there are many Smart Products targeting the Sports Industry, that are commercially available or developed for research applications. In general, these Products consist of smart devices that are capable of both transmitting stimulus via actuators to the athletes as well as receiving and recording their reactions using sensors. Such devices can either operate solely or they can be part of a larger interconnected System. Depending on their specific hardware, they can be incorporated in different exercise scenarios where they measure important physical and cognitive performance metrics [6]. Such scenarios could range from measuring the raw physical abilities of an athlete, such as strength and speed to performing physical abilities while following a series of evolving logical rules aiming to enhance the mind-body responsiveness [4]. The accumulated data are then transmitted either throughout a cable or wirelessly to a platform where they can be stored, processed and displayed. Fitlight[1] & BlazePot[2] are two examples of systems that comprise wirelessly interconnected devices. The above mentioned devices contain a light emitting source that can be adjusted to different colors, a ToF sensor that can measure distance and a touch sensor. Remedes [6] is a system that comprises similar smart devices in a star configuration and can be utilized both in sports and medical fields, extending the reflection measurements process in the direction of detecting neurodegenerative diseases. Another paradigm of such Solutions is Chronojump [5], which is rather a collection of different Products. Most of them comprise a single device that is connected via a USB cable (serial communication) and a sensor unit, while recently a wireless solution for race analysis was added. They include a jumping pad so as to measure jump height, piezoelectric sensors in order to measure force and linear encoders which are attached to an athlete via a string so as to analyze their acceleration performance.

The aforementioned Sport products, undoubtedly constitute solid and well-tested solutions, however all of them pose the issue of specialization in regard to their hardware, which inherently limits their adaptability and overall effectiveness. Different teams have different requirements and one can argue that the same rule applies to team's members as well. Technology in the context of Sports promises to provide a more personalized experience. It is the technology that should adapt to the player's need and not vice versa. Therefore while the monolithic design approach may offer additional robustness to the end product, it contradicts its original purpose. In this work, a modular architecture is presented where the hardware of such devices is separated into functionally independent blocks.

3 Design & Implementation

3.1. Methodology

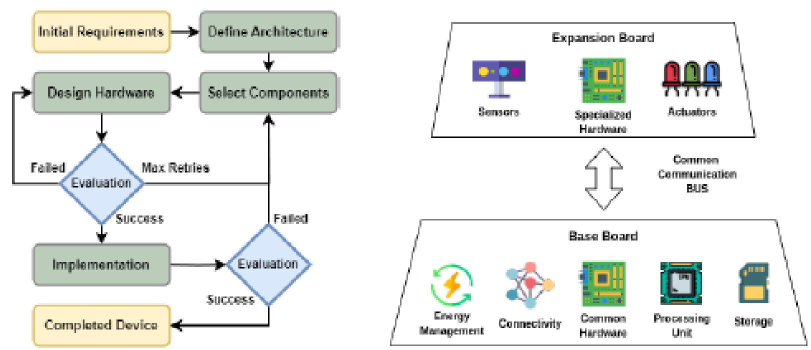
The methodology we adopted for the implementation of the proposed device follows the process described in figure 1a. In this process, the most crucial steps are the correct definition of the initial

[1] https://www.fitlighttraining.com/

[2] https://blazepod.eu/?tw_source=google&tw_adid=631785973612&tw_campaign=15546904716

requirements and the two evaluation processes. The criteria of the first evaluation relied on the component's datasheets, schematic simulations using LTspice[3], as well as testing and experimentation on a breadboard shown in figure 2a. In addition, the second evaluation was conducted in each of the constructed prototype devices using the Analog Discovery 2[4]. In this work, we achieved the specifications in just two full iterations.

The initial requirements derived from the collaborative knowledge of professional coaches, who utilize cutting edge technologies in the field of Sports as well as the experimental results gathered from an on-going project, Remedes[5]. Remedes is a field-tested project of the ISSEL[6] laboratory that relies upon similar devices and therefore it will be used as reference in order to assess the performance of this work. Along with user safety, some of the most important functional requirements are presented in the Table 1c.



(a) Methodology Algorithm. (b) Abstract Structure.

Specification	Margin
Min Battery Life	12 Hours
Max Responsiveness	50 msecs
Min Wireless Range	150 meters
Max Cost	100 €
Max Volume	500 cm^3

(c) Functional Requirements.

Figure 1: Requirements & Methodology of the proposed device.

3.2. Architecture

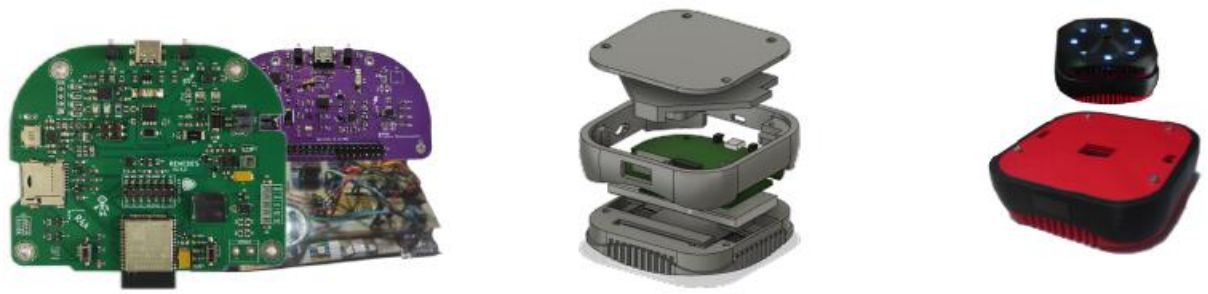
The adapted architecture structurally presents similarities with the paradigm of an Arduino ecosystem, where there are general purpose boards that can connect to one or multiple shield boards. In the same fashion, the proposed methodology assembles by the combination of components that we will refer to as Bases and Expansions. Bases are general purpose components that contain all the common functionality among devices such as power management, connectivity, storage & processing power. On the contrary, Expansions have all the specialized hardware to implement a specific Sports exercise. These components communicate through a common interface bus. In contrast, however, to the Arduino ecosystem our approach stands out in the following major aspects: 1) Specialization: The electronic parts of our device have been carefully selected in order to meet the requirements of Sports domain applications. 2) Robustness: The proposed device utilizes industry approved electronic components and is programmed using the powerful Riot RTOS, where Arduino is mainly used for education & rapid development purposes. 3) Software flexibility: Every Expansion can be virtually connected to any Base that possesses the peripheral support on the hardware level without any code modification. By utilizing Riot's abstraction layers, each software driver is written once and can be compiled to any of the supported architectures. 4)

[3] https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html
[4] https://digilent.com/reference/test-and-measurement/analog-discovery-2/start
[5] https://lab.issel.ee.auth.gr/remedes/
[6] https://issel.ee.auth.gr/en/13-2/

Ease of Use: Bases can automatically identify the connected Expansions through the common interface bus and load the appropriate drivers, resulting in a seamless transition between them.

3.3. Hardware Design

During the hardware design phase, the selection of the appropriate microcontroller unit is of paramount importance. In the current work, the Base board was developed using the ESP32- Wroom-32D7 MCU,



(a) Device hardware evolution. (b) Device casing design. (c) Assembled Device.

Figure 2: Construction steps of the proposed device.

Wroom-32D[7] MCU, developed by Espressif[8], as it satisfies most of the derived requirements from Section 3.1. Sports devices rely on sensors in order to accurately measure quantities such as distance or touch. ESP32 offers an abundance of peripherals (SPI, UART, I2C, ADC) that enables it to connect to hundreds of different sensors. Another great aspect of ESP32 is the integrated wireless connectivity via WiFi & Bluetooth, allowing it to publish the collected data to the cloud or into another smart device, where it can be processed and visualized in order to help coaches evaluate the performance of their athletes. In addition, ESP32 has a long range wireless communication protocol, ESP-NOW[9], which is useful for deploying outdoor track exercises over long distances. All in all, ESP32's high processing power, versatility and power management capabilities renders it an ideal choice.

Furthermore, the Base board includes an SD Card storage system, allowing the device to save the aggregated data while being in an environment without internet access. In order to facilitate the programming and debugging process a USB-to-UART bridge IC has been added which enables serial communication between the ESP32 and a PC. The Base also includes status leds and a passive buzzer so it can notify the user both visually and acoustically. Lastly, in the final design we attach a fully functional sound subsystem consisting of a dedicated class D PCM amplifier and two 8 ohm speakers, allowing the device to give vocal instructions to the athletes.

After identifying all the functional hardware components of the Base board and estimating the average power consumption of the Expansion boards, the Power Management System (PMS) was developed. The PMS is responsible for providing the appropriate voltage and sufficient current to all electronic components of both the Base and the Expansion Boards. This subsystem implements: 1) A continuous

[7] https://www.espressif.com/sites/default/files/documentation/esp32-wroom-32d_esp32-wroom-32u_datasheet_en.pdf
[8] https://www.espressif.com/
[9] https://www.espressif.com/en/solutions/low-power-solutions/esp-now

power delivery function, which automatically switches to the currently available power source, reassembling a single virtual power source that operates continuously. Currently there are two power sources in our device, a 2600mah LiPo Battery and the external power supply via the USB Type C port. 2) Battery charging capabilities: When the USB port is connected, the battery disconnects from the load and enters charging mode. 3) Battery safety mechanisms. 4) Power consumption gnostic functions. 5) Two switching voltage regulators in order to stabilize the voltage at 3.3v/4.3w & 5v/10w. 6)Power saving mode. During this state the ESP32 enters deep sleep mode, the 3.3v regulator enters pulse skipping mode and the rest of the components are disconnected from the battery via MOSFET switches. All the above can be viewed in the figures 2a, 3 & 4.

Figure 3: Reflexes & Jump Pad Expansions.

Figure 4: Balance & Screen Expansions.

Figure 5: Codin programming tool.

3.4. Implementation

The PCB's that were designed using the open source tool KICAD[10] were sent for manufacturing. Then, the PCB assembly process took place by hand using the reflow soldering method. In figures 2b & 2c , the 3D model as well as the actual proposed device are presented. The 3D case designs were developed in Fusion360[11]. The device was programmed using the IoT friendly Riot-OS [7]. Riot is a lightweight and energy efficient RTOS, containing multiple abstraction layers which hides the internal architecture of the host device. Therefore, the written firmware can be compiled into many different architectures. Finally, the device was successfully connected to to ISSEL's remote IoT inspection platform Codin[12], as shown in figure 5. Codin is a useful tool for creating customized GUI's, that can control and monitor IoT devices. The connection was possible through an intermediate Raspberry Pi node running Commlib [8].

3.5. Empirical Evaluation

In the direction of evaluating the practical usage of the proposed device regarding the modularity, four Expansion boards were developed, presented in figures 3 & 4. The first Expansion is similar to many of the devices presented in chapter 2 and consists of RGB leds and a TOF distance sensor, making it ideal to measure the reflexes of an athlete after a given optical stimulus. The second Expansion connects to a custom jumping pad enabling our device to measure the height of the athlete's jump. Athletes can receive more detailed instructions via the screen we installed on the third Expansion. Lastly the fourth Expansion has a IMU sensor and can be used to assess the athlete's balance capabilities by measuring the inclination of the XY plane.

[10] https://www.kicad.org/
[11] https://www.autodesk.com/products/fusion-360/overview
[12] https://codin.issel.ee.auth.gr/

4 Conclusions & Future work

In this work, we present and discuss our methodology and the implementation strategy of a modular, open-hardware/software IoT device targeting the Sports domain. Following the methodology described in chapter 3.1 we managed to create a working prototype Base with four different Expansion boards and meet the initial requirements by achieving an average battery life of 52 hours in normal Operation & 257 hours in Deep Sleep Mode, at a total cost of 74€ per device in small scale production. Due to COVID-19, compromises regarding the hardware component selection were made. In addition, direct testing in real conditions was difficult, therefore the verification process was conducted by comparing the proposed device with the devices of the on-going project Remedes, in which it showed superior functionality regarding the battery life & overall speed. The adopted architecture showed the following advantages: 1) Scalability: New athletic exercises of measurement configurations can be imported by just adding a new Expansion into the system. This is especially useful when a Sports team is expanding and therefore it cannot define its demands beforehand. 2) Reusability: Old Expansions can be combined with new Bases and via verse , creating multiple combinations. 3) Cost reduction: While each device separately may be more expensive, the total cost for a Sport team is greatly reduced. 4) Rapid Development: Each new Base and Expansion board can be developed independently and software drivers can be reused. While meeting the initial requirements, more Base boards should be designed in order to further investigate the capabilities of this architecture. An interesting extension in the current solution would be to further expand its modularity, by separating the connectivity form the Base and deploying it in a separate component. All the hardware schematics, software code and demos are available on github, in the form of open-source projects[13].

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