Monitoring the hydraulic stability of Antifer blocks: an IoT-based approach

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Abstract—**Breakwaters are resilient marine infrastructures, or barriers, built out into the sea to protect a coast or a harbour from the force of waves. The environmental conditions that these structures continuously face are challenging and the continuous monitorization of its hydraulic stability is a key success factor for preventive maintenance of these critical infrastructures. This paper introduces the architecture of an IoT solution designed to monitor the hydraulic stability of Antifer blocks, a common building block used for breakwater infrastructures construction, by measuring, recording, processing, and communicating the data related to the displacement of an Antifer block, in a laboratory context. The IoT device has been designed to meet the following requirements: 3D displacement measurement (up to 25 mm); corrosion-proof and waterproof; wireless charging and wireless communication; and autonomy above one month. Preliminary results have shown that the SmartAntifer prototype fulfills the core application requirements and presents an average consumption of 90 mA, which results in 11 hours of autonomy when equipped with a battery with a capacity of 1000 mAh.**

Index Terms—**IoT, Smart Monitoring, Antifer, Hydraulic Stability**

I. INTRODUCTION

A breakwater is a structure that aims to protect the coast or a port area from the action of sea waves and is commonly used to stop the force of the waves and limit the speed of the sea currents. An Antifer block is a massive concrete unit created as a result of laboratory research and is often used as a building block of breakwater infrastructures [1].

This work presents the design of the Smart-Antifer, a small-scale IoT-enabled Antifer block, capable of measuring, recording, processing, and communicating the data relating to the displacement of an Antifer block, in a laboratory context. The device was designed in collaboration with the Hydraulics Laboratory of the Department of Civil Engineering and with the Laboratory of Systems and Underwater Technology (LSTS), both with the Faculty of Engineering of Porto University.

The Hydraulics Laboratory procedure for carrying out a simulation test consists of constructing the structure under study with several concrete Antifer blocks [2], and then evaluate its displacement between experiments. After performing a laboratory test, the wave pool is emptied to proceed with the acquisition of the photographic evidence and obtain the displacement of the Antifer blocks. Then, after completing the displacement data collection, the pool is refilled again. After the pool is filled, all steps are performed again. The total duration to fill or empty the pool is 2 days.

The IoT-based solution presented in this paper aims to streamline the digitization of the experimental procedure, i.e. enable the collection of data from multiple experiments without human intervention and without the need to empty the pool between experiments.

The remainder of this document is organized as follows: Section II presents related works; Section III introduces and describes in detail the system architecture and its core elements; Section IV introduces the architecture of the SmartAntifer device in detail; Section V presents preliminary results. Lastly, in Section VI the main conclusions are introduced and future work guidelines presented.

II. RELATED WORKS

In the work presented in [3], authors describe a device composed of the following elements: a microcontroller Teensy 3.2, an accelerometer, and a gyroscope, to measure the 3D movement made during a hammer launch training. To try to predict the launch, the authors used mathematical calculations to test Kalman filters and Madgwick's filters. With the low sampling rate (50Hz), they had better results with Madgwick's filters. From the collected data authors were able to obtain the speed and distance of the movement.

In the work *Smart Rocking Armor Unit* [4], *Bas Hofland* describes an embedded system installed in a *Tetrapod* block machined in aluminum and scaled. The system was developed in Arduino and is based on a low-cost 9 axis IMU (*Inertial Measurement Unit*), normally used in conventional low-cost smartphones. The size of the embedded system is 20 x 20 x 20 mm and includes a battery, a USB connector, a microcontroller, a 9-axis IMU, and a memory card. The maximum sampling frequency that was obtained is 30 Hz, this limitation is caused by the writing speed to the memory card, although the IMU can operate using a sampling rate up o 100Hz.

2021 16th Iberian Conference on Information Systems and Technologies (CISTI)
23 – 26 June 2021, Chaves, Portugal
ISBN: 978-989-54659-1-0

In [7], a different version of the system is presented and its operation is described. The system is installed in an Antifer cube printed on a 3D printer. To turn the system on, it is necessary to remove a magnet from the ”reed switch”, so that the system starts to acquire data. To configure the system, a waterproof USB-C connector is also available.

A different approach was used by *D. Eden* [5] [8], based on a block of the type *Core-Loc* that was printed from PLA. The proposed system includes several pressure sensors from *Honnywell* at key points in the block and the sampling of the various pressure sensors is performed from a Raspberry Pi 3 with a sampling frequency of 320Hz. For the tests with *Core-Loc*, an ATI Mini45 IP68 was attached to measure the forces exerted on it. Additionally, the authors used a Nikon camera, recording video with a frequency of 30Hz, to be able to detect the surface of the water when the waves break.

In [6], Arefin opted to use a modular commercial solution from the Tinyduino brand. Tinyduino is programmed in Arduino C, thus allowing the installation of several boards with other components. The embedded system was initially installed in 4 cm high cubes. The sensors installed are a gyroscope and an accelerometer to allow reading the displacements, and communications are established with a PC, allowing the visualization of the data collected in real-time with a maximum sampling frequency of 62.5Hz. The system was then installed in a *Tetrapod* in which a small battery and memory were added. In this configuration, the sampling frequency used was 32.5 Hz.

Some companies offer IMU equipment with various sizes and different types of interfaces, for different application contexts. For example, the CS-IM100 equipment from CTi Sensors [9] consists of a box, which can be submerged up to 1 meter for up to 30 minutes, providing several communication interfaces (RS232, RS485, USB, among others) and a high rate sampling. This type of equipment can cost several hundred euros. In the context of the application under study, it is not possible to use this type of equipment due to its size.

Some companies offer sensor modules such as VectorNav’s VN-100 [10]. The VN-100 is available in SMD version (*Surface-Mount Device*) with a dimension of 24 x 22 x 3 mm. The module contains several sensors such as a 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer and barometer to communicate, a serial port, and an SPI bus (Serial Peripheral Interface). The maximum sampling frequency of the IMU is up to 800Hz. This type of equipment can have a price of several hundred euros, which makes its use prohibitive.

The systems presented in [4] and [6], by Bas Hofland and Arefin respectively, allows us to identify that they had different approaches despite having the same Armor Unit which is a Tetrapod. Arefin also installed the system in cubes in which each face has 4.03 cm.

An advantage of the Bas Hofland [4] approach is that the proposed system is powered by a battery, being a benefit of the system, as it allows Tetrapod to have greater freedom so that it can move, but in return, it will be limited by battery capacity, thus restricting operating time. It can be considered that this system has a lower acquisition frequency than that of Arefin [6], due to the greater storage capacity of the IMU data for being 9 axes, or for the choice of the interface between the card memory and the microcontroller.

As the Arefin system [6] is powered externally, it can lead to more restricted movements due to the position of the cables, but on the other hand, it has the advantage of working continuously. In turn, the system has the advantage of a high frequency of data acquisition, because it is also only sending data from two sensors (accelerometer and gyroscope) directly to the computer’s hard disk.

The D. Eden approach [5] is different from the previous approaches, having the same weak point as the Arefin system due to the use of a cable to communicate, and thus the values read by the sensors are sent for the Raspberry Pi, where it can influence the displacement during the test. The main advantage is sending data at a high frequency.

Table I compiles the works presented above, taking into account relevant criteria for the application case under study.

TABLE I: Related works comparison.

	Hofland et al. [4]	Eden et al. [5]	Arefin et al. [6]
Armour Unit	Tetrapod	Core-Loc	Cube
Material	Aluminium	3D Printed (PLA)	n.d.
Computational System	n.d.	Raspberry Pi 3	ATmega328P
Power	n.d.	External	External
Storage	8 Gb	n.d.	External
Sensors	IMU 9-AXIS	pressure 6 uni	accelerometer, gyroscope
Sampling Frequency	30 Hz	40—320 Hz	up to 62.5Hz

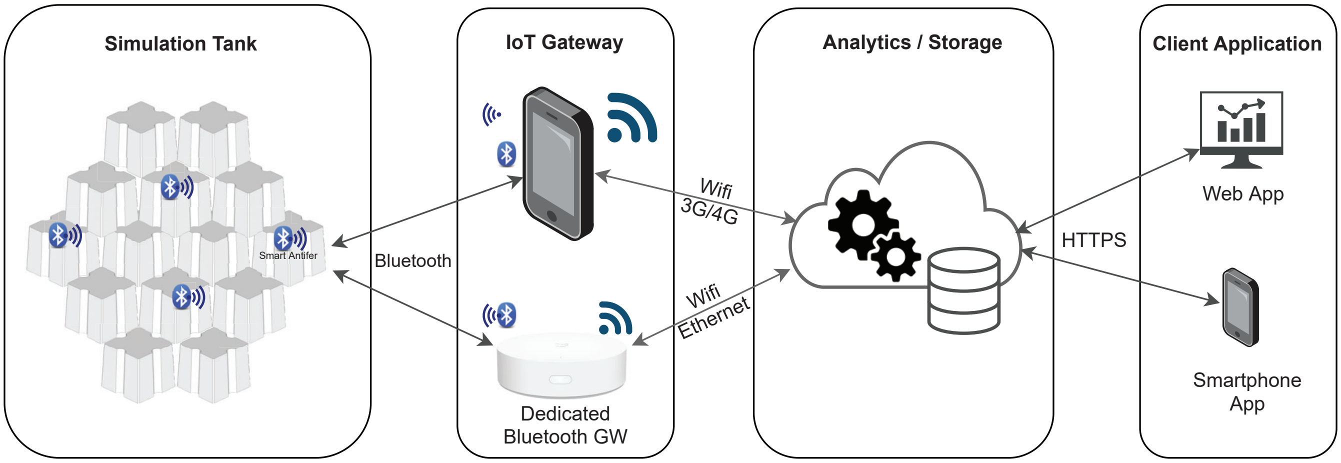


Fig. 1: Overall system architecture.

III. SYSTEM ARCHITECTURE

This section introduces the overall system architecture and describes its functional blocks, which can be divided into three main blocks, cf. Fig. 1. The purpose of the SmartAntifer block is to measure 3D displacements created by the force of the waves. For this purpose, constructions are made at the scale of the breakwaters to be studied [1] [7], e.g. a breakwater at a port. These breakwaters use common Antifer blocks in concrete which can be mixed with other SmartAntifer blocks, placed at specific key points. In our case, the SmartAntifer block was designed to comply with the following application requirements:

- 3D displacement measurement with 25 mm resolution;
- Wireless connectivity;
- Minimum sampling frequency of 4 Hz;
- Possibility to export data in CSV format;
- Be prepared to be installed in a watertight system;
- Charging without physical connectors;
- Autonomy between 6 and 8 hours.

Data is then collected through Bluetooth communications technology to the cloud using a mobile application running on a smartphone. The mobile application also allows changing the configuration parameters of each SmartAntifer block, and also, manage the stored data. Another functionality of the mobile application is that it can operate as a gateway because the collected data can be sent to the application server through Wi-Fi/4G which are natively available in the mobile device. Moreover, the SmartAntifer will also be able to transmit data to the cloud through a dedicated Bluetooth gateway, which will forward the received data to a cloud-based service using backhaul communications, such as 4G, Wi-Fi, or Ethernet. Other IoT communications protocols, such as LoRaWAN, NB-IoT, or LTE Cat M1 modules were not considered due to their lower bitrates and since the IoT device was specified to operate in the lab, in proximity to the operator/user. Moreover, using other IoT communication protocols, such as LoRaWAN or Sigfox, although they have the advantage of consuming little battery, would imply the use of additional gateways, in the case of LoRaWAN, or an operating fee, in the case of Sigfox [11].

Meanwhile, on the server-side, the data received from the mobile application is stored in a database and processed for visualization. Furthermore, a block of analytics is used to identify movements and evaluate the 3D displacement of each specific SmartAntifer block that has been used in a specific experiment.

IV. SMARTANTIFER IOT DEVICE

Figure 2 depicts the architecture of the SmartAntifer, which is divided into 5 main blocks: microcontroller, Bluetooth module for communications, external storage (microSD and EEPROM), Inertial Measurement Unit, and power management (including control logic, wireless charger).

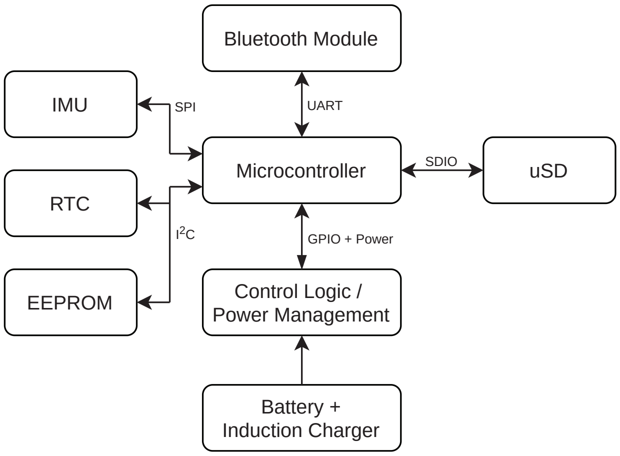


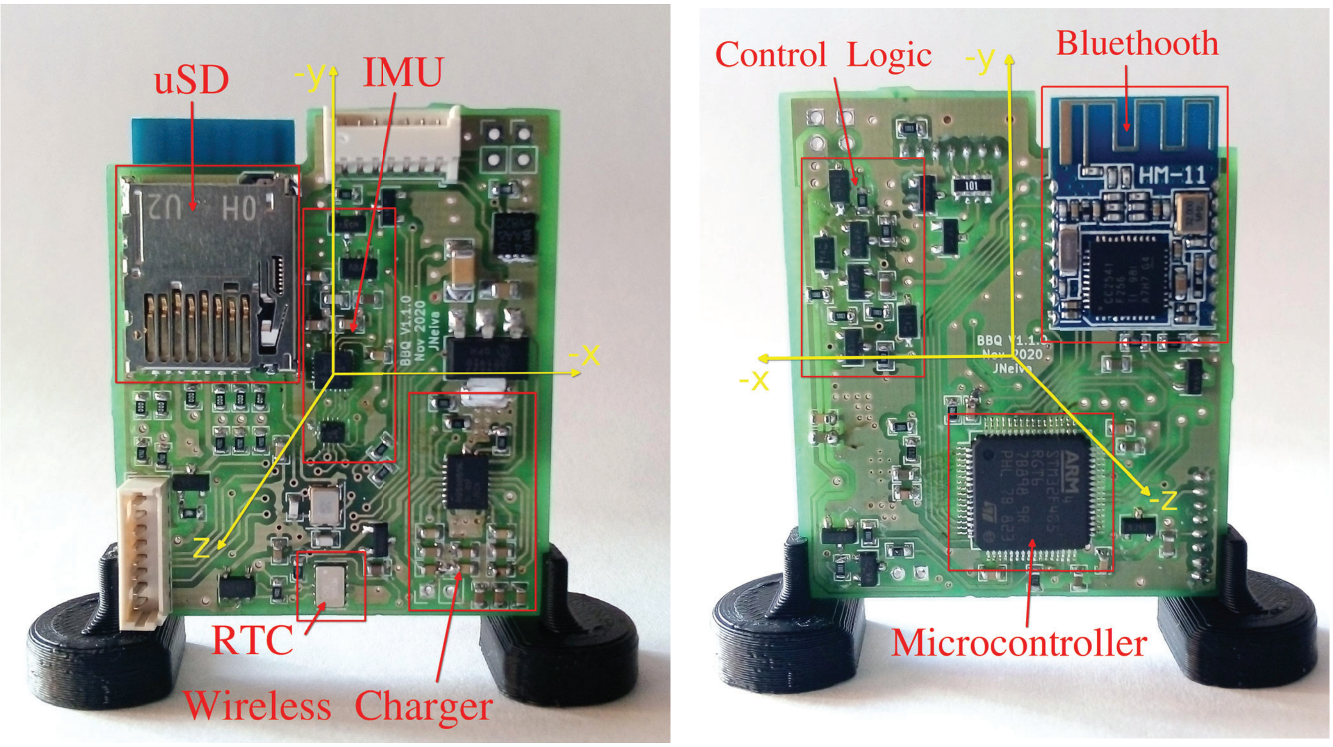
Fig. 2: SmartAntifer: IoT device architecture.

A. Hardware Development

The PCB design process was followed to place the IMU in the PCB center. This way, the IMU chip will be the closest to the center of mass of the SmartAntifer. Moreover, to simplify the assembly process, the integrated circuits were placed on the same side. Because the microSD card support and the Bluetooth module occupy a larger area, priority was given to the package choice to ensure the shortest distance with the microcontroller.

The SmartAntifer prototype was implemented in a two-layer PCB specifically designed to fulfill the application requirements previously introduced. In the upper layer, cf. Fig. 3a, it is possible to observe the ICM-20948 from TDK, a low power 9-axis IMU (Inertial Measurement Unit) that is ideally suited for IoT applications. The 9-axis IMU consists of an accelerometer, a gyroscope, a magnetometer, and an internal Digital Motion Processor (DMP). The DMP offloads computation from the host processor and can help in the improvement of the IoT device power performance, and presents a refresh rate of 200 Hz, regardless of what will be used in the application scenario. Initially, the sampling frequency is set to 5 Hz, but it can be changed to adapt to any simulation scenario. Moreover, it is also possible to identify the microSD card reader, which is used for data storing during the data acquisition stage. A second memory, an EEPROM, has also been added to store some important operational parameters, such as the IMU calibration data. Furthermore, a low-power Real-Time Clock (RTC) has also been added, so that when the data acquisition starts, it is possible to know the date and time of each acquisition. To charge the batteries, when inside a SmartAntifer, a wireless charging circuit compatible with the Qi protocol [12] has been used, which is compatible with LiPo or Li-Ion batteries. As presented in Fig. 3a, two connectors are available, one on the top (used to interface an external PCB with an RGB led), and another to connect the Hall effect sensor. The connector in the lower-left corner is used for MCU programming and serial port debugging.

The lower layer, cf. Fig. 3b, presents the MCU and the necessary circuitry to externally turn ON/OFF the device using a hall sensor when the system is installed in a watertight block. The selected MCU is the STM32F405 from STMicroelectronics, due to its high number of pins, its variety of peripherals, it also includes a dedicated SDIO interface, thus enabling higher reading and writing speeds, so that it is possible to store the data obtained inside a memory card. Additionally, a Bluetooth module was added, to enable external configuration and data transmission with mobile devices, such as Tablets or Smartphones. The Bluetooth module is the HM-11 from Seeed Studio, which allows the creation of an SPP (Serial Port Profile) connection, which emulates a serial port via Bluetooth.



(a) Top view.

(b) Bottom view.

Fig. 3: SmartAntifer prototype with all components identified in red and the 3D-axis identified in yellow.

B. Firmware Development

Figure 4 depicts the prototype firmware. After the initialization of the IMU, SD card, and I/O ports, the device checks if the key magnet is present, through a hall sensor. When the state variable toggles to ON, the system collects data from the IMU and then stores it in the microSD card. To stop data acquisition, it is necessary to approach the magnet to the hall sensor, for at least 5 seconds, and the sequence to switch off the device starts, i.e. after guarantee that the file that is being stored in the SD card is properly closed. The Hall sensor is intended to switch on/off the SmartAntifer, also having the functionality to switch between data acquisition and communication with the mobile device. Note that, during simulations, the SmartAntifer blocks will be underwater, so no wireless radio frequency communications will be possible. Therefore, to ensure that the data on the microSD card will not be corrupted during the written process, the battery voltage will be continuously monitored, and if a low voltage is detected, the file that is being used for storage will be closed, and the system will be turned off.

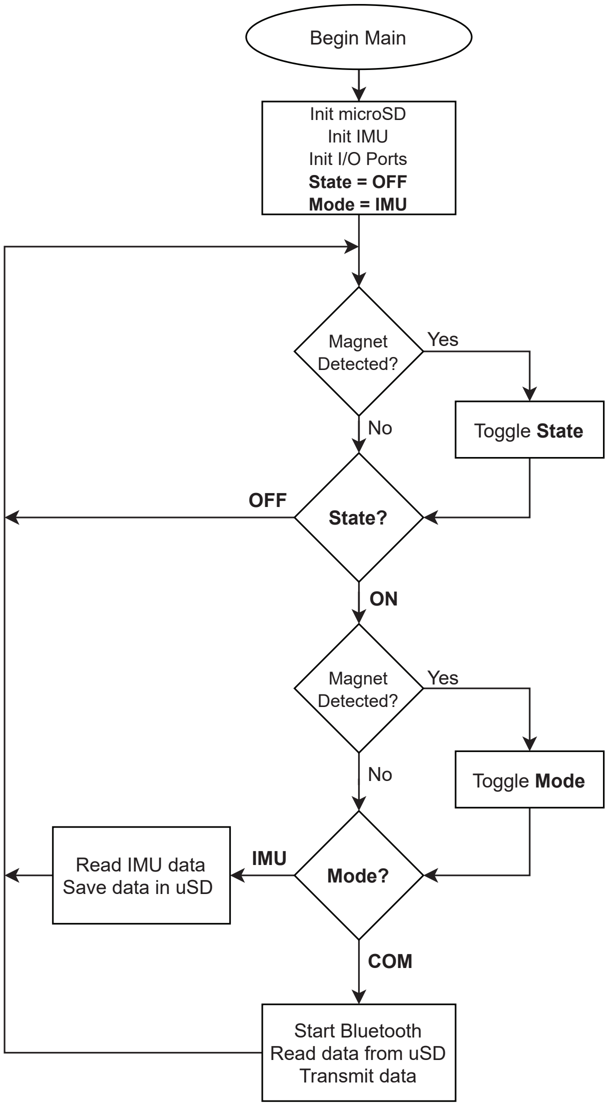


Fig. 4: Embedded Firmware Flowchart.

V. PRELIMINARY RESULTS

The prototype is 42.5mm long and 37mm wide, and the PCB was manufactured with only two layers. During the PCB design, it was necessary to change the IMU orientation to facilitate the connection with the microcontroller due to space constraints. Once it is intended to install the PCB with all components assembled inside an Antifer block, the axes must then be aligned concerning the block axes.

To perform the prototype validation we configured the device to operate with a sampling frequency of 40 Hz and to store the 6-axis data (accelerometer and gyroscope) into the microSD memory card. To confirm the prototype axis orientation, the following experiment was performed:

1) The prototype remained in the vertical position as presented in Fig. 3a for 20 s;
2) Then the prototype was rotated 90º to the horizontal position, again for 20 s;
3) Lastly, the prototype was rotated 90º to the position that was missing, again for 20 s.

As can be observed in Fig. 5, during the first 20s the prototype was in the vertical position, being possible to observe the gravity acceleration in the y-axis. After rotation to the horizontal position, which corresponds to the period between 20 s and 40 s, gravity acceleration appears in the z-axis, as expected. The procedure previously introduced can be used for calibration of the IMU once in a while, e.g. when the simulation is being prepared.

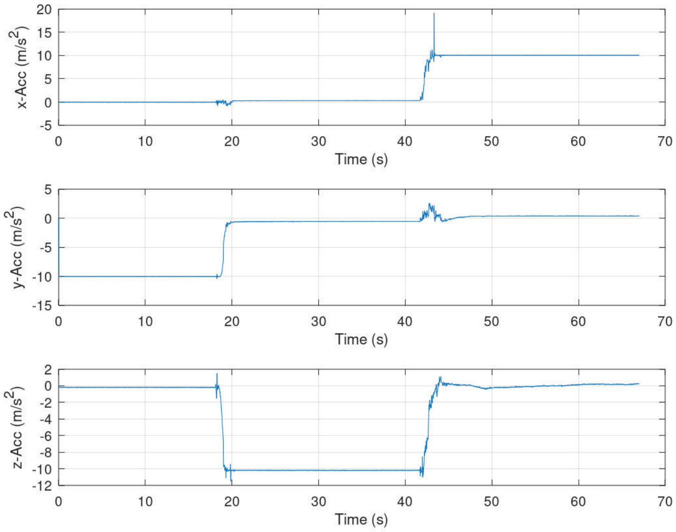


Fig. 5: Axis confirmation based on the accelerometer data.

VI. CONCLUSIONS & FUTURE WORK

This paper introduces the SmartAntifer, a small-scale IoT-enabled Antifer block, capable of measuring, recording, processing, and communicating the data relating to the displacement of an Antifer block, in a laboratory context. The SmartAntifer is an IoT solution designed to monitor the hydraulic stability of Antifer blocks, a common building block used for breakwater infrastructure construction. The proposed solution simplifies the digitization of the experimental procedure, by enabling the collection of data from multiple experiments without human intervention and without the need to empty the pool between experiments.

Preliminary results have shown that the SmartAntifer prototype fulfills the core application requirements. A PCB was developed and a prototype unit was fully assembled. All the building blocks were tested and validated. The prototype presents an average consumption of 90 mA, which results in 11 hours of autonomy when equipped with a battery with a capacity of 1000 mAh.

Regarding future work, four main tasks have been identified: i) a new PCB version is being considered with the aim of reducing the number of components and the overall PCB area; ii) Design and print a 3D enclosure for the device; iii) implementation of the mobile application that will be used to configure and manage the data obtained after experiments; and iv) implementation of server-side backed and the data analytics block that will be used for displacement estimation.

ACKNOWLEDGMENT

This contribution is a result of ongoing research, in the scope of a dissertation work of the M.Sc. in Informatics Engineering, in collaboration with the Applied Digital Transformation Laboratory (ADiT-Lab), and funded by the Polytechnic Institute of Viana do Castelo.

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