



IoT System for Monitoring of Workers at Height^a

Sistema IoT para el Monitoreo de Trabajadores en Alturas

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Abstract

Work at height is considered a high-risk task due to the exposure of personnel to non-daily or natural factors for the human being, such as changes in temperature, position and limited displacement, which might affect the person's metabolism. In Colombia, over the years, this activity has represented a significant number of accidents and deaths. In order to be able to detect a possible eventuality or issue with the worker at height, this project proposed and developed an IoT prototype system to monitor biological variables, such as, heart rate and blood oxygen level, and variables of protection for the worker, such as the securing of the carabiner on the line of life and the height at which the worker is positioned. In the materials and methods section, the system architecture and its connections are explained. To measure heart rate and blood oxygen level, the plethysmography technique is selected, a high-resolution barometer is selected to measure the worker's height, and a pressure sensor is selected to measure carabiner securing. This section also explains the development of electronic instrumentation and the connection of the different modules to guarantee the acquisition of information and its sending to the cloud. The results of the characterization of the prototype indicated errors of 3.56% for the heart rate, 1.1% for the blood oxygen level and 10% for the carabiner securing measurement. As a conclusion the IoT system was designed, implemented and verified for the proposed variables. The system allows real-time measurements and connectivity between physical variables and the cloud.

Keywords: Monitoring, Accident Prevention, Safety Devices, Internet of things

Resumen

El trabajo en alturas es considerado como una labor de alto riesgo debido a la exposición del personal a factores no cotidianos o naturales para el ser humano, como lo son cambios de temperatura, de posición y un desplazamiento limitado, lo que puede afectar el metabolismo de la persona. En Colombia, a través de los años, esta labor ha representado un número significativo de accidentes y muertes. Con el fin de poder monitorear y detectar una posible eventualidad o posible riesgo en el trabajador en alturas, en este proyecto se propuso y desarrolló un sistema prototipo IoT de monitoreo de variables biológicas, como lo son el ritmo cardiaco y nivel de oxígeno en la sangre, y variables de protección en el trabajador como el aseguramiento del mosquetón sobre la línea de vida y la altura a la que se encuentra el trabajador. En la sección de materiales y métodos, se explica la arquitectura del sistema y sus conexiones. Para la medida del ritmo cardiaco y el nivel de oxígeno en sangre se selecciona la técnica de pletismografía, para la medida de la altura del trabajador se selecciona un barómetro de alta resolución y para la medida del aseguramiento del mosquetón se selecciona un sensor de presión. En esta sección se explica el desarrollo de la instrumentación electrónica y la conexión de los diferentes módulos para garantizar la adquisición de la información y su envío a la nube. Los resultados de la caracterización del prototipo indicaron errores de 3.56% para el ritmo cardiaco, 1.1% para el nivel de oxígeno en la sangre y 10% para la medida del aseguramiento del mosquetón. Como conclusión se diseñó, implementó y verificó el sistema IoT para las variables propuestas. El sistema permite mediciones en tiempo real y conectividad entre variables físicas y la nube.

Palabras clave: Monitoreo, Prevención de accidentes, Dispositivos de seguridad, Internet de las cosas.

Introduction

Working at height is defined as any activity done at a height greater than 1.5 meters, over stairs, scaffolding, building, structures among others, as well this works can include activities inside a well and open areas [1]. These activities are considered as high risk, due the conditions to what the workers are exposed [2]. According to the Colombian Health Ministry, just in 2016, 806 deaths and 706.962 wounded were reported due this kind of job [3]. Despite the current regulations for work at height, such as resolution 1409 from 2012, which obligates the companies to follow certain requirements for the safety at work, the number of this kind of accidents is still significant [3]. Additionally, all the fatalities and accidents cause big losses for the companies, just in 2015 the companies had to pay about 55.3% of their compensation policies and 0.2% by funeral expenses [4]. Based on this, it is necessary to develop monitoring devices for workers at height that could guarantee their protection and integral health. These devices should verify the biological conditions of the workers while they are working at height, and at the same time verify that the job is made according to the proper procedures.

Currently, there is a lot of equipment that help to improve the safety and quality of the work at height, including safety protocols, personal protection equipment (EPP by its abbreviation in Spanish) such as harness, carabiner, hooks, helmet, among others, sadly, there are not enough technological equipment able for monitoring the biological variables and health of the workers in real time.

Honeywell and Intel are developing a safety personal prototype for factory workers and those first line actors such as: firemen, paramedics, civil defense and others. This prototype has an information storage module (Mobile Hub) which is able to check the heart rate, pulse, posture and movement. The results will be shown remotely in a visual screen and the data will be used to anticipate unsafe conditions to protect the workers [5].

MIT had developed Safety++, another related prototype, a wearable technology that integrates 4 devices: Undershirt++, including sensors to measure the heart rate, a gyroscope used to know the axial location of the worker, and engines that can vibrate as a warning to indicate possible falls and send the information to a main center; Jacket++, integrating sensors to detect toxic gases; Carabiner++, with a sensor that measures the pressure applied on the safety carabiner of the worker; and Shoes++, that can measure the pressure applied on the feet to know if the worker is charging a heavy load [6].

The aim of our project is to present a prototype capable of monitoring the heart rate, blood oxygen level, and other safety variables, such as securing the carabiner on the lifeline and the height at which the worker is positioned.

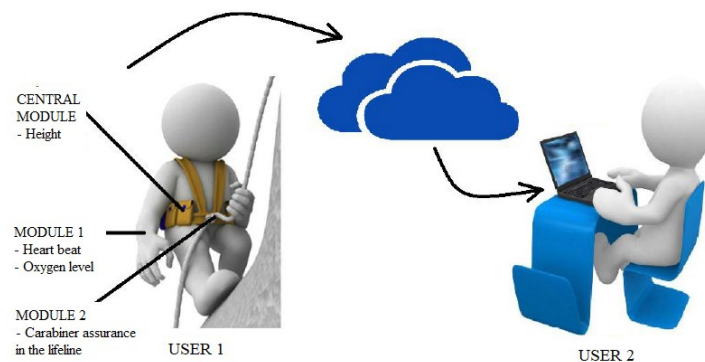
This kind of project shows the importance of technology transfer processes between the academia (universities, research centers and institutes) and the industry. On one hand, this transfer process allows the universities to incentive the participation of students into research projects that consider a real-case deployment scenario. On the other hand, the industry receives systems that integrate state-of-the-art technologies and mechanisms to solve its current challenges. However, the steps necessary to take a scientific concept into the market are not simple, but the first stage always involves the generation of a proof-of-concept device, such as the one described in this article.

Materials and methods

This work proposes a prototype system for monitoring biological variables of the workers while they are at height, such as: heart rate, blood oxygen level and protective variables for the worker, such as the carabiner assurance on the lifeline and the height at which the worker is positioned. The prototype system is called AEGIS, an originally Greek word that means shield, protection or defense [7-10].

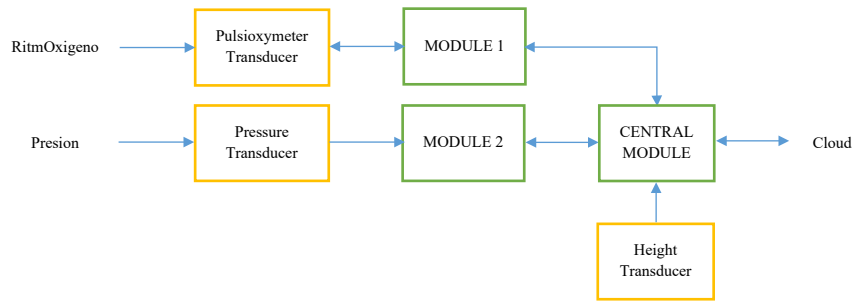
AEGIS is a prototype system integrated by 3 modules whose communication between them will be wireless. The first module measures the heart rate and blood oxygen level, the second will be responsible for measuring the carabiner assurance in the lifeline, while the third module is the central node where all the information will be collected and will also measure the height at which the worker is located. The information at the central module is uploaded to a cloud and can later be viewed on a web portal. For the AEGIS prototype there are two users, the worker at height (User 1) who is directly connected to the modules, and the person who will verify the data of the tester on the web, in order to see if there is any issue (User 2). The concept of this system is shown in Figure 1 and the general block diagram in Figure 2.

Figure 1. AEGIS concept diagram.



Source: Authors own creation

Figure 2. Aegis block diagram.



Source: Authors own creation

Module 1 – Biological Variables

Module 1 is responsible of monitoring the heartrate and blood oxygen level of “User 1”. Heartbeat is defined as the vibration produced in the arterial walls by the pass of bloods waves pumped through the ventricular contraction of the heart [11]. The heartbeat can be measured of several ways with many considerations, however, for works at height the main variable is taken from the number of pulses per minutes (ppm) - also known as beats per minutes (bpm). Blood oxygen level is defined as the carriage of oxygen in the blood, a 100% saturation means that all the red blood cells within the hemoglobin are transporting oxygen [11], and it can be measured by analyzing the light absorption for two wavelengths in arterial blood (AC/DC method). The AC/DC method considers the AC component of absorbency at each wavelength and divides this by the corresponding DC (amplitude) component. The ratio or proportion of absorption R is calculated, using Equation 1 [11, 12].

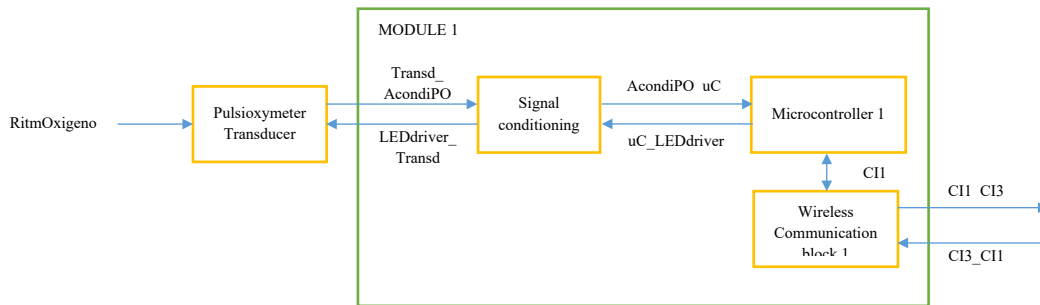
$$R = \frac{AC_RED}{DC_RED} / \frac{AC_IR}{DC_IR} \quad (1)$$

which takes into account the wavelengths for red (AC_RED/DC_RED) and infrared lights (AC_IR/DC_IR). With the absorption ratio (R), the oxygen saturation value is calculated using a typical calibration curve, which will vary according to the manufacturer of the pulse oximetry equipment.

The process of measuring the heartbeat and the blood oxygen level must comply with the standards and specifications established by the World Health Organization (WHO). For the case of the heartbeat, it should be measured at least in an interval between 30 and 240 bpm, with a minimum lag of 1 bpm, and the accuracy should be better than 4 ppm. The bandwidth of this signal would be approximately 0.5 to 5 Hz. For the case of blood oxygen level, it should be measured in a range between 70% to 99% with a minimum resolution of 1% and an accuracy better than 2% [13].

Module 1 has a conditioning stage that amplifies, filters and converts the analog signal that comes from the transducer into a digital signal; a processing stage where acquired measurements are stored, and the oxygen saturation in the blood and heartbeat are estimated. Finally, a stage of wireless communication sends all the collected information to the central module. Module 1 is located on the forearm of “User 1”. Figure 3 shows the block diagram related to Module 1.

Figure 3. Module 1 block diagram.



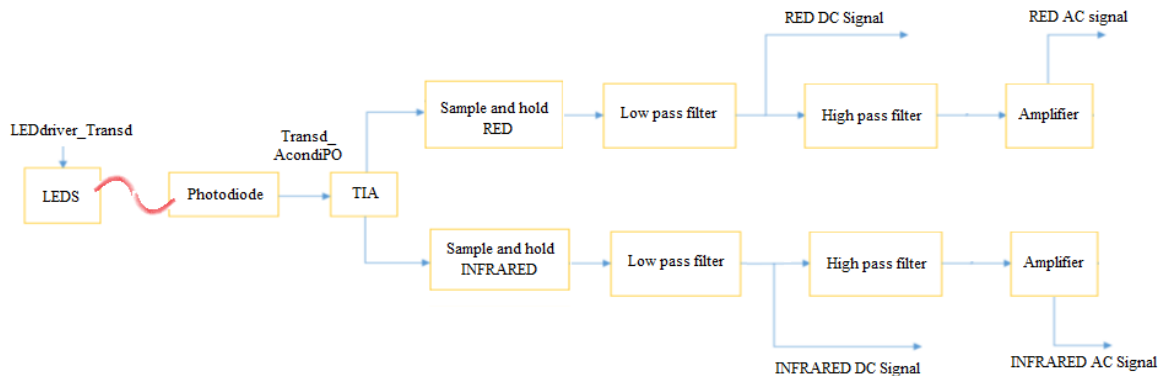
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Pulse oximetry transducer and signal conditioning block

The pulse oximetry method was chosen to measure the heartrate and blood oxygen level variables. With this method, the transducer is an optical element, which has more than one light emitting source and a light detector. Due the fact that the blood has a higher absorption coefficient in the wavelengths for red and infrared lights, the selected sensor must have these two LEDs. The selected sensor for this module is the SFH7050 from Osram Semiconductors, a MEMS technology sensor (Micro Electro Mechanical Systems) consisting of a red LED, an infrared LED and a photodiode.

The Signal conditioning block that measures the AC and DC signal provided by each LED is described in Figure 4.

Figure 4. Block diagram of Pulseoxymeter transducer and signal conditioning stage - AC and DC signal measurement with synchronous demodulation. Adapted from [13, 14, 15]



Source: Authors own creation

LEDs will be handled by two PWM signals from the microcontroller 1 (LEDdriver_Transd), one for the red LED and another one for the infrared LED. These signals must be square with a frequency of 500 Hz and with a duty cycle of 11%, and delayed 600us, so that in subsequent stages the correct sampling is done.

Transimpedance amplifier (TIA): It is a current-to-voltage converter, which is implemented for the conversion of the current passing through the photodiode to a voltage signal.

Sample and hold (S&H): Sample and hold allows us to obtain the TIA envelope signal. The chosen configuration has a MOSFET and a capacitor, with two amplifiers to be used as a voltage follower. The calculation of the capacitor will depend on whether the sampling of the signal is optimal or not.

Low pass filter (LPF): The LPF is used to obtain the DC signal component. The LPF is a Butterworth filter of order 8, with Sallen Key configuration. It was designed with a cut-off frequency at 3 dB of 5.5 Hz.

High pass filter (HPF): The HPF is used to obtain the AC signal component. The HPF is a Butterworth filter of order 8. It was designed with a cut-off frequency at 3 dB of 0,3 Hz.

Non-inverting amplifier: The signal is amplified so that it enters the microcontroller with the greatest possible excursion, and thus take advantage of its dynamic range. The amplifier gain is set at 11 V/V, so that the maximum value at the output in the signal is 3.3 Vpp.

Microcontroller block 1

This block is in charge of doing the analog-digital conversion, storing and processing the signals. Several signals are presented at the input, but they are mainly of two types: an analog voltage signal with the maximum AC input excursion, as allowed by the chosen device, and with a DC level of half that signal; it is a signal that will be between 0.5-5 Hz, and a DC voltage signal. The output signals of this block are digital signals that indicate the estimated heart rate and blood oxygen level.

For this stage it is required a micro controller with the following specifications: a minimum of 4 analog inputs, 3.3V supply voltage, analog-digital conversion with high resolution, surface type packaging, a minimum of 2 timers, low power consumption and serial communications. The microcontroller DSPIC33FJ128GP from MICROCHIP was selected, since it has a 10bits ADC, 21 I/O pins, I2C, SPI and USART communications, high processing capabilities at 40 MIPS, and low power consumption.

Indicator diodes: Pins 7, 8 and 9 were configured as output pins to control 3 LEDs (connected in series to 1 kW resistors) to visually check the behavior of the microcontroller.

Timers: The used 16-bit timers are the modules called Timer 1 and Timer 2 synchronized with the 32 kHz crystal oscillator available on the device, configured as shown in Table 1.

Table 1. Timers setting.

Timer	Counting	Pre-scale	Period
Timer 1	811	1	220 us
Timer 1	1180	1	320 us
Timer 1	4570	1	1240 us
Timer 2	14453	256	1 s
Timer 2	14453	256	1 s

Source: Authors own creation

Timer 1 controls the on and off of the pulse oximeter module LEDs, while Timer 2 creates 1 second time windows to perform the necessary calculations.

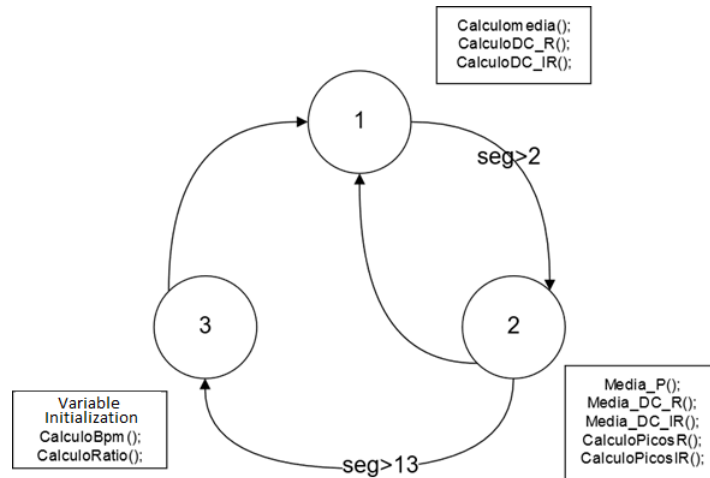
UART communication: The UART is initially disabled while the microcontroller is configured, but it is later activated to operate at a speed of 9600 bauds.

Analog to digital converter: It was configured at 10-bit mode and channels CH0, CH1, CH2 and CH3 were used. The reference voltages were established as follows: VREFH in 3.3 V and VREFL in GND. The output format data is unsigned integer format, and the operation was established in manual sampling and automatic conversion; setting the ASAM register to 0 and the SSRC register to 7. Therefore, the 4 analog signals enter to the microcontroller at

different times. The 4 signals are 2 AC signals and 2 DC signals of the red and infrared LEDs, they come from the conditioning stage. During the first 2 seconds of program execution, the average value of the AC signal of the red LED and the average value of the DC signal of the red and infrared LED are calculated. After the initial 2 seconds and for 10 more seconds, the program calculates the AC signal peaks of both LEDs.

The heart rate is detected and calculated when there is a rising edge that passes through the crossing of the average of the AC signal of the red LED, and the zero crossing counter is increased by one. Finally, upon reaching the second 13, the proportion R of the blood oxygen level is calculated and estimated according to the calibration equation, which will be found in the results section After processing, the information is sent to the wireless communication stage and initializes all the variables, setting them to 0. Figure 5 shows the state diagram of main program.

Figure 5. Main program state diagram Module 1.



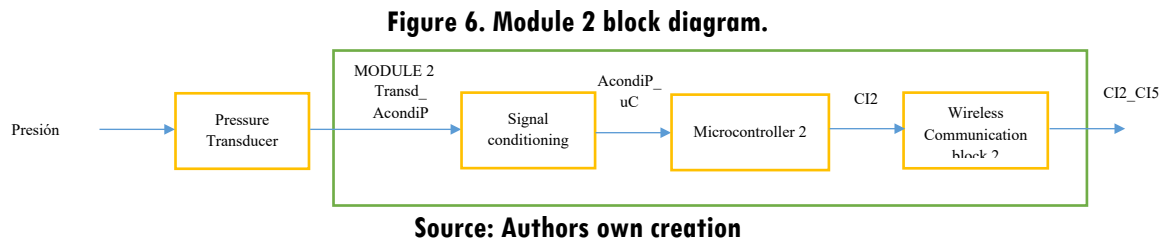
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Wireless communication block 1

This block is in charge of encoding and sending the acquired measurements through the wireless channels. This block uses Bluetooth technology, which works on the 2.4 GHz ISM band, allowing to create a small network of devices, within an acceptable communication range (~100 meters). Bluetooth 4.1 and its BLE mode (Bluetooth Low Energy) were selected, since it allows important battery savings during long periods of operation of the device. The MICROCHIP RN4020 module is selected because of its low power consumption characteristics in active mode and its low cost.

Module 2 – Safety

Module 2 is responsible for monitoring if the carabiner is secured to the lifeline. The module has a conditioning stage that adapts the signal coming from the transducer and a wireless communication stage to send the information to the central module. This is a digital signal, with each state representing the hook/release of the carabiner on the lifeline. It must withstand at least 700-900 g, which is the standard weight of a carabiner. This module will be located directly on the carabiner used by “User 1” to get attached to the lifeline. Figure 6 shows the block diagram related to Module 2.



Pressure transducer and signal conditioning block

This block is in charge of adjusting the analog signal which comes from the sensor, including a voltage converter amplifier and a comparator. The input signal is generated by the transducer and the output is an analog signal with an average different of 0.

To measure the safety of the carabiner on the lifeline, a contact or force pressure transducer is needed to detect when there is a connection between the carabiner and the lifeline. A Tekscan sensor is chosen because of the range of force measurement (0.1 a 44 N) and because of its smaller sensing area (3.80 mm).

Voltage converter amplifier: This stage is using an amplifier with voltage output, which for a given resistance has a voltage value, while if the transducer is not being pressed, the output is close to 0 V. A 1MHz bandwidth amplifier (MCP6001) was used for this purpose.

Comparator: A comparator (LM2904) is used to set the input signal in one of the two fix states, high voltage or low voltage, depending on the threshold, 900mV in this case. This stage’s power supply is +/- 3 V, therefore this module is powered with a 3 V battery, where the LM2937 regulator is utilized to generate 3 V, and the ICL7660 converter to generate -3 V.

Microcontroller block 2

In this stage, the same microcontroller from Module 1 is used, which implemented a solution for the debouncing effect produced by the conditioned signal of the pressure transducer using Timer1 and a Finite State Machine (FSM) software implementation.

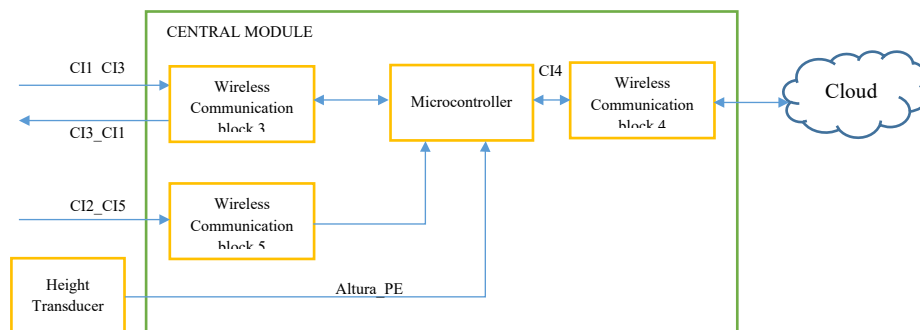
Wireless communication block 2

This block is in charge of encoding and sending the acquired data using the wireless communication module. In this stage the same Bluetooth communication device of Module 1 is integrated.

Central Module

This module is in charge of receiving all the information from the other modules, which is then uploaded to the cloud. This module is also responsible for monitoring the height at which “User 1” is located, and its goal is to communicate with the cloud and implement the data flow with “User 2”. This module has a processing stage to estimate the height through a transducer, a wireless stage to communicate with the other two modules of the system and another communication stage to send and receive data from the cloud. A block diagram of the Central Module is presented in 7.

Figure 7. Central module block diagram.



Source: Authors own creation

Height transducer

The height at which the worker is in relation to the ground is desired, however by using a barometric transducer we can estimate the height of the worker's position with respect to the sea level, with a resolution chosen of 1 meter. A sensor with low latency should be used, since “User 1” is in constant movement. A typical barometric transducer can measure this

height with less than 1m accuracy, and for this project the MS5611 sensor was selected because of its resolution (10cm) and pressure interval (10 to 1200 mbar).

Communication stage between modules

This stage has two RN4020 modules, implementing the wireless communication block 3 and block 4. Each one was configured as the central role, and they will be connected respectively to the communication interfaces of Modules 1 and 2.

Processing and cloud communication

For processing and wireless communication with the cloud, a robust communication protocol is required. The development board named “Particle Electron” supports 3G communication and it was chosen because it has 3 UART ports and 1 I2C port (necessary for this project) an extensive documentation for connecting to several IoT platforms, such as Ubidots, Microsoft Azure and Google Cloud, and a small size form (50 mm x 20 mm).

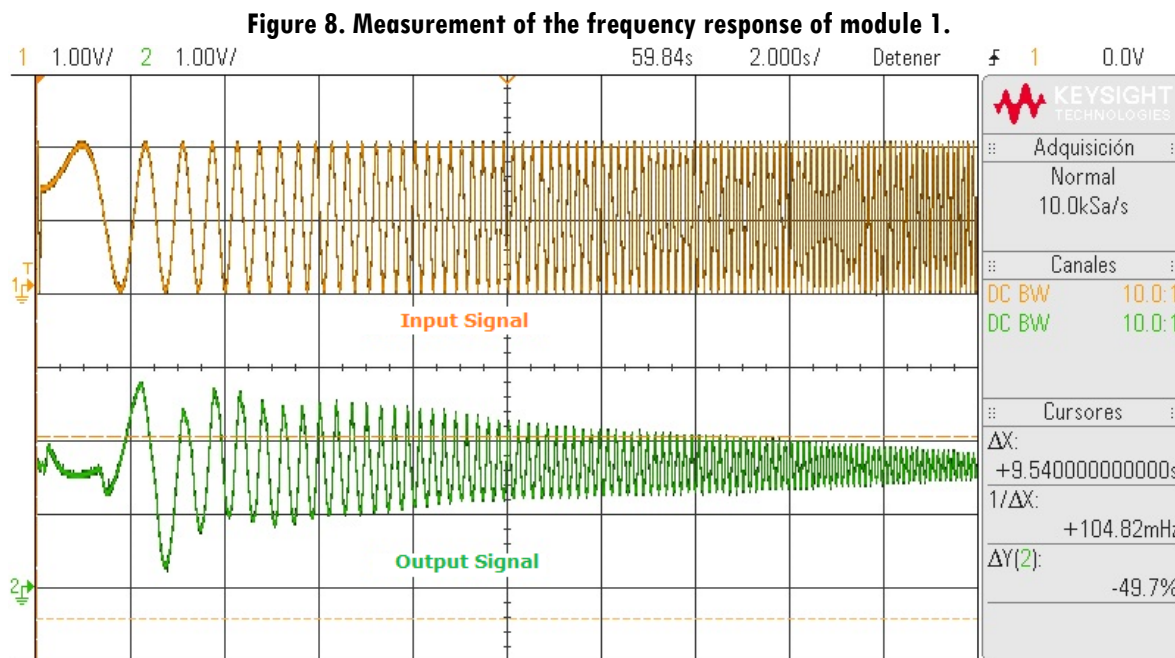
The ATOM ID platform was utilized to create a C code to program to implement the following functionality: 1) It should receive data from Bluetooth pairs 1-3 and 2-5 respectively; 2) It must initialize the height module, configure the sensor and receive the data; 3) Every 5 seconds it has to create the packet with the acquired information (heart rate, carabiner assurance, blood oxygen saturation and height). The developed code was also based on an FSM approach.

Cloud and website

Ubidots was chosen as our IoT cloud platform, because it is flexible, easy to integrate and visualize the information. The variables are sent from the Central Module through the Particle Electron using the TCP protocol and the POST method, where each variable is assigned a unique name for ID. By utilizing the Firebase platform, it was possible to create a hosting to access the website from any mobile device and/or computer. The website shows the data from the cloud, which are requested (every 5 seconds) using the Ubidots RESTful API using the GET method, where it is necessary to have the identification number of each variable and the Token value generated by Ubidots.

Results and Analysis

This section presents the executed experiments and the corresponding analysis. Module 1 conditioning stage frequency response is tested using a KEYSIGHT oscilloscope. Figure 8 shows the frequency response, coming from the filters and leaving through the non-inverting amplifier. The attenuation frequencies were measured at 3 dB, giving 204.6 mHz to 7.6 Hz. The cut frequency error was around 30%. Regarding signal amplification, the gain error was 5.6% for the red LED and 7.6% for the infrared LED.



Source: Authors own creation

Module 2 voltage measurements at the output of each block of the conditioning stage were recorded 20 times for two emulated situations (with resistance and open). It is observed that the results are as expected with an error in the order of tens of mV.

Table 2. Voltage measurements of the conditioning stage for module 2.

Resistance	Voltage output converter	Comparator output
500 K Ω	1,5 V	2,8 V
0 Ω	0 V	1 V

Source: Authors own creation

After the corresponding electronic characterization, modules validation is performed. First, Module 1 is calibrated and validated using the OxyWatch, a commercial pulse oximeter. The data were recorded 20 times for one user and when plotting this data and doing the linear

regression to obtain the relationship between the proportion R and the oxygen saturation in the blood, the results were inconclusive. It was then decided to use the standard calibration curve for commercial pulse oximeters given by Equation 2:

$$SPO_2 = -33,772 * R + 120,46 \quad (2)$$

After calibration, 20 values were taken for one user, with module 1 and with the OxyWatch. An absolute percentage error of 3.56% was estimated for heartrate, and 1.1% for blood oxygen level. The measurement of blood oxygen level compared to the specifications, gives a range of 90 to 99%, a resolution of 2% and an accuracy of less than 4%. While the measurement of heart rate compared to the specifications, gives an interval of 30 to 240 bpm, a resolution of 6 bpm and an accuracy of less than 4 bpm. These results are acceptable and are in the range established by the WHO.

For Module 2, 10 hitch-release repetitions were taken with the help of one user. It was recorded a success of 9/10, because sometimes the user did not place the carabiner completely on its main axis. The success percentage was of 90%, and this is because in the failed test the worker did not place the carabiner correctly on the main stand, which should not be the case for an experienced worker.

For the central module, the height sensor was validated recording 10 times the data for each floor of the Engineering Building of the Pontificia Universidad Javeriana (Table 3). Considering the average height for each floor is 2.5 to 3 m, it can be said that the sensor properly operates. The offset for these measurements is Bogota's altitude, which is around 2500m where the experiments were performed. As observed, the results are as expected with an error in the order of tens of cm.

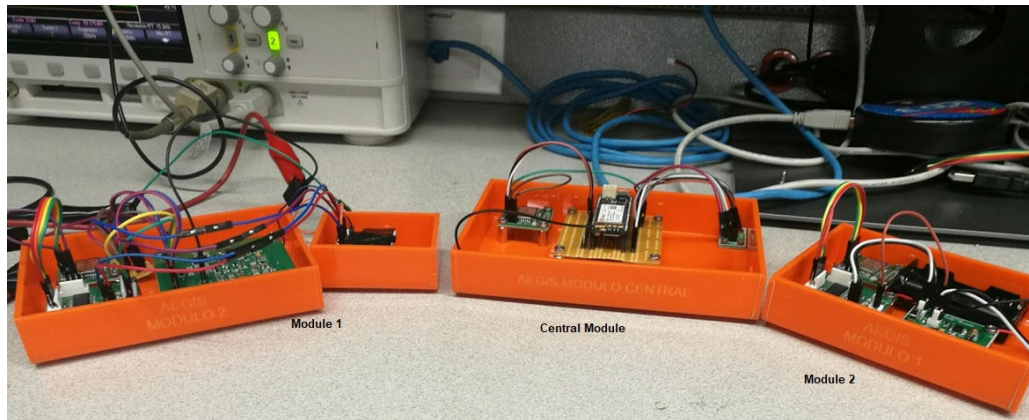
Table 3. Height measurement at the Engineering Building

Floor	Height
6	2514,75 m
5	2512,11 m
4	2509,14 m
3	2506,42 m
2	2503,61 m
1	2500,46 m

Source: Authors own creation

After modules validation, the integrated system was also tested. The final size of the prototype is 1,560 cm³, with a weight of 1 Kg and an approximate total consumption of 340 mA, where Module 1 consumes 100 mA, Module 2 consumes 20 mA, and the Central Module consumes approximately 220 mA, with transients between 800 mA and 1.8 A when it is uploading data to the cloud.

Figure 9. AEGIS system prototype.



Source: Authors own creation

Figure 9 presents the final prototype achieved in this project and Figure 10 shows the results on the website, compared to a measurement of the OxyWatch, when the carabiner is secured, and located at the sixth floor of the Engineering Building of the Pontificia Universidad Javeriana.

Figure 10. AEGIS system validation



Source: Authors own creation

Conclusions

A prototype IoT system was designed, implemented and verified for the monitoring and visualization of a worker at height. The system designed consists of three modules and a web interface. The system allows real-time measurements and connectivity between physical variables and the cloud, which is a basic requirement for IoT.

For Module 1, movement is a fundamental factor for the success of heartrate and oxygen saturation measurements. Therefore, a more complex analog design that has compensation for various factors, such as optical variation and motion, is required. In addition, flexible PCBs could be considered in order to ease the installation and usage of the system by the worker.

For Module 2, the presence of the carabiner on the lifeline has been properly detected. With this system, the dead weight of the user is not measured in the event of a fall. This equipment has low power consumption, very simple and cheap electronics and a positive anti-rebound system. Since the measured error was of 10%, it is necessary to consider more robust transducer options, which can guarantee the use of the module under different conditions, such as changing surfaces, different sizes of carabiners and workers' weight.

For the Central Module, it is suggested to perform calibration of the height transducer. It is also suggested to work on increasing the efficiency of sending data to the cloud, which implies, consolidating the collected data and transmitting the packets only when there is a significant change in the measured variables, which might reduce the power consumption and the data plan requirements.

As part of our future work, it is suggested to work on the miniaturization of the system and its ergonomics, because the system should be used in a daily basis, without preventing the normal movement and behavior of the worker.

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