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Instrumentation and digitalization of a hexapod robot aiming the inspection of aeronautical structures

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Abstract. *The use of robotics in the industry is a strategy that has been increasingly implemented, since it became a good alternative to substitute some manual work in order to optimize the safety of the process. In this context, the application of mobile became an important research topic due to the need of devices capable of dealing with irregular terrain and accessing hard-to-reach places. The main goal of this article is to develop the instrumentation and digitalization of a hexapod robot designed for the inspection of aeronautical structures. This is performed by the online monitoring of the activities of the mobile robot during its operation. Low-cost sensors and an ESP8266 fast-prototyping hardware are used to develop the monitoring system. Also, inspired by the IoT concept, understood as a connection capable of interconnecting physical objects to the web transmitting its data to the network, the sensor signals collected during the operation of hexapod are transmitted to a cloud-based IoT software called ThingSpeaks. It receives the data from the sensors read by the ESP8266 microcontroller through wireless communication. Then it transforms this data in a graphic dashboard representation that can be remotely monitored by the technical staff during the inspection of aeronautical parts.*
Keywords: *Low cost digital data acquisition system, Internet of Things, On line Monitoring, Robotics, ThingSpeak.*

1. INTRODUCTION

In the current globalized world, a country is measured economically by its technological capacity and increasing immersion in the digital world, following the new economic cycle based on industry 4.0. Such term is understood as the concept of industrial automation and integration of different Technologies – artificial intelligence, robotics, IoT (internet of things) and cloud computing – in order to promote the digitalization of factory activities with process improvement and productivity increase. In this way, through new technologies like Internet of Things (IoT) and computing in cloud organize production on a flexible Cyber Physical System (CPS) systems horizontal where the data generated at each stage of the process can be accessed quickly and used for factory changes. These are called "Smart Factories" (Bartodziej, 2017).

Specifically in the aeronautical sector, in order to maintain competitiveness, one of the main challenges for aircraft suppliers is the automation of structural assembly processes. Automation is essential to reduce costs, wastes, time of process cycle, and to improve the quality of the final product (Iovenitti *et al.*, 2001). One of the ways to achieve this goal is the implementation of industrial robots for general use and/or customized for a specific process.

There are several benefits associated with using robots. For the riveting process, for example, the elimination of the use of dedicated templates for drilling stands out. These templates are necessary when the operation is carried out manually and has a high cost for the supplier. For the Brazilian aviation industry, in particular, automation is an essential resource for its survival in the market (Villani *et al.*, 2010).

The evolution of robots, and in particular of mobile robots, has in recent years received a wide prominence with the media and society in general. Where in the past there was a lot of talk about industrial robots and robotic mechanical arms, nowadays the focus is on mobile robots, capable of moving in the environment in which they find themselves. It must also be considered that higher levels of autonomy will be achieved only as the robot starts to integrate other aspects considered of the greatest importance, such as: perception capacity (sensors that can "read" the environment where it operates), ability to act (actuators and motors capable of producing actions, such as the displacement of the robot in the environment), robustness and intelligence (ability to deal with the most diverse situations, in order to solve and execute tasks, however complex they may be). The use of robust planning and control techniques for navigation and autonomous operation of robots is known by the term "Intelligent Robotic Control", in which this intelligent control allows RMAs to be able to perform the most diverse and complex tasks (Wolf *et al.*, 2009).

Several studies have already been carried out, such as the control of a mobile robot via the internet with a Raspberry Pi board. The robot is equipped with a camera as well as smoke and presence sensors (PIR) in order to inspect locations to prevent burglaries or even fires (Vanitha *et al.*, 2016). Another study also in this subject is the development of a web application for mobile robots using the IoT platform. In this case, the system consists of a gas sensor, an ultrasonic sender/receiver, a micro controller Arduino board and an ESP8266 in order to measure air quality and detect obstacles during the maneuver of the robot. The ESP8266 is used to send the measurements through a router to the Android application developed for this case. Another interesting point is the activation and control of the robot's direction by the end-user through the mobile application (Jain *et al.*, 2020).

To achieve such an implementation, some platforms become supportive and essential in the process. It is at this moment that the connection with the concept of Internet of Things occurs. IoT is the ability to provide efficient data storage and exchange through the interconnection of physical devices through electronic sensors and the internet (Pasha, 2016). With this connection and automation, it is possible to avoid unhealthy and dangerous work so far performed in person by humans. Another interesting point to be mentioned is the ability to remotely monitor the activities to be performed and to store and manipulate data in the cloud, contributing to a more detailed analysis of the measurements and possible solution of unnoticed errors.

Given all these factors, the present paper aims to contribute to the extension of the use of robotics and sensors in a bio inspired hexapod robot which obeys animal patterns found in nature, since most of arthropods contains 6 legs, this type of robot can be considered robust in the case of failure in one of the legs, as the other can continue the movement (Miripour-Fard, 2010). The focus of this study is on the aeronautical segment, exploring versatility and mobility of this type of robot for productive purposes. Both in the manufacturing and assembly processes and in the maintenance of aircraft, certain quality inspections are carried out visually, which limits the precision involved in these tasks. For greater reliability of these analyzes, recent researches are exploring mobile robotics solutions. Thus, this study seeks to help in minimizing the safety problems mentioned above, which, by means of the instrumentation and digitalization of a hexapod robot, intends to conduct the inspection of rivets in the coatings automatically. In the present study, the instrumentation of the system as well as the integration of the sensors with an IoT platform is performed.

The article aims to perform the instrumentation and digitalization by an ESP8266 prototyping board for the monitoring of the operation of a hexapod robot. For this, a cloud storage platform (ThingSpeak) capable of obtaining the values read by the sensors at certain time intervals was used.

2. HEXAPOD ROBOT

The study of the applicability of the hexapod robot is not new. This kind of system has a diverse set of applications in many areas. A study by Andrade *et al.* (2017) showed the approach applied to use this system on uneven terrain using the FreeBSD operating system and the BeagleBone Black embedded systems board. The choice of a hexapod system was justified since it facilitates the movement and the avoidance of obstacles.

Nguyen *et al.* (2017), on the other hand, prepared an article in which an optimization of the bio-inspired hexapod based on the S-Hex I, the S-Hex II, was presented. The new robot had 5 degrees of freedom, instead of 3, and it was also smaller and lighter than previous versions, in addition to being driven by dielectric actuators.

Another relevant research to be mentioned is the construction of an hexapod robot with the objective of climbing a step up to 230% greater than the length of the leg of the robot (Chou *et al.*, 2012). It consisted of an inclinometer - to measure the inclination of the body and calculate the height of the step, allowing the robot to adjust its walking automatically - and an infrared sensor - to detect the step.

The present paper shows a continuation of the research development of an hexapod robot, which aims precisely at the inspection of rivets in aeronautical structures. The current version of the constructed system is illustrated in Fig. 1. The objective is to improve the robot's locomotion and location through the insertion of sensors to monitor the motion of the robot (accelerometers, gyroscopes, GPS, ultrasound and infrared). All performance data are sent to ThingSpeak which is an IoT platform used to interact physical objects through the internet. Thus, it is expected that this work will be able to encompass the entire context of industrial digitization and bring yet another improvement related to the hexapod robot, making its possible implementation in the aeronautical industry more concrete to assist in future operations more efficiently, quickly and accurately.

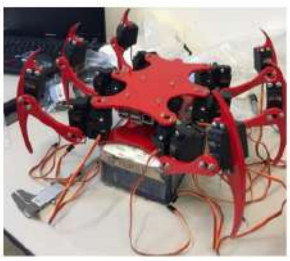


Figure 1. Illustration of used hexapod robot.

The proposed hexapod robot to perform this task is a model with three servo motors MG90s tower pro model per foot (18 in total), with operating voltage 4.8-6.0V, torque of 1.8kg/cm(4.8V), 2.2kg/cm(6V) and operating speed of 0.1sec/60degrees(4.8v),0.08sec/60degrees(6v), controlled by a SSC-32 servo motor controller. This device is connected to a Raspberry Pi 3 single-board computer. This hardware is connected to a camera, which is used to detect the presence/absence of fasteners in an aeronautical structure. A GPS (Global Positioning System) module and any other peripherals that need to be added to the robot are connected to the Raspberry Pi. The operating diagram of this hexapod robot is shown in Fig. 2 and the CAD model of the robot used is the one shown in Fig. 3.

About the robot, it is important to emphasize that it is not a commercial model and was developed by the UFSCar research group, but it is based on other hexapod robots like, for example, the hexapod robot shown by FAIGI and ČÍŽEK in "Adaptive Locomotion Control of Hexapod Walking Robot for Traversing Rough Terrains with Position Feedback Only". Your choice for its versatility in various types of terrain, while maintaining stability by maintaining three points of contact with the ground.

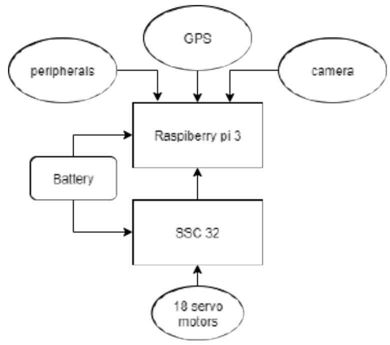


Figure 2. Operating Diagram of the Hexapod Robot System .

Figure 3. CAD model of the hexapod robot, made by the UFSCar study group .

As illustrated in simplified form in Fig. 4, the robot, with a processing unit, will send the data to the IoT platform - ThingSpeak - that enable one to remotely visualize information in real-time during the inspection operation carried out by the hexapod.

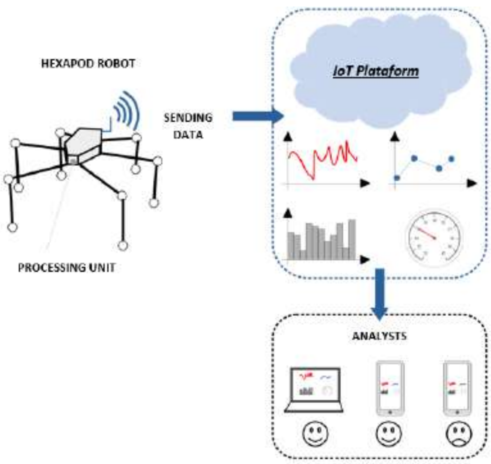


Figure 4. Schematic diagram of the proposed project.

3. MONITORING OF THE HEXAPOD ROBOT

3.1 Instrumentation Hardware

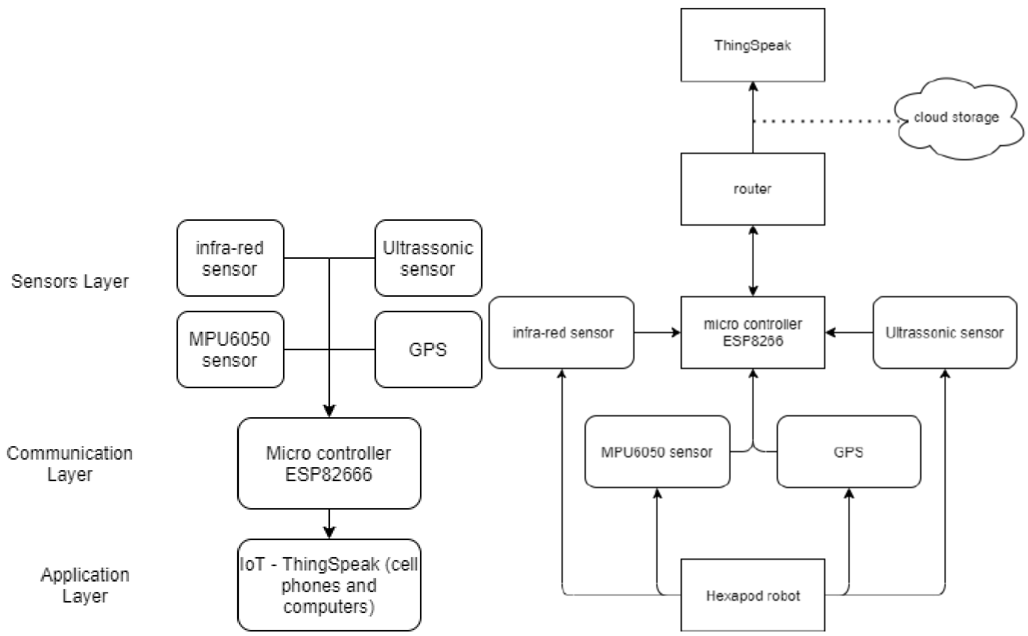
For the development of the project, the four types of sensors were specified to monitor the operation of the hexapod robot: an inertial measruement unit (IMU), ultrasound sender-receiver, GPS module and an infra-red sensor. The instrumentation proposed for this research is presented in Table 1.

Table 1. Sensors properties

Sensors	Communication with micro controller	Input voltage
Ultrasound (HC-SR04)	Two digital pins	5V
Inertial Measurement Unit (MPU-6050)	I2C port	5V
GPS Module GY-GPS6MV1	RX and TX	5V
Infra-red (E18-D80NK)	two digital pins	3,3-5V

The measurements were coordinated by the Raspberry Pi 3 computer and an ESP8266 fast-prototyping board. The last one is used as an interface with the sensors to be connected to the hexapod system. The MPU6050 module in an integrated chip with a triaxial accelerometer, gyroscope and a thermometer. In this paper, specially the accelerometers and gyroscopes were used to provide the spatial orientation to the robot during its maneuver in the inspection of aeronautical parts. This type of sensor will be important for the motion of the system, especially on curved surfaces like the case of airplane fuselages. A GPS GY-GPS6MV1 module will be attached to the robot to provide its positioning information, while the ultrasonic HC-SR04 and infrared sensor will allow to avoid obstacles during the maneuvers.

To allow the digitalization and remote monitoring of the operation and motion of the hexapod robot, the sensor data is sent over the wireless network by the ESP8266 chip to a free Internet of Things platform (ThingSpeak). It allows the sending and storage of measurements over time, in addition to enabling multi platform remote access by users and process analysts. The flowcharts in the Fig. 7 serve to more clearly exemplify the layers to be worked on, as well as their connections as a whole.



(a) Layer of the Robot Control System. (b) Hexapod Robot System applied to IoT.

Figure 5. Layers and connection of the system.

Figure 5a shows the 3 hardware layers present in the process, which are sensors, communication (microprocessor) and application (IoT platform). In Fig. 5b, it is possible to observe how these layers interact in a more detailed way, that is, what is the direction of the established processes from the robot to the sending and storing of data for the platform.

3.2 Description of the experimental test

In order to validate the measurement provided by the sensors, tests were necessary to simulate the robot's behavior during its operation in a real environment. For this paper, two sensors previously presented in Table 1 were tested: the ultrasound module (HC-SR04) and the inertial measurement unit (MPU-6050).

At first, the reading was performed and implemented individually in order to avoid errors in the analysis and bring more assertive data. After the validation of sensor readings, the interface with the ThingSpeak platform was implemented to illustrate the measured signals through a graphical representation in the online platform. Finally, after observing the proper working of the system for individual sensors, all the measurements were integrated to be performed in parallel in order to validate the ESP8266 as being able to handle the sensor data and sending it to the IoT platform.

In order to test the HC-SR04 module the experiment was based on the elaboration of a code capable of measuring the distance of an object placed in front of it as depicted in Fig. 6. This test simulates a situation where the robot has an obstacle in front of it. The experimental part was configured in such a way that the sensor was fixed on a flat base and an object was approached and removed. The measurement obtained, for validation, was done with the aid of a ruler or measuring tape to prove that the obtained values corresponded to the nominal value.

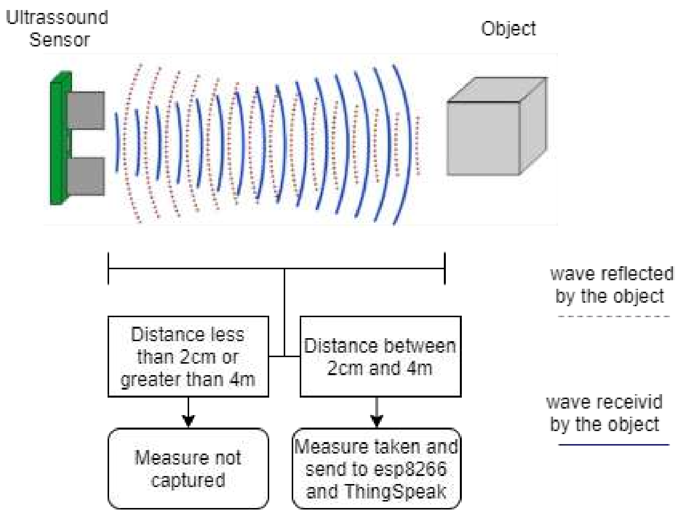
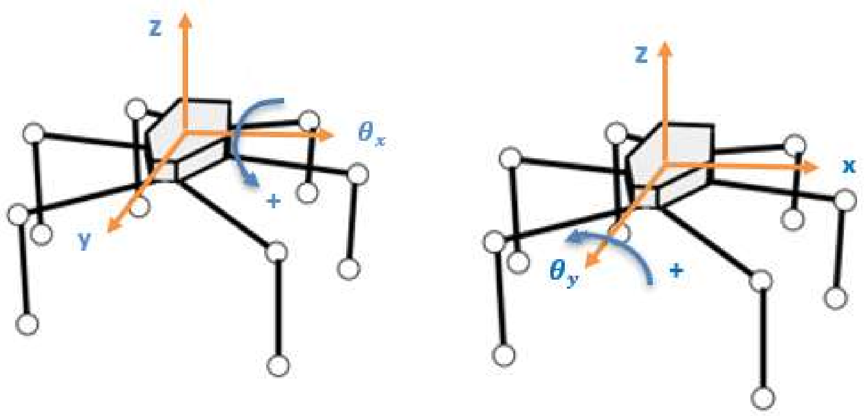


Figure 6. Test simulation with ultrasound sensor (Source: adapted from - https://www.ricardoteix.com/visao-geral-sobre-o-sonar-hc-sr04/).

As for the MPU-6050 module, it provides 7 measurements: from the triaxial accelerometer and gyroscope, and one from the temperature sensor. All these sensors are integrated in a single chip. To carry out the programming, it was necessary to establish a reference base of the coordinate axes shown on the sensor. In this case, the established measurement base is shown in Fig. 7.



(a) Positive rotation X. (b) Positive rotation Y.

Figure 7. Positive orientation based in initial orientation adopted.

The code to process the IMU data and provide the angular orientation of the hexapod robot was based on the a_X, a_Y and a_Z accelerations components measured by the module. The rotation of the robot with respect to the Y and X axes were calculated by a simple geometric relationship related to the orientation of the system with respect to the gravitational acceleration as shown by eq. (1) and (2):

$$\theta_X = \arctan\left(\frac{a_Y}{\sqrt{a_X^2 + a_Z^2}}\right) \tag{1}$$

$$\theta_Y = \arctan\left(\frac{a_X}{\sqrt{a_Y^2 + a_Z^2}}\right) \tag{2}$$

where θ_X and θ_Y are the rotation angles in radians with respect to X and Y respectively. These angles can be related to the roll (θ_Y) and pitch (θ_X) angles of the robot during the motion of this system in curved surfaces. The monitoring of these parameters can be important to avoid the fall of the robot during the inspection of aeronautical parts.

Despite being an easy way of calculating the orientation of the hexapod robot, if the structure suffers from significant accelerations other than gravitational acceleration or mechanical vibrations higher error values on θ_X and θ_Y are expected.

3.3 Integration of the hardware with an IoT platform

Before commenting on the results, it is interesting to give an overview of the IoT platform used in this application. ThingSpeak allows one to remotely aggregate, view and analyze data in the cloud. It provides instant visualizations of data posted by devices or equipment's, executes MATLAB codes and performs online processing of the data as it arrives. In this paper the platform is used due to its integration with the MATLAB language, as well as the possibility of free academic use during the tests.

For a proposed instrumentation, a programming performed on the Arduino Software and a free license from ThingSpeak. It includes a few limitations such as:

- 3 million messages per year;
- 8 fields per channel;
- Availability to create up to 4 channels;
- Messages up to 3000 bytes.

Despite these limitations, the platform can be used to remotely monitor the sensor data connected to the ESP8266 board. Also, it is possible to access the platform in multiple and different devices in parallel as computers and mobile devices through the internet.

4. RESULTS

This section presents the main results when testing the Ultrasound HC-SR04 sensor and MPU6050 module for the monitoring of the operation of an hexapod robot.

4.1 Test of the ultrasound sensor

The verification test was carried out in order to place an object at a distance close to 30 cm and gradually approach it to the sensor up to 2 cm. The curve follows a decay as the distance decreases and the values obtained were consistent with reality. The proof with the actual measurement was made by comparing the values presented by the sensor with the measurement of the measurement performed with the aid of a ruler. Therefore, there was consistency of the values obtained by the sensor, following a linearity with the expected result of the experiment.

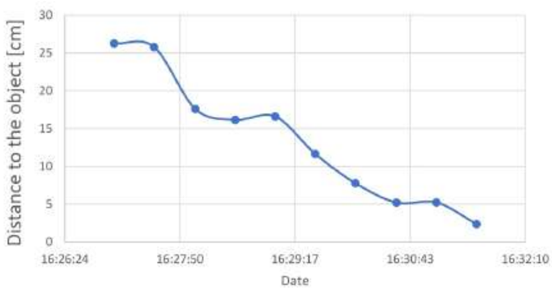


Figure 8. ThingSpeak Communication only with Ultrasound.

4.2 Test of the MPU6050 module

For the experimental part of the MPU6050, the following test was performed: the initial reading was taken in the established position as shown in Fig. 9. After that, θ_Y was rotated, in the positive direction, to about 45^o, then 60^o and finally 90^o. Right after, the sensor returned to the initial position and this same process was done for θ_Y rotating in the negative direction. The same procedure explained above was performed for θ_X after the end of the y rotation. Figures 9 and 10 shows the acceleration and rotation measurements calculated as previously explained during the maneuver. Meanwhile, the temperature sensor reading are also showed in Figure 11.

A relevant point to note is that, during θ_Y rotation, for values greater than 0 and less than +90^o the acceleration vector will have positive resulting components in x and z. For rotations between 0 and -90^o, the acceleration components in x and z will be negative. The same is true for θ_X. As it rotates between 0 and +90^o the acceleration will have resulting components in y and z with a positive sign and, for values between 0 and -90^o, it has a negative sign, showing agreement with the right hand rule as well as with the expected values for the analysis.

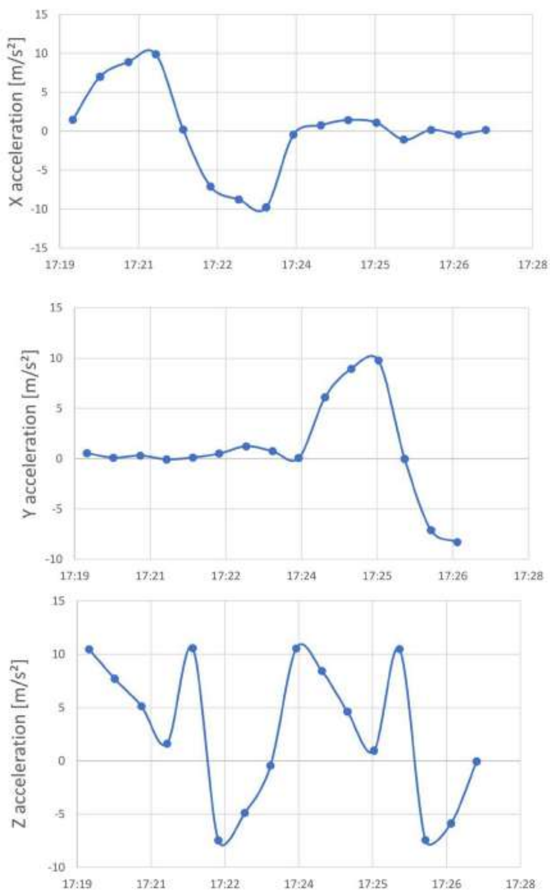


Figure 9. MPU6050 acceleration data seen on ThingsSpeak.

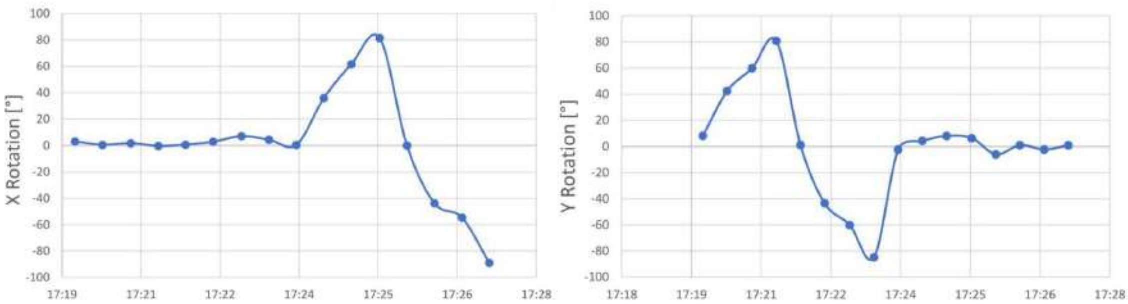


Figure 10. θ_Y and θ_X rotation measurements based on data received by ThingSpeak.

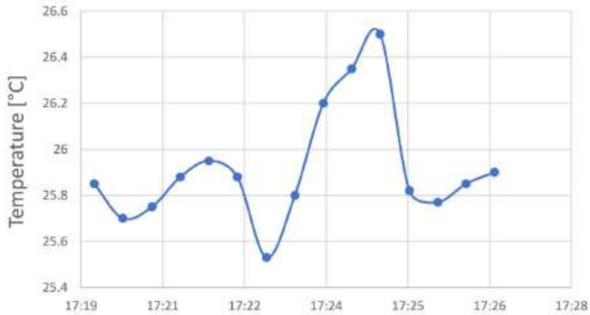


Figure 11. MPU6050 temperature data seen on ThingsSpeak.

4.3 Results for simultaneous measurement of multiple sensors

Finally, Fig. 12 illustrates the operation of the MPU6050 and Ultrasound at the same time, as well as the results obtained by ThingSpeak. Is is possible to observe the data every 15 seconds which allows one to observe the operation of the hexapod robot. It is important to notice that this time period is a limitation of the free version of the ThingSpeak platform used in this paper. Higher sampling rates are possible when using the ESP8266 prototyping board, although the cloud platform would only be able to show these information every 15 seconds. The authors found that sampling frequencies of up to 500 Hz are possible depending on the length of the signals to be stored in the internal memory of the ESP8266.

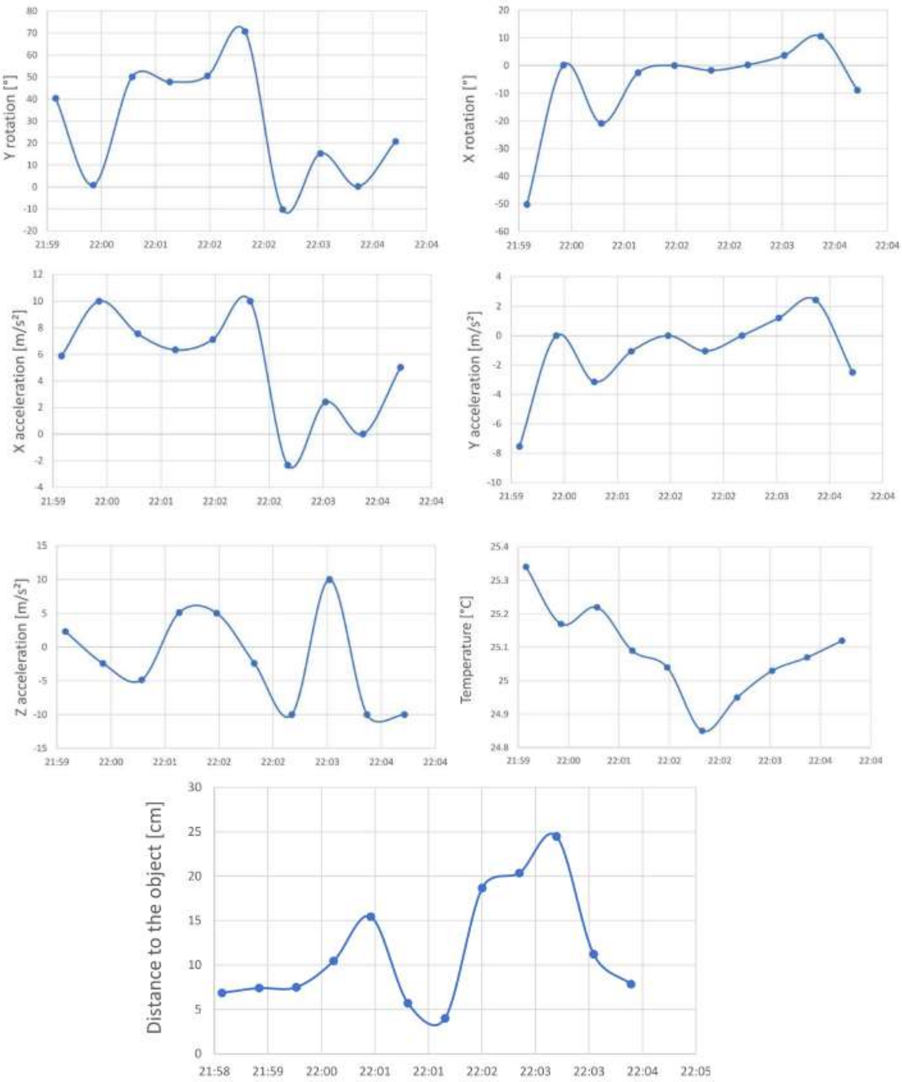


Figure 12. MPU6050 and Ultrasound measurements based on data received by ThingSpeak.

5. CONCLUSION

In the present study, the use of low-cost sensors, such as the MPU6050 and the Ultrasound HC-SR04, were experimentally verified. With the help of a code that met the purposes of the study and the use of the ThingSpeak IoT platform, it was possible to observe the analysis of the data collected in real time, in order to provide relevant information about the monitoring of the robot, such as the presence of obstacles, as well as the slope of the terrain and the temperature of the environment.

It was also possible to observe a great applicability of the created process. This is due to the fact that it brings new horizons regarding instrumentation and application in robotics. The use of such tools can be expanded so that it is not restricted to the inspection of aeronautical parts, but it can also also be explored in places that are difficult to access and not only in the field of aeronautics. The schedule provides a targeted activity and the IoT platform the collection of data that can be tracked remotely. The proposed monitoring system could also be used to monitor multiple robots performing different tasks in the shop-floor. This allows one to have a complete view of these systems.

However, some point must be taken into consideration about the article.The purpose of using the ESP8266 board was to integrate it into the sensor system used. The other components that are part of or that could be implemented in the robot do not necessarily need to be integrated with it.

6. ACKNOWLEDGEMENTS

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