A Low Cost Configurable Vibration Meter Based on Accelerometers

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***Abstract*—The study and understanding of physical phenomena of vibration and oscillation is an important field of engineering, contributing for the development of new materials and construction models, as well as for the improvement of safety in buildings and machines. The availability of good instrumentation, in this case, is essential for capturing data and validating analytic models. This paper describes the implementation of a system for the measurement of vibration and oscillation based on low-cost, good precision accelerometers. The proposed system is composed of six accelerometers, one microcontroller, two communications interfaces, one RTC module and one Bluetooth module. The control module is implemented with a customized microcontroller synthesized in FPGA. The implemented system is fully configurable, allowing the customization of the number of active sensors, the resolution of acquired data and the sampling frequency. Test results and comparison with a commercial accelerometer system show the correct functioning of the implemented vibration meter.**

***Index Terms*—accelerometer, sensor, PAMPIUM, vibration meter.**

I. INTRODUCTION

Understanding certain physical phenomena, such as oscillation and vibration, is of great importance, especially in the area of engineering [1]. It allows the development of new materials and construction systems that contribute to optimizing safety in engineering. A vibration meter is an instrument used in civil and mechanical engineering to measure the vibration of structures such as buildings, roads, bridges, rotating machines, pipe vibrations in industrial installations and vibration in transformer tanks. In addition, specialized vibration meter devices can be used to measure the vibration of the human body.

Some approaches to perform vibration measurement are proposed in the literature. In [2] a single-chip digital phase meter is proposed for rotating machine vibration analysis. An intelligent measuring system that includes multiple measuring nodes to acquire vibration data from a set of locations in an industrial piping system is described in [3]. In [4] the authors propose a sensor-based accelerometer monitoring system for bridge monitoring. A pipeline monitoring system composed of MPU 6050 sensors is used to measure vibrations on water pipeline [5]. In [6] a pipeline leakage wireless accelerometer sensor performance assessment is described, also using MPU 6050 as the vibration measuring sensor.

Although there are already equipment and systems capable of performing vibration and oscillation measurements in the market, most of them are not suitable for low-cost applications. Furthermore, they are in general available in a closed form, where the user has limited chance to configure the parameters and adapt for a broad range of applications. The implementation of a new system to measure vibration and oscillation aims to offer an alternative tool, providing low cost, full customization and adequate precision.

In the industrial area, the competitiveness of the world market stimulates the increase of production and improvement of products quality. This is achieved by increasing machine speed and reducing downtime. Preventive/predictive machine maintenance prevents downtime for corrective maintenance, reducing cost. Vibration meters are used to assist preventive maintenance programs. Vibration monitoring in machines used in industry includes some benefits such as: reduced production losses; enhanced efficiency, reliability, availability and longevity of machinery; reduced maintenance costs, maintenance downtime planning and optimizing safety [7]. Low cost, configurable vibration measurement systems with adequate accuracy are very important for large scale applications. With this, it is possible to reduce the cost of acquisition. The tool can be adapted to a wide range of applications and still ensures a reasonable accuracy in the collected data, which generates accurate diagnostics. In terms of industry, it would be possible to have a measuring system attached to each machine, which would allow the machine to be continuously monitored, allowing maintenance-related decisions to be made from the history of the data collected by the measurement system.

This paper describes the implementation of such a system for the measurement of vibration acceleration and oscillation based on low cost, medium precision accelerometers.

The proposed system is composed of six three-axis accelerometers, in which it is possible to measure acceleration in x, y and z coordinates. Each sensor can be activated or deactivated according to the needs of the application. The sensors are read and configured by a microcontroller, which processes the linear acceleration information delivered by the accelerometers and the correspondent measured time information provided by a Real Time Clock (RTC) module, and send them to a computer. On the computer side, we use a MATLAB interface for processing and saving data.

The implemented system is fully configurable and includes a dedicated PAMPIUM microcontroller [8]. This allows an easy adaptation to most applications. The communication with the computer takes place via Bluetooth, facilitating the connection and data transmission.

II. SYSTEM IMPLEMENTATION

The implemented system consists basically of six accelerometers, a microcontroller, two communication interfaces, a RTC module and a Bluetooth module. Fig. 1 depicts the block diagram of implemented system.

The acceleration data are collected through six MPU 6050 accelerometers, which provide linear acceleration on the x, y and z axes. The six sensors can be turned on or off according to the need of each application through switches. PAMPIUM microcontroller is used for control and configuration, as well as for reading the acceleration data collected by accelerometers. It is also responsible for transmitting acceleration and time data for a computer. The communication between the sensors and PAMPIUM is made through the I2C communication protocol. The communication between the PAMPIUM and the Bluetooth interface is implemented by the RS-232 communication protocol. Finally, the communication with the computer happens through the Bluetooth protocol [9].

Since six MPU 6050 are used, we use a multiplexer/demultiplexer unit implemented in code in the FPGA for communication between them and the microcontroller. This allows only a single I2C communication channel to be implemented in PAMPIUM. In our prototype, we used six sensors in order to attend most of the applications. For example, in vibration analysis and monitoring of rotating electrical machines, six measuring points are necessary, according to the standard regulations IEC 60034-14, NBR11390 and IEEE841 [10]. So, with the implemented system it is possible to monitor the six points at once.

Each MPU 6050 sensor has a three-axis accelerometer, responsible for measuring the linear acceleration on the x, y and z-axes, as well as a three-axis gyroscope that measures the angular acceleration over the x, y and z-axes. However for the implemented system we use only the linear acceleration data obtained through the accelerometers. The initial calibration tolerance is $\pm$ 3% and the sensitivity change in relation to temperature is $\pm$0.02 %/°C [9].

TABLE I: MPU 6050 Accelerometer Specification.

Scale Range	Sensitivity Scale Factor
± 2g	16,384 LSB/g
± 4g	8,192 LSB/g
± 8g	4,906 LSB/g
± 16g	2,048 LSB/g

The accelerometer is capable of measuring acceleration on the three axes separately up to 16g and has four programmable ranges and four sensitivity settings, as show in Table I. The unit g refers to the value of the Earth gravitational acceleration. By default, MPU 6050 is configured with a scale range of $\pm 2g$. This is the largest sensitivity scale range, which allows the measurement of small movements with reasonable accuracy [9].

The MPU 6050 sensor digitizes the x, y and z axes values collected from the accelerometers by means of three A/D (analog/digital) converters. Each accelerometer has an output data frequency of 1 kHz. The value read for each axis is stored in internal registers. The size of each internal register is 8-bits, and the precision of the accelerometers is 16 bits. Therefore, each collected value is stored in two internal registers, one for the 8 most significant bits and the other for 8 least significant ones. The values are stored in two's complement format. Communication with all registers of the device is performed through the I2C standard occurs at a maximum rate of 400 kHz and operates in a supply voltage range from 2.37 V to 3.46 V [9].

PAMPIUM is a fully configurable microcontroller developed by our group at UNIPAMPA. It consists of a general purpose microcontroller with 16-bit RISC architecture described in System Verilog. The circuit description is free and open source. Because it is configurable, it is possible to scale all the internal modules according to the applications needs, preventing the waste of area and power consumption while increasing the performance. As the description of the circuit is free and all PAMPIUM operations are performed between registers, we connect the communication interfaces as well as the activation keys of the sensors directly to the register bank, facilitating the implementation of control protocols. PAMPIUM is available in monocycle, multicycle, pipeline and superscalar versions [8]. For the prototype system implemented we used the monocycle version.

The internal organization of PAMPIUM consists of two memories - one for program and one for instructions -, two register banks, one arithmetic-logic unit (ALU) and one control unit. The register bank consists of two secondary banks. The number and the size of each register are configurable and defined by the user. In our project, 32 registers were used for each bank and each register has a word length of 16 bits. Some registers have specific functionalities for instructions or port configurations and others are for general purpose.

The program memory in the implemented version of PAMPIUM microcontroller is composed of a memory block with a 24-bit word size and a 16-bit program counter. The memory block has the capacity to store a maximum of 64 kWord instructions. The instruction word was defined with a size of 24 bits. The 6 most significant bits ate dedicated to the operation code, allowing the implementation of 64 different instructions. The next bits indicate in which secondary bank are allocated the registers used according to the instruction type. We implemented 32 out of 64 instructions in this version of PAMPIUM, suitable for the application needs [11].

PAMPIUM also has a data memory, configured in this project with 64 kB. The arithmetic logic unit (ALU) performs arithmetic and logic operations between registers, such as sum subtraction, multiplication and division. The logical operations are AND, OR, NOT and XOR.

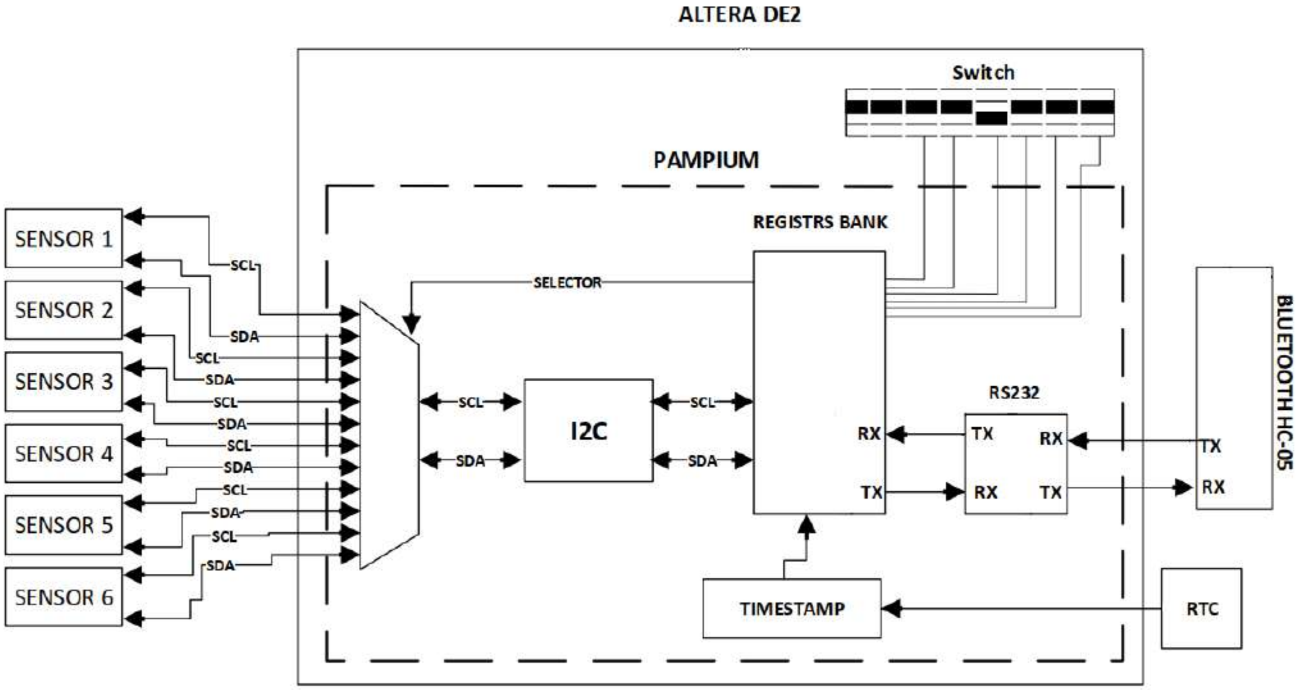


Fig. 1: Block diagram of the vibration meter based on accelerometers.

The PAMPIUM microcontroller, as well as the I2C and RS-232 communication interfaces, were implemented in FPGA using the Altera DE2 development board with a Cyclone II - EP2C35F672CN6.

The I2C interface is a two-wire serial communication protocol usually used for the connection of low complexity devices. Communication is done between a master and a slave in 8-bit packets, where the master commands the bus and the slave responds to the commands sent by the master. The communication between master and slave is performed through the SDA (serial data) pin, which is responsible for transmitting data, and SCL (serial clock), which performs the synchronization. We implemented the I2C communication interface so that its control is exercised directly by the PAMPIUM registers. For this, we allocate some bits of a specific register and connected them to the I2C interface. The communication interface connects the two input/output pins (SCL and SDA) to the sensors via multiplexer/demultiplexer. For the connection between PAMPIUM and sensors, we use the external connection pins in the FPGA [11].

The RS-232 interface is a standard for serial data communication which uses negative voltage signals for high logic level ”1” and positive for logic low level ”0”, ranging from ± 5V to ± 25V, depending on the application. This protocol presents two separate RX and TX communication channels, which makes it possible to send and receive data in parallel. We implemented the RS-232 interface in a similar way to the I2C interface, in which all control pins are connected directly to the register bank. For this, we allocated the bits of the control interface to dedicated registers in the register bank. For the communication between the interface and the Bluetooth module, we used two pins (RX and TX) [11].

Since Bluetooth protocol is asynchronous, we can not assure a constant time interval between samples. So, it is necessary to use a RTC circuit to append time information to acceleration data. The DS3231 is a serial RTC driven by a temperature compensated 32 kHz crystal oscillator. The TCXO (temperature compensated crystal oscillator) provides a stable and accurate reference clock, and maintains the RTC to within ±2 minutes per year accuracy from -40°C to +85°C. The TXCO frequency output is available at the 32 kHz pin. The DS3231 has internal registers that can be accessed through an I2C bus interface. Typical oscillator startup time is less than one second. Approximately 2 seconds after supply voltage is applied, the device makes a temperature measurement and applies the calculated correction to the oscillator. Once the oscillator is running, it continues to run as long as a valid power source is available, and the device continues to measure the temperature and correct the oscillator frequency every 64 seconds [12].

The clock/calendar of RTC module provides seconds, minutes, hours, day, date, month, and year information. The RTC module does not provide millisecond information, so we implemented a counter (Timestamp) using the 32 kHz clock provided by RTC as a reference for precise time count, compatible to the acceleration transmitting rate. The Timestamp module is connected directly to the PAMPIUM register bank, thus facilitating reading and sending time information [12].

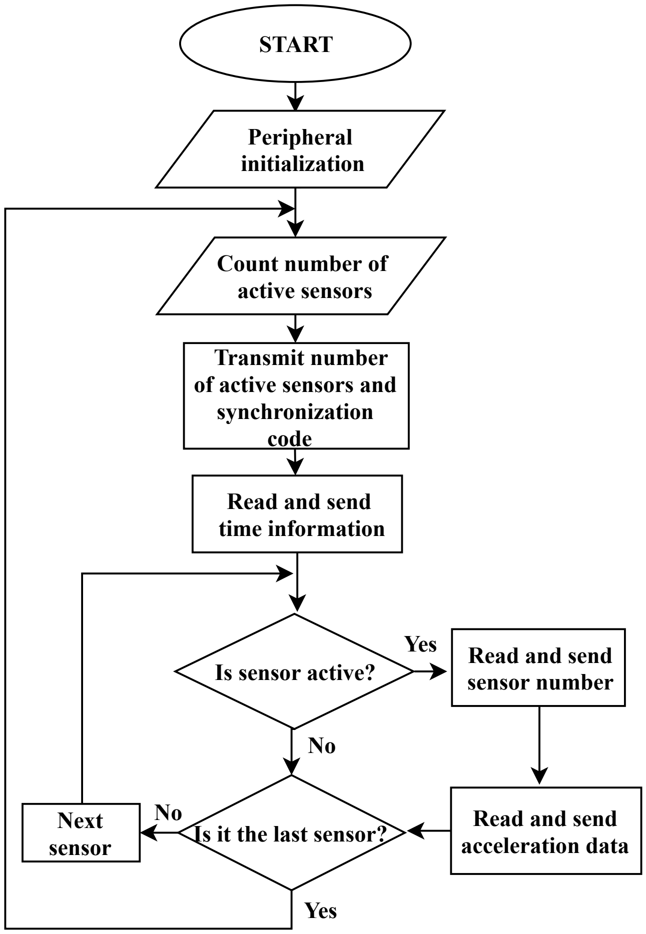


Fig. 2: Flowchart of the firmware stored in the PAMPIUM program memory.

For transmitting data to a computer, we use the HC05 chip, which implements a Bluetooth SPP (Serial Port Protocol) module. It is designed for transparent wireless serial communication, making it easy to interface with the computer.

A. Firmware operation flow

We implemented a dedicated firmware in the hardware device. The internal program stored in the PAMPIUM microcontroller is shown in the flowchart of Fig. 2.

The start condition occurs automatically when the PAMPIUM is powered with 3.3V, and the peripherals are initialized (MPU6050 sensors, DS321 RTC and HC05 Bluetooth). The program checks how many sensors are active for reading. For this, it tests the bit values that were connected to the switches. Then, the synchronization code and the information of how many sensors are active for reading are sent to the computer through the RS-232 interface. The synchronization code consists of two bytes that are set to 255 and 127 in decimal. After this, the current time information provided by the RTC module is sent. A test routine is started, where each sensor is checked if it is active or not. This test is done for all sensors, in sequence, starting with sensor one. If the sensor is not active, the program checks if the current sensor is the last one. This is possible because, for each tested sensor, a specific register is incremented. If current sensor is the last, it returns to the step of counting active sensors; if false, it tests the next sensor. In the case that the sensor is active, it sends the respective sensor number to the computer. Next, the acceleration data is read from the sensor and sent to the computer. At the end of this process, it tests if the current sensor is the last one and continues as previously described. This instruction flow is repeated as long as the system remains on.

B. Software interface

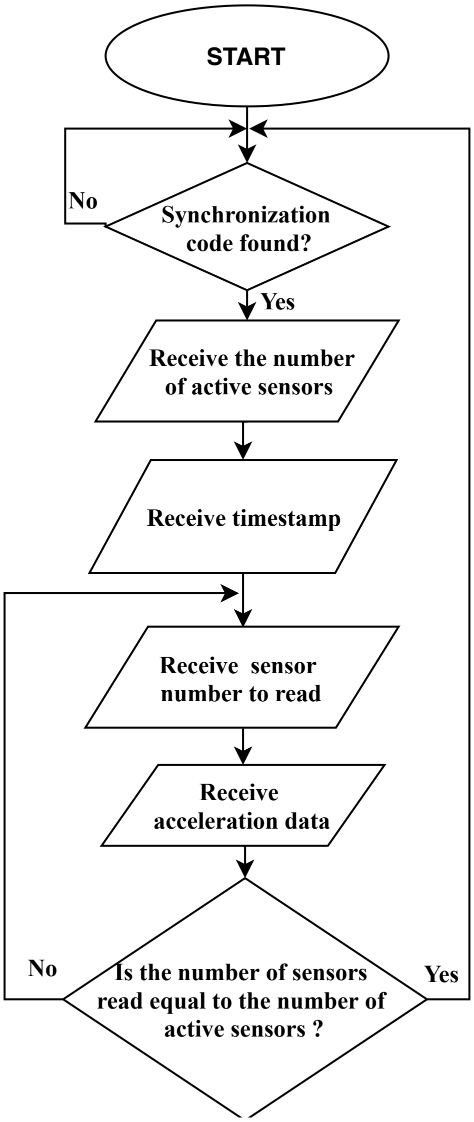


Fig. 3: Flowchart of the interface algorithm implemented in MATLAB.

We implemented an interface application for reading and processing data by a computer (final device) in MATLAB, as shown in Fig. 4. With this interface it is possible to view the three axes acceleration data plotted in real time, the number of active sensors and the acquisition rate (in points/s). We can also make some settings, such as change the graphs scale, select the axis to plot and save timing and acceleration information to a ".mat" file. The interface receives accelerometers and time data from the vibration meter via Bluetooth and processes the information. Fig. 3 shows the flowchart of the implemented interface algorithm.

The start condition occurs when MATLAB sets up communication with Bluetooth and begins receiving data sent by PAMPIUM. After initiating the communication, the algorithm waits for the reception of a synchronization code sent by PAMPIUM microcontroller. This code indicates the transmission start of a data stream. The synchronization code is implemented to prevent the algorithm from reading incorrect data at the start procedure or after reconnecting. After receiving the synchronization code the algorithm receives the information of how many sensors are active and timestamp. A routine to read the acceleration data is then executed for all active sensors. It first receives the number of the sensor being read and the respective acceleration data in the x, y and z axes. This process is repeated until the number of read accelerometers is equal to the number of active devices. The program returns to the synchronization step and repeats the loop again. The algorithm can be interrupted at any step by the user or by a communication error without losing data due to the constant verification of the synchronization code.

III. RESULTS

In order to test and calibrate the implemented system, we performed three tests: calibration test, oscillation test to verify the detection of large amplitude oscillations, and rupture test to verify the detection of small vibrations with very small amplitudes.

A. *Calibration test*

To perform the calibration of amplitude and frequencies of the system implemented, we prepared the setup experiment with a physical pendulum, a degree-scale rigid piece of paper and a camcorder. The pendulum rod was mounted on the scaled sheet of paper and one of the implemented system accelerometers was attached to the free end of the rod, as shown in Fig. 5. We released the pendulum from a known angle and it started to swing. This procedure was repeated three times for an oscillation angle of 140°. The pendulum swing was recorded through a camera positioned and adjusted frontally to the pendulum. Pendulum movement was also measured by the accelerometer attached to the rod.

With the recorded video we analyze frame by frame each step of the movement performed by the pendulum. This analysis was performed manually for an oscillation period. For each step of the movement we note the time in seconds and the angular position of the pendulum. Using the collected time and acceleration data, along with the physical laws that describe the pendulum physical movement, it was possible to calculate the pendulum angle at each point over time.

With the mathematically calculated data from the acceleration angle collected by the system and the analytically collected data analyzing the pendulum movement through the camera, we plotted, using MATLAB, a graph of the angle variation as a function of time for comparing the test results. Fig. 6 shows two angle variation curves as a function of time - in red the curve collected by our vibration meter and in blue the mathematically calculated data.

It is possible to see a small difference between the curves. This difference is a result of inaccuracy in data collection (angle and time), since this collection was done manually. Even with this small difference it is possible to see clearly the similarity of the plotted curves, both in amplitude and the frequency of oscillation. Comparing these two curves plotted using two different methods to describe the pendulum movement it is possible to conclude that the implemented system presents coherence in relation to the measured units (acceleration and time).

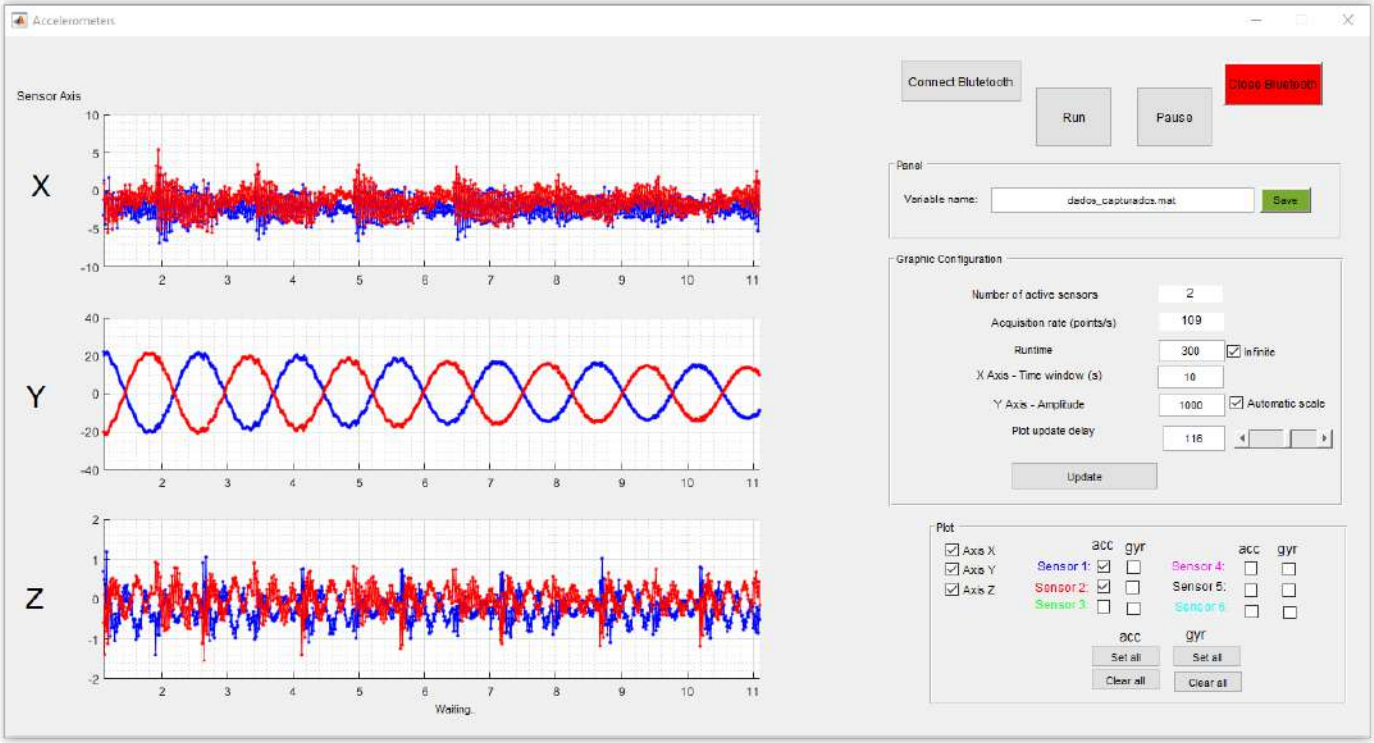
B. *Oscillation test*

To verify the functioning of the implemented system for wide amplitude oscillation, we performed a simple test with an inverted pendulum. This was done by attaching the accelerometer sensor to the extremity of the rod and placing the pendulum in oscillatory motion. The MPU6050 sensor measures acceleration in three axes, but the movement of a pendulum can be described using in a single accelerometer axe and time information. Fig. 7 shows the image of the systems mounted for testing. In the Fig. 8 we can see the graphs plotted with the acceleration and time data collected during the test. In the axes x and y graph, there are only noises related to the harmonic frequencies of the inverted pendulum stem where we fix the sensor. The y axis graph shows the pattern of the pendulum movement through the acceleration and time data collected by the implemented system. With the acceleration and time data obtained from the implemented system, it is possible to reproduce the signal of the pendulum oscillatory motion.

C. *Rupture test*

We performed a rupture test on an expanded polystyrene sample to test the system sensitivity. The goal is to compare the results obtained by our vibration meter and a commercial measuring system from Piezotronics PCB Accelerometers (model 352c03) using Bruel & Kjr RT Pro Photon 7.20 software.

The test performed basically consists of gradually applying a load to a bar composed of expanded polystyrene until rupture occurs. The accelerometer sensors were fixed in the bar. We seek to identify small movements generated by the propagation of the rupture energy of internal bonds of the material tested due to the applied shear force. To perform the test we used a testing machine to apply load to the sample. The machine was adjusted with a feed step of 5 mm/min. We used an expanded polystyrene bar of 100 cm long and 300 cm^2 of straight cross-sectional area. We connected one our accelerometers to one side of the sample and a commercial Piezotronics PCB (model



Panel

Variable name: dados_capturados.mat

Graphic Configuration

Number of active sensors: 2
Acquisition rate (points/s): 109
Runtime: 300 ☑ Infinite
X Axis - Time window (s): 10
Y Axis - Amplitude: 1000 ☑ Automatic scale
Plot update delay: 116

Plot

☑ Axis X
☑ Axis Y
☑ Axis Z

	acc	gyr		acc	gyr
Sensor 1:	☑	☐	Sensor 4:	☐	☐
Sensor 2:	☑	☐	Sensor 5:	☐	☐
Sensor 3:	☐	☐	Sensor 6	☐	☐

Fig. 4: Interface implemented in MATLAB.

352c03) accelerometer to another. We start the measurement with both synchronized measurement systems and remain with the active systems until after the rupture occurs. Fig. 9 shows the image of the setup test and Fig. 10 shows the image of the end of the test when the bar is already broken.

After the test we use MATLAB to process data obtained by both measurement systems. We plotted the data obtained through the commercial measurement system to use as a reference (Fig. 11). Acceleration information obtained through our system has been filtered to eliminate outliers and noise. We resampled the signals with a step of 1 ms in order to have constant time intervals between samples. After that, we applied a 301-point moving average filter to the signal for eliminating high frequency components. The filtered y and z axis acceleration data measured by our vibration measurement system are shown in Figs. 12a and 12b, respectively.

Comparing the graphs obtained by the two systems during the test, it is possible to see a peak in the graphs between 20 and 25 seconds. This peak corresponds to the moment of a fissure in the bar. It precedes by approximately 15 ms the complete rupture of the expanded polystyrene bar (not shown in the figures). With these results, it is possible to demonstrate that the implemented system works well for small vibrations. The noise found in the acceleration information read with the prototype system does not affect the obtained result, since it was possible to identify the moment a fissure occurs.

An advantage of the implemented vibration measuring system is that it allows acceleration information to be obtained on the three x, y and z axes, and it is possible to use the information from the three axes for a more accurate analysis of the results. For example in the rupture test described above it was possible to identify the pre-rupture vibration of the material in two of the three axes, y and z axes. The implemented system also allows to the user more configuration options as well as full access to the read information, since the system provides the raw read data.

The implemented system is totally configurable, allowing the customization of the amount of sensors that the user wants to use. This allows an easy adaptation to the most varied applications. However, one of the drawbacks of using many sensors is the reduction of acquisition rate. The system acquisition rate varies according to the number of active sensors, since the data reading process is sequential. The maximum obtained acquisition rate is 192 points/s for a single active sensor and the minimum is 40 points/s with all six active sensors. The variation of the acquisition rate as a function of the number of active sensors is shown in Table II.

TABLE II: Acquisition rate in terms of the number of active sensors.

Number of active sensors	Acquisition rate (points/s)
1	192
2	109
3	76
4	58
5	47
6	40

The cost of the implemented system is very low compared to commercial ones. The most expensive component is the

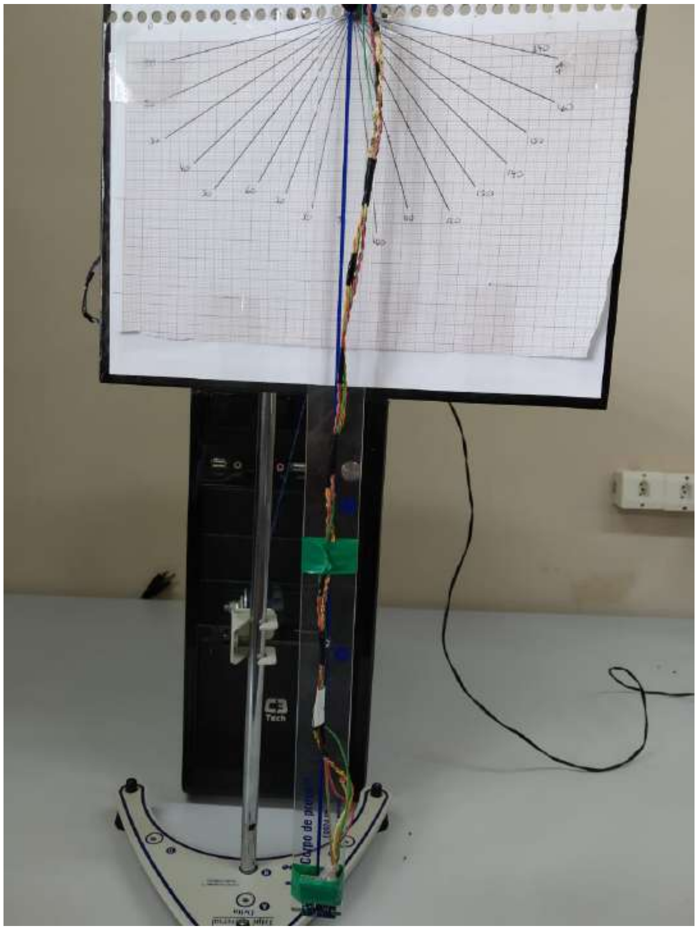


Fig. 5: Pendulum system used to calibrate the implemented vibration meter.

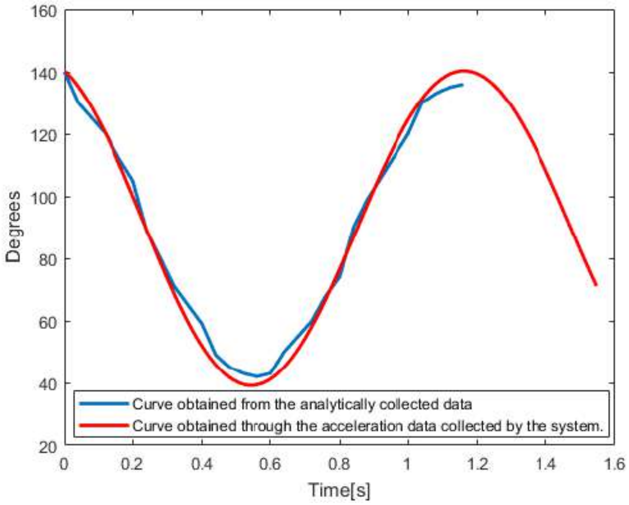


Fig. 6: Angle variation as a function of time.

Altera DE2 development board, which costs about US$ 800 in the conventional market. However, this development board could easily be replaced by a less robust board with a lower price. All other components of the system have a unit price of less than US$10.

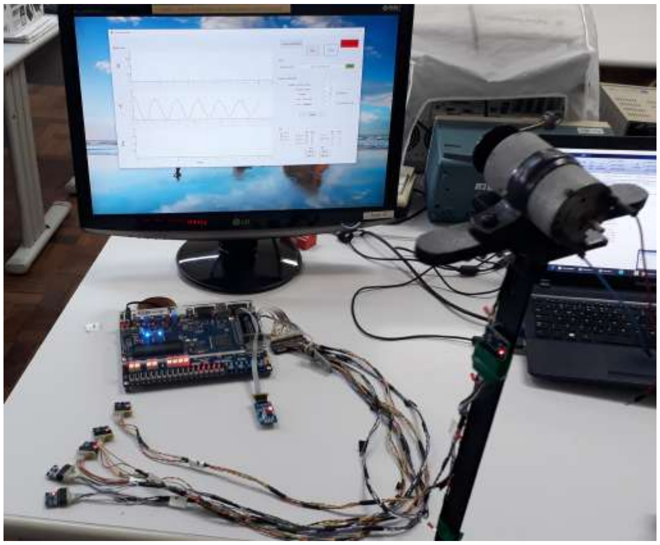


Fig. 7: Test of the implemented system applied to an inverted pendulum.

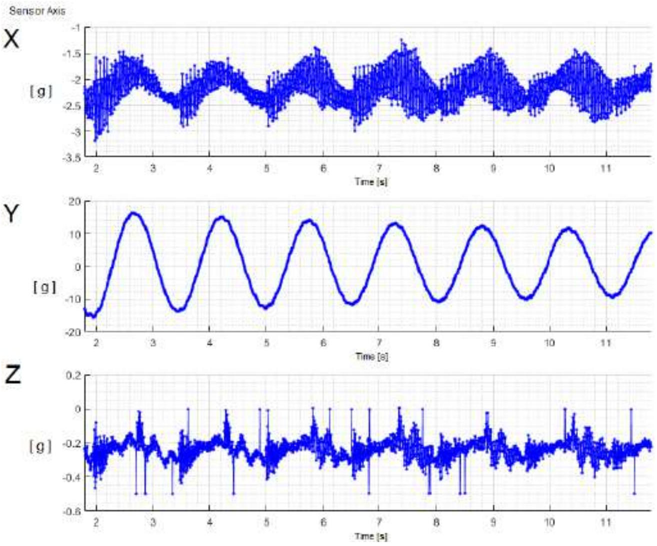


Fig. 8: Waveform obtained for the movement of an inverted pendulum.

IV. Conclusion

This paper described the development of a digital vibration meter system based on accelerometers. The communication between the implemented system and the computer is wireless, through the Bluetooth protocol, providing an easy connection for transmitting data. The design is configurable and includes the dedicated PAMPIUM microcontroller implemented in FPGA. It allows the communication interfaces, as well as the activation switches of the sensors, to be connected directly to the microcontroller register bank, thus facilitating the implementation of the control protocols.

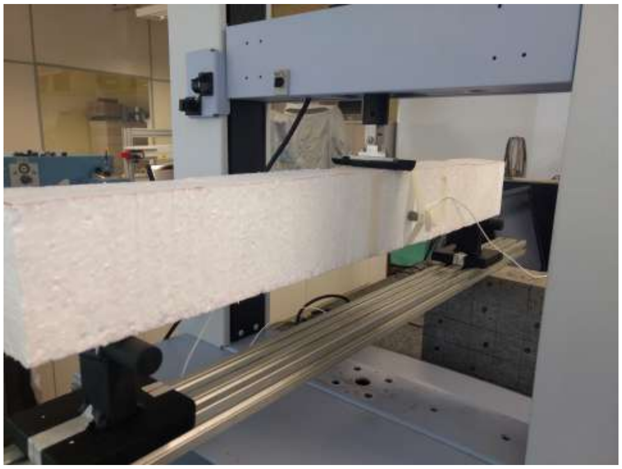


Fig. 9: Rupture test of a expanded polystyrene bar using a testing machine.

Fig. 10: Broken expanded polystyrene bar at the end of the rupture test.

The implemented system can be customizable, allowing the configuration on the number of active sensors. This allows an easy adaptation to most applications. The implemented system presents low cost and easy maintenance.

Although the implemented system has a reduction in the acquisition rate as we increase the number of active sensors, the prototype system presented good results in the tests performed. For the wide amplitude oscillation test it was possible to perfectly reconstruct the sinusoidal movement resulting from the pendulum oscillation. In the rupture test, in it was possible to identify the moment a fissure occurs in a expanded polystyrene bar under the effect of a load.

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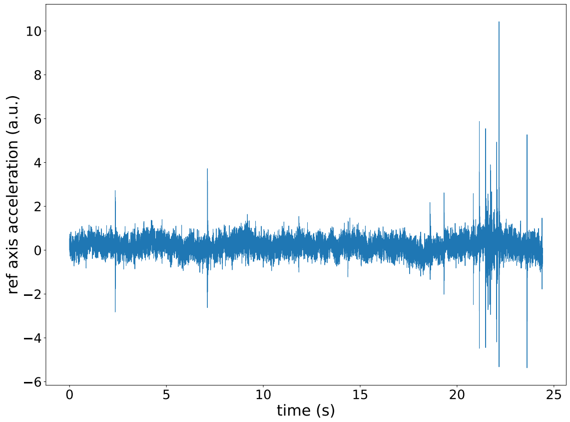
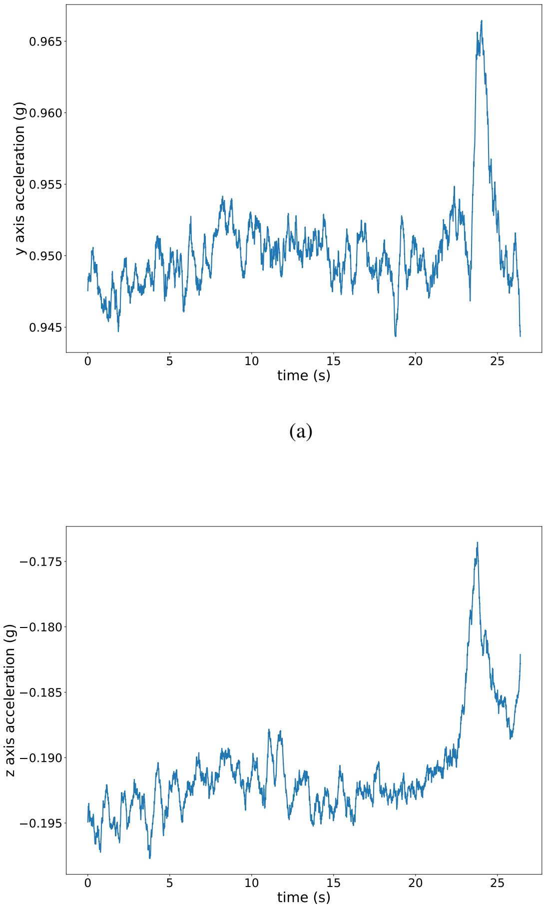


Fig. 11: Graph of acceleration as a function of time obtained from the commercial measurement system.



(a)

(b)

Fig. 12: Graph with acceleration data as a function of time obtained by our vibration meter system. a) y axis; b) z axis.

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