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Smart portable system for monitoring vibration based on the Raspberry Pi microcomputer and the MEMS accelerometer

Hajar Baghdadi[1,2], Karim Rhofir[2], Mohamed Lamhamdi[1]
[1]Department of Radiation-Material and Instrumentation, Faculty of Science and Technology, Hassan 1st University, Settat, Morocco
[2]LaSTI Laboratory, National School of Applied Sciences of Khouribga, Sultan Moulay Slimane University, Beni-Mellal, Morocco

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ABSTRACT

In this work, an internet of things (IoT) sensing and monitoring box has been developed. The proposed low-cost system is a portable device for smart buildings to measure vibrations, monitor, and control noise caused by the industrial machines. We will present an instrument and a method to measure the vibration and tilt of a mechanical system (air conditioner). The primary goal is to create a signal acquisition and monitoring system that is both user-friendly and affordable, while also delivering exceptional precision. The key concept is centered around acquiring and processing signals through the Raspberry Pi. We will use for the first time as an application, which does not exist before, a conversion method to control and monitor remotely the noise generated by the machines. Once the noise reaches a high value or the air conditioner is too much tilted, the system sends an alert in the form of an email. We will use the Python language to acquire and process the signal and send the alerts. The proposed approach is straightforward to implement, and the obtained results demonstrate a high level of accuracy that is consistent with the existing literature.

Corresponding Author:

Hajar Baghdadi
Department of Radiation-Material and Instrumentation, Faculty of Science and Technology
Hassan 1st University
Settat, Morocco
Email: hajar92.baghdadi@gmail.com

1. INTRODUCTION

The term "internet of things (IoT)" was coined by Kevin Ashton "to describe a system in which the internet is connected to the physical world by ubiquitous sensors" [1]. IoT can be defined as a network of objects connected to the internet and able to communicate with each other. These objects are equipped with sensors that enable them to interact with the environment. These sensors include temperature sensors, pressure sensors, proximity sensors, humidity sensors or vibration sensors, and communication modules [2]–[5].

Today, the IoT allows the real world and the virtual/or digital world to be interconnected. Through IoT, things will communicate with each other and develop their own intelligence. Smart-phones, cars, TVs, kitchen appliances, utility meters, thermostats, surveillance cameras, cardiac monitors, and almost everything, we can imagine will be connected every day, everywhere, and everytime [6]. The application of IoT technology will be present in all sectors and industries, from the smart home to the smart city, education, healthcare, manufacturing, energy, utilities, commerce, transportation, surveillance, supply chain, and logistics [7]–[9]. In general, the potential of IoT is not limited and its impact will be truly realised in the near future as more devices connect to the internet. Therefore, with IoT, one can control everything using the internet service. It can remotely control and monitor the washing machine, the dryer, the air conditioner and any appliance that vibrates and makes noise. In this work, the air conditioner was chosen because its noise can be a real pain and a source of stress in winter as well as in summer or sometimes during the whole year. This abnormal and unusual noise seems to be a sign of a future major breakdown. The noise from this equipment can be a source of stress and disturbance for the neighbourhood. Indeed, the decree of 31 August 2006 on the fight against neighbourhood noise specifies that the tolerable threshold for the neighbourhood is 25 decibels. Therefore, below this limit, the law is not being violated. However, the difference between the ambient noise measurement and the residual noise must not exceed 5 dB from 7 to 10 pm and 3 dB from 10 to 7 am. The penalty remains a fine of 450 €. The equipment causing the nuisance may also be confiscated [10].

If the noise persists, the air conditioner may be hiding a much more serious problem that requires immediate professional intervention. Most of the time, when an air conditioner suddenly becomes noisy, it is because the filters that blow cool air into the house are clogged. It can also be due to a motor failure, a ventilation failure, an overheated motor, and a lack of oil. In short, there are many causes, but it is usually due to a malfunction of the compressor and its air flow. Our solution is to measure the vibrations and send alerts for immediate intervention, maintenance or repair. Vibration measurements are essential in many applications, including machine condition monitoring or environmental noise testing [5]. In most cases, vibration is measured using a piezoelectric sensor or an accelerometer (such as the ADXL345 accelerometer). An accelerometer is a sensor that measures the dynamic acceleration of a physical device as a voltage [11]. Therefore, in condition monitoring, vibration measurements are used to indicate the operating status of machines such as compressors, turbines or pumps. These machines consist of many parts, and each of them produces a unique vibration signal. By tracking the evolution of different vibration signals over time, we can predict when a machine will fail and schedule maintenance correctly to improve safety and reduce costs. Vibration monitoring systems can solve many problems related to vibrations that occur during the operation of processing equipment (mechanisms, machines, CNC machine tools). Therefore, the development of systems for monitoring and analysing vibrations in technical objects is a current issue [12]–[16]. Several open researches are studied and discussed in order to push the technology further in this direction of vibration monitoring. A system based on micro electro mechanical systems (MEMS) accelerometers and Raspberry-Pi is presented in [17] which proposes a real-time urban seismic network in Sicily (Italy). Raspberry is also used in applications such as detection systems and robot control [18].

In buildings, we have many machines such as air conditioners and washing machines. It is in this context and in the field of IoT that we have developed an intelligent monitoring box that measures the vibrations of the air conditioner and sends alerts in the form of emails in case of danger (see Figure 1). Thus, to detect the exceeding of the permitted noise level, we have used, for the first time, an application, which does not exist before, of a conversion method. In addition, in order to have a global view of the machine's operation, the box records the history of the measurements. If the noise level is close to the tolerable threshold, the owner will receive an alert to service the machine. If the noise level is exceeded, he will receive a warning to stop the machine immediately to avoid disturbing the neighbors and also to avoid any penalty.

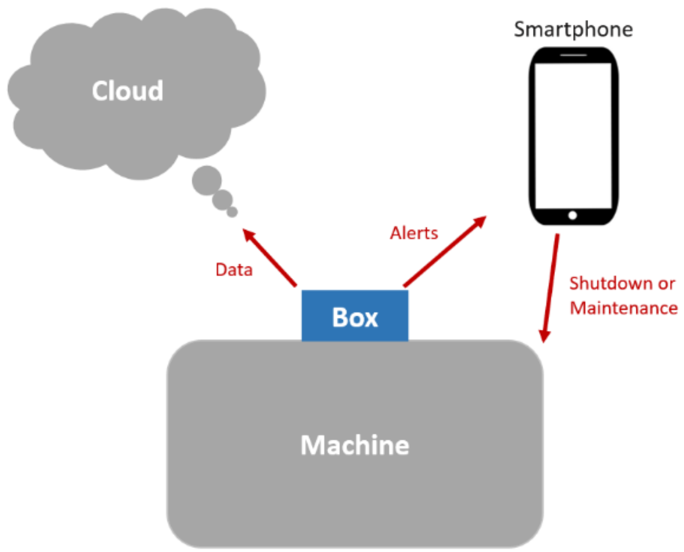

Figure 1. Role and functioning of the proposed prototype

2. MATERIALS

To develop the system, we need the following components (see Figure 2): i) a Raspberry Pi 3 single board microcomputer, ii) an ADXL345 triaxial accelerometer (MEMS sensor), iii) flash memory for installation of the operating system, drivers, software and data storage, iv) monitor, v) keyboard, and vi) ethernet or wireless communication interfaces for remote information exchange with the PC. IoT technology utilizes small, powerful device called Raspberry Pi using Python 3 in conjunction with MEMS sensor (ADXL345) in order to avoid the complexity of the experiments and especially the high cost involved (see schematic in Figure 3). Therefore, the physical model of the home automation box includes the following main components (see Figure 4): i) a single board Raspberry Pi 3 microcomputer and ii) a triaxial ADXL345 accelerometer (MEMS sensor). As mentioned, this solution can be applied to any device that vibrates and makes noise. In this work, the system studied is the air conditioner (see Figure 5).

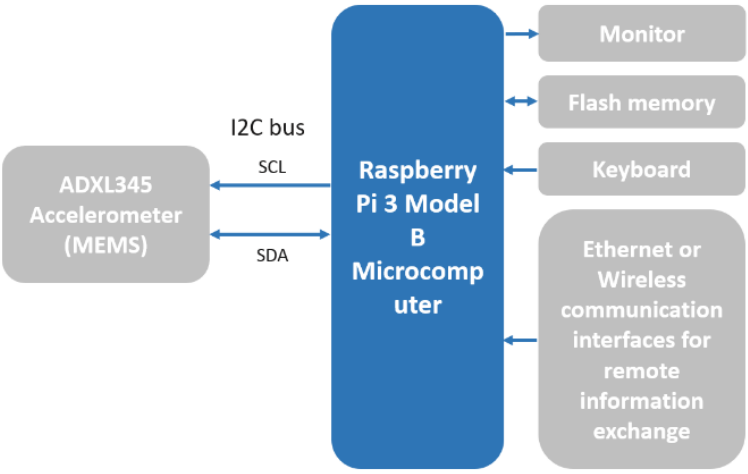

Figure 2. Expanded structure of the system block diagram

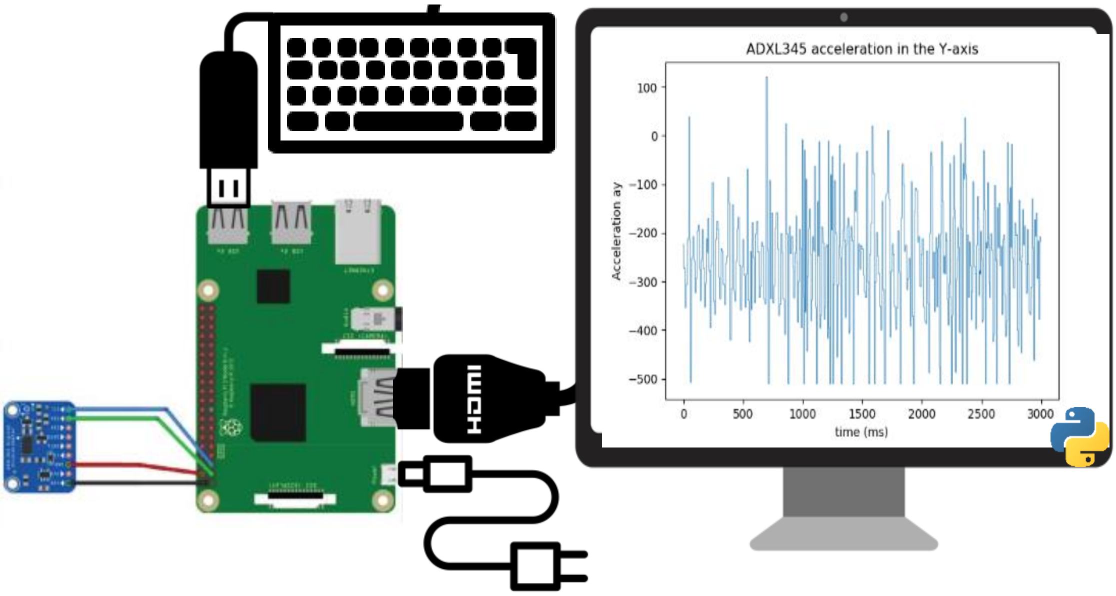

Figure 3. Schematic of the developed structure

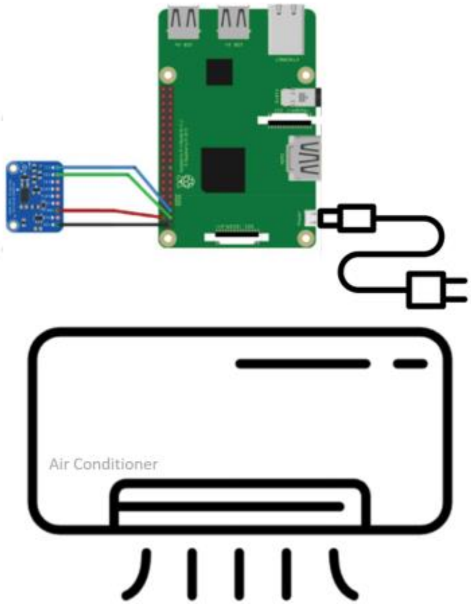

Figure 4. The physical model of the home automation box on the mechanical system studied (air conditioner)

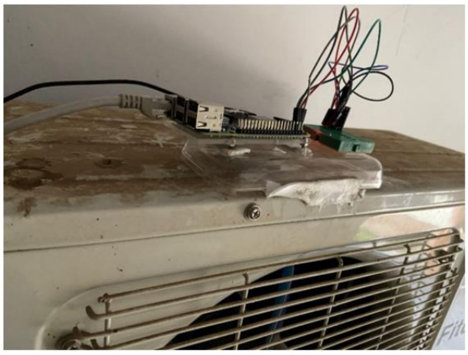

Figure 5. Location of the solution on the air conditioner

2.1. Micro electro mechanical systems sensor of the ADXL family

The first accelerometers type MEMS (1980) occupied a board of about 50 cm^2 [19]. By 1995, the active part of an ADXL50 (the original accelerometer for airbag applications) had been reduced to a 16 mm^2 square. The component we are studying in 2021 occupies only 3 mm^2. We now have sensors capable of measuring one, two or three components of acceleration. Depending on their measurement range, they are described as low-g for accelerations below twenty times the acceleration of gravity and high-g beyond that. ADXL103 (low-g) and ADXL78 (high-g) are important representatives of this series. In the ADXL series, the MEMS sensor itself and its conditioning electronics are integrated in the same component, in accordance with standard practice. MEMS sensors are basically used in our phone to know in which direction our phone is facing, to know if holding the phone vertically or horizontally. In this work, we chose the MEMS accelerometer type ADXL345. The ADXL345 is a highly precise three-axis accelerometer that offers a digital output. With a slim profile and minimal power consumption, this device provides accurate measurements at a resolution of 13 bits, with a maximum range of 16 g (gravity). It offers selectable measurement ranges of 2 g, 4 g, 8 g, and 16 g, allowing for the detection of motion at various amplitudes. The ADXL345 has a fixed sensitivity of 4 mg/LSB (see Table 1).

These bits define the g range as shown in Table 1. The ADXL345 is only 3×5×1 mm in size, with low power consumption ranging from 40 A to 145 A, and connects via the I2C and SPI digital interface [20]. The ADXL345 has a range of output data rates available between 6.25 Hz and 3,200 Hz, and a bandwidth that spans between 3.125 Hz and 1,600 Hz. It is designed to function within a broad temperature range, with a minimum operating temperature of -40 °C and a maximum operating temperature of +85 °C.

Table 1. Range setting

Setting		
D1	D0	g range
0	0	±2 g
0	1	±4 g
1	0	±8 g
1	1	±16 g

2.2. Raspberry Pi

The Raspberry Pi was developed by the Raspberry Pi foundation. There are five different types of Raspberry Pi, namely: original Raspberry Pi, Raspberry Pi, Raspberry Pi 2, Raspberry Pi 3 and Raspberry Pi 4. The five different types are available in model A and model B versions. Different platforms can be used as the operating system for the Raspberry Pi, including: RISC OS, Arch Linux, Pidora, Raspbian, and Microsoft Windows 10 IoT core. For this study, we utilized the Raspberry Pi 3 model B version board. This board is equipped with a Broadcom BCM2837B0 chipset, clocked at 1.4 GHz, and has 1 GB of RAM. An 8 GB SD card serves as the removable hard drive memory. The board also boasts built-in Bluetooth 4.1, wireless capabilities, an HDMI port, four USB ports, an Ethernet input, and 40 pin GPIO connections for custom hardware integration. It requires 2.5 A of power and must be connected to a stable 5 V power source. Despite its robust feature set, the board is compact, measuring just 8.56×5.6×2.1 cm. Once the necessary configuration steps are taken (as detailed in the Python programming section), the Raspberry Pi can readily detect and communicate with the MEMS accelerometer via its designated addresses. The Python-based program will be able to configure and capture digital data from the MEMS accelerometer using the Raspberry Pi's built-in modules.

2.3. Configuration

After identifying the characteristics of the sensor, we need to consider the hardware and software required to properly condition, acquire and display the accelerometer measurements. Indeed, before using the Raspberry Pi, we need to configure it correctly. As it is not already configured at the factory, it is crucial to install the operating system onto an SD card using a computer equipped with a SD card reader and an internet connection. This initial configuration is essential, as the Raspbian operating system includes all the programming software and other necessary applications required for the proposed project. Once the OS has been installed onto the SD card, it can be inserted into the board. At this point, we can establish a physical connection between the Raspberry Pi and the MEMS accelerometer by connecting the I2C digital transmission cables to the appropriate pins on the board, as illustrated in Figure 6.

The proposed project makes use of a MEMS accelerometer in the development of an intelligent, portable vibration monitoring system. Once the operating system has been installed onto the SD card and inserted into the Raspberry Pi board, a physical connection can be established between the board and the MEMS accelerometer. This is achieved by connecting the I2C digital transmission cables to the corresponding pins on the Raspberry Pi, as illustrated in Figure 6.

Even after establishing the correct physical connection, communication between the Raspberry Pi and the sensor is not yet achieved. Firstly, it is necessary to enable the I2C port in the Raspberry Pi's configurations to allow the microprocessor to initialize and use the I2C port. Secondly, a toolkit must be installed to detect the ADXL345 addresses that are connected to the I2C port. Additionally, in most cases, further configuration is required within the directories containing the I2C communication parameters to increase the transmission speed limit using terminal commands within the Raspbian system. Finally, the necessary modules for the Python software, such as system management Bus (SMBus), datetime, and numpy, must be installed to complete the configuration process.

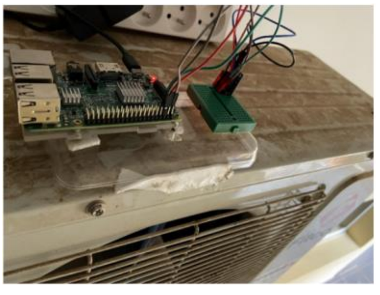

Figure 6. Connecting the ADXL345 to the GPIO ports

2.4. Server part

In this part, we used libraries on python to send a mail from the Gmail box as we see on the following code. We saved our results in a file.csv containing the date of the measurements, the date of the peak and the date of sending and, if necessary, the corresponding graphic curve.

```
import smtplib
from os.path import basename
from email.mime.application import MIMEApplication
from email.mime.multipart import MIMEMultipart
from email.mime.text import MIMEText
from email.utils import COMMASPACE, formatdate
s = smtplib.SMTP('smtp.gmail.com', 587)
s.starttls()
s.ehlo()
username='helpdeskensa@gmail.com'
password='*************'
s.login(username,password)
sendto=['mesvibmonitor@googlegroups.com']
msg = MIMEMultipart()
msg["From"] = username
msg["To"] = sendto[0]
msg["Date"] = formatdate(localtime=True)
msg["Subject"] = f"Graph for {datestring}"
files    =    ["/home/pi/Documents/Vibrations-Monitor/picalert.png",    "/home/pi/Documents/
Vibrations-Monitor/picdata.csv"]
for f in files:
    with open(f, "rb") as fil:
        part = MIMEApplication(
            fil.read(),
            Name=basename(f)
        )
  .part['Content-Disposition'] = 'attachment; filename="%s"' % basename(f)
    msg.attach(part)
s.sendmail(username, sendto, msg.as_string())
```

3. METHOD

3.1. Measuring vibrations

The ADXL345 was used as an accelerometer to calculate the acceleration in a specific direction from gravity and motion. Basically, it can measure the acceleration in 3 directions simultaneously: x, y, and z (see Figure 7). After receiving the x, y and z vibration values from the Raspberry Pi board, we perform the correction using essentially (1):

$$x_c = \frac{(x - x_t)}{gain} \tag{1}$$

Where gain is the reference gain of the sensor (from the ADXL345 datasheet).

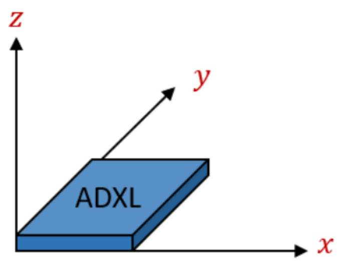

Figure 7. ADXL345 x, y, z directions

3.2. Measuring tilts

As mentioned, the accelerometer on a flat surface would produce 1g on one of its axes (most likely Z). Thus, the output of the accelerometer is not linear but rather a sine wave, so cannot simply convert the g-forces proportional to the tilt into degrees. To get the best possible accuracy when measuring the tilt, should use all three axes to determine the angle. Basically, the same arctan equation is used, but instead of just dividing by one axis, the magnitude between the other two axes is calculated (see Figure 8).

$$\theta = \arctan\left(\frac{x}{sqrt(z^2+y^2)}\right) \quad (2)$$

In our case, we calculate the pitch and roll as (3) and (4):

$$Pitch = \arctan\left(\frac{x}{sqrt(z^2+y^2)}\right) \quad (3)$$

$$Roll = \arctan\left(\frac{y}{sqrt(z^2+x^2)}\right) \quad (4)$$

To implement the two equations in code, we used the function atan2, provided by the maths library. The function atan2 returns the angle in radians. For this we use 1 radian=180/π.
Pitch=(math.atan2(accel.x,math.sqrt(accel.y*accel.y+accel.z*accel.z))* 180.0)/math.pi
Roll=(math.atan2(accel.y,math.sqrt(accel.x*accel.x+accel.z*accel.z))* 180.0)/ math.pi

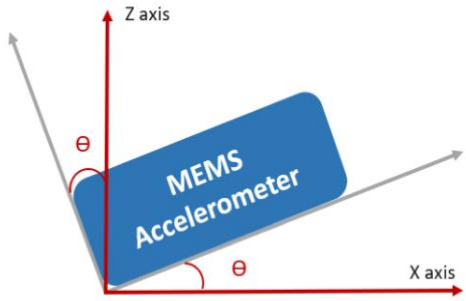

Figure 8. ADXL345 tilt measurement

3.3. Nuisance measurement (in dB)

We measure the accelerations with our prototype placed on the air conditioner (see Figure 9) and then convert these accelerations into vibrations or nuisance in dB. The following formula is used for the conversion:

$$N(dB) = 10\log\left(\frac{A}{a_0}\right)^2 = 20\log\left(\frac{A}{a_0}\right) \quad (5)$$

Where N is the nuisance converted to dB, A is the measured acceleration, and a_0 is the reference acceleration of the ADXL345 accelerometer.

Figure 9. Location of the box during monitoring

4. RESULTS

We place the box on the air conditioner as shown in the Figure 9 and read the x, y, and z vibration values. Figure 10 shows the position of the ADXL345 on the air conditioner. In fact, the horizontal direction z becomes (-y). The evolution of the acceleration received from the accelerometer along the x, y, and z axes, respectively will be presented graphically in the following Figure 9.

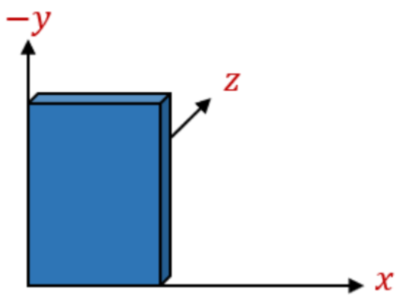

Figure 10. The x, y, and z directions of the ADXL345

4.1. Case of an air conditioner A

Figures 11(a)-(c), illustrate the acceleration curves for the X, Y, and Z axes, respectively, beginning at 0 milliseconds and concluding at 3,000 milliseconds. We can see that the Y-axis acceleration is more important since it is the horizontal axis. In fact, this is due to the position of the air conditioner (see Figure 10).

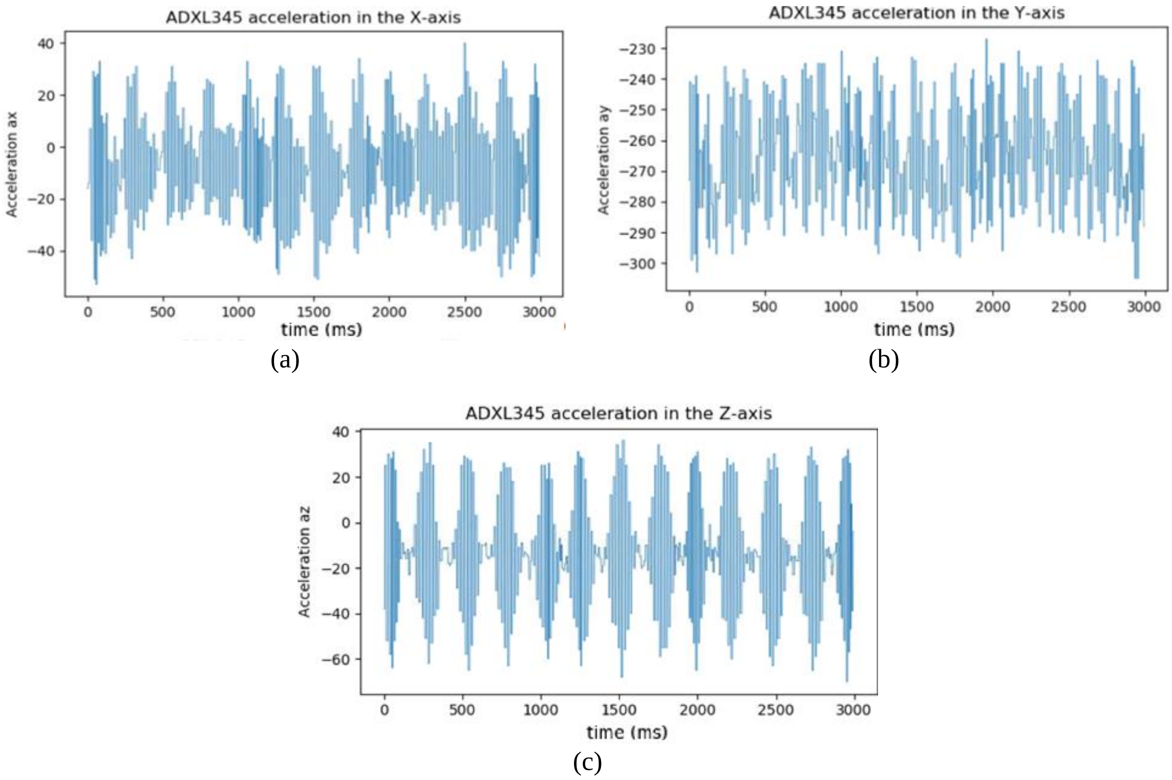

Figure 11. Accelerations of the ADXL345 (a) along the X axis, (b) along the Y axis, and (c) along the Z axis

4.2. Case of an air conditioner B

In Figure 12, we get this curve in blue with large peak values along the vertical X axis. It starts from 0 to 3,000 milliseconds. This is the blue data set along the X-axis, which shows the intensity of the nuisance generated during the operation of two air conditioners, but the second air conditioner B is more harmful. As shown in Figure 13, the accelerations along the Y-axis are larger since it is the horizontal axis. This also shows the malfunction of both machines. Figure 14 shows the measurement of the accelerations along the Z-axis for 3,000 ms. This is the blue data set in the Z-axis, which shows after conversion the noise generated during the operation of the two air conditioners.

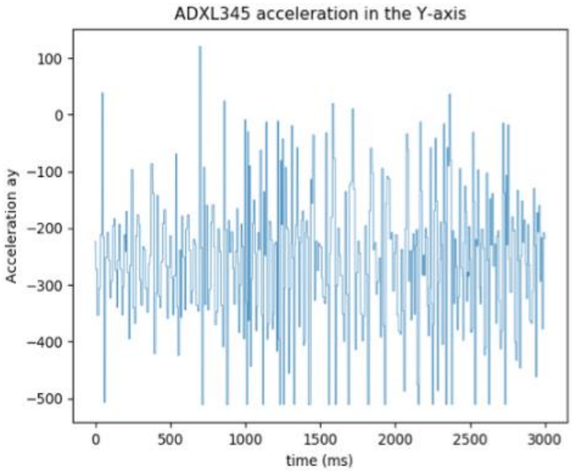

Figure 12. Acceleration of the ADXL345 along the Y axis

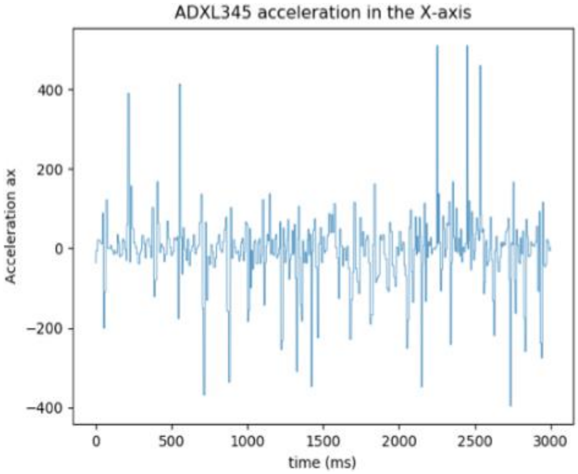

Figure 13. Acceleration of the ADXL345 along the X axis

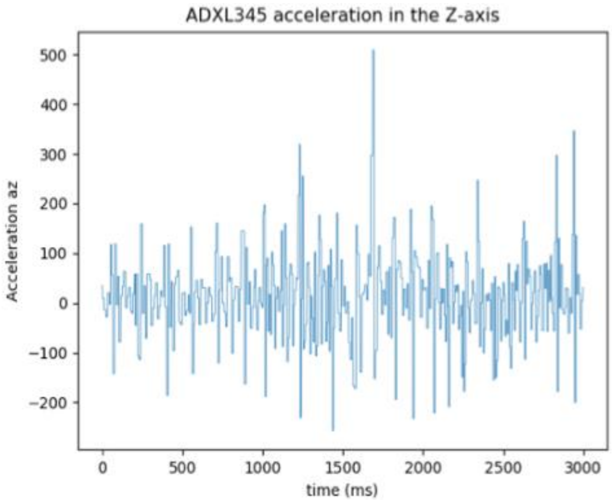

Figure 14. Acceleration of the ADXL345 along the Z axis

4.3. Discussion

We can deduce that this case is catastrophic. Indeed, there are vibrations along the 3 axes x, y, and z. Therefore, there is a nuisance with a risk of destruction of the machine and even the furniture in case of several air conditioners. After a correction using the method presented in the methods section and a measurement of the Euler angles (pitch and roll), we draw the above curve in blue (see Figures 15 and 16). Our study has shown that we sometimes have a strong nuisance due to a failure of the air conditioner because of its age or environmental conditions. These machines, in this case the air conditioner, are made up of many parts, each producing a unique vibration reading. By tracking and monitoring the evolution of the various vibration signals over time, we can predict when a machine will fail and properly schedule maintenance to ensure safety and minimize costs. The proposed system can operate in real time and allows us to perform an analysis of the vibration signals. If the peak nuisance value exceeds the limit, the system sends an alert.

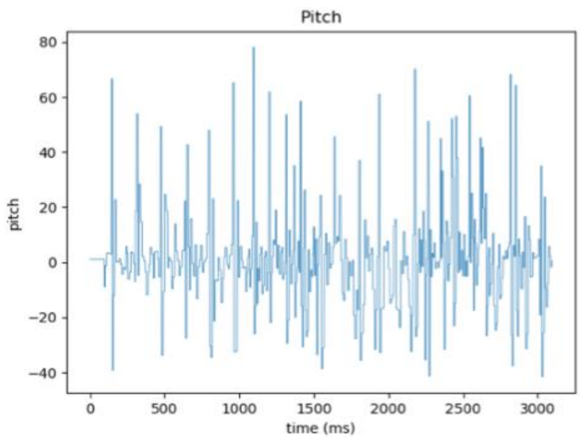

Figure 15. Pitch measurement

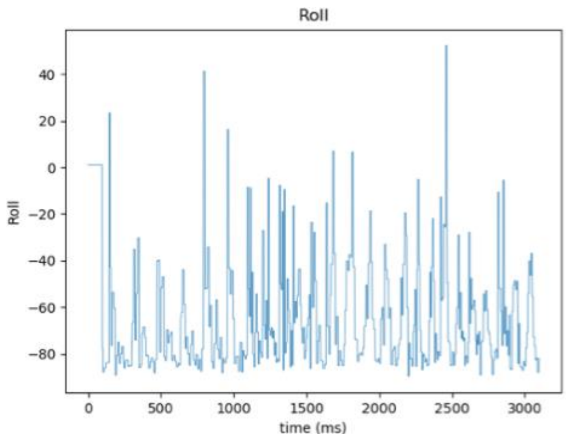

Figure 16. Roll measurement

5. CONCLUSION

Raspberry Pi microcomputer associated with MEMS sensors to measure the vibrations of a mechanical system is developed. In this paper we design a home automation box in the IoT domain. It is a low-cost concept based on a Raspberry Pi microcomputer acting as a server in conjunction with MEMS sensors. The whole system is a wearable device for intelligent buildings to measure vibrations, monitor and control noise caused by industrial machines (such as air conditioner). By using a conversion method for the first time as an application, which does not exist before, this box can operate in real time mode and allows us to perform the analysis of vibration signals. We perform the sensor setup, data acquisition and processing of the MEMS sensor. By monitoring this generated noise, the system sends alerts to the owner to stop or service the machine. We have used low cost chips wherever possible, which can measure accurate results. Our system can be integrated into any device and can be connected to the intelligent building network. In a simplified package and since our institution has just bought a 3D printer, we can design commercial products. In future work, we will develop an android application to globally manage the smart box and all its interactions in the intelligent building network. In addition, the whole system will be powered by a rechargeable solar battery, which completely avoids the need for wiring work on building sites.

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BIOGRAPHIES OF AUTHORS

Hajar Baghdadi a Doctor from the Radiation-Material and Instrumentation Laboratory (RMI). In 2022, she received her Ph.D in Electrical Engineering and Embedded Systems from Faculty of Science and Technology of Settat (Hassan 1st University, Settat, Morocco). She received her engineering diploma in Electrical Engineering in 2016 from the National School of Applied Sciences of Khouribga. Her main research interest includes embedded systems and MEMS technology. She can be contacted at email: h.baghdadi@uhp.ac.ma.

Karim Rhofir an Associate Professor at the National School of Applied Sciences in Khouribga (Sultan Moulay Slimane University, Beni-Mellal, Morocco). In 1998, he received his Ph.D in Mathematiques from the University of Besançon, France. Since 2011, he has been working in the field of scientific computing. He can be contacted at email: krhofir@gmail.com.

Mohamed Lamhamdi an Associate Professor at the Faculty of Science and Technology (Hassan 1st University, Settat, Morocco). He received his Ph.D in Materials and Technology of Electronic Components in 2008 from the Paul Sabatier University, Laboratory for Analysis and Architecture of Systems (LAAS), Toulouse, France. From 2008 to 2012, he was a researcher in the LMP ST Micro Electronics, Tours. In 2012, he became an Assistant Professor at the National School for Applied Sciences, Khouribga, Morocco, where he became an Associate Professor in 2016. In January 2018, he joined the Faculty of Technical Sciences, Settat, Morocco. His research interests include material characterization, MEMS/NEMS technology, thin films and nanotechnology. He can be contacted at email: mohamed.lamhamdi@gmail.com.