Comparative Analysis of Low-Cost Wireless Vibration Monitoring System for Rotating Machines

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Abstract. In industry, the maintenance and optimal performance of rotating machinery in factories and power plants are of paramount importance. Vibration, a pivotal factor in the operation of such systems, necessitates careful monitoring to prevent potential damages to motor mechanisms. This study addresses this need by presenting the development of a prototype wireless vibration monitoring system tailored for rotating machines. The aim is to mitigate the risks associated with high vibration levels that can lead to machine breakdown. The research compares two computing platforms, the Raspberry Pi 4 processor and Arduino UNO microcontroller, both integrated with ADXL345 accelerometer sensor. The sensor serves as the cornerstone for the vibration monitoring system. The study evaluates the performance of these platforms, emphasizing their efficiency in processing and transmitting data. Additionally, MATLAB software is employed for comprehensive graphical data analysis and visualization. Experimental testing of the prototype was conducted on a DC motor. The findings reveal that the Arduino platform outperforms the Raspberry Pi in detecting DC motor vibrations. Arduino's capability to process a higher volume of data per second positions it as a superior choice for real-time vibration monitoring applications. Originality of this project is in the development of vibration monitoring system using commercially available components that are low cost, and signal analysis of the vibration amplitude displacement and frequency at different motor speed. The developed vibration monitoring system stands as a tool, offering preventive measures for plant operators. Enabling continuous health monitoring of rotating machines empowers operators to proactively detect and address potential issues. This proactive approach significantly reduces the likelihood of unexpected machine breakdowns, thereby enhancing operational efficiency and minimizing downtime in industrial environments.

INTRODUCTION

Rotating machinery constitutes a fundamental component in diverse industrial domains including ships, factories, and power plants. These systems, enduring harsh environments and prolonged operational periods, are susceptible to various faults such as cracks, pitting, wear, and breakage. The undetected defects can lead to system failures, potentially resulting in catastrophic incidents. Addressing these concerns, researchers from both industry and academia have underscored the importance of early fault detection, diagnosis, and prognostics in rotating machinery [1]–[4].

A rotating machines consist of a stator and a rotor, with the latter functions to convert the electromagnetic energy into rotational motion [5]. Maintaining the balance of rotors is essential, as an imbalanced rotor compromises operational efficiency and safety. Rotor balancing systems play a crucial role in preventing issues arising from imbalance, thereby mitigating noise, vibration, and extending the motor system's lifespan. The consequences of equipment breakdown manifest in three distinct stages. Firstly, availability loss occurs when the machine is non-operational while production is necessary. This downtime could result from breakdowns or waiting periods, during which the machine remains idle or faces line constraints. Subsequently, performance loss arises when the machine operates below its optimal efficiency, functioning at minimal speed. The most profound impact, however, materializes as quality loss, as faulty machines elevate the likelihood of producing defective items [6].

In rotating machinery, the presence of faults generates vibrations. If the vibrations is not addressed, it will affect the operational efficiency and leading to leading to an increase in energy consumption and reduced equipment service life. Therefore, detecting and analyzing these vibrations at an early stage is crucial.

Meanwhile, the components utilized in vibration detectors are of critical significance. The components used in industrial tools and machines are costly, often requiring international procurement. This will usually affect project execution and might escalate repair expenses in case of damage. Therefore, this study proposes the development of a localized vibration detection tool employing readily available commercially available components, thus ensuring uninterrupted operational continuity.

Mechanical components within rotating machinery, including electrical engines, rotors, and bearings, are critical components that can lead to complete system shutdowns. Research conducted in 2018 by educators from Vishwakarma Institute of Technology in Pune, Maharashtra, India, emphasized that bearing failures are a major source of faults and a common cause of degradation in rotating machines [7]. The linguistic performance of bearings significantly influences the overall functioning of rotating machinery. Misalignments or looseness in any part can result in system imbalance. An imbalanced rotor exerts dynamic loads on bearings, mountings, and the machine's structural support, leading to wear and potentially high vibrations [8][9].

Researchers have explored vibration studies for rotating systems in the context of wireless monitoring [10]–[12]. In 2018, a high-performance wireless node for vibration analysis, utilizing the Xilinx Zynq FPGA platform, was introduced, capable of collecting tri-axes vibration data and performing Fast Fourier Transform (FFT) computations [12]. Concurrently, in 2019, an experiment measuring large rotor vibration utilized wireless Microelectromechanical Systems (MEMS) accelerometers, offering a cost-effective alternative to traditional piezo-based accelerometers [10]. Additionally, a wireless remote monitoring system for mechanical vibration, designed using embedded technology and ZigBee technology, was presented in 2020 [11].

Proposing a modern approach, a method for rotating mechanical vibration fault detection based on deep autoencoder and integrated SVDD (DAE-ISVDD) was introduced in 2019, demonstrating enhanced accuracy and noise resilience [12]. In a different domain, a vibration monitoring system based on Fiber Bragg Grating (FBG) sensor arrays was developed in 2021, showcasing adaptability across various structures such as buildings, bridges, and railways, as exemplified in a real-world case study involving the San Diego story office building [6].

The application of vibration monitoring systems spans diverse sectors, from industrial applications to aviation and healthcare. In 2017, vibration detection on a bridge was proposed using a vibrating-wire sensor as the basic measuring device and Texas Instruments MSP430F1612 as its microcontroller, which requirements of ultralow power consumption [13][14]. Besides, the researchers applied short-distance Zigbee technology and GPRS technology in its monitoring system to remote and real-time online monitoring of bridge vibrations. Additionally, in the industrial sector, different devices and prototypes used can be seen in many research papers [10], [15], [16]. In January 2021, the use of IMU sensor (Bosch BMI160) and accelerometer (Rohm Semiconductor Kx220) in vibration monitoring to monitor real-time conditions for non-stationary heavy machinery in mining operations was proposed. Apart from that, several industries have used low-cost devices instead of commercially available in the industry for vibration monitoring. Paper [10] uses an ESP32 microcontroller and ADXL366 accelerometer to detect vibration in paper machine roll in a CNC grinding machine. Similarly, researchers from Coimbatore, India stated that they used ESP32 WROOM microcontroller and three sensors (temperature, vibration, and speed) in the paper [16]. In 2020, researchers from Czech Republic implemented their vibration monitoring system on turboprop engines for aircraft. They use a vibration sensor and rotation speed sensor for the system [17].

Notably, a wireless vibration monitoring system utilizing ADXL345 accelerometers and ATTINY85 microprocessors on Unmanned Aerial Vehicles (UAVs) was proposed in June 2021, exemplifying the versatility of vibration monitoring technology [18]. Furthermore, in the biomedical sector, vibration monitoring employing Arduino NANO microcontrollers and IMU MPU6050 sensors demonstrated its potential in detecting vibrations in patients with Parkinson's disease [19].

The evolution of microcomputers, specifically the Raspberry Pi series, has opened new avenues for vibration monitoring research. Various studies have explored the application of Raspberry Pi in vibration analysis. For instance, a spectrum analyzer of vibration accelerations utilizing Raspberry Pi 3 model B and ADXL345 accelerometers was introduced in 2017 [22]. In 2019, an International Conference on Systems Computation Automation and Networking paper detailed the integration of Raspberry Pi into vehicle security systems, showcasing its utility in real-time vibration detection [24]. Similarly, Italian researchers employed Raspberry Pi 3 B+ in conjunction with WeMos Lolin D1 Mini microcontrollers for data sampling from ADXL1002 sensors, further expanding the applications of Raspberry Pi in vibration research [25].

Over the years, the Raspberry Pi Foundation always come out with different versions of Raspberry Pi with different kinds of variations and capabilities with improved design, models ranging from the Pi 1, Pi 2, Pi 3, Pi 4, as well as Pi 400 [20]. The higher the number representing the latest version. The Raspberry Pi hardware has been updated multiple times, including differences in the kind of central processor unit, memory capacity, networking capabilities, and peripheral device support. Generation of Raspberry Pi has started with models B, A, B+, A+ and Zero. Each model has different features and benefits.

There are several works published related to vibration monitoring using microcomputer Raspberry Pi [21]–[25]. A project conducted by Assoc. Prof. Dr Özkan Kafadar from Kocaeli University in Turkey utilized Raspberry Pi 2 B and Arduino UNO in tandem with seismic sensors for monitoring and recording seismic ambient noise, further diversifying the applications of Raspberry Pi in vibration research [21]. In 2017, a spectrum analyzer of vibration accelerations using a Raspberry Pi 3 model B for their microcontroller and ADXL345 accelerometer was proposed [22]. In 2018, a system for vehicle security and driver surveillance by using a Raspberry Pi model B was designed. The microcontroller operates with help of GSM and GPS module. It will alter its idle status once the vibration sensor detects any sudden heavy vibrations. This change in status will immediately notify the controller and give a command to camera to take a picture and alert the owner by sending the captured image to the owner's email address [23].

As in 2019, proceeding of International Conference on Systems Computation Automation and Networking have published a paper, entitled 'Parameter Monitoring and Functionality Control in Automobiles using Raspberry Pi' [24]. This paper uses the same model of Raspberry Pi as [22] and [23]. The purpose of this paper is to incorporate a security system into ordinary car to make it a smart car. Vibration sensor involve in this project is to detect abnormal vibrations comes from the car door. Also, GSM module (SIM 800C Modem) used in prototype capable the car to give an alert to user. Other than that, in Italy, Giuseppe Lorenzini et all from Politecnico di Milano Milan, Italy have used one of the latest Raspberry Pi model which is Raspberry Pi 3 B+ into their project [25]. They have connected the Raspberry Pi to WeMos Lolin D1 Mini microcontrollers, which to manage a data sampling from ADXL1002 sensor. Analog-todigital, ADC (ADS 1220) also contribute in this project to ease the measurement of ADXL1002 MEMS accelerometer [10].

In summary, the ongoing advancements in vibration monitoring systems, coupled with the versatility of microcomputers like Raspberry Pi, underscore the breadth and depth of research in this field. These efforts have contributed significantly to the enhancement and diversification of vibration monitoring technologies, making them invaluable tools in various sectors.

This paper focuses on the development of a vibration monitoring system (VMS) utilizing two computing platforms, the Raspberry Pi 4 processor and Arduino UNO microcontroller, both integrated with ADXL345 accelerometer sensor. The sensor serves as the cornerstone for the vibration monitoring system. The study evaluates the performance of these platforms, emphasizing their efficiency in processing and transmitting data

RESEARCH METHODOLOGY

This section outlines the configuration of the Vibration Monitoring System (VMS) utilizing Arduino and Raspberry Pi. In general, the block diagram for VMS is comprised of three parts, which are sensing and processing, wireless communication and data store and visualization, as shown in Figure 1.

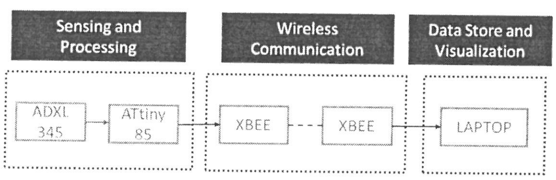

FIGURE 1. General block diagram of Vibration Monitoring System (VMS)

For VMS using Arduino, the hardware components utilized are ADXL354 accelerometer, ATTINY85 microcontroller, XBee modules, and Arduino. The process starts with the detection of vibrations emanating from a DC motor, facilitated by the ADXL345 accelerometer. Subsequently, the acquired data is stored in ATTINY85 and transmitted to the first XBee module at the transmitter. The first XBee module engages in wireless communication with the second XBee module, situated within the receiver module. Data storage and visualization operations are performed on a laptop.through CoolTerm software. Figure 2 shows the setup of VMS using Arduino as the computing platform.

Meanwhile, the VMS using Raspberry Pi is much simpler in comparison to utilizing an Arduino. The hardware component only includes the ADXL345 accelerometer as the primary sensor for detecting vibrations generated by a

DC motor. The ADXL345 sensor is equipped with several internal registers that may be read and written through I2C or SPI interfaces. The acquired data is stored within the Raspberry Pi interface. Figure 3 shows the setup of VMS using Raspberry Pi as the computing platform.

The purpose of this testing is to capture vibration along the x, y, and z axis generated by a DC motor and analyze the changes of amplitude and frequency as rpm is increased to 25%, 50%, and 75% of its maximum speed. In the Arduino setup, the transmitter components, including the ATtiny85 microcontroller, ADXL345 accelerometer, and XBee transmitter, are positioned at the central top of the motor, while the receiver module, comprising an Arduino UNO and XBee receiver is connected to a laptop as shown in Figure 2. Similarly in the Raspberry Pi setup, the ADXL345 accelerometer is also located at the motor's center and top as shown in Figure 3. The DC motor is operated at four specific rpm values: 650min^{-1} , 1320min^{-1}, 1950min^{-1} and 2636min^{-1} for both Arduino and Raspberry Pi interface. The duration of the data is 60 seconds for each speed.

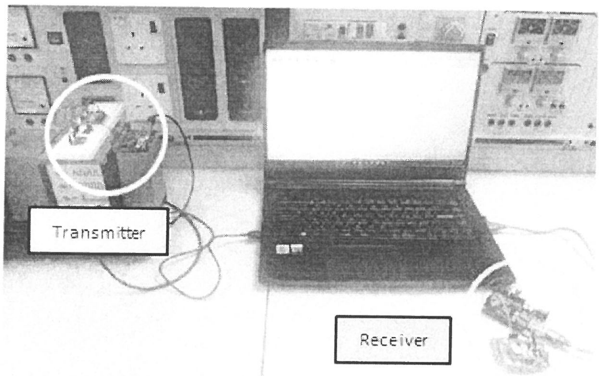

FIGURE 2. Setup of VMS using Arduino

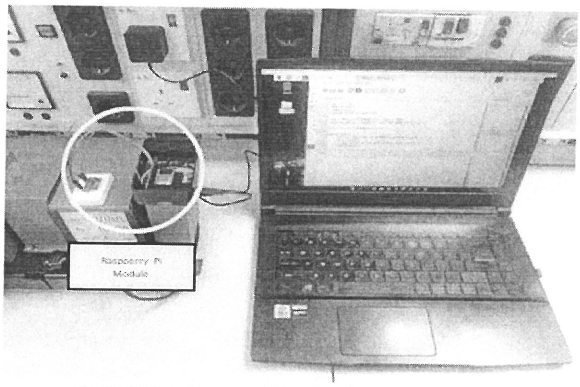

FIGURE 3. Setup of VMS using Raspberry Pi

Table 1 shows the testing parameter starts with no load which is torque equal to zero. The speed of the DC motor has been increased by 25%, 50%, 75% then to the highest rpm. When the machine rotates with increasing rpm, the speed will increase and the current will decrease, then the torque will decrease as well. This is because current and torque are perpendicular to each other.

TABLE 1. Motor Configuration

Set Data	RPM (min^{-1})	Torque (Nm)	Current (A)
1	0	0	0
2	650	0.75	2.1
3	1320	0.56	1.4
4	1950	0.43	1.0
5	2636	0.36	0.8

RESULTS AND DISCUSSION

The primary objective of this section is to assess and contrast the performance of data acquired from the VMS employing Arduino and VMS Raspberry Pi. The data sourced from the ADXL345 accelerometer affixed to the DC motor is utilized to construct harmonic vibration patterns, as depicted in Figures 4 and 5.

A distinct outcome emerges in the real-time vibration data acquired *from VMS* utilizing the Raspberry Pi 4 and Arduino in detecting DC motor vibration at a motor speed of 650min^{-1} and 2636min^{-1}. The magnitude of amplitude displacement for Raspberry Pi is higher than Arduino at 650min^{-1}, as shown in Figure 4. However, as the DC motor increases to maximum speed of 2636min^{-1}, the range of amplitude displacement is growing larger for VMS using Arduino compared to VMS using Raspberry Pi, as shown in Figure 5.

Meanwhile, Figure 6 and Figure 7 show the frequency spectrum of the vibration data acquired from VMS utilizing Raspberry Pi and VMS using Arduino. It is shown that the range of frequency spectrum of VMS using Arduino is larger than VMS using Raspberry Pi. When the DC motor runs at low speed, the amplitude of the frequency spectrum is small, as shown in Figure 6. However, as the DC motor runs at maximum speed, the VMS using Arduino is capable of acquiring more data compared to the VMS Raspberry Pi. This reflects the high amplitude of the frequency spectrum as shown in Figure 7. Table 2 concludes the comparison results from Arduino and Raspberry Pi. The result shows Arduino can receive around 6 data in a second, while Raspberry Pi can only receive 1 data, resulting Arduino obtaining 418 data in a minute.

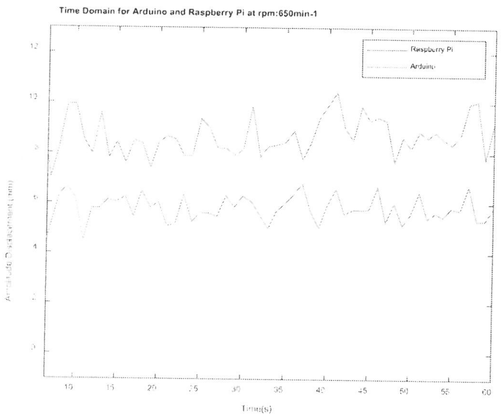

FIGURE 4. Performance comparison of data acquired from VMS utilizing the Raspberry Pi 4 and Arduino UNO in detecting vibration of DC motor at minimum speed of 650min^{-1}

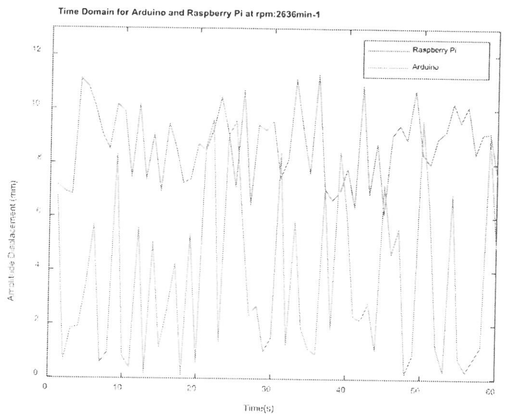

FIGURE 5. Performance comparison of data acquired from VMS utilizing the Raspberry Pi 4 and Arduino UNO in detecting vibration of DC motor at the maximum speed of 2636min^{-1}

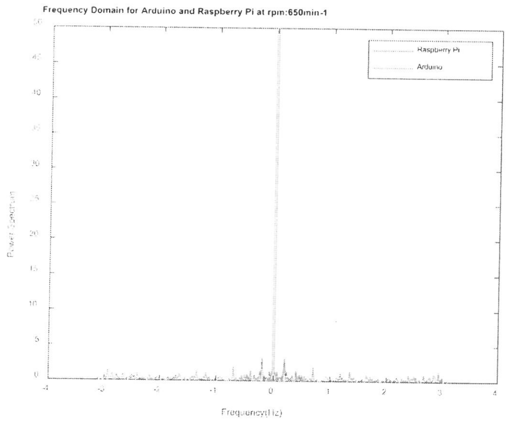

FIGURE 6. Comparison of the frequency spectrum for the VMS in detecting vibration of DC motor at minimum speed of 650min^{-1}

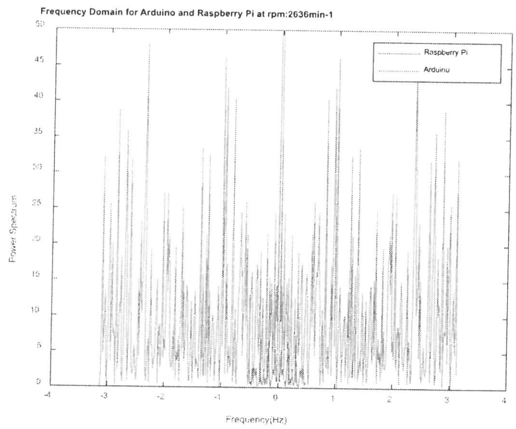

FIGURE 7. Comparison of the frequency spectrum for the VMS in detecting vibration of DC motor at maximum speed of 2636min^{-1}

TABLE 2. Sampling Data Result

	Number of Sample Data	Sampling Data (sample/sec)
Arduino	418	6.97
Raspberry Pi	66	1.1

CONCLUSION

The project successfully compared the performance of Arduino and Raspberry Pi as data acquisition tools in a low-cost vibration monitoring system, utilizing off-the-shelf components. The study involved testing two distinct vibration monitoring prototypes—Arduino and Raspberry Pi—to analyze variations in amplitude and frequency with varying motor speeds. The results indicated that as motor speed increased, both amplitude and frequency exhibited a corresponding increase, with Arduino outperforming Raspberry Pi.

The novelty of this project lies in the development of an economical vibration monitoring system, the analysis of vibration characteristics at different RPMs, and the comparative assessment of Arduino and Raspberry Pi as data acquisition tools. This study provides a valuable resource for technicians to monitor the health of DC motors and assess severity through amplitude displacement and frequency spectrum analysis.

To enhance the system further, it is recommended to incorporate a vibration alert feature, alerting technicians to potential DC motor issues. Such an improvement would bolster the project's utility and support sustainability initiatives by providing early warnings of machine problems before major breakdowns occur.

ACKNOWLEDGEMENT

This research was supported by the Collaborative Research Grant Scheme, CRGS (grant no. CRG/UPNM/2023/TK/01).

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