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IoT based Condition Monitoring System Design for Investigation of Non-Oil Ball Bearing in terms of Vibration, Temperature, Acoustic Emission, Current and Revolution Parameters

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ABSTRACT

The Internet of Things (IoT) concept facilitates our life in many areas. One of the facilities provided in this area is undoubtedly condition monitoring. Unlike regular maintenance, IoT systems that perform continuous control operations can provide great advantages to the company with a warning that a serious failure will occur. It is a vital importance to determine defective bearings during the rotation of the power generating and power consuming machines without reaching the critical level.

In this study; an experimental setup was created, and a Condition Monitoring Application (CMA) was performed in the laboratory environment which could monitor vibration, temperature, acoustic emission (AE), current and revolution measurements for ORS 6203 type defective bearing detection. In the designed test setup, a microcontroller platform used as a system brain, a direct current machine with a shaft mounted bearing, and miscellaneous sensors used such as 3-axis accelerometer that senses vibrations, a hall sensor module for revolution measure, a microphone module for AE detection, current and voltage sensor modules for power consumption measurement, contactless temperature sensor module for temperature measurement. CMA has been designed for monitoring of system via Bluetooth module. With the help of the microcontroller platform, the data collected from the sensors is transmitted wirelessly to the Android smartphone to be plotted and recorded. After the data exceeds certain thresholds, the control system is able to provide SMS and/or e-mail notification to the related maintenance team with the Android smartphone. Linear Discriminant Analysis (LDA), Random Forest (RF), Support Vector Machine (SVM), k-Nearest Neighbor (kNN), and Decision Tree (DT) algorithms applied to the collected data and models were created. As a result of accuracy analysis over %96 success was achieved for all models.

1 INTRODUCTION

Many of the products we use in our daily lives go through industrial production processes. The continuation of these processes without interruption or with minimal interruption is directly related to the maintenance of the equipment used in the production stages. Possible stop of the plant due to unexpected faults cause production delay, work accident, loss of production and product cost increase [1]. Maintenance costs have an important role in the total operating cost. Especially in an environment where global competition is increasing day by day, to present the best product with the lowest cost is among the main targets of the producers. One of the most critical elements of the production stages is undoubtedly electric motors.

Electric motors are all around us. We see them in many areas form industry to daily life. People use them in pumps, manufacturing floors, elevators, wind turbines, HVAC, etc. It is seen that electric motors are used in almost every field in order to meet operational requirements. The health status of the engines must be checked because of the critical duty at the place of operation. According to the literature review [2] motor failures are basically divided into two groups; electrical and mechanical faults especially bearing faults. As reported by [3], bearing failures account for half of the total motor failures.

Bearings are one of the most critical components in motors because they connect the motor stator and motor rotor [4]. Bearing defects for small and medium-sized machines account for the majority of all defects [5]. Preventing possible failures is very important in terms of reducing economic losses and the safe operation of industrial facilities. That's why condition monitoring of the motors is crucial.

According to [6], condition monitoring techniques are divided into two categories: offline and online monitoring. Offline condition monitoring is also called a periodic condition monitoring system. In this method, the reading from the sensors on the machine is performed within a certain time interval. Analysis of the read sensor data is performed in a laboratory environment away from the operating machine. Another method; online condition monitoring is called continuous condition monitoring. In this system, data is continuously collected by sensors from the running machine and compared to an acceptable value or in other words a threshold value. Recently online systems are much popular due to the development of IoT technologies.

IoT concept facilitates our life in many areas. One of the facilities provided in this area is undoubtedly condition monitoring. Unlike regular maintenance, IoT systems that perform continuous control operations can provide great advantages to the company with a warning that a serious failure will occur. It is a vital importance to determine defective bearings during the rotation of the power generating and power consuming machines without reaching the critical level.

The size of the data transmitted to the cloud system, that is associated with IoT technology, is quite high. The analysis of these huge data blocks, which is also called Big Data, can be analyzed with Artificial Intelligence (AI) approaches in a shorter period of time compared to classical approaches. There is much different AI software to develop solutions to real-life problems. But some of them need a license and some of them are open-source.

The use of open-source software is becoming more common. The lack of license fees for that kind of software offers many advantages to the user. In addition, many libraries developed by users are open-source. The developer can contribute to the development of libraries with the code he developed. Machine Learning (ML), which is a subfield of AI, is very popular in this issue. ML tool kits serve with licensed programs as well as free open-source software tool kits [7] such as Weka and R. Open-source R, which is an environmental for statistic computing and a programming language, is widely used in data analysis [8]. Since the R programming language interface is not user-friendly, code development is usually performed by most programmers in the RStudio environment. Detection of bearing damage requires extensive research. For this reason, researchers analyze data with ML tool kits.

Many methods have been developed based on the ML system such as Artificial Neural Network (ANN), Genetic Algorithm (GA), Ant Colony Optimization (ACO), Fuzzy Logic (FL), Hidden Markov Model (HMM), Random Forest (RF), Support Vector Machine (SVM), etc. The use of SVM for bearing condition monitoring and diagnostics has continued to increase in recent years. SVM has excellent performance in the generalization process, so the machine can provide high accuracy in classification for condition monitoring [9].

Although the analyzing of vibration is the most commonly used method to detect bearing damage, monitoring of other parameters such as temperature [10], aquatic emission [11], current [12], and revolution with vibration will increase the accuracy of the damage detection.

2 MATERIALS AND METHODS

Condition Monitoring System consists of four parts; first one is setup for the experiment, the second one is the CMA that runs on Android system to visualize the data, the third one is cloud system that used for storing the data to analyze and the last one is PLX-DAQ that allows data transfer to computer environment. The test setup consists of a microcontroller unit and peripheral units. CMA was created with a program called Virtuino. The electronic connection scheme of the setup, is shown in Figure 1, was created with Fritzing which is the open-source software.

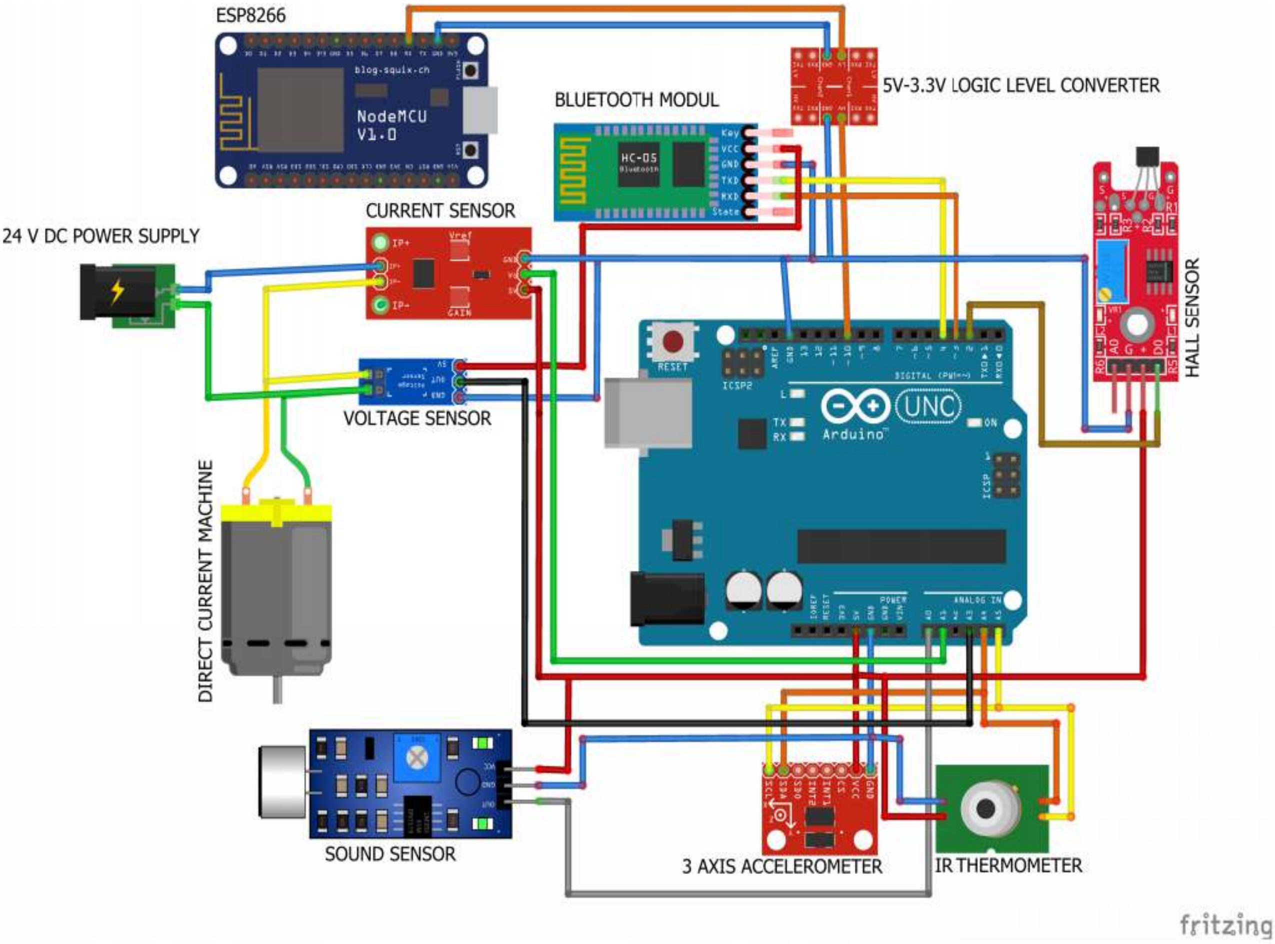
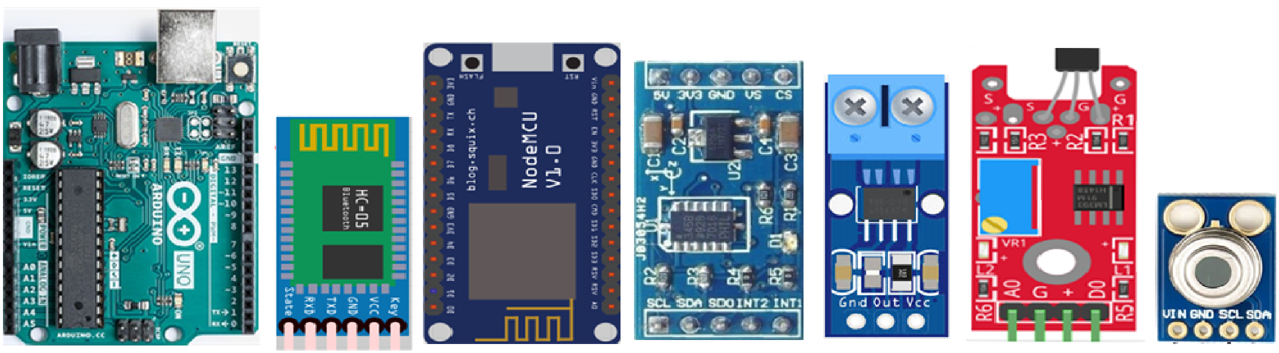


Figure 1: Fritzing schematic of electronics control system of CMA

A detailed description of the hardware and software materials can be found in the following sections.

2.1 Hardware Materials



(a) (b) (c) (d) (e) (f) (g)

Figure 2: Hardware materials

2.1.1 Microcontroller Platform (Arduino Uno)

It is an open-source microcontroller platform based on the ATmega328P microcontroller. It has 14 digital Input/Output (I/O) pins, 6 analog inputs, a 16 MHz quartz crystal and 8-bit microcontroller. It includes everything needed to make the microcontroller ready for operation; simply plug the USB cable into a computer, or run on an AC-DC adapter or battery to start. [13]. Microcontroller platform that used in setup is shown in Figure 2(a). Microcontroller platform is used as a brain of the system to collect sensors data and communicate with the designed CMA that runs on a mobile device over Bluetooth module.

2.1.2 Bluetooth Module (HC-05)

HC-05 Bluetooth module, shown in Figure 2(b), is a key part of the CMA because of providing communication between microcontroller and smartphone. It operates over unlicensed ISM (**I**ndustrial-**S**cientific-**M**edical) band, globally available frequency of 2.4GHz. It can link digital devices up to 10m.

2.1.3 WiFi Module (NodeMCU)

ESP8266 based Wi-Fi module, shown in Figure 2(c), is a very popular electronic part because of its use for IoT based projects [14]. This platform is designed for low-cost internet applications and has a structure similar to the Arduino boards such as having Input / Output units, PWM outputs and I^2C, SPI communication support. In addition to the Arduino Uno platform, Wi-Fi is available.

2.1.4 Accelerometer (ADXL345)

The ADXL345, which is shown in Figure 2(d), has 3-axis accelerometer with 13-bit resolution. It supports up to ±16 g acceleration and easy to use with the microcontroller over Serial Peripheral Interface (SPI) or Inter-Integrated Circuit (I2C) communication protocol [15]. It is ideal for vibration measurement on bearing housing for CMA because of its features such as cheap, small, thin and has ultra-low power consumption as low as 23 µA in measurement mode and 0.1 µA in standby mode.

One of the most important dynamic problems of design engineering to be solved is undoubtedly mechanical vibrations [16]. There are some negative effects of mechanical vibrations. These are material fatigue, abrasion, high stresses, and noise. Systems exposed to mechanical vibrations due to these effects can take serious damage. If the necessary precautions aren't taken, the system may be damaged. Therefore, it is vital to carry out mechanical vibration measurements. Mechanical vibrations can be axial, radial and torsional. Hence, the measurements of vibration should be collected from 3-axis.

2.1.5 Current Sensor Module (ACS712)

The ACS712, which is shown in Figure 2(e), is fully integrated, nearly zero magnetic hystereses, hall effect-based linear current sensor (AC/DC) with 5V single supply operation and a low-resistance current conductor [17].

2.1.6 Linear Magnetic Hall Sensor Module

The module, which is shown in Figure 2(f), has A3141 chipset which detects the magnetic field and LM393 operational amplifier on the board. The potentiometer can control the sensitivity of the sensor. If a magnetic field is detected by the sensor, a signal sends over D0 pin. Neodymium magnets have been placed on the motor shaft to measure revolution value as shown in Figure 3.

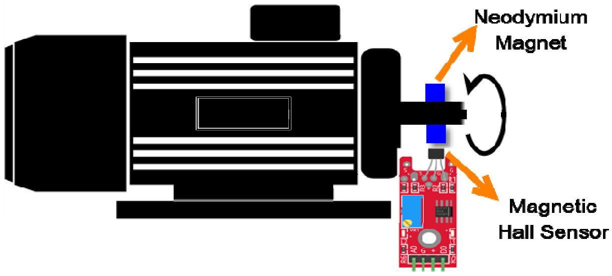


Figure 3: Hall sensor placement with neodymium magnets for revolution measurement

2.1.7 Contactless Temperature Sensor Module (MLX90614)

The MLX90614, which is shown in Figure 2(g), is an Infra-Red thermometer and uses for non-contact temperature measurements. It has a wide range and high accuracy temperature measure, from -40 to 125 ˚C for sensor temperature and form -70 to 380 ˚C for object temperature [18]. And also, it is tiny and has a low cost. Because of these features, it is ideal for industrial temperature control of moving parts.

As design criteria, bearing metal temperatures should not exceed specified operating conditions. The rising temperature of the bearing may be due to loss of grease or bearing failure. It should be provided bearing temperature alarm and shutdown limits. Otherwise, the bearings' fault may cause serious damage to machines. Therefore, it would be useful to monitor the temperature of bearing for the health of machines.

2.1.8 Voltage Sensor Module

The analog input of the microcontroller platform used in the designed system is limited to 5 Volt DC. If higher voltage values are to be measured, it is necessary to use a voltage divider. The direct current machine uses 220AC to 24V DC power supply. In the design of the electronic system was used a 5:1 voltage divider with a 4XΩ and an XΩ resistor. This type of design is restricted to voltages that are less than 25V. More than that voltage will exceed the voltage limit of analog input and cause damage on the microcontroller platform. Microcontroller which is used in the setup has 10-bit Analog Digital Converter (ADC) so the resolution is 0.00489 V (5V/1023). The voltage divider circuit used in the setup is shown in Figure 4.

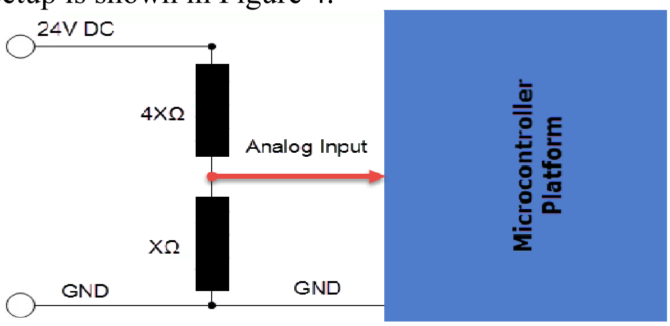


Figure 4: Voltage divider for less than 25V supply voltage measurement

2.2 Software Materials

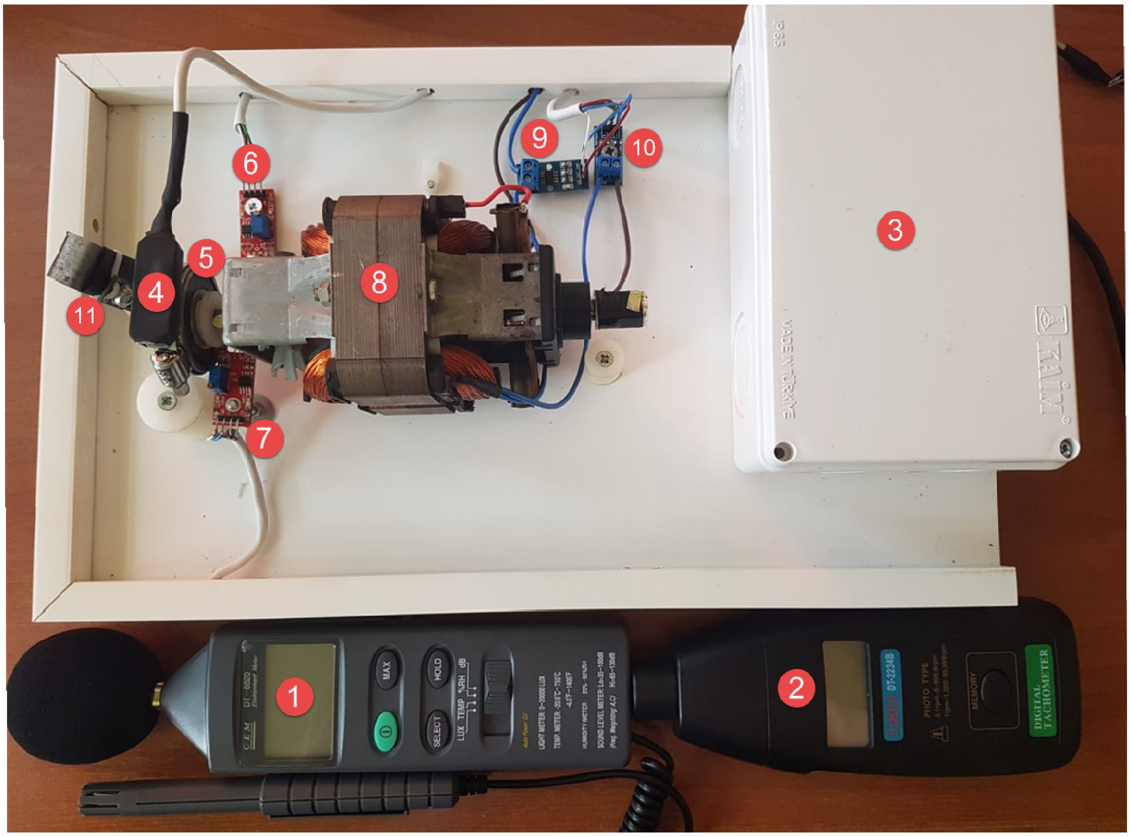
2.2.1 Condition Monitoring Application (CMA)

CMA is a monitoring application to view sensor values on the screen of the android based mobile device. Not only it has monitoring feature but it also has an alarming feature with sound over the buzzer of the smartphone, notification feature with e-mail/SMS if threshold values exceed and exporting data to excel format etc. It can communicate with the microcontroller platform over the Bluetooth module. Hence, the microcontroller platform sends the data comes from sensors to the mobile device. The CMA has analog displays to show the instant value of sensors and charts to show continuous value.

The CMA used for this study has been designed by Virtuino app because it has a user-friendly interface. It can communicate efficiently with control boards such as Arduino and ESP, to send a control signal to the boards and to monitor the condition of the designed system with mobile devices wirelessly The Virtuino app has been used for different applications such as Smart Home Automation [19], Classroom Monitoring [20], Smart Agriculture [21], and Intelligent Healthcare Monitoring [22].

2.3 Method

The all system (CMA and Setup) designed step by step. This section explains all these design steps. The setup has an electric motor, healthy and damaged ORS 6203 type bearings, an Arduino UNO, an ESP8266 Wi-Fi module, an HC-05 Bluetooth module, and miscellaneous sensors. The sensors are an accelerometer, a hall sensor, a current sensor, a voltage sensor, a microphone, and a contactless temperature sensor. The top view of the setup used for experiments is shown in Figure 5.



1: Sound Meter 2: Digital Tachograph 3: Control Box (Arduino UNO – NodeMCU) 4: Vibration Sensor 5:Bearing 6: Microphone 7: Hall Sensor 8: Direct Current Machine 9:Current Sensor 10: Voltage Sensor 11: Contactless Temperature Sensor

Figure 5: Top view of Setup

The first step of designing the system was to make connections to the peripheral units (sensors and communication modules) to the microcontroller platform. These connections had been shown in Figure 1 before. The second step was to calibrate all the sensors with measurement devices which have high accuracy. And the third step was to do experiment with healthy and non-oil ball bearings and collect data from the test setup to the PC via PLX-DAQ [23] (Parallax Data Acquisition Tool Software). The collected data were also transferred to the cloud over the ESP8266 Wi-Fi module. The general structure of the system is basically shown in Figure 6.

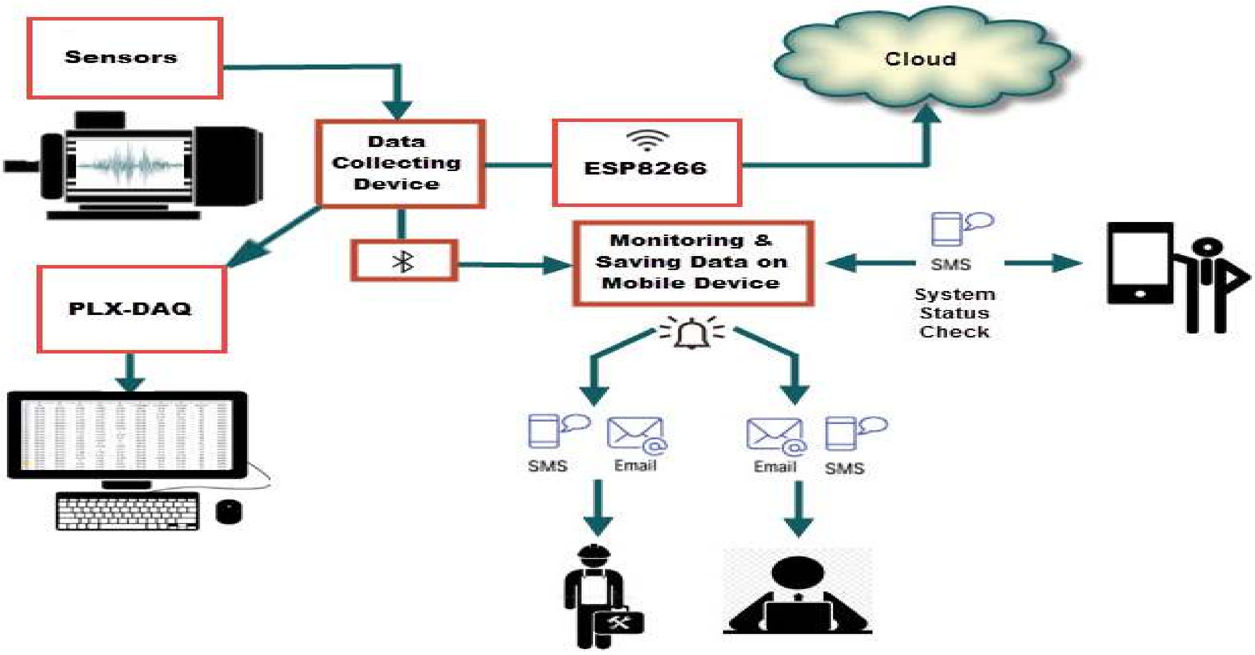


Figure 6: General structure of the designed system

At the fourth step, the CMA interface was designed with the Virtuino App. The collected data was transferred to the smartphone screen over the Bluetooth module. Thus, the data were visualized with charts and analog instruments on the smartphone display. In the designed CMA, all sensor data are displayed continuously with charts and instantly with analog displays. The CMA's interface with 5 different panels is shown in Figure 7. The first four panels show respectively ambient and bearing temperature, x-y-z vibration level, revolution and AE, current and voltage at chart widgets. The last panel shows all sensor value on analog instruments.

Figure 7: CMA interface for displaying all sensor values on analog instruments and charts

The next step was to analyze the data with Decision Tree (DT) algorithm, popular ML tool kit, to determine the threshold values for parameters of vibration, temperature, AE, current and revolution. Then, the alarms were set to the experimental system parameters due to the result of DT.

Microcontroller platform is used as a brain of the system to collect sensors data and communicate with CMA that runs on a mobile device over Bluetooth module. If the measured value of sensors is above the acceptable values, this means that the bearing is damaged and a warning is issued. After the oil-free ball bearing is mounted on the motor shaft, the vibration level exceeds the threshold. In this case, the CMA sends e-mail and SMS notification. This is illustrated in Figure 8.

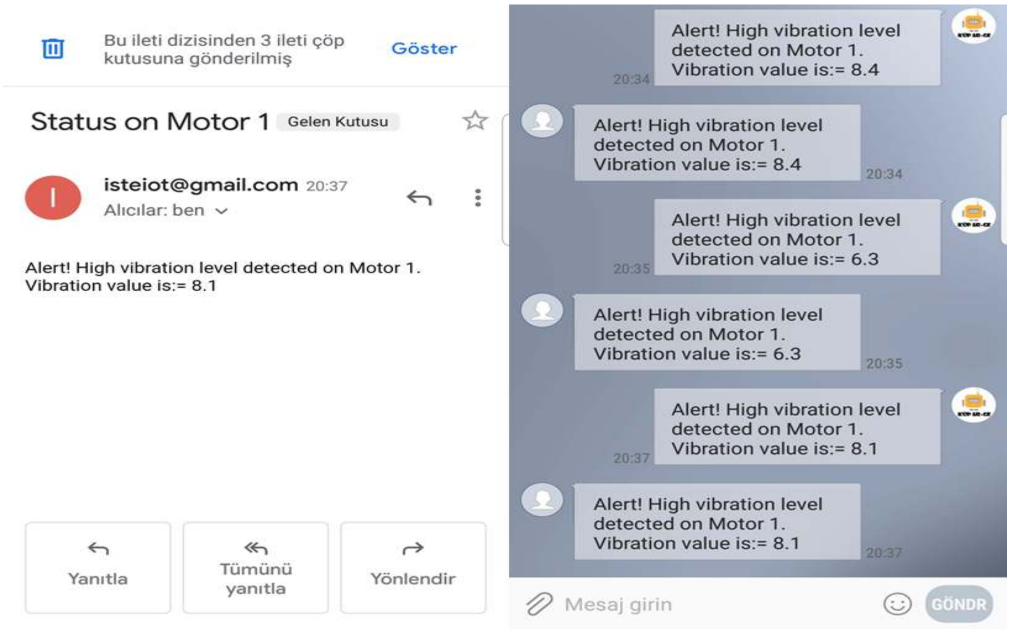


Figure 8: SMS and e-mail alarm notification from the CMA to the maintenance team

The last step was to analyze all data with ML tool kits. Models were created from the CART, LDA, kNN, SVM, and RF algorithms. Then accuracy analysis was performed on these models.

3 RESULTS

The experiments in this study consist of two parts. The first test with healthy ball bearing mounted on the motor shaft and the second test with non-oil ball bearing. Observation data obtained from the first test were classified as "0-Healthy Bearing" and observation data obtained from the second experiment were classified as "1-Damaged Bearing". The data obtained data consists of 8 different parameters. These parameters are, Gx (x-axis vibration), Gy (y-axis vibration), Gz (z-axis vibration), Temperature (ambient and bearing), I (Current), AE and Revolution. The size of all data has 12264 rows and 8 columns. This data was transferred to RStudio environment in *csv* format. The data, 70 % of all, was used for training purposes and the remaining 30% was used for test analysis. CART model was used to determine the threshold of parameters. Parameters based prediction results of CART model is shown in Figure 9.

Other popular models were created as LDA, kNN, SVM, and RF from the library named “caret”, “kernlab”, “caTools”, “rpart”, and “ROCR” in RStudio for accuracy analysis. As a result of accuracy analysis, 96.13% for LDA, 97.48% for kNN, 98.25% for SVM and 98.11% success was achieved for RF models.

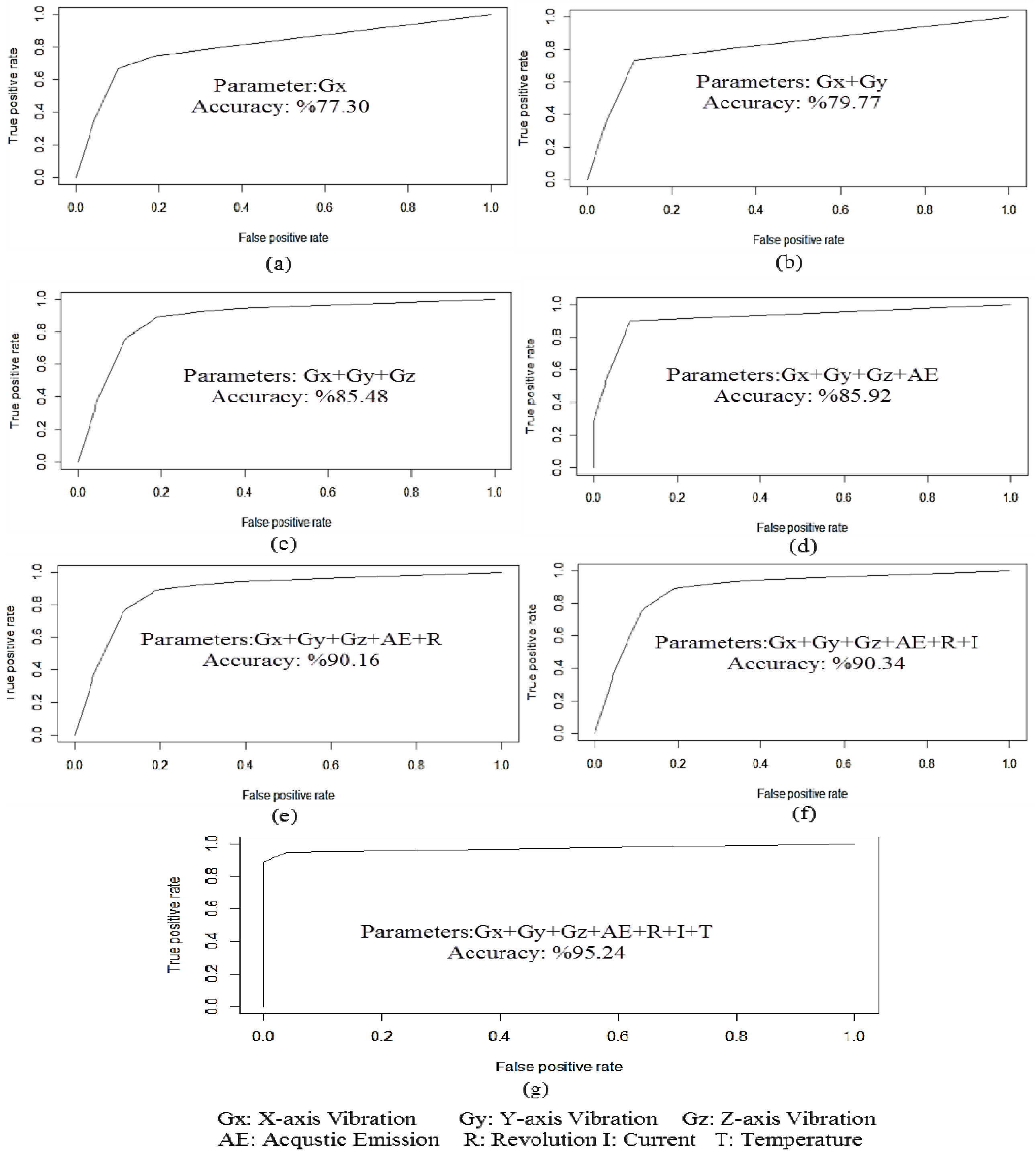


Figure 9 Parameters based prediction results of CART models

4 CONCLUSION

Although the analyzing of vibration is the most commonly used method to detect faulted bearing, monitoring of other parameters such as temperature, AE, current and revolution with vibration increased the accuracy rate of the damage detection. In the estimation made by vibration analysis, the analysis of the data obtained from 3-axes increases the accuracy of the estimation. An 8% difference was observed between the estimation based on the vibration data obtained from the single axes and the estimation based on the vibration data obtained from the 3-axes. If AE and current data are added in addition to the vibration data, the accuracy rate increases by less than 1%. On the other hand, if revolution data is added, it increases nearly 5% and finally, if temperature data is added, a 5% increase is observed.

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