Developing Predictive Maintenance Model Based on Fault Diagnosis Technique for Miniature Sewage Treatment Unit

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Abstract

One of the best strategies to decrease unexpected downtime, save maintenance costs, and increase asset longevity is to monitor mechanical components of equipment. Given that most failures can be prevented, condition monitoring is a key part of predictive maintenance and is thus more effective than corrective maintenance. The process of condition monitoring includes fault diagnosis, which enables operators to not only identify mechanical anomalies but also to identify the underlying source of the problem and make the necessary repairs. In order to detect and identify flaws, a fault diagnostic system based on predictive maintenance approach has been built in this work. The developed model has been used to monitor and diagnose the operational behavior of a mechanical aeration plant. Arduino, sensors (temperature and vibration sensors), and PC software have been used as the system's major building blocks for the suggested system's predictive maintenance plan. Using the Arduino programming language and LabVIEW software, online data collecting, signal analysis, defect diagnosis, and results presentation activities were written and simulated. According to their severity, fault representation types are categorized into (N, C, Ci, Cs, and D) levels based on vibration and temperature measurements. Based on the online data from the case study used in the defects identification model, the findings determine whether a fault occurred or not. They also analyze the potential causes of the faults so that the proper remedial action may be done. The fault-diagnostic system's adoption has led to improved decision-making that helps to update the maintenance plan, which helps to lower overall maintenance costs and downtime for all equipment.

Introduction:

A kind of preventative maintenance called predictive maintenance aims to prevent unplanned work stops that interfere with production schedules. The ability to check the unit while it is running sets it apart from preventative maintenance. It depends on anticipating malfunctions by keeping an eye on the machine's performance, including vibrations, high temperatures, noise they produce, and other characteristics, either manually or by performing routine inspections with the aid of sensors and inspection tools that are connected to the computer to gather and process data [1]. The process of diagnostics involves employing sensors in a working environment to search for issues and evaluate the health of components. In order to identify components and provide details on the present performance state, inspection is required during maintenance [2]. For the reliability, safety, and effectiveness of industrial operations, diagnostic issues are important and essential. In the event that a component fails, there might be large financial losses, which would impair overall performance and, in the worst cases, put operators in danger [3]. Automated failure detection and diagnosis prevents planned and expensive equipment maintenance by continuously identifying performance issues and bringing them to the attention of the operator [4]. The significance of efficient automated fault detection and diagnosis in contemporary technological installations is rapidly increasing as systems become more intricate and need little downtime or malfunction time [5]. The research presented in this paper is based on online data collected from a small-scale model of the mechanical aeration unit equipment of wastewater treatment plants. Mechanical issues, such as problems with gearboxes, motors, bearings, rotating shafts, and critical components, have gotten worse over the past two decades as a result of the ineffective corrective maintenance approach. In order to enhance and evolve the maintenance plan for wastewater treatment facilities, a prediction-based fault diagnostic system has been created. It attempts to enhance the amount of treated water produced, lower overall maintenance costs, and shorten equipment downtime.

Related Work:

There are many important studies and related research in field of fault diagnosis technique have been introduced and presented, as follows: -

Yuanhang W., et al. ,2013, suggested a comprehensive corrective maintenance plan for engineering equipment. First, the multiple failure modes were organized using an expanded version of the failure mode, effects, and criticality analysis (FMECA). The failure propagation model (FPM), which shows the cause-and-effect relationship between failures, was described next. Thirdly, traditional corrective maintenance advises determining the malfunction with the highest likelihood first. Moreover, to quantify the risk of failure, the term risk metric of the failure (REN) was developed. A scenario is shown to use the suggested strategy on the boring machine tool's ram feed section. The outcome validated the applicability and validity of the suggested approach for corrective maintenance of engineering machinery [6].

Ana C., et al., 2018, presented the design of an Industry- 4.0 compliant, which is a predictive maintenance system that follows the Open System Architecture for Condition-Based Maintenance's functional block structure (OSA-CBM). The system architecture takes into account sophisticated and real-time analysis of the data collected for the early identification of potential machine faults. It also aids workers in making informed decisions when performing maintenance interventions. In order to improve the interaction between people and machines and the effectiveness of the execution of maintenance interventions, the proposed system expands the fundamental condition-based maintenance (CBM) functionalities through the integration of decision support systems and augmented reality technologies [7].

Li Y., et al., 2018, proposed a model of two-phase preventive maintenance plan for a single component. The maintenance policy is divided into two sections: An imperfect maintenance phase examination was carried out to identify the faulty state and pave the way for a potential fix (a) The examination and the repair both have defects. (b) A phase of delayed replacement preventive replacement was carried out during the forthcoming planned maintenance window in the postponed replacement phase; no inspection or repair was carried out beforehand. The inspection interval, number of inspections, and preventive replacement interval were jointly optimized to maximize the predicted net income under performance-based contracting (PBC). The results demonstrated that the suggested maintenance policy outperforms several current maintenance policies in terms of net income when the model was applied to a scenario from a steel converter plant [8].

Andrey I., et al., 2018, contributed to creation of an automated expert system for analyzing vacuum equipment maintenance methods and techniques. The study aimed to analyze the stages of information expert system's design and operation. Vacuum devices serve as an illustration of analytical support for industrial machinery. With the aid of the programming language of Visual Basic for Applications, the implementation of this predictive maintenance system resulted in the reduction of equipment downtime, a reduction in equipment repair costs, a reduction in the number of unplanned repairs, control of operating mode breaches, and an improvement in the control efficiency of the organization [9].

Amjad B., and Ammar I.,2018 introduced an enhanced RCM methodology based on quantitative relationships was implemented at system component level and the overall system reliability was applied to identify the distribution components that are critical to system reliability. Only unit one of the Second Power Plant of South Baghdad were selected as a case study. The results obtained from the case study showed that the application of proposed RCM methodology based on preventive maintenance planning will decrease the total cost value of maintenance about 463469.85 $. That Indicates saving about 59% of the total downtime cost compared with current maintenance. [10].

Khanh T., et al., 2019, offered an innovative sensor-based system for dynamic predictive maintenance. The prognostics stage in this architecture, which is based on the Long Short-Term Memory network, was tailored to the needs of operation planners. It offered the likelihood that the system will fail across several time periods, allowing users to choose the best time to start planning and carrying out maintenance tasks. In order to quickly assess the costs of maintenance and inventory choices and select the best course of action at the start of the decision period, the suggested technique also contains a decision model. When compared to the ideal anticipated prognostics findings generated from turbofan engines data supplied by the NASA Ames Prognostics, the efficiency and performance of the suggested model were demonstrated and emphasized [11].

Shan W., et al., 2018, introduced a framework for collaborative maintenance planning to link many stakeholders and incorporate their expertise into the maintenance and service process using content management systems (CMS). According to the research, CMS has various benefits over conventional engineering information systems, particularly when it comes to managing dynamic and unstructured content [12].

Werneret, et al., 2019, showed an approach for a predictive maintenance strategy dealing with acquisition, processing, and analysis of historical field data as well as the generation of respective simulation data [13].

Jack C., et al. ,2020, Building facilities can benefit from better maintenance strategies thanks to Internet of Things (IoT) technology for facility maintenance management (FMM). The information layer collects data and integrates it across the BIM models, the FM system, and the IoT network, while the application layer has four modules to accomplish predictive analytics, including the following modules for maintenance: (1) condition monitoring and fault alarms; (2) condition evaluation; (3) condition forecast; and (4) maintenance planning. The results indicated that machine learning techniques in the application layer combined with continuously updated data from the information layer can accurately forecast the future state of MEP components for maintenance planning [14].

Weifeng S., et al., 2020, introduced two intelligent grid maintenance frameworks—the evolutionary algorithm and the K-medias clustering approach, respectively—were suggested taking into account the aforementioned three conditions. The two suggested intelligent grid maintenance frameworks' efficacy was tested using five real-world datasets gathered from five different local cities and counties in eastern China. The study's findings revealed a more complex severity level algorithm [15].

Zeki M., et al., 2020, by categorizing the research according to the ML algorithms, ML category, machinery, and equipment employed, offered a thorough analysis of the most current improvements of ML techniques frequently applied to PdM for smart manufacturing in Industrial 4.0 [16].

As mention in the previous studies most researches focus on using different advanced techniques such as artificial intelligent, IoT, and Industry 4.0 for faults diagnosis. While, in this paper will focus on developing new model based on knowledge based technique using sensing and microcontroller systems for faults diagnosis to monitor and control of equipment maintenance plan, which leads to decrease total maintenance cost and downtime.

Proposed Fault Diagnosis System:

Because it affects a company's ability to compete, choosing a maintenance policy is one of the most crucial decisions that must be made. To do this, a maintenance team needs to have access to practical experience, which requires researching all the factors that affect maintenance and debating their effects. The selection of a predictive maintenance plan depends on a number of variables and various standards for comparing maintenance alternatives plans to gauge the effectiveness of maintenance operations. This study proposes a defects diagnostic system based on online data collection to determine the best course of maintenance for a planned preventive maintenance program. The fault diagnostic feature is important for automatically gathering data for system operation, monitoring, and protection. The fault diagnostic system's online maintenance technique, as seen in figure (1), has been presented. This technology offers real-time data obtained online from the diagnosis of equipment defects and enhances maintenance schedule. Signal processing, feature selection, and data collecting. The major phases of the proposed system are fault detection and fault diagnosis, which are described as follows:

Architecture of System Component:

A fault detection system-based predictive maintenance plan has been created for monitoring and diagnosis using temperature and vibration sensors. one of the most typical reasons for aeration unit mixer malfunctions in treated water plants. As seen in figure (2), a fault diagnostic system was constructed utilizing an Arduino, sensors, and a computer. The Arduino programming language and LabVIEW software were used to code and simulate the activities of data gathering, signal analysis, defect diagnosis, and results presentation.

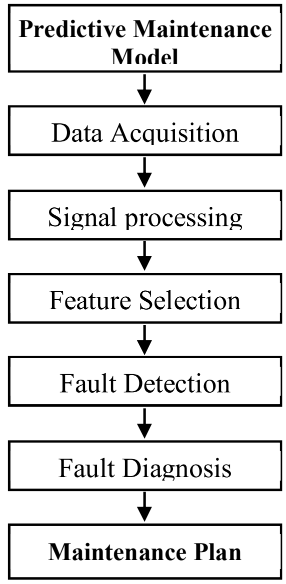

Figure (1) Proposed Fault Diagnosis System.

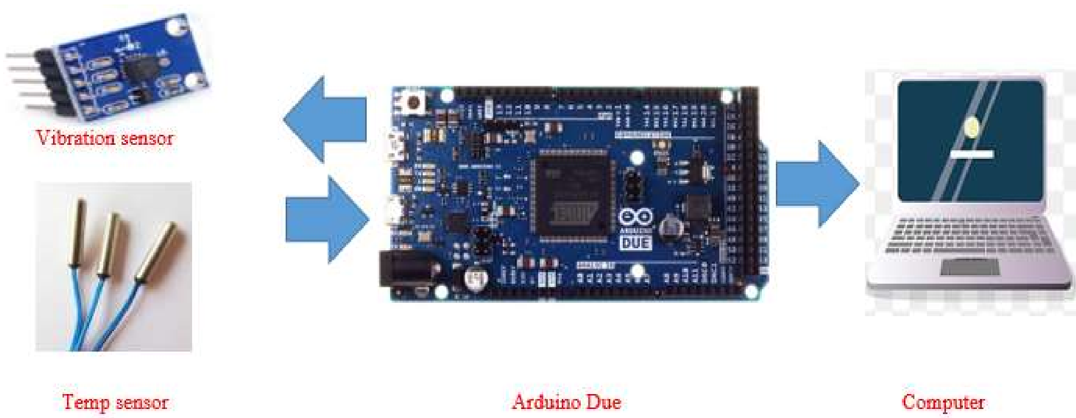

Figure (2) System Component Architecture.

The main components of the fault diagnosis system explained as follows: -

A-Vibration Sensor (ADXL335):

The ADXL335 is a compact, thin, fully functional 3-axis accelerometer with voltage outputs that are signal-conditioned. The sensor detects acceleration with a minimum full-scale range of 3 g and a frequency range for the X, Y, and Z axes of 0.5 Hz to 550 Hz and 0.5 Hz to 1600 Hz, respectively. In tilt sensing applications, it may monitor the static acceleration of gravity as well as the dynamic acceleration brought on by motion, shock, or vibration. The ADXL335 is offered in a tiny, low profile, 16-lead, plastic lead frame chip scale package (LFCSP_LQ), measuring 4 mm by 4 mm by 1.45 mm.

B- Temperature Sensor (10K ohms):

This 10K ohms at 25°C standard sensor is typically used in invertor and UPS heatsink applications, where it may be used as a readily accessible and widely used temperature sensor. With specifications like "Resistance at 25 deg C 1K ohm, Operating Temperature

Range -40 to +150degree C, Resistance Tolerance+/-1%, Thermal Time Constant 14s, Surface Finish Teflon Coated," this kind is also used in air conditioning.

C- Arduino Due:

One of the first Arduino boards, the Arduino Duo, used an Atmel SAM3XBE ARM Cortex-M3 AT91SAM3X8E microcontroller. This microcontroller is a member of the 32Bit family and is characterized by greater storage capacity, greater capabilities, and faster data processing and equations. The Arduino Duo may be different from other Arduino kinds in that it works on 3.3 volts, which is far faster than the rest of the Arduino types' processing speeds of up to AME. The Arduino Duo board features 54 digital ports (inputs and outputs) and two USB ports in addition to additional ports and heads like DAC and ATC header. It also has a reboot and erase button. In addition to having 12 analog ports and 12 PWM ports, it also has 12 bits for converting signals from analog to digital and vice versa. Because of its low price, adaptable design, small size, open source, portability, accessibility, availability, and support, Arduino is employed in practical and industrial applications.

D- LabVIEW Software:

One of the most well-known engineering programs created by the American electronics business National Instruments is LabVIEW. It is utilized in the fields of data acquisition, control tool, automation systems test, signal analysis and processing, and industrial control and runs on all operating systems (Windows, Linux, and Mac). design of embedded systems. The language G, sometimes known as the Dataflow creation Language, was employed in the creation of the LabVIEW environment. Using LabVIEW software, a defect diagnostic system computer application is created. This application can track the temperature and vibrations of the aeration unit's machinery and detect issues. This computer software acts as a connection between the program block's primary processing unit and the nodes in charge of carrying out the program's execution. The accelerometer's data value for vibration (Readings) must be calibrated before it can be transformed into an acceleration formula. The velocity is then determined using a singular integration, while the displacement is determined using a double integration.

Fault Diagnosis Function:

The activities involved in fault diagnosis, such as defect detection and identification, call on an understanding of the equipment's malfunctioning behavior. In the event of predicted defects, this method can produce satisfactory diagnosis results. However, it is not always feasible to predict every issue in detail; as a result, only faults that are expressly taken into account in the equipment model may be found and named.

Fault Detection:

This work demands the usage of the internal analysis of fault diagnostic system and various quantifiable output signals. A signal analysis is a supplementary source of information for many observed signals that exhibit oscillations linked to the sensor. The goal of fault detection is to determine the precise nature of the defect (its scope, status, and explanation of potential causes). Therefore, in order to forecast potential causes and remedial measures for an aeration unit, fault detection requires a model of the equipment's normal behavior and problems' severity. These duties are described below:

- ✓ **Temperature:** Table (1) describes how to identify faults based on temperature range, color, and condition. The table (2) in relation to temperature limitations, potential reasons, and remedial action.
- ✓ **Vibration**: Table (3) further explains how defect detection relates to displacement range, color, and status. In addition, it is connected to the displacement limitations, potential causes, and correction measures described in table 4).

Table (1) Temperature Data as It Appears on The Program Interface.

Temperature range	Color	Status
0-59.9 C°	(black)	Out of range
60-75.9 C°	(green)	Normal
76-85.9 C°	(orange)	Critical
86-105 C°	(red)	Danger

Table (2) Describe Possible Causes of Overheating and Corrective Action.

Temperature Limits	Possible causes	Corrective action
T<=75.9	Normal	____________
76=<T=<85.9	Looseness in the electrical connection	Cleaning and adjusting electrical connections
76=<T=<85.9	damage to the motor cooling fan	checking the motor cooling fan
76=<T=<85.9	Decrease or leakage of gearbox oil	Checking gearbox oil level and lubricating the moving parts
86=<T=<105	damage to the coupling bearing	checking the coupling bearing work
86=<T=<105	A large amount of sludge has accumulated above the impeller	Cleaning and removing the deposited sludge from the impeller

Table (3) Displacement Data as Its Appears on The Program Interface.

Displacement range	Color	Status
0 - 0.39 mM	(black)	Out of range
0.4 - 0.859 mM	(green)	Normal
0.86 - 1.69 mM	(orange)	Critical
1.7 – 2 mM	(red)	Danger

Table (4) Describe Possible Causes of Displacement and Corrective Action.

Displacement	Possible Causes	Corrective Action
0.4 - 0.859 mM	Normal	______________
0.86=< D =<1.69 mM	Loosen the engine and gearbox mounting base bolts	Ensure that the screws of the base are tightened.
0.86=< D =< 1.69 mM	Loosen to the rotating shaft bolts	Ensure that the screws of the rotating shaft are tightened
0.86=< D=< 1.69 mM	Corrosion on the rotating shaft	Removing rust from the rotating shaft or replacing it
1.7=< D =< 2 mM	A large amount of sludge accumulated on one side of the impeller	Cleaning and removing the accumulated sludge
1.7=< D =< 2 mM	one of its fins was broken	replacing the impeller

Fault Identification: The performance variation of an equipment component is deemed important if it results in a breakdown or failure. Whether a malfunction has occurred or not, the aeration unit equipment functions properly. This activity seeks to identify the specific pieces of equipment that are at issue. This job has been included in the proposed fault diagnostic system to monitor and diagnose equipment work behavior based on temperature and vibration sources. Models for fault identification use several fault representations to determine if a problem has occurred. Explain the intensity of defects based on vibration measurement and temperature data as follows:

1-Normal (N): It indicates that there is no increase in temperature or vibration, indicating that preventative maintenance is performed as scheduled.

2-Critical (C): choose a certain range and follow the maintenance team engineer's directions, which comprise the following two types: -

- **a.** Critical Incremental (Ci) within range but stable. Maintenance is performed as scheduled and on time.
- **b.** Critical Stable (Cs) Within range but incrementally. For both temperature and vibration taken together, defects are gradual. The maintenance engineer ultimately decides whether to update the maintenance plan, notwithstanding the defects diagnostic system's recommendations. The maintenance plan won't need to be changed if the fault date is close to the preventive maintenance date, but it will need to be updated if the fault date is distant from the preventive maintenance date.

3-Danger (D): accordance to the maintenance team engineer's directions, within a specific range. Therefore, for problems caused by rising one of the two (temp or vibration) or both, preventative maintenance must be performed on the day of the fault and the time of the maintenance must be updated. The problems diagnostic system is coded according to the aforementioned fault status standards so that the best maintenance decisions can be made and the necessary remedial measures can be taken. Therefore, the table (5) provides an explanation of these regulations together with any relevant remedial action and proposed maintenance programs.

Table (5) Rules Related with Corrective Action and Suggested Maintenance Plans.

No.	T. Status	V. Status	Corrective Action	Maintenance plan
1	D	D	1-Cleaning and removing the deposited sludge from the impeller. 2-Checking fins status.	Updating the maintenance plan according to the malfunction day.
2	D	Cs or N	1-Cleaning and removing the deposited sludge from the impeller. 2- Cleaning and adjusting electrical connections.	Updating the maintenance plan according to the malfunction day.
3	Cs or N	D	1- Ensure that the screws of the basement and rotating shaft are tightened. 2-Checking fins status.	Updating the maintenance plan according to the malfunction day.
4	Ci	Ci	1-checking the coupling bearing lubricating. 2-Removing rust from the rotating shaft. 3-Checking the oil level and lubricating the moving parts	Updating the maintenance plan according to the malfunction day.
5	Ci	Cs or N	————————	The maintenance plan remains on the previously specified day.
6	Cs or N	Ci	————————	The maintenance plan remains on the previously specified day.
7	Cs	Cs	————————	The maintenance plan remains on the previously specified day.
8	N	N	————————	The maintenance plan remains on the previously specified day.
9	N	Cs	————————	The maintenance plan remains on the previously specified day.
10	Cs	N	————————	The maintenance plan remains on the previously specified day.

Case Study and System Implementation:

The mechanical Aeration Basins sewage treatment facility was chosen as the case study for this work's tiny model. The primary step of sewage treatment is the Aeration Basins unit. This system depends on creating the ideal environment for bacterial growth. There are several mechanical mixers inside the aeration basins. As illustrated in Figure (3), each mixer has a motor, gear box, shaft, and impeller that deliver the dissolved oxygen required for bacterial development.

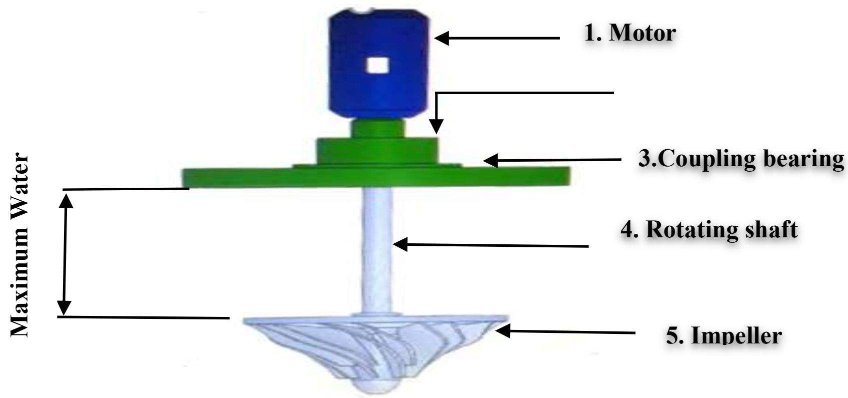

Figure (3) Mixer components of Aeration equipment

The aeration basin unit prototype equipment was equipped with the suggested fault diagnosis system. as seen in Figure (4) to identify flaws and forecast them before they worsen. Some flaws have been discovered during the system work verification phase.

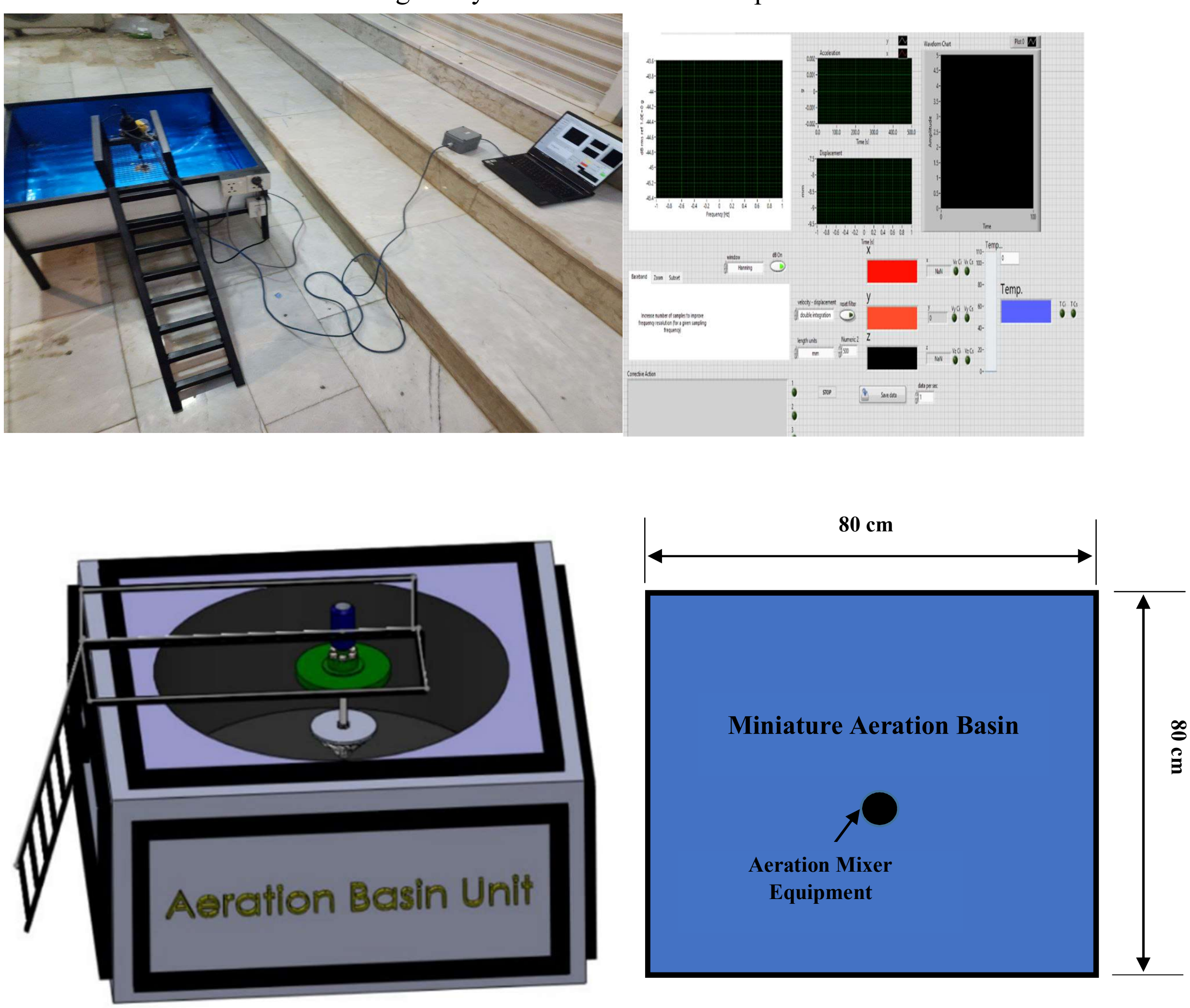

Figure (4) Fault Diagnosis System with the Developed Prototype.

The predictive maintenance plan of the aeration unit equipment in the treatment plant suggests that the motor maintenance plan must be implemented in order to investigate and test the suggested system's competence on monitoring defects diagnostics to update maintenance plan. The proposed system shows that the temperature and vibration measurements are in a dangerous state and that the fault diagnostic status fits Rule 1 as mentioned earlier in table (5). This information is for inspection and testing of a fault diagnosis system. Therefore, as per Rule 1 below, the decision-making process must update the maintenance plan and implement the necessary corrective measures. Figure (5) depicts the output of the problem diagnosis, remedial measures, and maintenance plan based on the temperature and vibration input measurements.

<u>Rule 1:</u> If T. Status = (D) and V. Status= (D) then

Corrective Action:

- **Cleaning and removing the deposited sludge from the impeller.**
- **Checking fins status.**

Maintenance plan:

- **Updating the maintenance plan according to the malfunction day.**

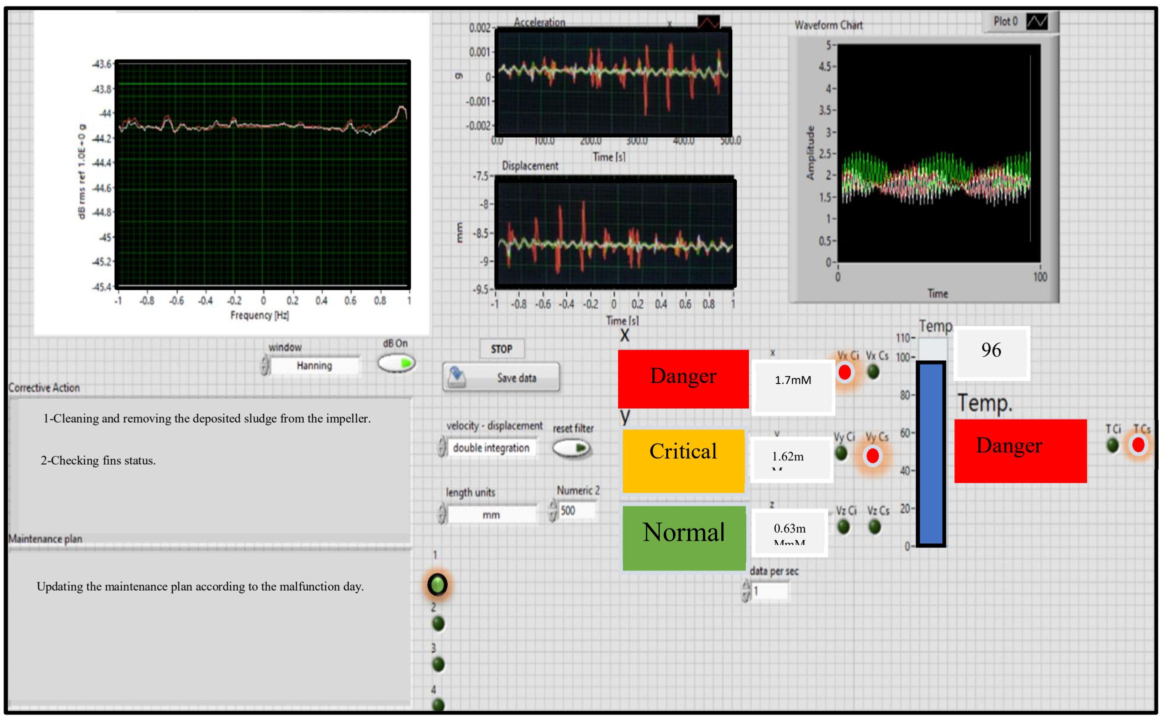

Figure (5) User Interface of LabVIEW.

Final Results and Discussion:

Due to its continuous operation, the mechanical aeration unit in sewage treatment facilities was chosen as a case study. The aeration unit equipment was connected to the temperature and vibration sensors. It utilizes Arduino to communicate the signal to and from the computer, which runs the software application (Lab View) created to track out defects, explain their potential causes, and suggest the best course of action. The model and fault diagnostic system are being built with the intention of assisting in decision-making that supports and integrates the maintenance plan based on information gathered from the equipment online. On the basis of online data obtained from the aeration unit, a fault diagnostic method has been devised. The defects' severity was represented numerically, with the colors denoting the faults' severity. On the interface of the planned fault diagnostic, the potential causes of the faults and the suitable remedial action for each fault are also shown. The model's final findings analyze the fault's occurrence and potential causes so that the proper corrective action may be taken. The management may update the maintenance schedule with the support of a fault-diagnostic system, which leads to improved decision-making, more yearly treated water, lower overall maintenance costs, and less downtime for all of the equipment.

Conclusions:

The implementation of the suggested maintenance strategy based on the fault diagnosis system can be seen as an aiding and influencing factor in improving the effectiveness of preventive maintenance, and it may eventually result in higher availability rates, less downtime, fewer annual treatments, and lower overall maintenance costs for all obsolete parts of the aeration equipment. The speed with which faults are diagnosed, their causes are identified, and the proper course of action is then suggested, thanks in large part to the use of sensors that are connected to the mechanical parts. This improves maintenance effectiveness and decreases total equipment downtime, both of which have a positive impact on the lowering of high maintenance costs.

References:

1- Liu, Yuekai, Liang Guo, Hongli Gao, Zhichao You, Yunguang Ye, and Bin Zhang. "Machine vision based condition monitoring and fault diagnosis of machine tools using information from machined surface texture: A review." Mechanical Systems and Signal Processing 164 (2022): 108068.

2- Bajaj, Naman S., Abhishek D. Patange, R. Jegadeeshwaran, Kaushal A. Kulkarni, Rohan S. Ghatpande, and Atharva M. Kapadnis. "A Bayesian optimized discriminant analysis model for condition monitoring of face milling cutter using vibration datasets." Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems 5, no. 2 (2022): 021002.

3- Fredriksson, Gustav, and Hanna Larsson. "An analysis of maintenance strategies and development of a model for strategy formulation-A case study." Göteborg: Chalmers University of Technology (2012).

4- Aghezzaf, El Houssaine, Mohamed Anouar Jamali, and Daoud Ait-Kadi. "An integrated production and preventive maintenance planning model." European journal of operational research 181, no. 2 (2007): 679-685.

5- Batul Ibraheem, Sawsan S. A. Al-Zubaidi, "Computer System Construction to Select Maintenance Strategy for Industrial Establishment." Production and Metallurgy Engineering Department, University of Technology/baghdad,2008.

6- Wang, Yuanhang, Chao Deng, Jun Wu, Yingchun Wang, and Yao Xiong. "A corrective maintenance scheme for engineering equipment." Engineering Failure Analysis 36 (2013): 269-283.

7- Cachada, Ana, Jose Barbosa, Paulo Leitño, Carla AS Gcraldcs, Leonel Deusdado, Jacinta Costa, Carlos Teixeira et al. "Maintenance 4.0: Intelligent and predictive maintenance system architecture." In 2018 IEEE 23rd international conference on emerging technologies and factory automation (ETFA), vol. 1, pp. 139-146. IEEE, 2018.

8- Yang, Li, Zhi-sheng Ye, Chi-Guhn Lee, Su-fen Yang, and Rui Peng. "A two-phase preventive maintenance policy considering imperfect repair and postponed replacement." European Journal of Operational Research 274, no. 3 (2018): 966-977.

9- Vlasov, Andrey I., Vladimir V. Echeistov, Aleksey I. Krivoshein, Vadim A. Shakhnov, Sergey S. Filin, and Vladimir S. Migalin. "An information system of predictive maintenance analytical support of industrial equipment." Journal of Applied Engineering Science 16, no. 4 (2018): 515-522.

10- Abdulghafour, Amjad B., and Ammar I. Abdulwahed. "Developing of Reliability-Centered Maintenance Methodology in Second Power Plant of South Baghdad." Engineering and Technology Journal 36, no. 8 (2018): 842-852.

11- Nguyen, Khanh TP, and Kamal Medjaher. "A new dynamic predictive maintenance framework using deep learning for failure prognostics." Reliability Engineering & System Safety 188 (2019): 251-262.

12- Wan, Shan, Dongbo Li, James Gao, Rajkumar Roy, and Fei He. "A collaborative machine tool maintenance planning system based on content management technologies." The International Journal of Advanced Manufacturing Technology 94 (2018): 1639-1653.

13- Werner, Andreas, Nikolas Zimmermann, and Joachim Lentes. "Approach for a holistic predictive maintenance strategy by incorporating a digital twin." Procedia Manufacturing 39 (2019): 1743-1751.

14- Cheng, Jack CP, Weiwei Chen, Keyu Chen, and Qian Wang. "Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms." Automation in Construction 112 (2020): 103087.

15- Wang, Weifeng, Bing Lou, Xiong Li, Xizhong Lou, Ning Jin, and Ke Yan. "Intelligent maintenance frameworks of large-scale grid using genetic algorithm and k-mediods clustering methods." World Wide Web 23 (2020): 1177-1195.

16- Çınar, Zeki Murat, Abubakar Abdussalam Nuhu, Qasim Zeeshan, Orhan Korhan, Mohammed Asmael, and Babak Safaei. "Machine learning in predictive maintenance towards sustainable smart manufacturing in industry 4.0." Sustainability 12, no. 19 (2020): 8211.