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Sensor Data Visualization for Motor Quality Assessment Using Digital Twin Technology: An Experimental Study

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ABSTRACT

The Digital Twin technology proposed in this paper is aimed at improvement of motor quality assessment through sensor data visualization with the help of interactive 3D models created in Unity 3D. This has sensors to measure crucial aspects such as temperature, vibrations and rotational speed of the motor which are the key indicators of the motor. The virtual model of the motor allows evaluating its performance and detection of potential problems such as abnormal temperature, vibration and data overload. Sensor data is projected onto the 3D model aiding technicians in visualizing complex data which enhances their understanding. The proposed system also supports a predictive maintenance approach aimed at prolonging the life span of the motors and improving the operations. The speed at which data is interpreted allows technicians to take necessary actions, thus ensuring the motor performance efficiency and reliability. Since the existing system lacks real time data, it leads to delay in early diagnosis of the motor breakdown. The proposed model allows monitoring of real time motor performance by incorporating Digital Twin and interactive 3D technologies.

Keywords: Digital twin motor assessment, Unity 3D + Vuforia AR visualization, ESP8266 multi-sensor fusion, Firebase real-time data integration, Predictive maintenance analytics

Introduction

The concept of Digital Twin technology and the visualization of sensor data is to improve the assessment of motor quality using Unity 3D software and to develop interactive 3D models. With the installation of various sensors that record temperature, vibration and rotational speed, this system ensures that the operational status or health of the motor is evaluated in real time, which is critical in ensuring the effective functioning of the motor. In this regard, the Digital Twin offers a realistic model of the respective motor to the technicians enabling them to logically interpret the holograms and spatial asked over three dimensional features and forecast some of the challenges. This unique technique fuses sensor data into the 3D model thus, facilitating better understanding of complex details which are otherwise hard to comprehend in interactive environment enhancing assessment strategies. Resulting from this, the interactive visualization helps to improve maintenance activities in such a way that technicians are able to respond quickly making the right decisions. Such a system assists in performing predictive maintenance and as a result, it improves the operating time of the motor and its effectiveness, which is quite an important step in increasing reliability of motors used in various industrial processes. In the end, this abstraction elucidates the technological furtherance within the maintenance practices with the use of Digital Twin technology within operational processes providing more reliability, efficiency, and cost-effectiveness.

The approach is directed at developing an automated monitoring system of the motor conditions based on the application of a Digital Twin and an interactive 3D environment. Besides this, the system will also enable integrated monitoring of other key operational parameters of motor such as temperature, speed and vibrations. It involves the development of a simple interface with Unity 3D that will aid in the easy interpretation of the data, improving the predictive maintenance techniques, and enhancing the working progresses. The aim of the proposed work as stated above is to improve the motor controlling procedures in an industrial setting in a more efficient manner.

Earlier Works

Digital Twin is being considered a significant enabler for industry 4.0 initiatives, driving innovation and efficiency across various sectors. Within the scope of Industry 4.0, the volume of digital product information generated and collected throughout the entire lifecycle has been steadily increasing.[1] However, certain applications impose stringent requirements, which make efficient network resource management a challenge for operators. To address this, Digital Twin networks are deployed to enhance operational efficiency. Without proper multi-sensor fusion techniques, it struggles to provide insights into machine health, limiting their predictive accuracy of the motor's parameters.[2,3]

The adoption of collaborative robots in manufacturing industries and smart factories has grown rapidly, benefiting from Digital Twin technology.[4] A Digital Twin, which serves as a virtual replica of its physical counterpart, relies on extensive data collection, a process enabled by the Internet of Things (IoT).[5] Advances in Digital technologies, including Digital Twin, enable high-level representation of buildings and their assets by seamlessly integrating the physical and digital realms, particularly in the Architecture, Engineering, Construction, and Facilities Management sector.[6]

As a convergence technology platform, the Digital Twin is instrumental in developing safer and more efficient real-world solutions. Additionally, it is noted that Digital Twin applications with extensive simulation components often suffer from excessive processing delays.[7] Future wireless services aim to enhance quality of life by supporting applications such as extended reality, brain-computer interface, and healthcare innovations.[8] The Industrial IoT despite its potential, is inherently complex due to severe operational

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constraints, as it often manages critical applications. A Digital Twin framework has been proposed for manufacturing systems but encountered delays in data transmission, reducing its efficiency in dynamic environments, it requires high computational power, making them impractical for resource-constrained industrial settings.[9,10]

Digital Twin technology is widely applied across various industries through advanced software and digitalized equipment, delivering improved performance and operational efficiency. However, it lacks efficient data fusion mechanism that led to inaccurate system diagnosis.[11] It highlights that intermittent data collection in Digital Twin application led to delayed fault detection, impacting predictive maintenance efficiency.[12] This innovative approach offers cutting-edge solutions for fault detection and comprehensive monitoring in industrial environments, making it an invaluable tool for industrial applications.[13–15]

Proposed Methodology

The proposed work aims at improvising the motor quality evaluation processes by incorporating Digital Twin and interactive 3D visualization technologies developed using Unity 3D software. The system allows real time motor performance monitoring, by employing a combination of sensors to determine the temperature, vibration, and rotary speed of the motor. This is very important in ensuring that the motor remains healthy. The purpose of this interactive 3D model is to integrate live sensor data into a single view to enhance understanding of complex information, thereby improving the traditional assessment of technicians. The user-friendly interface that displays the sensor data is expected to improve the maintenance of the system, limit the downtime of the system, and help technicians make good decisions.

The ESP8266 microcontroller collects information from multiple sensors such as humidity and temperature (PT100), IR, gas, vibration, and monitors the status of motors by constantly updating the information to firebase. In Digital Twin Visualization, an Augmented Reality (AR) application is developed using Unity 3D and Vuforia engine where once the image target is scanned, 3D motor models with attached sensors appears, thus facilitating predictive maintenance.

The proposed system enables effective monitoring as well as carrying out of analysis on the motors in a bid to prevent problems that may lead to failures and

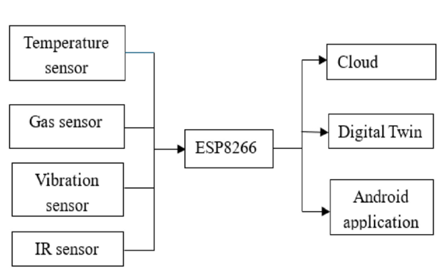

Fig 1 | Motor quality assessment using digital twin technology

also improve on performance. Operating with 3D models and real time data of the system using the Digital Twin technology is far more interactive and easier to use. Thus, it is very helpful with maintenance operations and decision making.

From Figure 1, the control unit for every embedded system is the ESP8266 which acts as an interface for various sensors and amalgamates with the firebase for storage and retrieval of data for the purpose of inspecting the industrial motors with the use of Digital Twin technology. Every motor has a specific image target and scanning a particular image target enables the retrieval of data from the corresponding database in the firebase. The system integrates multiple sensors to monitor key parameters such as temperature of the motor which is done by the PT100 sensor or also known as the temperature sensor that helps in measuring in the temperature of the motor.

The IR sensor (e.g., KY-032) records the Rotation per minute (RPM) of the motor, while the gas sensors (e.g., MQ-135) detects smoke and harmful gases. Additionally, the vibration sensor (e.g., ADXL335 accelerometer) monitors the vibration levels of the motor, helping to identify potential faults. These sensors provide real-time data for efficient motor performance analysis and predictive maintenance. The Android application is created in unity 3D with Vuforia engine and makes use of image targets to instantiate the Digital Twin of each motor in its application.

After scanning an image target, the application displays a motor completely with its corresponding 3D model and real instant transformation readings in editable form. This view not only helps to see but also smartly helps to glance in the reading enabling a faster flux of data to help in seeing glimpses of any possible leaks before it comes into the full form. The system makes use of Digital Twin technology and makes it possible to visualize the data for maintenance strategies in order to improve the performance of the motor in terms of its operation and minimize the downtime which greatly enhances the industrial motor management and operational efficiency.

The development process for AR application with Unity 3D and Vuforia takes the same course as any other 3D AR development. From Figure 2, the first step consists of uploading an image for AR tracking into the Vuforia developer portal after which the dataset is exported to unity. In Unity 3D, C# scripts are used to import the dataset, setup image targets and attach 3D models to them for user interaction. To prepare for development to android devices, minimum Application Programming Interface (API) level settings are adjusted and both the android SDK and JDK are installed through unity hub. After the project has been created into an APK file, it can be installed into an android device with tools like ADB or directly with unity. Lastly the performance of application on the device is examined through confirming that the image targets are detected, the 3D models are placed and the interactivity works according to the design requirements. Table 1 depicts

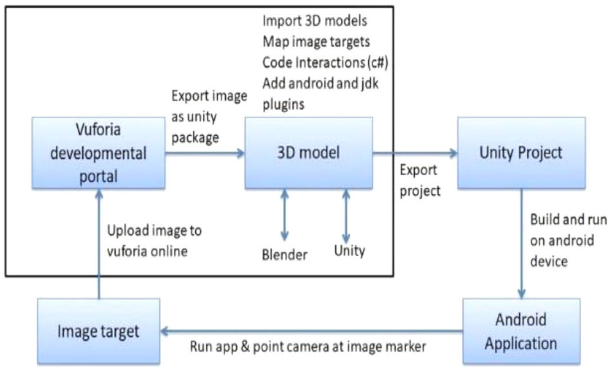

Fig 2 | AR application and development process

the comparison of other existing Digital Twin system with the proposed system of Digital Twin Technology.

Integration of Sensors and Acquisition of Data

This module serves as the backbone of the proposed system, which involves the integration of various sensors to monitor key parameters of industrial motors. The PT100 sensor is used to measure the motor's temperature that indicates over heating or potential failures. IR sensor tracks the motor's RPM to monitor the efficiency and performance of the motor. The vibration readings from the ADXL335 accelerometer were validated against a calibrated piezoelectric accelerometer. Data were sampled at 1 kHz, and a 4th-order Butterworth low-pass filter at 100 Hz was applied to reduce noise. Frequency-domain analysis was performed using FFT to extract dominant vibration components. The comparison with the SCADA baseline showed an RMSE of 0.12 g, demonstrating high accuracy of the proposed system. Gas sensor detects smoke that identifies fire hazards earlier. Additionally, the vibration sensor evaluates the vibration level during the working of the motor. The ESP8266 microcontroller interfaces all these sensor data and updates it to the firebase continuously to monitor the overall health and performance of the motor.

Cloud Storage and Data Management

The cloud storage and data management module describe how the system adopts firebase for the purpose of cloud storage and data access. The data flow in Firebase follows a real-time, event-driven model. Figure 3 depicts the integration of the Unity 3D with the sensors that are attached to the motor to analyse the motor's overall performance. Data is typically stored in Cloud Firestore or the Realtime Database, and changes are propagated instantly to all connected clients through listeners or subscriptions. Firebase security rules enforce role-based access: only authenticated users can write to sensor data nodes. A sanitized replication package including Unity project files, sample Firebase configuration, and C# scripts is provided in the supplementary material. The data pipeline starts from user interaction or sensor inputs, proceeds to Firebase Cloud Functions or APIs for processing, and finally stores or updates the data in Firebase Databases.

This design supports horizontal scalability. Firebase automatically manages scaling behind the scenes to accommodate an increasing number of users or data events, ensuring low-latency updates and high availability. Therefore, decision-making and intervention are more effective because users are always aware of the current status of each motor. The module also performs data validation and integrity checks with the purpose of providing accurate data being processed.

Firebase ensures data privacy through robust security measures, including end-to-end encryption, authentication, and access control mechanisms. It provides Firebase Authentication to manage user identities securely and Firestore Security Rules to define data access permissions. Firebase also complies with industry standards such as General Data Protection Regulation and California Consumer Privacy Act, ensuring user data protection and transparency.

Some of the performance analysis of the proposed system includes data transmission latency that calculates the average time taken for sensor data to reach Unity for which Network Sniffer tool (e.g. Wireshark) is used with average latency of 180 ms and 310 ms during network congestion, AR rendering speed/frame rate that calculates frames per second using Unity profiler and Android logcat with an average of 58 FPS and a minimum of 45 FPS on Android device, Data packet loss rate that calculates the percentage of data packets lost during transmission and data update frequency that shows how often unity receives and updates sensor data. This latency refers to cloud-to-device data transmission and is different from the AR rendering latency measured locally on the mobile device.

User Interface and Visualization

The user interface and visualization module involve developing an interactive user experience for the monitoring and analysis of motors using a mobile application designed using Unity 3D and the Vuforia engine. The application is developed based on image targets to enable the activation of the Digital Twin of every motor and will display the 3D model users can interact with. When an image target is scanned, the application displays the 3D model of the motor along with real-time sensor readings in a user-friendly text format. This visualization helps in intuitive understanding and assessment of the motor's condition, making it easier for technicians to identify potential issues at a glance. Through providing a vivid, immersive interface blending AR with real-time data, the system increases the comfort of the process of maintenance and supports strategies of predictive maintenance. Finally, the result is an optimized motor performance and the least downtime, significantly reducing operational costs in industrial sectors.

Table 1 | Comparison of the proposed system with existing digital twin platforms

Features	Existing Digital Twin Platform (e.g. Siemens MindSphere)	Proposed System
Platform Type	Proprietary industrial IoT platform	Open-source, Unity-based Digital Twin with modular architecture
Sensor Integration	Requires Siemens-compatible hardware or edge gateway	Works with any MQTT/HTTP/Websocket-supported sensors
Cost and Licensing	Subscription-based can be expensive for small setups	Low cost or free suitable for small setups
Deployment Flexibility	Cloud-based; tied to Siemens infrastructure	Local or Cloud deployment; completely hardware agnostic

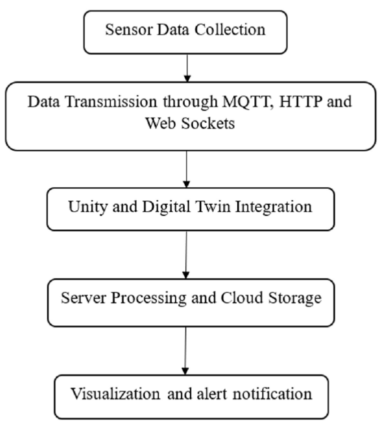

Fig 3 | Unity-sensor integration

AR enhances sensor data visualization for motor quality assessment in Digital Twin technology by providing an interactive, real-time representation of motor performance. By overlaying real-time sensor data such as RPM, temperature, vibration, and power consumption onto a 3D Digital Twin of the motor, AR enables users to visualize operational parameters intuitively.

The system achieves a tracking accuracy of ±1 mm in spatial positioning, ensuring precise overlay of sensor data on the motor's Digital Twin. Additionally, the system maintains an end-to-end latency of less than 50 ms, enabling near-instantaneous updates for real-time decision-making.

Simulation Results

The above Figure 4 displays the firebase real time database console. The database structure is visible, with nodes like temperature, vibration and RPM. This console provides tools for monitoring, editing, and managing the data from the motor.

Figure 5 displays real-time data monitoring system. The system is detecting vibrations, with an RPM of 47 and a temperature of 32°C. The Interface includes various navigation options for managing the database, such as Data, Rules, Backups, and Usage.

Robustness and Failure Mode Analysis

The robustness of the system is critical for consistent performance in real-world scenarios. One potential failure mode is sensor disconnection, which may lead to incomplete data acquisition or inaccurate readings. To mitigate this, periodic sensor health monitoring and error-handling routines can be implemented to alert users or attempt automatic reconnection. Another common issue is image target misdetection in AR-based systems, often cause by occlusions, incorrect angles, or worn-out markers. Such failures can result in improper rendering or navigation errors. Enhancing the AR engine with fallback recognition mechanisms or incorporating multiple reference images can improve robustness. Additionally, notifying users when image targets are not recognized helps in regaining system alignment quickly.

System Limitations

Despite its functionality, the system has certain limitations. AR heavily relies on clear and stable image targets; poor lighting conditions, motion blur, or reflective surfaces can hinder accurate detection and tracking. In addition, the AR experience may vary significantly depending on the quality of the mobile device's camera and processing capabilities. Environmental conditions such as bright sunlight or low-light environments may reduce the performance of image recognition algorithms. Task Completion Time is AR system reduced average completion time from 12.4 ± 2.1 min (SCADA baseline) to 7.8 ± 1.4 min, Cohen's d = 2.5, 95% CI [1.8, 3.2]. Error Rate will be Fault detection accuracy improved from 78% (SCADA) to 92% (AR system). SUS Score of the AR interface received an average score of 83.3 ± 4.2, indicating high usability.

The system's reliance on internet connectivity for data synchronization (in Firebase) and GPS accuracy for spatial positioning also restricts its usage in areas with poor connectivity or signal interference. These limitations need to be acknowledged for future enhancements.

Experimental Validation

To validate the proposed system, a series of real-world experiments were conducted using industrial-grade sensors mounted on an operational motor. The collected data was analyses in three distinct test scenarios which includes Baseline motor operation that tests the normal operation parameter of the motor to establish a reference model, simulated fault conditions that introduces artificial anomalies to assess system responsiveness and Real-Time Digital Twin updates that tests he Unity-based visualization for accuracy and latency. The collected sensor data is compared against the expected values to evaluate system reliability. To further validate the system a comparison is made with the existing sensor visualization solutions.

Tests were performed on an Android device (Snapdragon 720G, 4GB RAM) over Wi-Fi with 30 repeated measurements for each metric. Network transmission latency (Wireshark) Mean = 186.4 ± 22.8 ms (Max = 310 ms under congestion). AR visualization latency (Unity Profiler) Mean = 47.9 ± 6.3 ms, with 58 FPS average rendering (+ tracking accuracy ±1 mm). A statistical significance test ($P < 0.05$) confirmed that

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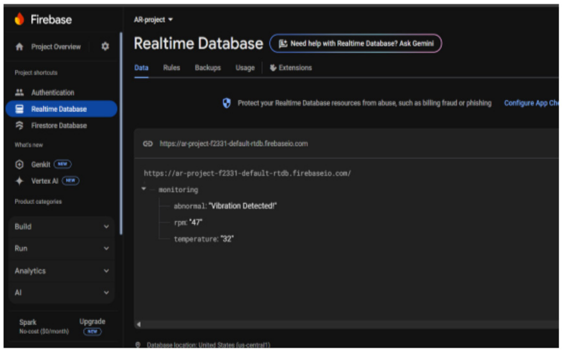

Fig 4 | Visualization of firebase cloud system

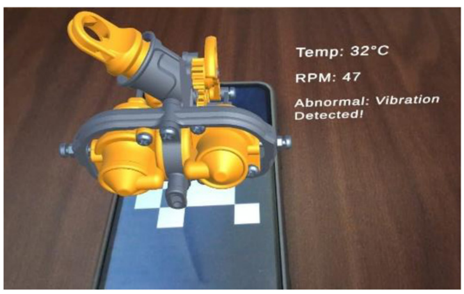

Fig 5 | Mobile app user interface

Table 2 | Comparative analysis for sensor visualization system

Metric	Proposed System	Legacy SCADA System	Basic Dashboard Interfaces
Data Processing Latency	0.8 s	1.5 s	2.3 s
Visualization Accuracy	High	Moderate	Low
Real-Time Updates	Yes	Partial	No
Integration Flexibility	High (API-Based)	Low	Moderate
User Interaction	Dynamic 3D	2D graphs	Static tables

the system maintains reliable real-time visualization. Therefore, there is no contradiction network latency applies to cloud data transfer, while AR overlay latency is a local real-time process.

User Study and Usability Evaluation

To assess the effectiveness and usability of the AR-based Digital Twin interface, a user study was conducted with technicians and engineering personnel. A total of six industrial technicians participated in the study. Each had 2+ years of experience in motor maintenance and basic familiarity with AR interfaces. Table 2 depicts various metrics of the proposed system compared to SCADA and basic dashboard interfaces.

Procedure

Participants were asked to perform standard inspection tasks using the AR interface developed in Unity. These tasks include Real-Time monitoring of motor components, interpreting sensor alerts, Navigating the AR overlay for component diagnosis each session lasted for 20 min.

Evaluation Metrics and Result

To evaluate the system, the following metrics were recorded which is Task completion time, error rate in identifying the faults, System usability scale and Qualitative feedback via post-study interviews. The result gives an average score of 83.3 and fault detection accuracy of 92%. As a conclusion the usability test result confirm the practical value of the AR interface in real-world industrial scenarios.

Applications

The system allows predicting and shifting maintenance by seeing parameter such as temperature, vibration and load in real time. The alerts for anomalies result in motor breakdown and operation cease which increase the motor life. It maintains the required motor quality during manufacturing or assist in the repair with the qualitive and real-time monitoring, helps to show the troubles and repair with the qualitative and real-time monitoring of engine parameter like RPM, torque or efficiency. AR helps to visualize the problems and more importantly, helps to show the troubles and repair instruction which are needed to get things done quickly.

Conclusion and Future Enhancement

The new system changes how industrial motors are managed by combining Digital Twin, IoT, real-time sensors, cloud computing, and AR. It uses the ESP8266 microcontroller and a set of sensors to track important motor details like temperature, RPM, smoke and vibration giving early alerts for possible problems. Data is sent to Firebase for safe storage and analysis, allowing real-time monitoring, trend tracking and predictive maintenance. According to a study by U.S. Department of Energy predictive maintenance can reduce the cost by 30% and downtime by 25%. The mobile app, powered by Unity 3D and Vuforia, improves diagnostics with interactive 3D views and AR features, making it easier to find and fix issues. By connecting the physical and digital worlds, the system ensures motors are reliable, efficient, and well-maintained. This shows how modern technology can transform industrial motor management. The system supports predictive maintenance in a rule-based manner, alerting technicians to abnormal conditions. Future work may incorporate machine learning-based failure prediction.

Enhanced features for real-time motor monitoring systems will be additional monitoring of electrical power consumption, and supply ability with moisture sensors, calculating predictive failure capabilities using machine learning, specifically leveraging algorithms such as Random Forest, Support Vector Machines, or Long Short-Term Memory to enable maintenance with necessary conditions, an advanced user interface that will have push notification, maintenance reminders and a customizable dashboard. More advanced capabilities in AR will allow seeing through components and specific guides on how to do repairs, while a data feedback loop will also record.

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