*Proceedings of the 2024 Winter Simulation Conference*
*H. Lam, E. Azar, D. Batur, S. Gao, W. Xie, S. R. Hunter, and M. D. Rossetti, eds.*

# REAL-TIME PREDICTIVE MAINTENANCE: A DIGITAL TWIN APPROACH WITH LLM-GENERATED WORK INSTRUCTIONS

John Williams[1], Gerald Jones[1], Xueping Li[1], Tom Berg[1], Luke Birt[2], and Ashley Stowe[2]

[1]Dept. of Industrial & Systems Engineering, The University of Tennessee-Knoxville, Knoxville, TN, USA
[2]Y-12 National Security Complex, Oak Ridge, TN, USA

## ABSTRACT

This paper introduces a digital twin system using Unreal Engine 5 (UE5), large language models (LLM), and the Message Queue Telemetry Transport (MQTT) protocol for real-time data synchronization, and visualization. LLMs generate accurate work instructions for maintenance, displayed in the virtual reality (VR) environment. Through a VR headset, managers visualize asset conditions, interact with virtual controls, and observe real-world reactions. The digital twin also serves as a training platform for personnel operating in high-security areas, enabling realistic scenario training before clearance. This system bridges the gap between physical asset monitoring and virtual simulation by leveraging MQTT for efficient data exchange, large language models for work instruction generation, and UE5 for immersive visualization.

## 1 INTRODUCTION

The concept of digital twins involves creating a virtual replica of a physical asset or system that mirrors its real-time state and behavior. This technology provides valuable insights into asset performance, enabling proactive maintenance strategies (Starly et al. 2023). The use of MQTT as a communication protocol offers a lightweight, publish-subscribe mechanism ideal for real-time data transfer in IoT applications (Chen et al. 2023). By integrating LLMs, trained on instruction data, accurate work instructions for various tasks can be generated when prompted. This paper explores the integration of MQTT with UE5 to develop a digital twin system capable of visualizing and analyzing data from physical assets in a virtual environment. Such tools would provide the ability to monitor assets from anywhere, and train craft workers in a safe, low security environment.

## 2 SYSTEM OVERVIEW

The digital twin system is designed to interface with a physical asset equipped with sensors and an MQTT client as seen in Figure 1. The system architecture includes an MQTT broker, which manages the communication between the physical asset and the UE5 simulation. Data from the asset is published via MQTT and consumed by the UE5 application to update the virtual representation of the asset to simulate its real world condition. The UE5 environment is configured to display real-time data and LLM-generated work instructions through dynamic visualizations triggered by predictions from a random forest classifier, enabling users to monitor the digital twin, and provide the information to fix any issues that arise.

## 3 METHODOLOGY

This work employs a methodology involving multiple steps. First, live sensor data is acquired from a motor under various fault conditions, as shown in Figure 1. This data is then used to train a random forest classifier, which is subsequently integrated into the UE5 environment using MQTT protocol.

While the simulation is active, the transmitted data is used to inform the animation in the virtual environment. The motor condition is predicted by a random forest classifier (see Table 1) and visualized

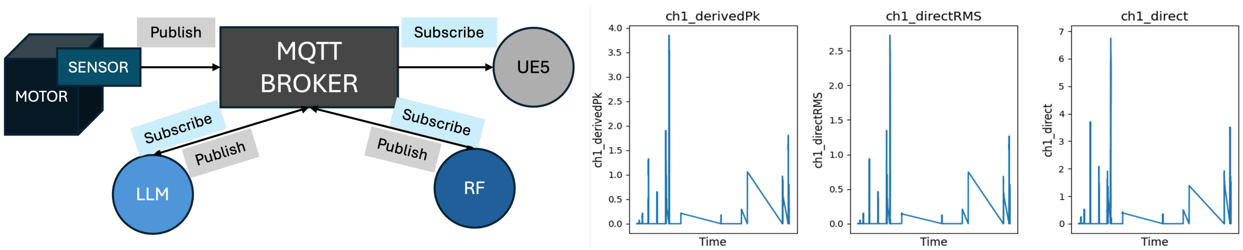


Figure 1: Component architecture (*left*) with sample motor data (*right*).

using motor animations in the virtual space. Figure 2 compares the real-world motor and the virtualized models under three fault conditions. When a fault is detected, the LLM is prompted with the fault to provide the set of work instructions, via MQTT, to repair the fault as demonstrated in Figure 3. To allow for the digital twin to be manipulated in the VR space, a motor controller is planned that will utilize the MQTT connection to pass control signals that will operate the controller to modify the state of the asset. This aspect of the digital twin will allow for interactive control of the motor from within the UE5 environment.

Table 1: Random forest accuracy results for classifying faults.

| **State** | Baseline | Bent Shaft | Eccentric Rotor | Offset Misalignment | Resonance | Imbalance | Faulted Coupling | Faulted Bearing | Angular Misalignment | Looseness |
|---|---|---|---|---|---|---|---|---|---|---|
| **Accuracy** | 0.76 | 0.89 | 0.90 | 0.99 | 0.95 | 0.91 | 0.96 | 0.85 | 0.99 | 0.87 |

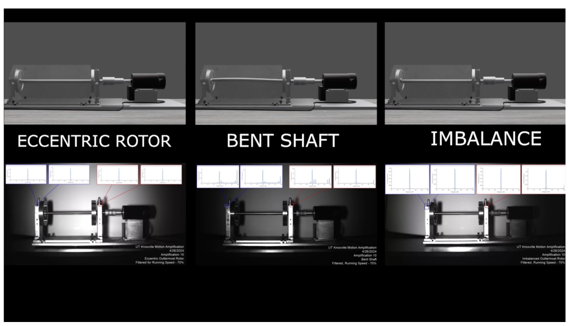


Figure 2: Three virtualized models (top) displayed with physical asset (bottom).

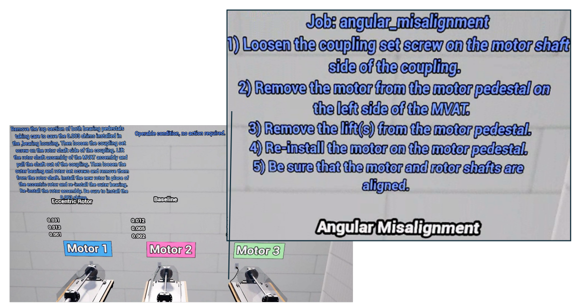


Figure 3: Simulation running in Unreal Engine 5 demonstrating incoming data and instructions.

## 4 CONCLUSION

The integration of the technologies discussed in this paper within a digital twin system offers powerful tools for real-time reliability engineering and maintenance. By providing fault predictions, work instructions, and an immersive VR environment, this system bridges the gap between physical and virtual environments to optimize asset management and reliability engineering, enhancing both operational efficiency and personnel training.

## REFERENCES

Chen, J., Z. Shi, X. Wang, and J. Wu. 2023. "UBER: An Unreal Engine Based Simulation Platform with Extensibility and Real-time Capability *". In *2023 IEEE International Conference on Real-time Computing and Robotics (RCAR)*, 322–327: IEEE.

Starly, B., P. Koprov, A. Bharadwaj, T. Batchelder and B. Breitenbach. 2023. "Unreal factories: Next generation of digital twins of machines and factories in the Industrial Metaverse". *Manufacturing Letters* 37:50–52.