Final Year Design Project Showcase

Batch-2022
Year 2026

	Department: Mechanical Engineering Programme: Mechanical Engineering
1	**Project Title:** Implementation of Digital Twin Framework for Smart Monitoring of Mechanical Systems
2	**Project Idea** The project addresses the limitations of traditional, static mechanical monitoring (such as unscheduled failures, unexpected downtime, and high maintenance costs) by creating a Digital Twin (DT) framework for a centrifugal pump system. By integrating IoT sensor networks with real-time data streaming and machine learning, the project establishes a continuous dynamic connection between the physical pump and its virtual counterpart. This enables real-time condition tracking, predictive analytics, and automated fault diagnosis aligned with Industry 4.0 standards.
3	**Process** The project began with an in-depth literature review on Industry 4.0 principles and Cyber- Physical Systems. Hardware selection was rigorously evaluated using the Analytical Hierarchy Process (AHP), leading to the strategic installation of pressure, flow, vibration, temperature, and current sensors across the centrifugal pump test rig. Data acquisition was handled through an Arduino Mega, paired with an ESP32 edge node to transmit telemetry wirelessly via the lightweight MQTT protocol. On the software side, a custom Python dashboard was built to process incoming sensor streams and deliver real-time system monitoring. Finally, this live data was used to train and evaluate multiple machine learning classifiers, including Random Forest, Decision Tree, SVM, and KNN, ultimately establishing a functional, end-to-end Digital Twin platform capable of real-time health monitoring and dynamic fault prediction
4	**Outcome** The project successfully developed a fully functional, low-latency cyber-physical Digital Twin framework for a centrifugal pump system, enabling seamless bi-directional communication between the physical asset and its virtual counterpart. The platform facilitates real-time data acquisition, processing, and visualization through cloud- and local web-based dashboards, providing continuous monitoring and enhanced operational awareness. Advanced machine learning models were developed and evaluated for real-time fault diagnosis, with the Random Forest algorithm achieving an outstanding **99.5% classification accuracy** and an **F1-score of 99.72%**, demonstrating exceptional capability in detecting and classifying multiple mechanical and electrical fault conditions. Furthermore, the proposed framework successfully transitions conventional reactive and time-based maintenance practices to a condition-based predictive maintenance strategy. By continuously analyzing sensor data and predicting potential failures before they occur, the system minimizes unplanned downtime,

	reduces maintenance costs, extends equipment service life, and significantly improves the reliability and efficiency of industrial operations.
5	**Evidence (Theoretical Basis)** This Final Year Project presents the implementation of a Digital Twin framework for smart monitoring of a centrifugal pump system. The system integrates IoT sensors, Arduino Mega, ESP32, MQTT communication protocol, Python-based visualization, and Machine Learning algorithms to continuously monitor pump performance. Real-time sensor data are synchronized with a virtual model to detect abnormal operating conditions and predict equipment faults before failure occurs. Random Forest, Decision Tree, Support Vector Machine, and K-Nearest Neighbor models were trained and evaluated for fault classification. The developed framework demonstrates how Digital Twin technology improves predictive maintenance, operational efficiency, and reliability while supporting Industry 4.0 concepts.
6	**Competitive Advantage or Unique Selling Proposition**
a	**Attainment of any SDG** The project directly contributes to **United Nations Sustainable Development Goal 9** by promoting smart industrial infrastructure through Digital Twin technology. It integrates IoT, Artificial Intelligence, and Machine Learning to enhance industrial monitoring and predictive maintenance, reducing downtime and improving equipment reliability.
b	**Any Environmental Aspect** The proposed framework reduces maintenance-related emissions by minimizing unnecessary maintenance activities and component replacements while extending the operational lifespan of equipment. This approach enhances resource efficiency, decreases material waste, and supports environmentally sustainable industrial practices through optimized asset utilization and energy-efficient operation.
c	**Cost Reduction of Existing Product** The proposed framework significantly reduces maintenance costs by enabling early detection and prediction of potential equipment failures before they result in critical breakdowns. By adopting this strategy instead of conventional time based maintenance, the framework minimizes unplanned downtime, lowers repair and replacement expenses, reduces production interruptions, and enhances overall operational efficiency and asset reliability.

d	**Process Improvement which Leads to Superior Product or Cost Reduction, Efficiency Improvement of the Whole Process** Conventional maintenance practices for mechanical systems primarily rely on periodic inspections or corrective repairs after a failure has occurred. Such approaches often result in undetected equipment degradation, unexpected breakdowns, increased downtime, higher maintenance costs, and inefficient energy utilization. To address these challenges, this project presents an IoT-enabled Digital Twin framework that integrates real-time sensor data with advanced machine learning algorithms for continuous condition monitoring and intelligent fault diagnosis. By enabling a transition from traditional reactive maintenance to condition-based predictive maintenance, the proposed

	system improves operational reliability, reduces unplanned outages, optimizes energy consumption, extends equipment service life, and significantly lowers overall maintenance and operational costs.
e	**Expanding of Market share** The proposed Digital Twin framework expands the market potential of smart condition-monitoring solutions by providing a cost-effective and scalable platform for industries seeking to adopt Industry 4.0 technologies. Many small and medium-sized enterprises (SMEs) are unable to implement conventional predictive maintenance systems due to their high deployment and operational costs. By integrating low-cost IoT hardware, cloud connectivity, and machine learning-based fault diagnosis, this project offers an affordable alternative that addresses the needs of previously underserved industrial sectors. Its flexibility and ease of integration enable adoption across manufacturing, water treatment, energy, oil and gas, and process industries, thereby broadening the market for intelligent asset monitoring and predictive maintenance solutions.
f	**Capture New Market** The proposed Digital Twin framework addresses an underserved market by delivering an affordable and scalable predictive maintenance solution for small and medium-sized industries that often lack access to advanced industrial monitoring technologies. Unlike conventional Digital Twin systems, which typically require expensive proprietary hardware and software, this solution leverages low-cost IoT devices, open communication protocols, and machine learning to provide enterprise-level monitoring at a significantly lower cost. This creates opportunities in niche markets such as small manufacturing units, water pumping stations, municipal utilities, educational and research laboratories, and process industries undergoing digital transformation. By making Digital Twin technology more accessible, the project enables organizations with limited resources to adopt smart maintenance practices and accelerate their transition toward Industry 4.0.
g	**Any Other Aspect** **N/A**

7	**Target Market** The proposed Digital Twin framework is designed for industries that rely on centrifugal pumps and rotating machinery, including manufacturing, water treatment, oil and gas, chemical processing, power generation, and HVAC sectors. Its primary end users are plant managers, maintenance engineers, and reliability teams seeking to improve equipment performance through real-time monitoring, intelligent fault diagnosis, and predictive maintenance while reducing downtime and operational costs.	
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11	**Video (If any)**	**N/A**

Pictures (to be pasted below)

Figure 1 Physical Setup

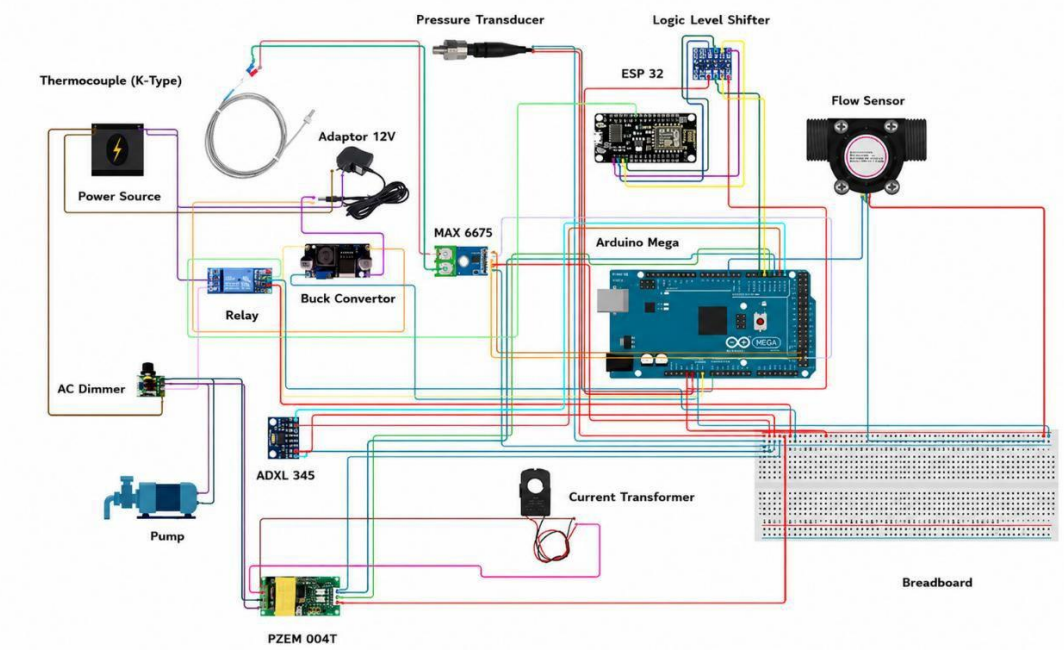

Figure 2 Electric Line Diagram

Figure 3 Python Dashboard

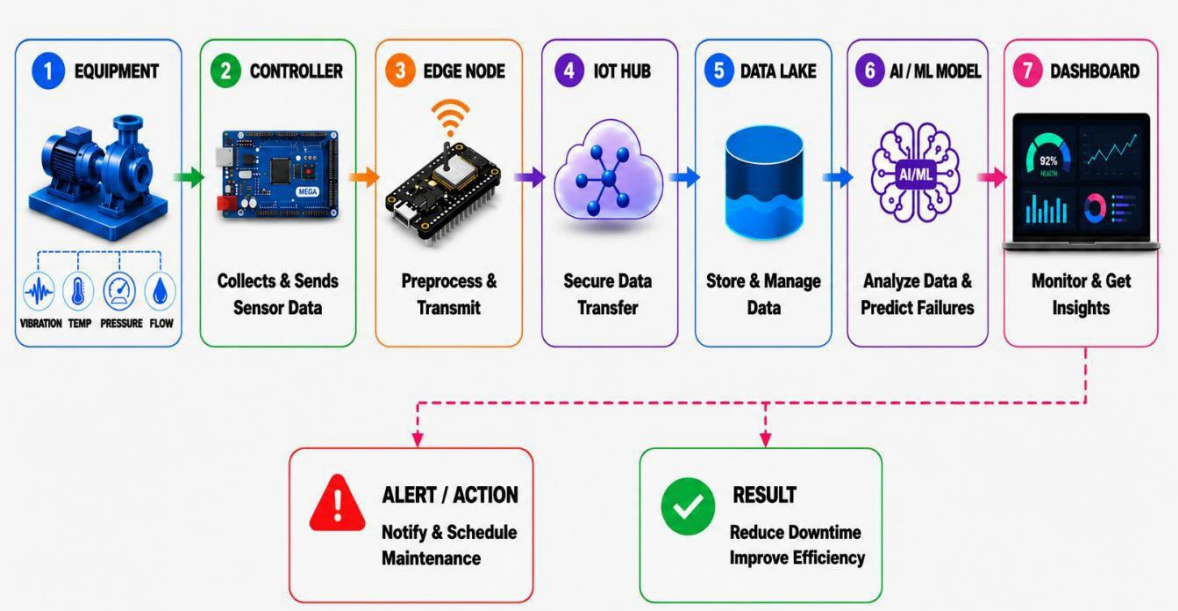

Figure 4 Data flow for Digital Twin Development