Predictive Maintenance of HVAC Equipment

1 Problem Statement

The Air Handling Unit (AHU) or the Fan Coil Unit (FCU) is the heart of the Heating, Ventilation, and Air Conditioning (HVAC) industry. Their cost is about $2000 per piece of equipment. Any building that employs HVAC infrastructure might be using hundreds of these units. Thus, their maintenance requirement must be met timely so that they can be useful for the entire lifespan.

2 Proposed Solution and Innovation

The traditional methods of maintenance are reactive. I have proposed that the maintenance must be automated efficiently according to the needs of individual equipment. This will ultimately ensure the energy optimization of HVAC equipment.

My proposed solution, HVAC Sentinel, is an AI-driven predictive maintenance platform. Unlike traditional Building Management Systems (BMS) that set alarms for total failure, HVAC Sentinel identifies faults before they even occur.

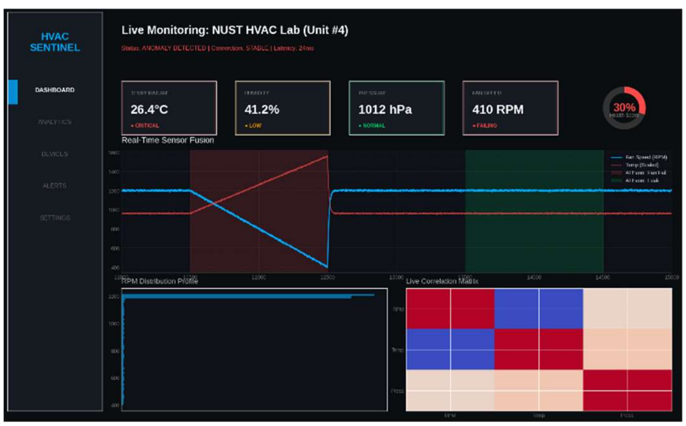

Figure 1: HVAC Sentinel Dashboard

For my initiative project, I have used the "Re-Circulating Air Conditioning Unit" in the HVAC Lab of National University of Sciences & Technology (NUST), Pakistan after approval by the department.

Figure 2: Re-Circulating Air Conditioning Unit in HVAC Lab, NUST

3 Technical Approach

The project is divided into the following stages

- Data Collection Stage
- Model Selection and Development Stage

3.1 Data Collection Stage

The main sources of failure in the Re-Circulating Air Conditioning Unit are due to Temperature, Humidity, Pressure, and Rotation of the fan blades. Therefore, we have used sensors to record real-time data for each of these concerns as listed in the following table:

Controlled Variables	**Sensor**
Air Temperature and Humidity	DHT11
Air Pressure	BMP180
Rotation	IR
Server	ESP8266

3.1.1 DHT11 + BMP180

Air Temperature and Humidity levels were recorded during the operation from the DHT11 Sensor. Air Pressure in the Equipment was measured using BMP180 sensor. The Arduino Uno was used to record these values after the compression stage in the thermodynamic cycle.

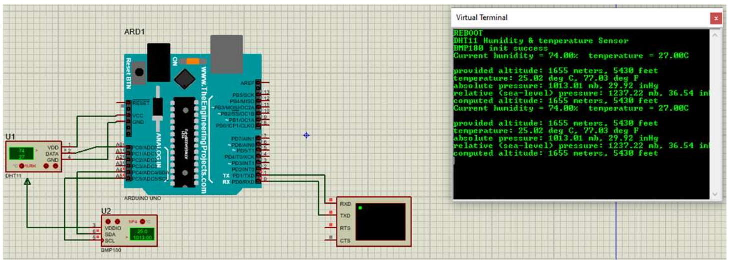

Figure 3: Simulation of DHT11 + BMP180 Module

3.1.2 IR Module

The Arduino Nano was used with the IR Module to sense the rotation count of the fan blades at location of fan in the HVAC equipment.

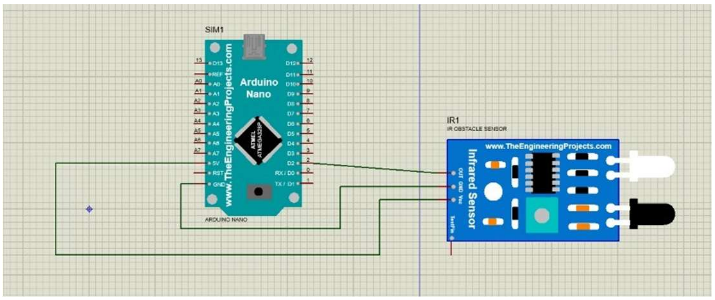

Figure 4: Simulation of IR Module

3.1.3 Server System

After collecting data from the sensors, ESP8266 sends the sensor data to firebase server where it's updated at each new timestep.

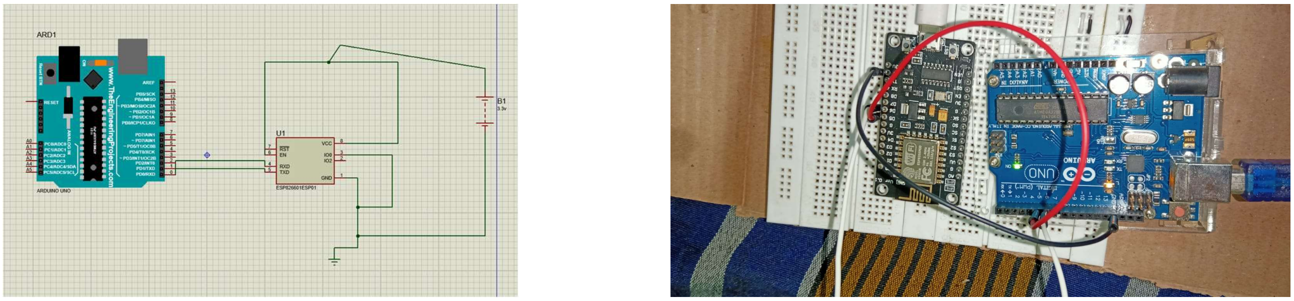

Figure 5: Simulation of ESP8266 Module

3.2 Model Selection and Development Stage

3.2.1 Experimental Setup

In my first experiment to collect "normal data", I started the machine and recorded observations from the sensors during normal working of the equipment. This experiment is used for calibration of my machine learning model for fault detection.

In my second experiment, I opened the cover door slightly to simulate leakage in the equipment under controlled environment. This gave me normal sensor readings as well as readings in failure mode as well.

3.2.2 Data Cleaning and Pre-Processing

After data-cleaning and pre-processing, I found the following statistical variation from the sensor readings in the 2 experiments. We can observe that majority data from Experiment 2 lies close to readings from Experiment 1; however, there is a larger variance for all sensors due to intentional failure simulation.

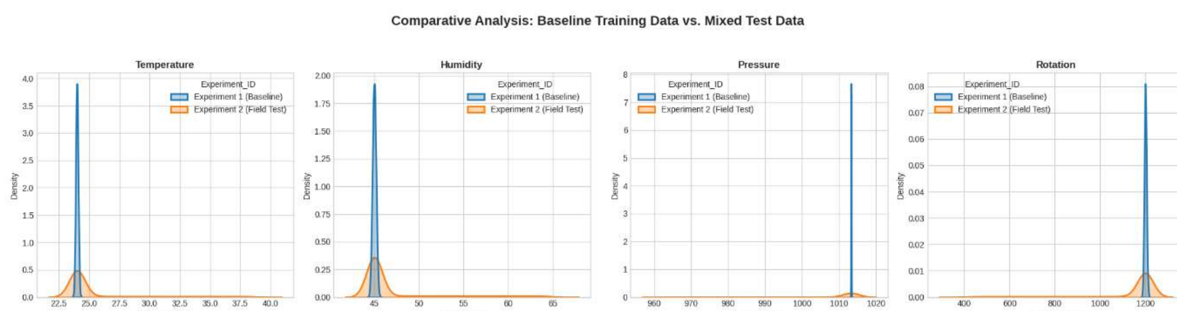

Figure 6: Comparative Analysis

3.2.3 Model Selection

I have trained my model on the normal data from Experiment 1. The core logic is that my model first trains on the normal working of the equipment. Once trained on Experiment 1, it collects data in Experiment 2 regularly to see if the data aligns with normal. If there's an anomaly in data of Experiment 2, then this indicates a failure.

I have used "Deep Learning Autoencoder". The model looks at normal data and learns to compress and reconstruct it perfectly. When it sees anomaly, it fails to reconstruct it perfectly resulting in a high reconstruction error. This error score triggers the alarm.

3.2.4 Model Development

The following Loss Curves (Figure 7) plot shows the decrease in loss over the number of epochs.

Figure 7: Model Loss Curves

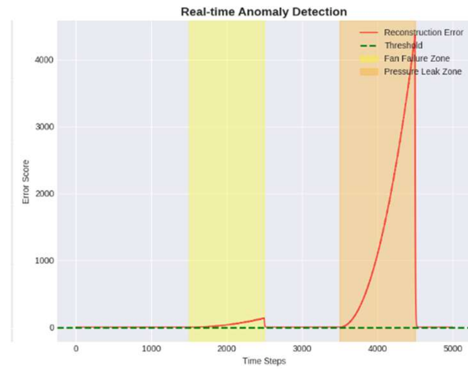

Figure 8: Model Real-Time Testing

In the testing phase (Figure 8), I observed that there are two times when the anomaly alarm was triggered. Upon closer inspection, there is the Pressure Leak Zone (intentional failure) with a very high error and a small error in the Fan Failure Zone as well at an earlier timestep. This indicates that the equipment fan is facing issues and needs immediate maintenance.

3.2.5 Root Cause Analysis

The root cause analysis shows that Fan Failure Zone is characterized by high errors in Temperature, Humidity, and Rotation Sensors. There's a relatively small error observed in Pressure sensor. Since, a fan failure will deviate the temperature and humidity readings from normal, while pressure readings will face a small change. During the pressure leak zone (due to intentional cover door opening), the pressure sensor has shown considerable deviation from normal readings while humidity sensor error increases but remained constant afterwards. There's only a slight effect on rotation of fan during pressure leak zone. This analysis confirms the thermodynamic principles and relations between the four variables.

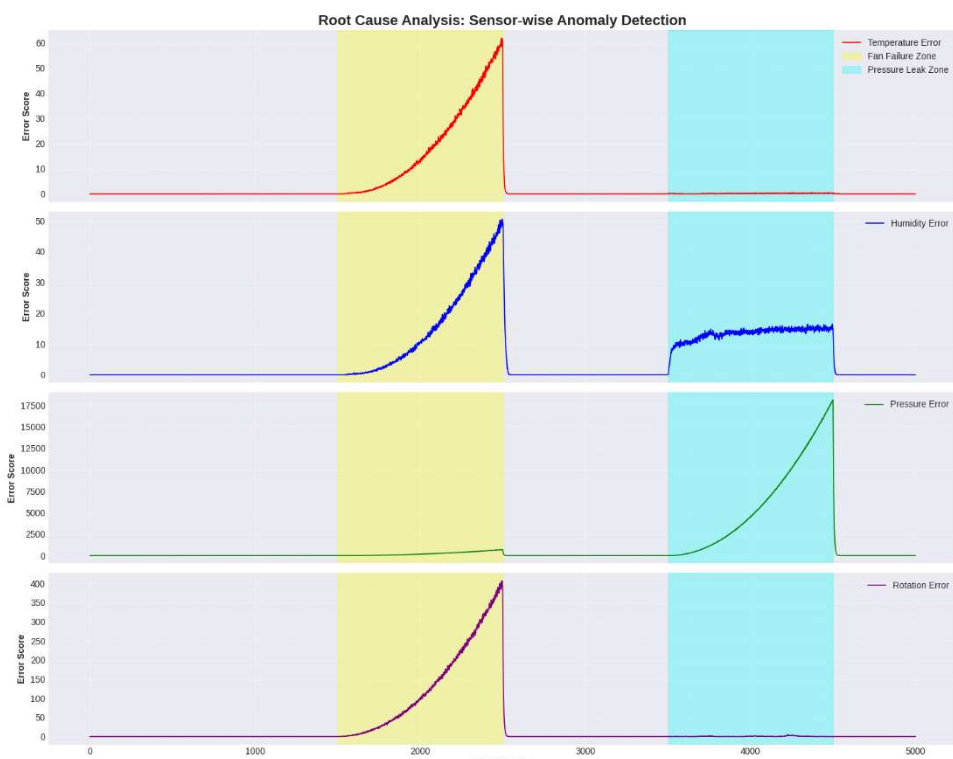

Figure 7: Root Cause Analysis

4 Expected Impact

The expected impact of HVAC Sentinel is listed below:

- **Carbon Footprint:** Large commercial buildings can directly contribute to reducing carbon footprint.
- **Electricity Saving:** The solution will save clients an estimated 15-20% on HVAC electricity bills.
- **Increase Lifespan:** HVAC Sentinel can extend lifespan of expensive machines by 3-5 years.
- **Stable Efficiency:** The 5-10% efficiency is lost due to filter clogging which AI will detect immediately.
- **Operational Saving:** Reduces the need for manual inspections for large buildings. The HVAC industry can shift from reactive to predictive maintenance.

5 Feasibility and Scalability

My startup will build a Hardware-enabled SaaS model:

- Our model package will contain necessary sensors in a complete package unit. This unit will be integrated with the Data Control rooms or HVAC plant rooms.
- The initial unit installation cost is affordable (~$30), lowering the barrier to entry.
- A monthly subscription fee will be charged for the Predictive Dashboard which will provide real-time alerts and monthly energy-saving reports.

The initial target market focuses on high-energy consumers in public and commercial sectors in Pakistan, specifically:

- **Universities:** My university has hundreds of AC units where manual inspection is not possible.
- **Hospitals:** HVAC failure is matter of life or death in surgical wards and ICUs.

Recognition will accelerate ambition and boost the progress to achieve a clean and sustainable environment.

- **Phase 1 (Q1-Q2 2026):** Deploy a pilot project of 10 nodes at NUST HVAC plant room to validate results.
- **Phase 2 (Q3 2026 to Q1 2027):** Use the results to pitch to Green Energy Investors for seed funding.
- **Phase 3 (Q2-Q4 2027):** Expansion in other ECO regions (Turkey, Azerbaijan) where HVAC energy consumption is a shared challenge.