TEMPERATURE AND HUMIDITY CONTROL SYSTEM FOR A MUNITIONS WAREHOUSE: INTEGRATING IOT, MACHINE LEARNING, AND INDEPENDENT CONTROL

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Abstract: *Maintaining stable temperature and humidity in ammunition storage facilities is essential to ensure safety and reliability. Environmental fluctuations can degrade explosive materials, shorten their lifespan, and increase the risk of fire or accidental detonation. Conventional manual monitoring methods are often inefficient and lack predictive capabilities, creating the need for a smarter and more reliable solution.*

This study presents the design of an integrated system that combines Internet of Things (IoT), Machine Learning (ML), and autonomous automatic control to regulate environmental conditions in ammunition depots. The system employs BME680 and DHT11 sensors to measure temperature, humidity, and air quality in real-time. Data are processed by microcontrollers such as ESP32 or STM32 and analysed using a linear regression model, enabling accurate predictions of future environmental changes.

To ensure resilience, a backup NodeMCU-based controller is included, which maintains actuator functionality (fans, humidifiers, and ventilation systems) even in the event of internet or server failures. A sensor clustering method is also applied to optimise sensor deployment, reducing costs without sacrificing accuracy.

Experimental results demonstrate that the system provides accurate real-time monitoring, predictive insights with less than 10% error, and reliable autonomous control. Compared to conventional approaches, the integration of IoT, ML, and fallback control improves safety, reduces operational costs, and ensures continuous functionality under adverse conditions.

This research highlights the effectiveness of combining IoT and ML for ammunition warehouse management and indicates potential applications in other industries requiring strict environmental control, such as pharmaceuticals, logistics, and food storage.

Keywords: *IoT, Machine Learning, Autonomous Control, Ammunition Storage, Temperature and Humidity*

INTRODUCTION

Ammunition depots are places where different types of explosives and military supplies are kept. These items can be affected by changes in the weather, like temperature and humidity. If these conditions aren't controlled, the explosives can break down faster, become less reliable, last shorter, and even cause fires or explosions by accident. Because of this, it's very important to keep the environment inside these depots under control. This helps protect the people working there, keeps the place safe, and makes sure that the country's defense systems are always ready when needed.

Even though these systems are very important, many depots still use old ways of controlling things, mostly done by hand or with wires. These methods have big problems, like not being able to access them from far away, costing a lot to set up and fix, and not being able to predict changes in the environment. These issues highlight important questions that need answers.

- In what ways can an ammunition storage monitoring system be designed to achieve higher efficiency, flexibility, and real-time capability while ensuring the timely delivery of environmental information?
- How can such a system be developed to not only capture current temperature and humidity conditions but also accurately forecast future environmental trends?
- What design strategies can guarantee that the monitoring and control system operates autonomously and reliably, even under conditions of internet connectivity loss or central server failure?

These research questions also set out the main goals of this study, which is to create a better system for controlling temperature and humidity in ammunition storage areas. This system will use the Internet of Things (IoT), Machine Learning (ML), and automatic control methods. By using these technologies together, the system should be able to:

- Monitor warehouse conditions in real time using BME680/DHT11 sensors connected to ESP32/STM32 microcontrollers.
- Predict temperature and humidity changes using machine learning algorithms based on historical data.
- Automatically control environmental devices (humidifiers, coolers), even when not connected to a central server, by utilizing NodeMCU-based local control.
- Create a safe, adaptive, and cost-effective ammunition storage system.

RESEARCH METHODS

The research method used in this study is an experimental one, namely designing, implementing, and testing a temperature and humidity control system based on the Internet of Things (IoT), Machine Learning (ML), and autonomous automatic control. This method was chosen so that the system design could be directly validated through field testing, allowing the research results to be measured in terms of performance and reliability.

This study involved two main variables:

- The independent variables were environmental parameters, consisting of temperature and humidity.
- The dependent variables were the system responses in the form of Machine Learning predictions and automatic control actions on the actuators.

System Components

1. Temperature and Humidity Sensors

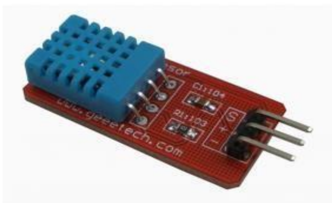

Figure 1. sensor DHT11
(source : www.geetech.com)

Figure 2. sensor BME680
(source: www.nusabot.id.com)

This research uses BME680 and DHT11 sensors to measure the temperature and humidity of ammunition depots in real time. The BME680 offers more comprehensive capabilities with high accuracy, while the DHT11 is used as a low-cost alternative sensor.

2. Microcontroller

Figure 3. Microcontroller ESP32
(source : www.predictabledesigns.com)

The ESP32 microcontroller was chosen as the main processor due to its adequate processing performance, Wi-Fi connectivity, and low power consumption. The ESP32 reads sensor data and sends it to a cloud platform.

3. IoT Communication Platform

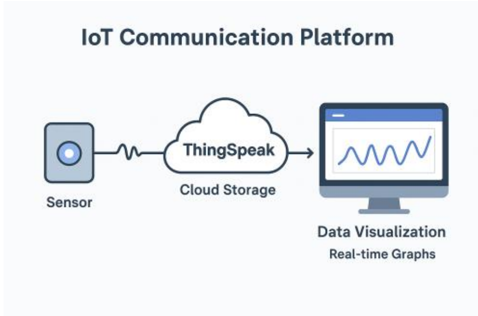

Figure 4. Iot simulation

Sensor data is sent to ThingSpeak, which serves as a cloud storage. ThingSpeak provides data visualisation in the form of real-time graphs that can be monitored over the internet.

4. Android Application

Figure 4. Android Application
(source : www.predictabledesigns.com)

To facilitate monitoring, an Android application was developed that displays temperature and humidity conditions in real time. This application also has a notification feature to provide early warnings if environmental conditions exceed safe thresholds.

5. Machine Learning

The prediction system uses a linear regression algorithm to model temperature and humidity change patterns. Historical data from the sensors is stored in AWS DynamoDB, then processed with AWS Lambda functions to train the prediction model serverlessly. The prediction results are used as a reference in making environmental control decisions.

6. Standalone Automatic Control

To anticipate internet network disruptions, the system is equipped with a Node MCU as a local fallback controller. The Node MCU is programmed to activate actuators such as fans, vents, or humidifiers based on real-time sensor readings. Furthermore, the Node MCU also performs local data logging to ensure information remains stored even if the cloud is inaccessible.

FLOWCARHT

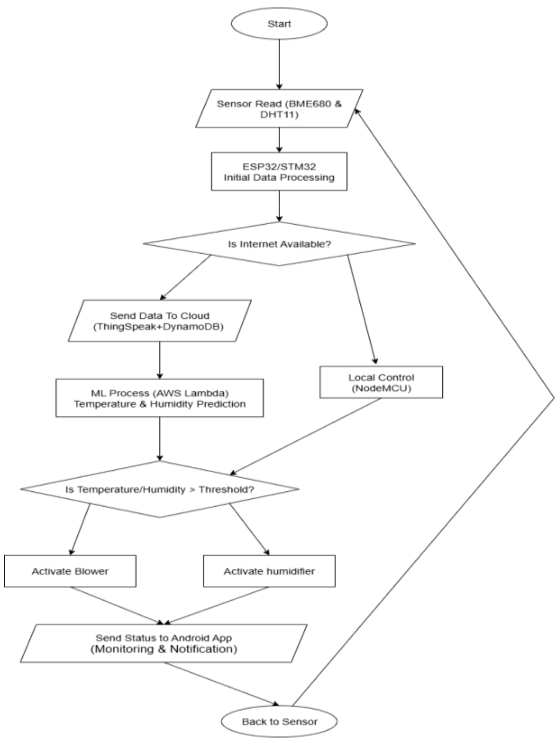

Figure 5.Overall flowchart
(source: planning)

The flowchart illustrates the operational sequence of the temperature and humidity control system in the ammunition warehouse. The process begins with data acquisition from BME680 and DHT11 sensors, which are processed by the ESP32/STM32 microcontroller. The system then checks internet availability: if available, data are transmitted to ThingSpeak and AWS DynamoDB for storage and further analysed using Machine Learning (AWS Lambda) to predict environmental trends. In case of network failure, Node MCU functions as a local fallback controller, directly managing the actuators. Based on measured or predicted values, the system activates the blower/ventilation when conditions exceed thresholds, or the humidifier when conditions fall below safe limits. Finally, system status and warehouse conditions are delivered to the Android application for real-time monitoring and notifications. This loop ensures continuous and reliable environmental control.

SYSTEM PLANNING

The system for controlling temperature and humidity in the ammunition depot is made to handle smart, efficient, and flexible monitoring of the environment. It uses IoT sensors, machine learning, and automatic controls that work on their own. This setup lets the depot be watched in real time, forecast environmental changes, and keep

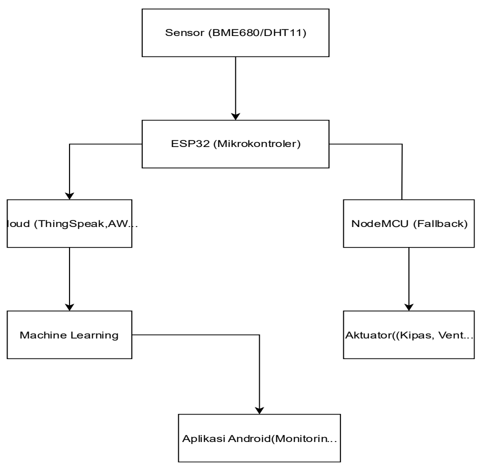

Figure 6.Planning Block
(Source: Planning,2025)

things running automatically even when there's no internet connection.

The block diagram shows how the different parts of the system are connected to work together as a whole. The process starts with the BME680 and DHT11 sensors, which are used to collect information about temperature and humidity inside the ammunition storage area. Once the sensors gather this data, it is sent to the ESP32 microcontroller, which acts as the main brain of the system. The ESP32 reads the data from the sensors, does some basic processing, and then sends the information to cloud platforms like ThingSpeak and AWS DynamoDB using the Wi-Fi connection.

Inside the cloud, data is kept, shown, and studied using a machine learning method called linear regression. This helps the system find patterns and predict what the environment might be like in the future. The information from checking things as they happen and making predictions is then shown on an Android app. Users can view what the warehouse is doing and receive alerts if any measurements exceed safe limits.

In addition to the cloud-based workflow, the system has its own automatic control system using a Node MCU module. The Node MCU takes over as the main controller if there is no internet connection or if the server is not working. When that happens, the Node MCU receives data from the ESP32 sensors and controls the actuators, such as fans, ventilation systems, or humidifiers. This helps keep the warehouse environment, even when there is no access to cloud services.

Therefore, the block diagram shows the whole process of the system, which can be divided into three main parts:

1. **Input** – data acquisition of temperature and humidity through sensors.
2. **Process** – data handling by the ESP32, cloud-based analysis and prediction using Machine Learning, and local automatic control through the Node MCU.
3. **Output** – activation of actuators to regulate environmental conditions and presentation of information to the user via the Android application.

This system is made to monitor accurately, predict reliably, and control automatically in a step-by-step and connected way, making sure operations keep running smoothly whether the network is working normally or facing issues.

RESULTS CHART

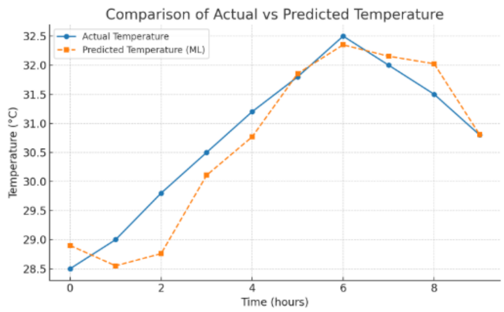

Figure 7. Comparison of actual temperature with Machine Learning

*Figure 7***.** Comparison of actual humidity measurements and Machine Learning (ML) predictions. The predicted values closely follow the trend of the actual data, with minor deviations and an average error below 10%, demonstrating the effectiveness of the ML model in forecasting humidity changes.

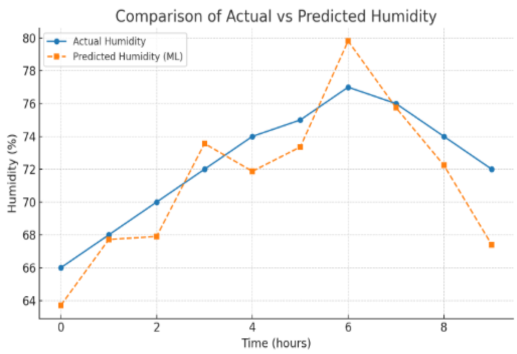

Figure 8. Comparison of Actual Humidity with Machine Learning

Figure 8. Comparison of actual humidity values with Machine Learning (ML) predictions. The ML model successfully

follows the overall trend of humidity changes, with small deviations at certain points. The average error remains below 10%, indicating reliable predictive performance for real-time environmental control.

RESULTS AND ANALYSIS

The experimental results demonstrate that the developed system is capable of monitoring the temperature and humidity of ammunition storage facilities in real time with a high degree of accuracy. The BME680 and DHT11 sensors produced consistent readings with the actual data, with temperature fluctuations ranging between 28°C–33°C and humidity levels between 65%–80%. These findings are in line with (Li et al., 2018), who emphasised that IoT-based monitoring systems employing portable environmental sensors can overcome the limitations of conventional wired systems, which are often costly and inflexible.

The integration of a Machine Learning algorithm (linear regression) for predicting temperature and humidity trends also yielded satisfactory results. A comparison between the actual data and the predicted values showed an average error of less than 10%. This finding corroborates the study of (Vamseekrishna et al., 2021), which demonstrated that the integration of IoT and ML can enhance the accuracy of environmental condition prediction and accelerate decision-making processes. Consequently, the system not only provides real-time data but also delivers predictive insights essential for preventive measures.

Furthermore, the implementation of Node MCU as a fallback controller proved to be effective. In the event of an internet connection failure, Node MCU was able to activate actuators (fan, ventilation, and humidifier) with a response time of less than 5 seconds. This outcome reinforces the findings of (Seman et al., 2020), who developed a Node MCU-based system for automatic control when environmental conditions exceed threshold values, thereby ensuring operational continuity even under network disruptions.

From an efficiency perspective, the application of clustering methods for sensor optimisation effectively reduced operational costs without compromising monitoring accuracy. This aligns with the study of (Dao et al., 2024), which showed that monitoring multiple warehouses within the same geographic area can reliably represent conditions across the entire region. Such an approach is particularly relevant for large-scale implementations in ammunition storage facilities.

Moreover, the integration of the BME680 sensor with the ESP32 microcontroller demonstrated that the system can operate with low power consumption while maintaining high accuracy. This finding supports (Kolev, 2023), who highlighted the suitability of combining ESP32 and BME680 sensors for indoor environmental monitoring with cloud-based data storage capabilities.

Overall, the analysis indicates that the developed system performs consistently with previous research. The key advantages of the system include:

- Accurate real-time monitoring.
- Low-error environmental condition prediction using Machine Learning.
- Automatic control functionality under network failure conditions.
- Cost efficiency through sensor optimisation

CONCLUSION

The findings of this study successfully address the research questions regarding the design of a more efficient, adaptive, and reliable temperature and humidity control system for ammunition depots.

the IoT-based system demonstrated high accuracy in real-time monitoring of environmental conditions. This capability effectively overcomes the limitations of conventional wired systems, which are often less flexible, as also emphasised by (Li et al., 2018).

the application of a Machine Learning algorithm (linear regression) provided predictive capabilities as an added value. With an average error rate of less than 10%, the system was able to project temperature and humidity trends, enabling faster preventive decision-making. These findings are consistent with the study of (Vamseekrishna et al., 2021), which highlighted that integrating IoT and ML can enhance predictive accuracy and the effectiveness of environmental management systems.

the automatic control mechanism implemented through Node MCU demonstrated system resilience by maintaining functionality even during internet disruptions, with a response time of less than five seconds. This result reinforces the observations of (Seman et al., 2020), who underscored the importance of resilience in systems designed for security-sensitive applications.

the use of clustering methods to optimise the number of sensors achieved cost efficiency without compromising monitoring accuracy. This approach supports the work of (Dao et al., 2024), which showed that optimised sensor deployment can be effectively applied to large-scale monitoring across multiple storage facilities.

Beyond its consistency with previous research, this study makes further advancements. The proposed system can be integrated with edge computing to enhance local data processing speed, or combined with more sophisticated ML algorithms—such as random forest or neural networks—to improve predictive performance. Moreover, the concept holds potential for broader applications in other sectors, including pharmaceuticals, food industries, and logistics, where strict temperature and humidity regulation is critical.

In conclusion, this study not only validates the effectiveness of integrating IoT, ML, and autonomous control for ammunition depot management but also highlights its potential for wider adoption in intelligent environmental monitoring across diverse industrial contexts.

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