A Raspberry Pi Smart Manufacturing System Model: An Industry 4.0 Production Line

SEP 728: Internet of Things and industrial Internet of Things Systems (IOT)

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Abstract

This project demonstrates the implementation of a multi-sensor and actuator Internet of Things (IoT) system designed for real-time monitoring and quality assurance of products in a manufacturing environment. The system incorporates an MQ2 gas sensor, a HuskyLens for object recognition, an ultrasonic proximity sensor, and a servo motor. This configuration facilitates real-time data monitoring, identifies product inconsistencies, and alerts an operator when the components are prepared for unloading. The MQ2 sensor consistently tracks and relays gas concentration information, thereby ensuring that environmental conditions are upheld at safe and optimal levels. The HuskyLens employs its AI-powered object recognition capabilities to detect and report product anomalies, thereby strengthening quality control processes. Additionally, the ultrasonic sensor measures the distance to the finished product, enhancing unloading operations and logistics management. This integrated approach allows for remote monitoring and data-driven decision-making, resulting in increased operational efficiency, improved product quality, and greater automation of processes. The collected data is visualized and analyzed through a cloud-based platform, facilitating prompt responses to environmental changes and product issues. This project underscores the transformative impact of IoT in creating intelligent and adaptive industrial environments.

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1. Introduction

In today's competitive manufacturing environment, even small-scale production and assembly lines encounter significant challenges in maintaining consistent product quality and optimizing material flow. This project aims to tackle these issues by developing an intelligent, sensor-based system designed specifically for a conveyor-driven production process that involves the creation and transportation of colored cubes. In this context, each cube serves as a production unit, and any deviation from the designated color palette indicates a product defect, which can lead to waste and quality concerns. Additionally, environmental factors, such as gas concentration, are crucial for maintaining optimal operational and safety conditions. Our system adopts a comprehensive strategy to automate quality control and enhance material handling efficiency.

Central to this system is the HuskyLens, an AI-enabled vision sensor that conducts real-time visual inspections of each cube as it moves along the conveyor. This sensor is programmed to identify color discrepancies, promptly flagging any cube that strays from the expected color range. Concurrently, a gas concentration sensor continuously tracks the surrounding environment, ensuring that operational conditions stay within acceptable limits. Any significant gas concentration variation triggers 1 second alert via a buzzer, indicating a potential environmental issue that could affect product and process quality. The system's capabilities extend beyond merely detecting defects; it also automates material handling processes. An ultrasonic sensor, strategically placed near the conveyor's exit, measures the distance to the leading cube. When the sensor detects that a finished product is within a specified range of the end of the main assembly line, it alerts an operator via LED to safely remove the item. The combination of these sensors and actuators forms a closed-loop system that reduces operational disruptions and enhances overall efficiency.

2. Literature Review

The Industry 4.0 paradigm advocates for the incorporation of Industrial IoT (IIoT) technologies within manufacturing processes to facilitate real-time oversight, automation, and predictive maintenance. Lu and Xu (2019) assert that IIoT enhances factory operations by enabling intelligent decision-making through data collection from sensors and edge devices. However, they also point out that these solutions can be prohibitively expensive and overly complicated for smaller operations, underscoring the necessity for more user-friendly systems, such as the one proposed in this project. While Raspberry Pi is commonly used for prototyping and educational purposes, its application in industrial environments is on the rise due to its adaptability and affordability. Upton and Halfacree (2016) discuss the GPIO features of the Raspberry Pi and its effectiveness in sensor-based monitoring applications, particularly when integrated with cloud services. This reinforces its potential in developing modular IIoT systems, similar to the one outlined in this project.

Becerra and Velasquez (2018) introduced an economical embedded quality control system designed to identify defects in small manufacturing operations using microcontrollers and basic sensors. Their findings demonstrated that the integration of vibration and position sensors can successfully detect early production line anomalies. This approach aligns well with the objectives of the Raspberry Pi-based solution proposed in this project. The implementation of real-time monitoring through embedded sensors has become essential for enhancing the efficiency and safety of manufacturing systems. Rani and Babu (2020) presented a system that employed temperature and proximity sensors to monitor assembly line operations in real time. Their research highlighted the critical role of rapid anomaly detection and proactive measures in minimizing product defects, which directly supports the methodology applied in this Raspberry Pi initiative.

3. System Design and Architecture

The Raspberry Pi Smart Manufacturing System Model is a modular solution for real-time monitoring and control, specifically designed for a conveyor assembly line handling colored cubes. This system emphasizes the detection of anomalies and the automation of material handling by incorporating a vision sensor, a gas concentration sensor, an ultrasonic proximity sensor and a servo motor. At its core, the architecture utilizes a Raspberry Pi 4, which serves as the central processing unit, overseeing sensor inputs, actuator controls, and network communications. This section outlines the components, design framework, and data flow of the system, with a particular focus on the unique requirements of the colored cube application.

3.1. System Overview

The system illustrated in Figure 1 is tasked with the ongoing surveillance of colored cubes on the conveyor belt, detecting any irregularities concerning color and gas concentration, as well as managing the unloading of the finished product. It analyzes real-time data from sensors and contrasts it with predefined thresholds. Any deviations from these thresholds trigger local notifications and, if required, activate automated actions. This design guarantees that operators obtain prompt feedback through MES terminals, thereby promoting an efficient production workflow.

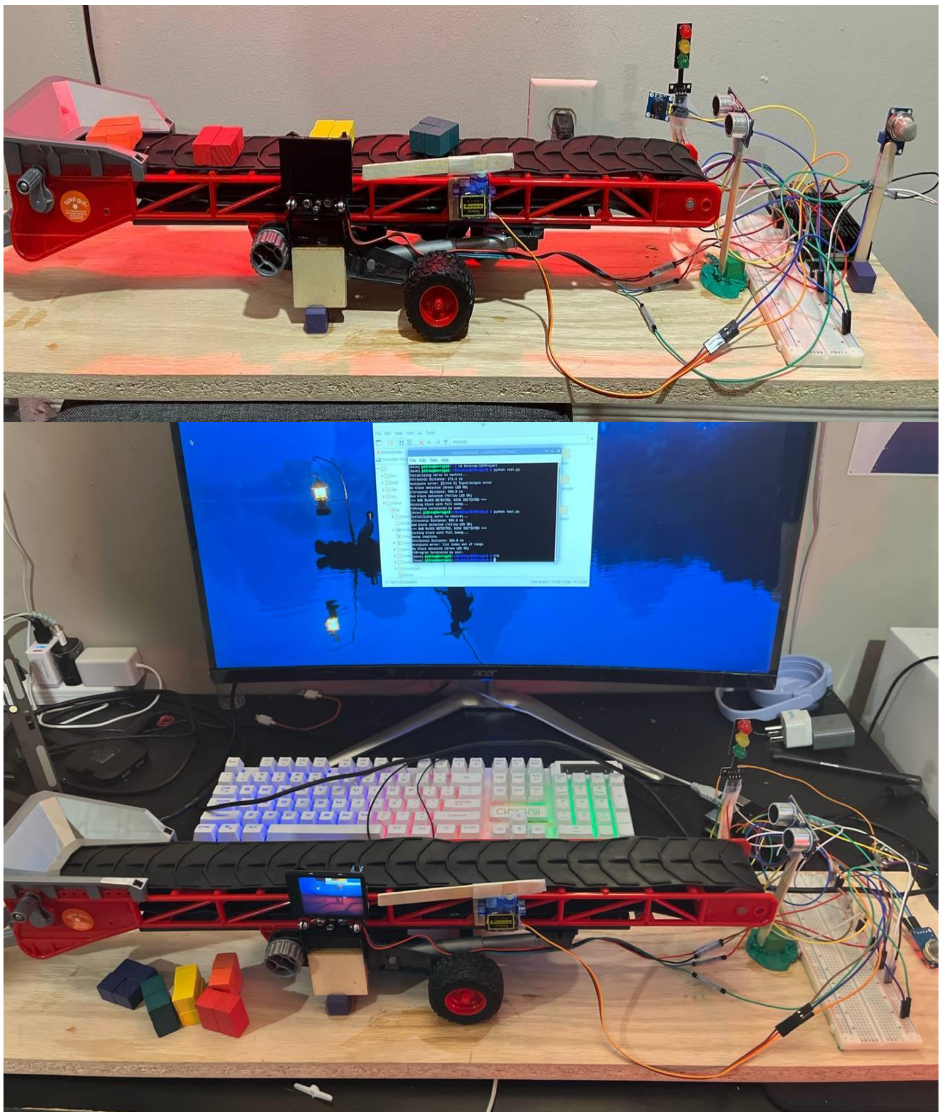


Figure 1: The Raspberry Pi Smart Manufacturing System Model

3.2. Hardware Components

The following are the hardware components utilized in this project.

- **Raspberry Pi 4**: Serves as the central processing unit, handling sensor data processing, actuator control, and network communication.

- **HuskyLens**: An AI-powered vision sensor used for real-time color anomaly detection. It analyzes each cube's color, identifying any deviations from the expected color palette.

- **MQ2 Gas Sensor**: Monitors gas concentration near the assembly line, ensuring optimal operating conditions.

- **HC-SR04 Ultrasonic Sensor**: Measures the distance of the finished cubes to the assembly line end, enabling automated re-routing control for efficient unloading.

- **Traffic LED Indicator**: Provides visual alerts when the HuskyLens detects an anomalous cube, or the temperature sensor registers a deviation.

- **Servo Motor:** Controls the re-routing of the cubes based on the ultrasonic sensor's distance measurements.

- **Buzzer:** Sounds an alert when gas is detected (1-second beep).

3.3. System Architecture

This system architecture diagram illustrates a smart, sensor-integrated conveyor system driven by a Raspberry Pi 4, suitable for flexible manufacturing environments. It effectively combines multiple sensors—HuskyLens for color-based part detection, gas concentration monitoring, and HC-SR04 (proximity sensor) for object distance measurement. The Raspberry Pi acts as the central processor, receiving data from sensors and coordinating actions such as triggering traffic LEDs, a buzzer, controlling a servo motor for part sorting, and sending alerts to a cloud dashboard for remote monitoring. This setup exemplifies a compact yet powerful IoT-enabled industrial automation system with real-time data processing and network communication for enhanced operational efficiency.

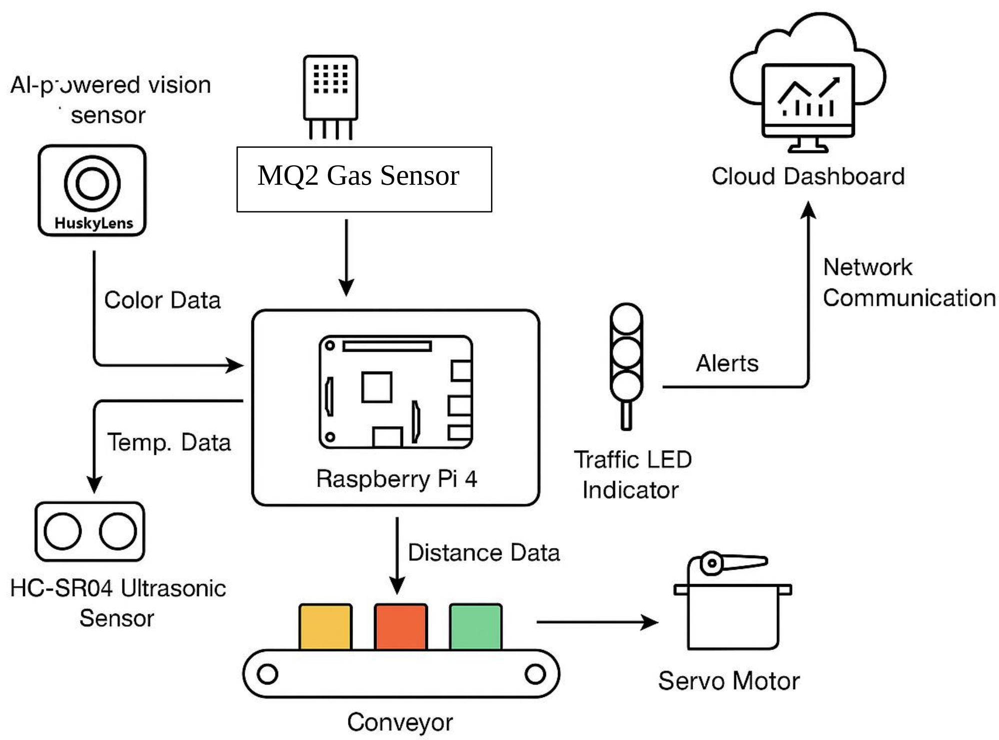


Figure 2. The Raspberry Pi Smart Manufacturing System Model (Generated by GPT)

4. Data Flow and Processing

4.1. Initial Calibration and Baseline Setup:

Upon system initialization, the Raspberry Pi initiates a calibration phase. During this phase, the system captures a series of initial readings from the HuskyLens (color data), the MQ2 gas sensor, and the HC-SR04 ultrasonic sensor. The Raspberry Pi processes this data to establish baseline values for color consistency, gas concentration, and product proximity. These baseline values define the acceptable operational ranges for subsequent monitoring.

4.2. Real-time Monitoring and Anomaly Detection

Following the calibration phase, the system transitions to real-time monitoring. The HuskyLens continuously analyzes the color of each passing cube, comparing it against the established baseline color palette. The MQ2 sensor continuously monitors the gas concentration, comparing it to the baseline concentration. The HC-SR04 sensor constantly measures the distance of the cubes relative to the end of the production line, comparing it to the defined proximity threshold. Python scripts running on the Raspberry Pi constantly process the incoming sensor data.

If the HuskyLens detects a color anomaly, or if the gas concentration deviates beyond a predefined tolerance, or if the distance from the cube to the end of the line is within the set distance, the system triggers the following actions:

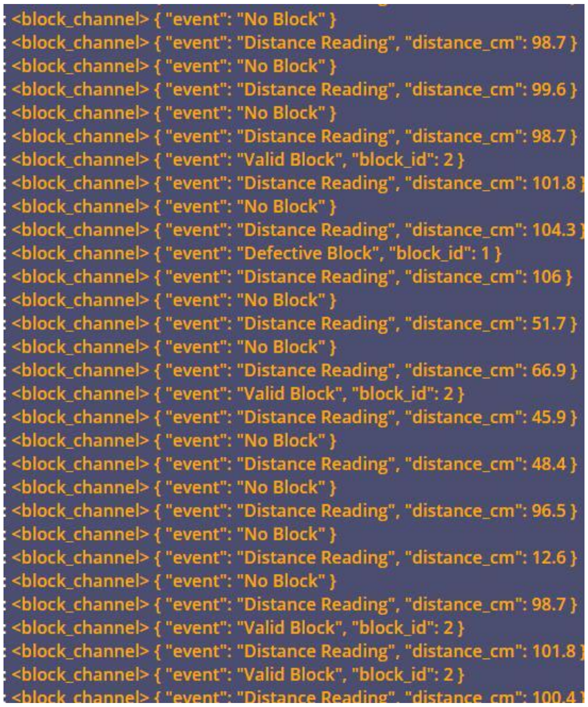
- The LED Indicator displays a red/yellow light to alert the operator.
- In the event of a color anomaly of the cube, the servo motor will reject the cube.
- In the event of gas concentration being above a specified amount, a buzzer would activate.
- Should the distance from the cube to the end of the assembly line fall within the predetermined range, the red LED light will illuminate to alert the operator to unload the component.
- All sensor data and alert statuses are published on the PubNub cloud dashboard.

4.3. Cloud Communication and Remote Monitoring:

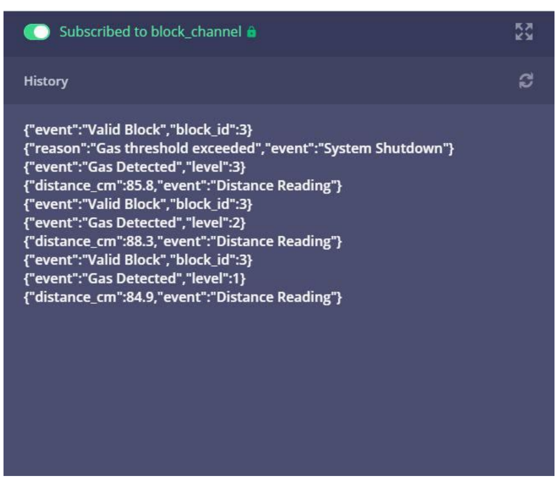
Real-time sensor readings, anomaly alerts, and the servo motor status are transmitted to the PubNub cloud platform. The cloud dashboard provides a user-friendly interface for remote monitoring, displaying graphical representations of sensor data, current system statuses, and event logs. This allows operators and managers to monitor the production process from any location with internet access.

4.4. Pub Nub

Pub nub real-time Monitoring, Blocks Movements



Pub nub real-time Monitoring, Blocks anomaly Detection or Gas Detection



5. Security Considerations

Given that the system relies on real-time data transmission and cloud-based monitoring, several security measures were considered to protect data integrity, system functionality, and user privacy. The Pub Nub platform provides secure communication channels with built-in encryption (TLS/SSL) to ensure that data transferred between the Raspberry Pi and the cloud remains confidential and protected from tampering. Authentication keys were used to prevent unauthorized access to the dashboard and control channels.

At the device level, GPIO access and system scripts were restricted using Linux-based user permissions to avoid unintended control or interference. Furthermore, regular updates to the Raspberry Pi OS and installed libraries were maintained to mitigate vulnerabilities. Although the system was developed for a controlled environment, it is recommended to implement firewall settings, network isolation, and secure credential storage if deployed in a real industrial setting. Future enhancements could include device authentication, intrusion detection systems, and data logging for audit trails.

6. Implementation

The development and deployment of the Raspberry Pi Smart Manufacturing System followed a systematic approach, encompassing hardware integration, software development, cloud connectivity, and thorough testing. This section details the steps taken to bring the system to operational readiness.

1. Hardware Integration and Setup:

The Raspberry Pi 4 was configured with the latest version of Raspberry Pi OS, providing a stable operating system. Wi-Fi was employed to establish network connectivity, enabling effective communication with the cloud. The required GPIO pins and interfaces were set up to accommodate connections for sensors and actuators. The HuskyLens was integrated to facilitate real-time visual inspection, connecting to the Raspberry Pi via its specified communication protocol. The MQ2 sensor was used to monitor gas concentration, while the HC-SR04 ultrasonic sensor was incorporated to evaluate product proximity. Furthermore, the traffic LED indicator, servo motor, and the buzzer module were connected to the GPIO pins of the Raspberry Pi, allowing for visual/audio alerts and automated functions. All components were securely mounted on a physical model of the conveyor line, designed to accurately simulate the production environment.

2. Software Development:

Python scripts were created to oversee the acquisition, processing, and control of sensor data and actuators. The HuskyLens Python library was employed for detecting color anomalies, facilitating real-time inspection of cubes. Algorithms were designed to compare sensor outputs with established baseline thresholds, activating alerts and responses when deviations occurred. Control logic was established to operate the servo motor for defect rejection. A specific script was crafted to automate the initial calibration process, gathering sensor data and setting baseline values for color, gas concentration, and distance. A continuous monitoring loop was implemented to track sensor data, identify anomalies, and initiate appropriate actions in real-time. For cloud integration, the PubNub Python SDK was incorporated to ensure smooth data transmission to the cloud dashboard.

3. Cloud Integration and Dashboard Development:

A PubNub account was established, and API keys were acquired to enable secure data transmission. Channels within PubNub were set up to relay sensor data and alert notifications.

4. **Testing and Validation:**

System testing was conducted to confirm that the system accurately responded to all anticipated inputs and irregularities. Various scenarios were utilized to assess the system's functionality, encompassing anomaly detection, alert activation, and actuator management. Simulated anomaly situations were employed to evaluate the system's responses. Python scripts were refined to enhance data processing efficiency and ensure real-time performance.

5. **Deployment and Operation:**

The system was implemented in a regulated, simulated production setting. The cloud dashboard was set up for remote oversight, allowing for real-time data visualization and management of the system.

7. Demonstration and Results

The demonstration was conducted using a physical model of a conveyor system, with colored cubes moving along the line. An anomalous cube of a contrasting color was introduced to simulate a defect. The gas concentration was manipulated to test the gas monitoring capabilities. Finally, the cubes were allowed to reach the end of the assembly line to LED functionality. The following outlines the demonstration procedure:

Baseline Calibration: The system was initiated, and the baseline calibration phase was allowed to complete, establishing the normal operating parameters.

Anomaly Detection (Color): An anomalous cube was introduced onto the conveyor. The HuskyLens successfully detected the color deviation, triggering the red/yellow LED alert. A servo motor was activated to discard the component through a flapping mechanism in response to the identified color variation.

Anomaly Detection (Gas concentration): The gas concentration was artificially raised. The MQ2 sensor detected the change and activated a buzzer.

Unloading Notification: Cubes were permitted to arrive to the end of the assembly line. The ultrasonic sensor identified the cube's closeness, triggering a red LED light to alert the operator to remove the component.

Cloud Dashboard Monitoring: Throughout the demonstration, the cloud dashboard displayed real-time sensor data and alert statuses, demonstrating remote monitoring capabilities.

8. Results and Discussion

Accurate Anomaly Detection: The HuskyLens consistently and accurately detected the anomalous cube, demonstrating its effectiveness in real-time quality control.

Reliable Gas Concentration Monitoring: The MQ2 sensor accurately measured and reported gas concentration variations, triggering alerts as expected.

Precise Distance Measurement: The ultrasonic sensor provided accurate distance measurements, enabling precise and reliable unloading of the parts.

Real-time Cloud Monitoring: The PubNub cloud dashboard provided real-time data visualization, enabling remote monitoring and control. The dashboard displayed accurate sensor readings, alert statuses, and gate control signals.

System Responsiveness: The system demonstrated a rapid response to detected anomalies and proximity triggers, ensuring minimal delay in alert generation and actuator control.

System Stability: The system operated reliably throughout the demonstration, maintaining consistent performance and data accuracy.

The demonstrated system effectively integrates real-time sensor data with automated control, showcasing the potential of IoT in enhancing small-scale manufacturing processes. The system's ability to accurately detect color anomalies and gas concentration deviations highlights its value in quality control. The system's reliance on predefined baselines, while effective, underscores the importance of accurate calibration. Real-time cloud monitoring via PubNub provides valuable remote access but also emphasizes the need for robust security measures.

This project's modular design allows for future expansion, potentially incorporating additional sensors or actuators to enhance functionality. The system's cost-effectiveness makes it a viable solution for educational and resource-constrained manufacturing environments, offering a steppingstone towards Industry 4.0 adoption.

9. Conclusion

This project successfully developed and demonstrated a cost-effective, real-time quality control and material handling system using a Raspberry Pi 4 and integrated sensors. The system's ability to detect color anomalies, monitor gas concentration, and automate defect rejection showcases the practical application of IoT in small-scale manufacturing. The integration of cloud-based monitoring via PubNub provides valuable remote access and data visualization.

This system serves as a scalable and adaptable solution, bridging the gap between advanced industrial automation and the needs of resource-constrained environments, and offers a strong foundation for future enhancements and broader Industry 4.0 integration.

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Final project & Diagram