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Dynamic Fault Recovery in Smart Warehouse Using Software Defined Control

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Abstract: With the rapid advancement of Software-Defined Networking (SDN), Automated Guided Vehicles (AGVs) in warehouse automation systems increasingly depend on wireless communication with the Industrial Control System (ICS) for efficient task coordination and accurate freight distribution. However, wireless communication is highly susceptible to link failures, signal interference, and congestion, causing message delays, packet loss, and ultimately reduced system efficiency. To address these challenges, the SoftwareDefined Fast Failure Recovery (SD-FFR) mechanism leverages SDN principles to monitor the network in real time, detect link failures within milliseconds, and dynamically reroute traffic to maintain uninterrupted communication between AGVs and the ICS. Load balancing is also integrated into routing decisions to minimize congestion and optimize resource utilization for smoother operations. Complementing SD-FFR, the AGV Task Transfer Protocol (ATTP) is introduced as a robust softwarebased feature to ensure operational continuity. In the event an AGV loses connection or fails during task execution, the system promptly detects the fault and automatically reallocates the remaining task to a nearby AGV, ensuring goods continue moving toward their intended destination without manual intervention. To further enhance communication reliability, a wireless mesh network topology is employed, offering multiple redundant communication paths that improve fault tolerance and ensure stable connectivity between AGVs. The overall system is evaluated through detailed software simulations, measuring performance indicators such as recovery time, throughput, packet delivery ratio, and task completion success rate. Results clearly demonstrate that integrating SD-FFR with ATTP significantly enhances overall reliability, resilience, and efficiency in warehouse automation systems under diverse and challenging network conditions.

Keywords: Smart Warehouse, Software-Defined Networking, AGVs, Fault Recovery, Wireless Mesh Network, Fast Failure Recovery, Task Reallocation, Task Transfer Protocol (ATTP).

I. INTRODUCTION

The Centralized Dashboard provides a real-time view of warehouse operations, allowing managers to monitor AGV movements, task assignments, and system health. This feature enables proactive decisionmaking by visualizing live operations, fault recovery actions, and key performance indicators, reducing reliance on manual intervention. The Analytics and Reporting Module supports continuous optimization by maintaining detailed logs of faults, recovery actions, and warehouse performance. Using visualization tools, it presents key metrics such as throughput, recovery time, and fault trends. These insights help managers identify bottlenecks and enhance system efficiency over time. Additionally, the system leverages Software Defined Networking (SDN) and cloud technologies to provide scalability, flexibility, and high availability. This architecture ensures dynamic communication paths, fault tolerance, and reliable performance even in large-scale warehouse environments.

II. LITERATURE SURVEY

Several research works have explored fault tolerance, failure recovery, and secure data communication in real-time and cloud-based systems. [1] Mohiuddin et al. proposed Axo, a fault detection and recovery framework for realtime control systems that handles delay and crash faults using active replication and soft-state design. The framework improves system reliability but does not support Byzantine faults and depends on accurate time synchronization. [2] Franco et al. introduced vFFR, a fast failure recovery strategy using programmable data plane hardware, achieving sub-millisecond recovery suitable for next-generation networks. However, its dependence on specialized hardware and complex configuration limits its use in legacy or cost-sensitive environments. [3] Rao presented a cloud-based secure financial data sharing model using homomorphic encryption, enabling computations on encrypted data while preserving privacy, though with high computational overhead. [4] Yang et al. proposed an optimized relinearization algorithm for multikey homomorphic encryption to reduce computational cost and error growth, but the scheme still remains complex for real-time applications. [5] Zhao et al. introduced the PKETVET scheme to verify encrypted data equality in cloud

systems, increasing security but adding ciphertext and computation overhead. [6] Tu et al. proposed a multi-identity fully homomorphic encryption scheme to improve scalability for multi-user environments, though it still suffers from high computational complexity. Overall, existing works show advancements in fault recovery and secure data processing but face limitations in realtime industrial deployment, motivating the need for a dynamic and lightweight fault recovery framework for smart warehouse systems.

III. PROPOSED METHODOLOGY

A. System Architecture

The system architecture for the Dynamic Fault Recovery in Smart Warehouse is designed to be robust, scalable, and adaptive. It integrates modules for fault detection, task rescheduling, resource reallocation, and AGV monitoring. The User Interface Layer provides dashboards and visualization tools for real-time monitoring, while the Application Layer manages task execution, scheduling, and dynamic fault recovery. The Data Layer securely stores warehouse tasks, system logs, and performance analytics, and the Integration Layer enables communication with external systems and cloud services. In addition, Software Defined Networking (SDN) ensures dynamic routing and reliable connectivity. This layered design ensures seamless, faulttolerant, and efficient warehouse operations. Overall, the architecture enhances reliability, flexibility, and scalability in smart warehouse management. This layered approach ensures that the system is flexible, maintainable, and capable of supporting a large user base while delivering a smooth and engaging user experience.

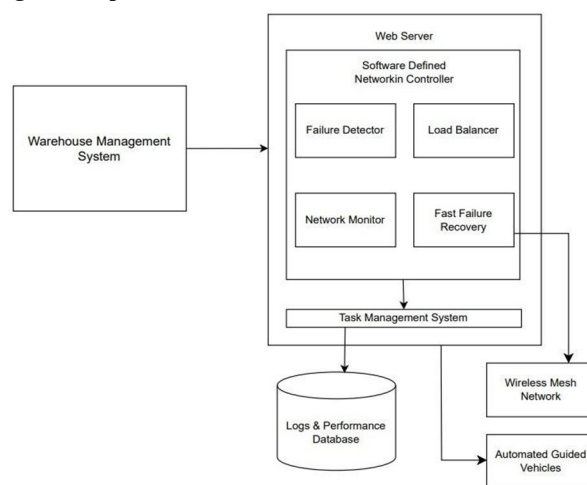


Figure 1: System Architecture

B. Proposed System

The proposed system is a dynamic fault recovery platform for smart warehouses that ensures reliable, adaptive, and uninterrupted operations. It integrates fault detection, task rescheduling, resource reallocation, and AGV monitoring to automatically recover from failures and conflicts in real time. By leveraging Software Defined Control (SDC) and Software Defined Networking (SDN), the system provides centralized management and flexible communication. An interactive dashboard interface further enables real-time monitoring, enhancing overall efficiency, scalability, and fault tolerance. The system also offers features for real-time fault detection, task rescheduling, and resource reallocation, providing a one-stop platform for reliable and adaptive warehouse operations. Built with robustness, scalability, and security in mind, the proposed system aims to streamline warehouse management by ensuring continuous monitoring, dynamic recovery, and efficient task execution. It makes operations more fault tolerant, flexible, and resilient, while enhancing overall productivity and reliability in smart warehouse environments.

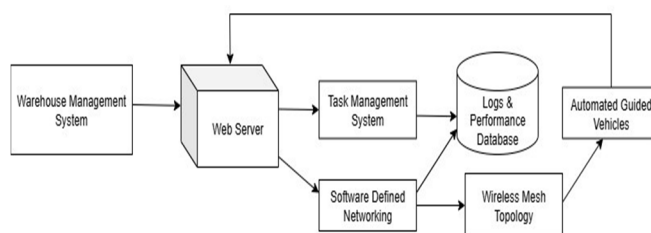
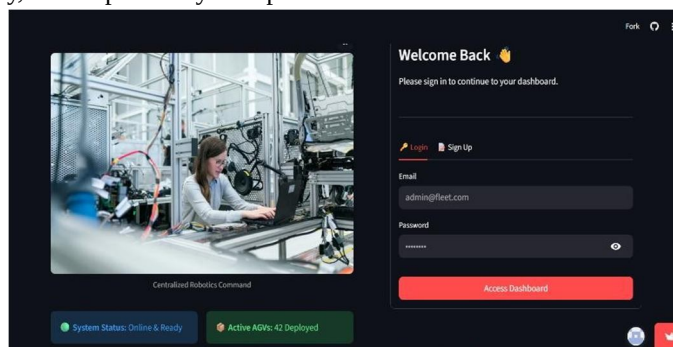


Figure 2: Proposed System

IV. RESULTS AND DISCUSSION

Software Defined Control enables real-time fault detection and recovery in smart warehouse systems. The proposed system dynamically reroutes tasks and network traffic to minimize downtime and improve operational efficiency. The results show enhanced reliability, faster recovery, and improved system performance in automated warehouse environments.



The figure illustrates a login interface for a centralized robotics management dashboard, designed to provide secure access to a smart industrial monitoring and control system. The interface includes a user authentication panel where authorized users can enter their email address and password to access the platform. It provides options for both Login and Sign Up, allowing existing users to sign in while enabling new users to create an account. The “Access Dashboard” button allows users to proceed to the main system interface after successful authentication. In addition to the authentication features, the interface also displays system status indicators that provide quick operational insights, such as the current system status and the number of active Automated Guided Vehicles (AGVs) deployed in the environment.

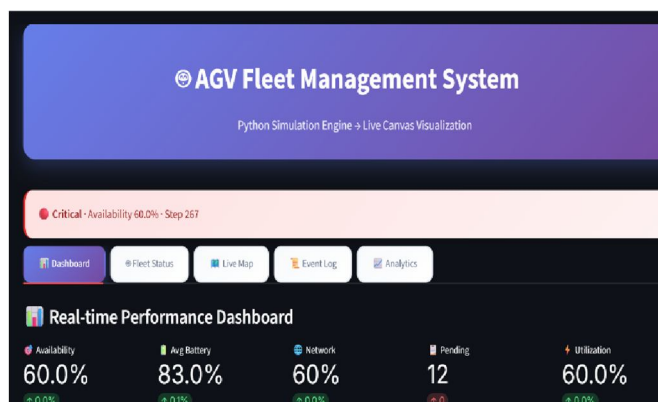


Figure 3.1: Home Page

The Dashboard page provides administrators with real-time access to warehouse operations, including task assignment, AGV fleet monitoring, live maps, and fault recovery controls. Users can initiate smart task assignments, recover lost tasks, or trigger emergency recovery directly from the control panel. The dashboard also displays system health, performance KPIs, event logs, and fault analysis, ensuring complete visibility of operations.

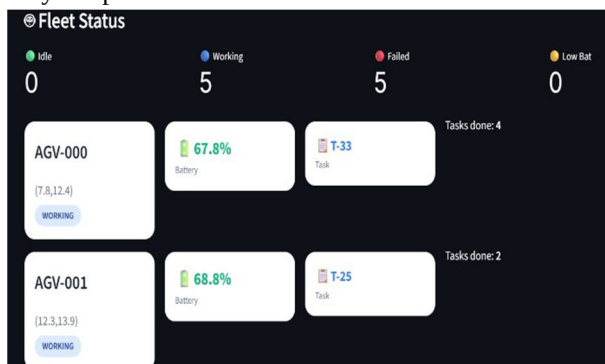


Figure 3.2: Fleet Status & Health Monitoring

The Fleet Status & Health Monitoring page provides a real-time visualization of warehouse operations, showing the current positions of AGVs (Automated Guided Vehicles) and their assigned tasks. It allows administrators to track AGV movements, monitor task progress, and identify potential conflicts or idle vehicles instantly.

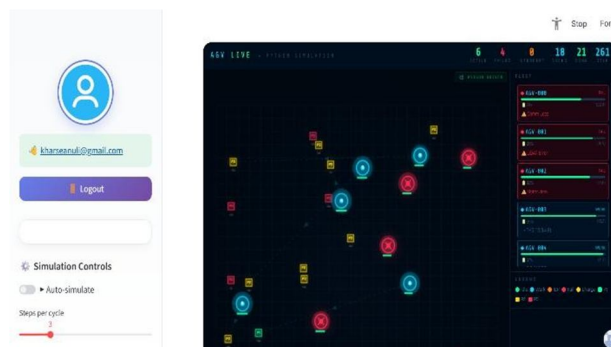


Figure 3.3: Live AGVs Status

This dashboard shows that lists multiple tasks with their details such as task ID, priority level, status, assigned agent, and deadlines. It uses color coding to indicate urgency, where green represents low urgency and yellow indicates medium urgency tasks. The table also displays task age and reassignment count to help track workload and performance. This type of interface is commonly used in project management systems to monitor task progress and prioritize work efficiently.

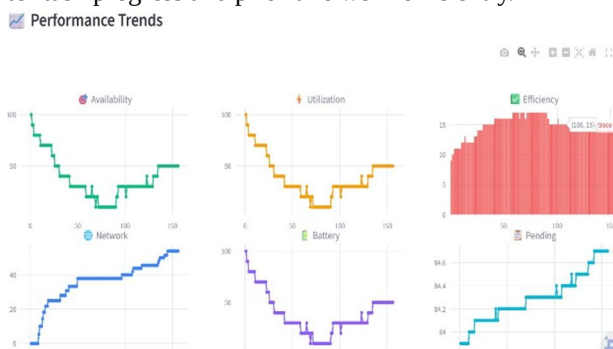


Figure 3.4: Performance Trends

The figure presents a Performance Trends dashboard that visualizes important system metrics over time, including Availability, Utilization, Efficiency, Network activity, Battery level, and Pending tasks, which together help evaluate the overall behavior and performance of the system. The Availability graph begins at a high level and gradually decreases due to increasing workload or resource usage before showing a slight recovery. Similarly, Utilization starts at a high value, indicating intensive resource usage, then declines as tasks are processed and later increases again with the arrival of new workloads. The Efficiency metric initially improves as the system stabilizes and reaches optimal operation, after which it remains relatively stable with minor fluctuations. The Network activity graph shows a steady upward trend, suggesting increasing data communication between system components. The Battery level decreases at the beginning due to continuous system operation and later stabilizes, indicating controlled energy consumption or possible recharging.



Figure 3.3: Analytics Dashboard

The figure presents an Advanced Analytics dashboard designed to evaluate system performance using visual analytical tools. It contains two main components: an Availability vs. Efficiency scatter plot and a System Health Heatmap, which together help analyze operational efficiency and resource conditions. The Availability vs. Efficiency chart shows the relationship between fleet availability and task efficiency. Each data point represents a system instance or operational state, illustrating how efficiency varies as the percentage of available resources changes. The distribution of points indicates that efficiency tends to fluctuate with changes in availability, suggesting that optimal performance depends on balanced resource allocation rather than simply maximizing availability.

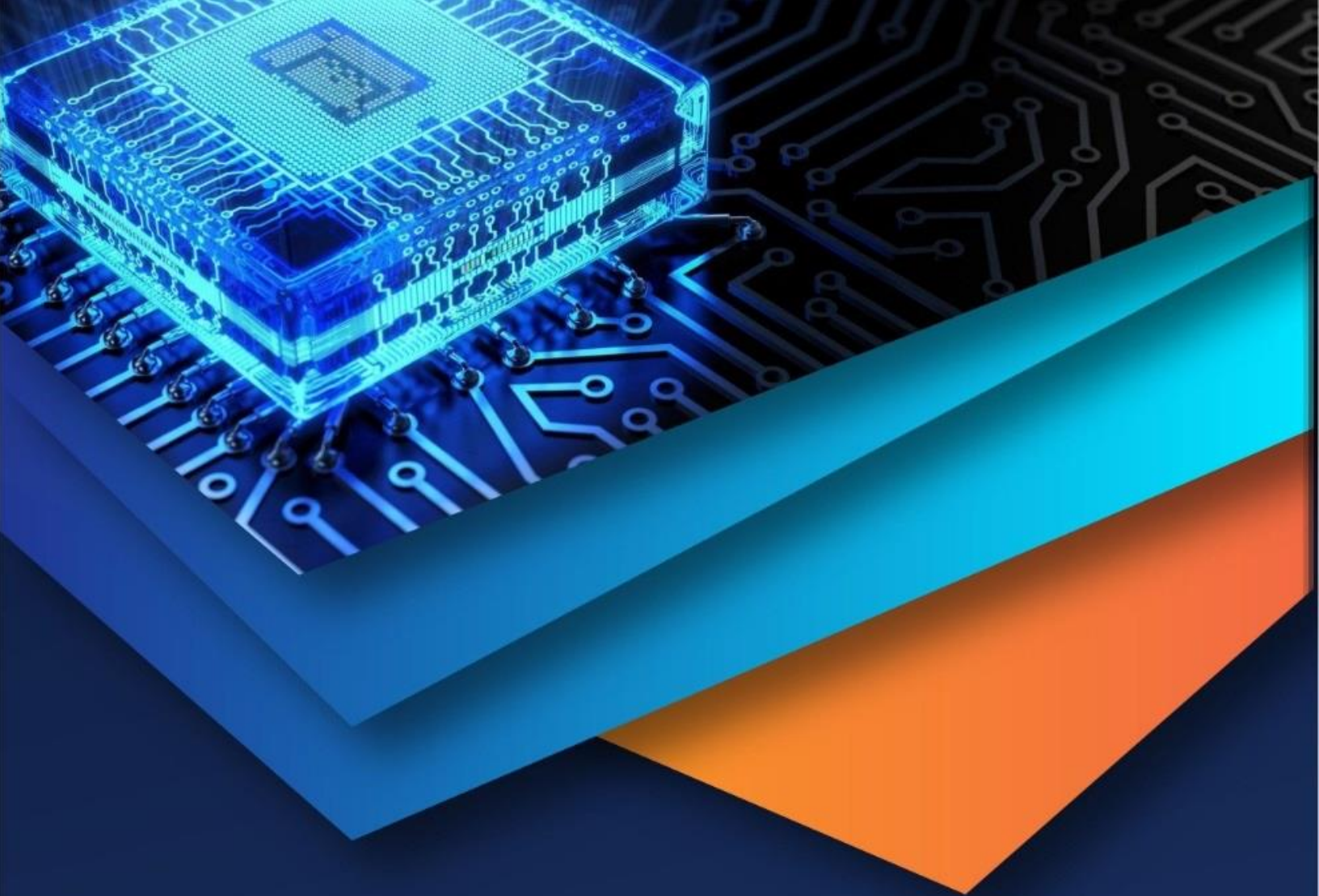
V. CONCLUSION

Using Software Defined Control in smart warehouse systems helps improve reliability and efficiency by detecting and recovering from faults in real time. This method overcomes the limitations of traditional static control systems by dynamically managing tasks and network resources during failures. The proposed framework supports fast failure recovery, load balancing, and automatic task reassignment, ensuring smooth and continuous warehouse operations. Overall, the system offers a flexible and scalable solution for intelligent and fault-tolerant warehouse automation.

In addition, the centralized control layer enables better monitoring and decision-making across warehouse components such as robots, sensors, and inventory systems. It enhances system adaptability by allowing real-time configuration changes based on workload and network conditions. The framework also reduces downtime and operational costs by minimizing manual intervention during faults. Furthermore, it improves system security and performance through programmable policies and optimized resource utilization. This makes the warehouse system more resilient, efficient, and suitable for large-scale industrial environments.

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