SMART MAINTENANCE ALERTS ENHANCING CLEANROOM EFFICIENCY WITH WEARABLE TECHNOLOGY

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ABSTRACT

In high-precision manufacturing environments such as cleanrooms, minimizing equipment downtime is critical to maintaining throughput and product quality. This paper presents a novel system that leverages smart wearable devices worn by cleanroom operators to enable real-time error detection and response. When a machine encounters a fault or process deviation, it autonomously transmits an alert to the wearable device assigned to the relevant operator, eliminating the delay associated with manual fault reporting or periodic machine checks. This immediate notification mechanism significantly reduces mean time to repair (MTTR), enhances operational responsiveness, and optimizes labor allocation. The proposed system integrates Industrial Internet of Things (IIoT) protocols, real-time machine monitoring, and secure wireless communication to ensure seamless and low-latency alerting in compliance with cleanroom standards. Preliminary deployment results indicate measurable improvements in system availability and operator efficiency, demonstrating the potential of smart wearables as a core enabler of proactive maintenance strategies in Industry 4.0-enabled cleanroom manufacturing environments.

1. 0 INTRODUCTION

In advanced manufacturing environments, particularly those involving cleanroom operations such as semiconductor fabrication, pharmaceutical production, or high-precision optics, equipment uptime and immediate response to faults are vital for maintaining product integrity, throughput, and yield. Traditional fault management practices often rely on centralized monitoring systems or periodic checks by human operators, both of which introduce latency in detection and response. As manufacturing lines become increasingly complex and automated under the Industry 4.0 paradigm, there is a growing need for decentralized, real-time, and human-centric alerting systems that enhance operational responsiveness without compromising cleanliness or safety standards.

This paper proposes a smart manufacturing solution based on smart wearable devices integrated into the cleanroom workforce. These wearables—ranging from smartwatches to wearable bands equipped with haptic and visual feedback—act as immediate notification endpoints for machine-generated alerts. Upon detection of a machine error or process anomaly, the machine controller sends a wireless signal to the designated operator’s wearable device, thereby enabling instantaneous fault awareness and response. This system circumvents the latency associated with manual checks or remote dashboards, significantly reducing the Mean Time To Repair (MTTR), two critical metrics in equipment effectiveness.

1.1 Internet of Things

The advent of Industry 4.0 has catalyzed a paradigm shift in manufacturing by embedding advanced digital technologies into industrial systems, with the Internet of Things (IoT) serving as a foundational enabler of this transformation. IoT, and more specifically the Industrial Internet of Things (IIoT), refers to the interconnection of physical devices—equipped with sensors, actuators, and communication interfaces—that facilitate the autonomous exchange, analysis, and utilization of data across machines and processes. This connectivity enables real-time monitoring, predictive maintenance, decentralized control, and improved decision-making, thereby enhancing overall equipment effectiveness, operational transparency, and resource efficiency. Furthermore, IoT integrates synergistically with other core Industry 4.0 technologies such as cyber-physical systems, artificial intelligence, cloud computing, and digital twins, forming the backbone of intelligent and adaptive manufacturing environments. As industrial operations become increasingly complex and demand responsiveness, the deployment of IIoT systems supports the transition from reactive to proactive strategies, contributing to higher productivity, flexibility, and sustainability. Consequently, IoT is recognized as a critical driver in realizing the vision of smart factories and fully digitized, interconnected manufacturing ecosystems.

1.2 Smart Wearables

Smart wearables have emerged as a pivotal component in the digital transformation of various industries, including healthcare, logistics, and manufacturing. These wearable technologies—such as smartwatches, smart glasses, fitness bands, and sensor-embedded clothing—are equipped with advanced sensing, processing, and communication capabilities, enabling real-time monitoring and feedback in dynamic environments. In industrial settings, smart wearables facilitate enhanced situational awareness, hands-free data access, worker safety monitoring, and faster response to operational anomalies, thereby contributing to overall productivity and occupational safety improvements [1, 2]. Integrated with Industrial Internet of Things (IIoT) frameworks, these devices provide context-aware information and support decision-making by delivering timely alerts, tracking personnel movement, and collecting biometric or environmental data[3]. As a key enabler of human-centric Industry 4.0 systems, smart wearables bridge the gap between cyber-physical systems and human operators, ensuring that workers remain integral yet augmented elements of automated workflows[4]. The adoption of wearable technology continues to grow across industries, driven by advancements in miniaturized electronics, low-power wireless communication, and real-time analytics platforms[5].

1.2.1 Smart Watches

Smartwatches represent a rapidly evolving segment of wearable technology, offering multifunctional capabilities that extend well beyond traditional timekeeping. Equipped with sensors, wireless connectivity, and embedded processors, smartwatches enable continuous monitoring of physiological parameters, real-time notifications, and seamless integration with smartphones and cloud platforms. Their compact form factor, combined with features such as heart rate monitoring, GPS tracking, accelerometry, and voice input, has led to widespread adoption in both consumer and professional domains[6]. In industrial and occupational contexts, smartwatches serve as effective tools for enhancing worker safety, productivity, and situational awareness by delivering time-sensitive alerts, enabling hands-free communication, and tracking biometric and environmental data[7, 8]. Moreover, when integrated into the Internet of Things (IoT) ecosystems, smartwatches can facilitate real-time decision-making, support emergency response, and assist in workflow optimization in sectors such as healthcare, logistics, and manufacturing[9]. As part of the broader movement toward human-centered Industry 4.0 systems, smartwatches exemplify how wearable technology can enhance human–machine interaction and extend digital connectivity to frontline workers[10].

2.0 REVIEW OF RELATED WORK

Several leading global companies have adopted smart wearables to enhance operational efficiency, employee safety, and real-time communication in their industrial workflows. For instance, Boeing employs Google Glass to assist technicians in wire harness assembly, resulting in a 25% reduction in production time and a significant decrease in error rates[11]. Volkswagen Group has integrated smart glasses in its logistics operations to provide workers with hands-free access to order information, thereby improving picking efficiency and reducing paper-based processes[12]. DHL, a major logistics firm, piloted smart glasses in its warehouses, achieving a 15% improvement in picking efficiency through augmented reality-based guidance[13]. Similarly, General Electric (GE) has utilized smart wearables such as RealWear headsets to support remote assistance and hands-free diagnostics in its field service operations[14]. In the cleanroom manufacturing environment, companies like TSMC and Samsung are exploring smart wristbands and badges to monitor worker location, activity levels, and exposure to hazardous conditions, as part of broader Industry 4.0 safety and efficiency initiatives[15]. These examples demonstrate the growing relevance of wearable technologies in enabling smarter, safer, and more connected industrial environments.

Several forward-looking companies have incorporated smartwatches into their manufacturing and assembly line operations to improve real-time communication, enhance worker safety, and streamline task management. Siemens has implemented smartwatch-based systems in its industrial settings to monitor worker fatigue and send real-time alerts, thereby reducing the likelihood of accidents and operational downtime[16]. Toyota has explored the use of smartwatches for managing workflows on its production floor, enabling supervisors to monitor processes and receive alerts on anomalies without being tethered to a control room[17]. In the logistics sector, DHL has integrated smartwatch technology alongside other wearables to provide pickers and sorters with task notifications and to track productivity metrics in real time[18]. Bosch has tested smartwatches in its assembly lines for providing contextual work instructions and safety warnings, improving both efficiency and compliance[19]. These examples underscore how smartwatches, when integrated into the broader Industrial Internet of Things

(IIoT) framework, support dynamic, decentralized decision-making and contribute to the goals of Industry 4.0.

3.0 METHODOLOGY

This system is developed to monitor machine status in a production line. When a machine stops or encounters a fault, the event is detected by sensors or control signals and sent to a centralized server. The server first records the downtime information into a database for logging and tracking purposes.

Before notifying, the system runs a task assignment algorithm to determine which operator or technician is currently available. The algorithm considers factors such as user role, task status, and availability. Based on this evaluation, the system selects the most appropriate person for the task.

After task assignment, the system sends a real-time alert through a WebSocket connection to the wearable device of the selected individual. This allows immediate response and helps reduce machine downtime during production.

The following are the algorithms that are being introduced in framework.

3.1 Backend System

The backend component is the brain of the system. It performs real-time monitoring of error events, applies business logic to determine who should handle a task, and manages task states including 'Holding', 'Assigned', 'Ignored', and 'Completed'. It integrates with a database to persist task states and communicates with the mobile client through WebSocket for real-time notifications.

3.1.1 Backend Task Assignment Algorithm

The backend task assignment algorithm will be triggered upon successful insertion of an error event into the database cache.

Algorithm:

1. Retrieve error events sorted by priority.
2. If the task is already marked as a holding task, skip.
3. Check if the device is actively being processed:
   a. If yes, mark the task as holding and skip.
4. Assignment decision-making:
   a. If the same machine and error code exists, assign to existing operator.
   b. If different machine but same error type and limit not exceeded (max 2), assign to same operator.
   c. If different machine or no operator match:
      i. Find available users in the same area based on role.
5. For operator-related errors:
   a. Assign to the user with the least number of active jobs.
6. For technician errors:
   a. Notify all available technicians via WebSocket.

3.2 Mobile Application

The mobile application receives WebSocket alerts, presents interactive UI elements (e.g., overlays), and manages user interactions such as attending to tasks or rejecting them. It supports features like vibration, ringtone notifications, countdown timers, and route navigation post-acknowledgement.

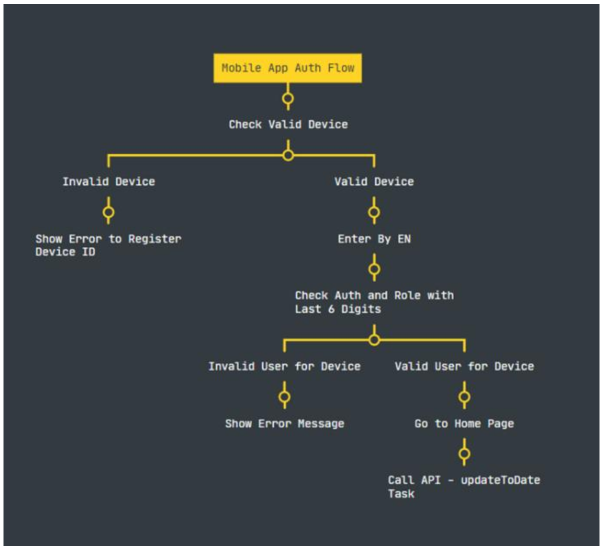

Figure 1: Mobile App Authentication Flow

3.2.1 User Interaction Flow

1. The Request necessary app permissions (if not granted).
2. Display an overlay popup with task information.
3. Start the countdown for acknowledgment.
4. Play the notification sound and vibration.
5. Upon attending:
   a. Cancel pop-up for others (if technician role).
   b. Route the user to the task detail screen.
6. Upon timeout:
   a. Update task status to 'Ignored' and trigger reassignment logic.

3.2.2 WebSocket Listener

Mobile clients maintain a persistent WebSocket connection to receive task alerts in real-time. On receiving a message:

1. If the message is an error alert, trigger permission checks and show an overlay popup.
2. If the message is a task closure alert, dismiss active popups for other users in the same role.

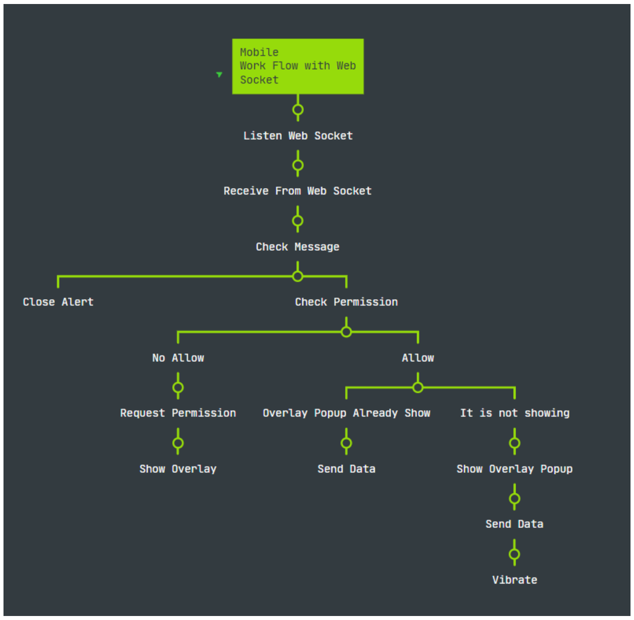

Figure 2: Web Socket workflow

3.3 Overlay Popup Lifecycle

1. Listens to incoming task data via stream.
2. Binds data to UI, triggers ringtone and vibration.
3. Starts countdown timer.
4. On user interaction:
   a. Attend: Update task status and notify server.
   b. Finish: Mark task complete, check for any holding tasks.
   c. Timeout: Mark as ignored and run Ignore Assignment.

3.4 Hold Task Algorithm

Handles queued tasks for machines already being processed.

1. If no holding tasks → use standard assignment.
2. If holding tasks exist:
3. Check if the current working operator is available.
   a. If not: Reset holding and rerun assignment.
   b. If available:
      i. Assign the first holding task.
      ii. If multiple with the same error code, assign all.
      iii. If different, assign separately

3.5 Dual Machine Task Handling Algorithm

1. Display both machines in task view.
2. On finishing one:
   a. Reassign the second task accordingly.
3. On finishing last:
   a. Complete both and reset flags.

3.6 Ignore Task Assignment Algorithm

This algorithm is executed when no user accepts the task before the timeout.

1. For Technician errors: mark task as ignored.
2. For Operator errors:
   a. Look for other same-area operators.
   b. Assign to the one with the fewest tasks if available.
   c. Otherwise, mark task as ignored.
3. Then rerun the Task Assignment Algorithm.

More information about the task assignment workflow is show in the figure below:

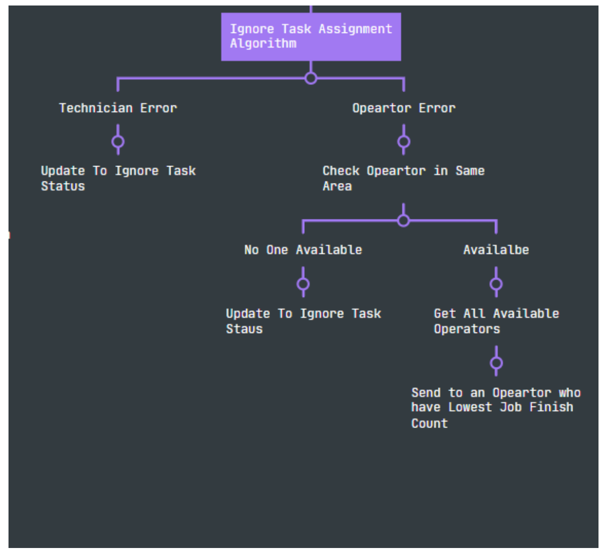

Figure 3: Task Assignment Workflow

4.0 RESULTS AND DISCUSSION

There are some constraints in this whole framework. They are listed below:

- Max 2 concurrent tasks per operator for the same error code.
- Holding tasks are prioritized only if the current device is in use.
- Task assignment respects area-location and user role match.
- Technician errors notify all; operator errors use load balancing.

The system was tested in a simulated production environment with multiple machine stop scenarios. Each downtime event was successfully captured and stored in the database. The task assignment algorithm consistently selected available users based on current task data.

Alerts were pushed to the wearable devices using WebSocket, and most were received within 1 to 2 seconds. The quick delivery enabled maintenance staff to respond more promptly. While performance was generally stable, occasional delays were observed during high network usage, which may be improved with optimization.

5.0 CONCLUSION

The machine alert system supports real-time fault detection, task allocation, and wearable notifications. The integration of a task assignment algorithm and WebSocket communication contributes to fast and accurate response handling. This system helps reduce downtime and improve production efficiency in manufacturing settings.

6.0 RECOMMENDATIONS

Further improvements could include: Development of a detailed dashboard for monitoring and historical data analysis.

7.0 ACKNOWLEDGMENT

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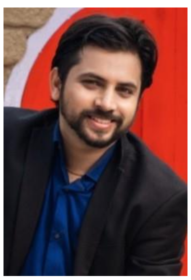

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