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AI Digital Twin Safety Badge

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Abstract: *This Paper introduces an ontological model of digital twins and explores their classification specifically in the context of ensuring human life safety. Workers in mines, construction sites, chemical plants, and heavy industry are exposed to toxic gases, high temperature, physical fatigue, and falls. Safety checks in many of these places are still carried out manually and at fixed intervals, so a hazard can develop and cause harm before anyone responds. This paper presents the AI Digital Twin Safety Badge, a small wearable device that continuously observes a worker and the immediate surroundings and reports the information to a cloud platform. The badge uses an ESP32 microcontroller to read a gas sensor, a temperature sensor, a heart-rate sensor, and a motion sensor, and it adds GPS and LoRa modules for location and long-range communication. In the cloud, the incoming data are used to keep a digital twin, a live virtual record of each worker. A machine-learning module studies the twin, estimates the risk level, and generates graded alerts for the worker and the supervisor. The paper explains the architecture, hardware connections, control algorithm, mathematical model, and test plan of the badge. The device is designed as a low-cost unit that small and medium industries can afford to deploy on a large number of workers.*

Keywords: Digital Twin, IoT, ESP32, Wearable Safety Device, Machine Learning, Embedded System, Worker Safety, LoRa, Industry 4.0**.**

I. INTRODUCTION

Digital twins have become one of the key technologies in the modern world, particularly in ensuring human safety. They represent virtual models of physical objects or systems that allow for monitoring their status, predicting potential risks, and preventing accidents and emergencies. Digital twin technology is increasingly used to support proactive safety management, but existing studies span diverse domains and provide limited direct evidence for process-industry loss prevention. This study adopts a two-level bibliometric design. A broad corpus of 1526 records on digital twin-enabled safety applications was retrieved from the Web of Science Core Collection using bibliometric methods. A process-safety-specific corpus of 198 records was then constructed to support a focused analysis of process safety and loss prevention. The broad corpus shows that digital twin safety research is distributed across construction safety, structural health monitoring, robotics, vehicle systems, battery systems, smart manufacturing, and real-time monitoring. The focused corpus is more closely associated with high-risk process and energy systems, with sources in nuclear energy, process safety, reliability engineering, and interdisciplinary engineering. Locally cited documents highlight digital twins for oil and gas, digitalization and Industry 4.0 in process safety, and autonomous monitoring of advanced reactors. Keyword results identify visible themes including digital twin frameworks, simulation, optimization, artificial intelligence, machine learning, physical–virtual integration, and industrial process systems. These findings, from a bibliometric perspective, show several directions that could be considered for priority in loss prevention for the process industries: model validation, reliable physical-virtual integration, sensor data quality, AI-assisted diagnosis and optimization, and closer integration with established process-safety methods. These efforts aim to advance both the theoretical foundation and practical implementation of digital twin-enabled safety management, supporting the safe and sustainable development of industrial systems.

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II. SYSTEM OVERVIEW

Industrial safety is a problem of timing. A gas leak, a rise in body temperature, or a collapse is usually preceded by a short period in which the situation can still be corrected. If the warning reaches the right person during that period, the accident can be avoided. In practice, however, warning signs are often noticed late because nobody is watching the worker or the surroundings continuously. Embedded systems and the Internet of Things (IoT) make continuous observation possible at low cost. A microcontroller with built-in wireless communication can read several sensors and send the values to a remote server. When the received data are used to maintain a digital twin, a virtual counterpart that follows the state of the physical object, the information becomes more useful than a simple display of numbers. The twin keeps history, shows trends, and can be analysed by software [1], [2]. The digital twin idea has mostly been applied to machines and production lines. Applying it to a worker is a natural extension, because a person also has a measurable state: location, heart rate, body temperature, movement, and exposure to the surroundings. Artificial intelligence and machine learning (AI/ML) can then be used on this state to predict danger instead of only reporting it after the event. The main difference between a simple wearable alarm and the system discussed here is the use of the digital twin together with an AI stage. A simple alarm compares one value with one limit. The proposed badge combines several signals, compares them with the recent history of the same worker, and raises a graded alert for both the worker and the supervisor. It also keeps a local alarm on the device so that serious conditions are announced even when the network is not available.

Objective

The main objectives of the proposed system are:

1. To develop a wearable IoT badge that monitors gas level, temperature, heart rate, and motion of a worker.
2. To use an ESP32 microcontroller for sensor processing and wireless communication.
3. To determine the position of the worker using a GPS module.
4. To send the collected data to the cloud through Wi-Fi or LoRa.
5. To create and update a digital twin of each worker in the cloud.
6. To apply a machine-learning model to the twin for estimating risk.
7. To generate a local alarm on the badge when a critical condition is detected.
8. To notify the supervisor with the identity and location of the worker.
9. To store incidents so that they can be reviewed later.
10. To keep the cost of the badge low so that it can be used on a large scale.

III. LITERATURE REVIEW

The digital twin concept was introduced for product lifecycle management as a virtual representation linked to a physical product through a continuous flow of data [1]. A later survey of industrial applications identified real-time data acquisition, model accuracy, and synchronisation between the physical and virtual sides as the main technical challenges [2]. Recurrent neural networks, and especially the long short-term memory (LSTM) network [3], are widely used for sequences of sensor readings because they can use the recent past to estimate what will happen next. Machine-learning frameworks such as TensorFlow [4] allow models to be trained on a computer and a smaller version to be used for inference. The ESP32 platform is commonly chosen for IoT prototypes because it provides a dual-core processor, Wi-Fi, Bluetooth, several communication interfaces, and low-power modes at a low price [5]. The MAX30102 module is an integrated optical sensor for pulse and blood-oxygen measurement and is often used for heart-rate sensing in wearable prototypes [6]. For areas where Wi-Fi is weak, LoRa provides a long-range, low-data-rate link [7], [9]. Fall detection from body-worn motion sensors has been reviewed in the literature, which points out that the main difficulty is separating real falls from normal daily movement [8]. The studies above show that each building block of the proposed badge is already available and well understood. What is less common is a single low-cost wearable that joins gas, temperature, heart-rate, motion, and position sensing and links them to a cloud digital twin with a predictive AI stage. The present work follows this approach.

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Now the global industry is in an era of profound transformation. In the background of the Industry 4.0 era, industrial systems, especially those in key fields such as manufacturing, energy, chemical engineering and transportation, have reached an unprecedented level of complexity and interconnection (Liu et al., 2025; Lu, 2017; Yuan et al., 2024). Driven by digitalization, networking and intelligence, although production efficiency and resource utilization have been greatly improved, such improvements have also introduced safety risks that are more numerous, more insidious, and more destructive. The traditional safety management model, which mainly relies on manual experience accumulation and emergency response after accidents, is too passive and has been difficult to cope with dynamic, complex and unknown safety threats, which easily leads to safety accidents, causing heavy casualties, serious environmental damage and huge economic losses (Bartulović, 2021; Fragouli et al., 2019). To ensure the efficient and sustainable development of industry, seeking a new technological paradigm that can realize all-round, full-cycle and forward-looking safety management, and scientifically identify and eliminate hidden dangers in various industries has become an urgent demand of the global industrial community. In this background, digital twin technology emerges as the times require. It can realize real-time, two-way interaction and in-depth integration between the physical world and the information world by constructing a "digital mirror" of physical entities, and thus becomes a key enabling technology to promote the digital transformation and reform of the safety field (Tao et al., 2019b; Zhang et al., 2022). At present, many international and industry organizations around the world are actively promoting the integration of digital twin with safety in various industries. For example, the European Union has revised the Product Liability Directive to adapt to the needs of the digital era; the Chinese government is also increasing investment in the research and development of digital twin technology, and actively promoting the application of digital twin in the safety field of various industries (Li and Schütte, 2023; Tao et al., 2019b). However, there are still many challenges in the large-scale promotion of digital twin technology. Its high cost and investment in later maintenance and upgrading bring challenges to enterprises' investment decisions in this regard (Singh et al., 2021; Tzachor et al., 2023; Winter and Chico, 2023).

At present, many scholars and research institutions have carried out research on the application of digital twin in the safety field. As an internationally recognized top journal in the field of safety science and engineering, Safety Science has begun to accept papers involving Industry 4.0 and digital twin in recent years, especially interdisciplinary studies on the integration of digital twin with Construction Safety or Industrial Process Safety. In addition, Jia et al. (2024) proposed that digital twin technology can meet the high safety requirements in chemical production processes through bidirectional real-time interaction and can greatly support the achievement of full-process safety performance. Liu et al. (2021) focused on hoisting operations of prefabricated buildings and constructed a digital twin-based safety risk management framework to solve the problems of insufficient cyber-physical fusion and neglected interaction among risk factors in traditional safety management. Lewis et al. (2024) proposed a fire and smoke digital twin framework named FireCOM for real-time tracking of urban fire events and smoke diffusion prediction, so as to protect public health and inform the public of fire and air quality risks. Liang et al. (2023) combined digital twin technology with recurrent neural networks and proposed a digital twin monitoring system architecture for mine hoists, realizing real-time monitoring and advanced prediction of mine hoist motor temperature, and improving the safety and reliability of mine hoisting systems. Li et al. (2022) focused on the whole process of loading, unloading and transportation of hazardous chemicals, and realized panoramic monitoring and advance risk judgment of the hazardous chemical supply chain by combining digital twin technology, effectively reducing accident risks. Hu et al. (2021) proposed a reference architecture and method for constructing a digital twin system for condition monitoring and fault diagnosis according to the complex and high-risk characteristics of petrochemical processes, so as to improve the safety and controllability of the production process. Among various application domains, the process industry is a typical high-risk sector. This industry involves hazardous materials, coupled complex processes, and prolonged exposure to high-temperature and high-pressure conditions, which can readily trigger cascading accidents. In facilities such as chemical plants, refineries, storage sites, and pipelines, digital twins can be used to identify abnormal operations, monitor conditions in real time, and support emergency decision-making. However, research on process industries is only one branch of digital twin safety applications. This study does not construct a dedicated literature set on process industry safety; instead, it

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reviews the overall research landscape of digital twin safety applications, covering multiple directions including construction safety, structural health monitoring, robotics, transportation systems, battery safety, smart manufacturing, and process industry safety. On this basis, it explores the reference value of various existing research outcomes for process industry accident prevention, while also pointing out the limitations of these methods.

IV. PROPOSE METHODOLOGY

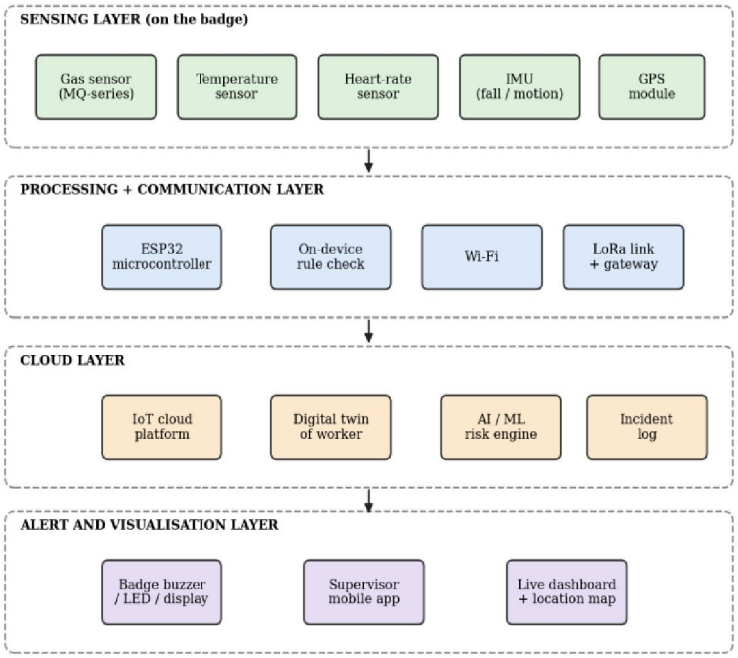


Fig. 1: System Architecture of Purpose system

Overall System Flow: Worker → Sensors → ESP32 → Wi-Fi/LoRa → Cloud Digital Twin → AI Risk Analysis → Alert to Worker and Supervisor.

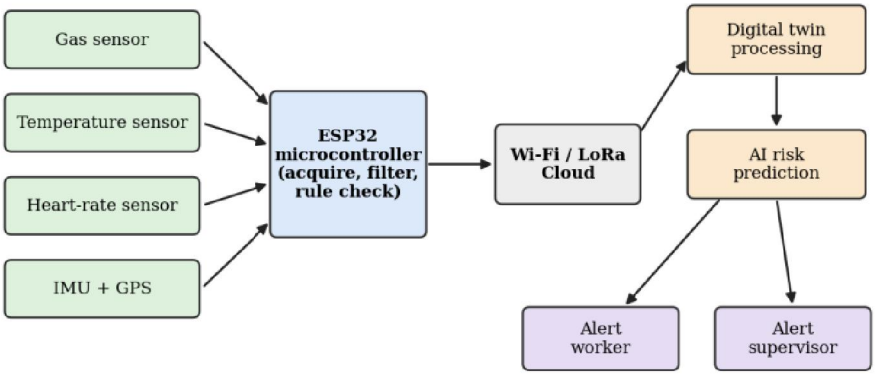


Fig. 2: System Block Diagram of Purpose system

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A. Data Acquisition and Sensor Integration

1. Gas Sensing

A metal-oxide gas sensor of the MQ type gives an analog output those changes with gas concentration. The output is read by an analog input of the ESP32. Because such sensors need warm-up time and are affected by temperature and humidity, calibration against a reference is necessary.

2. Temperature Sensing

A digital temperature sensor such as the DS18B20 is used to monitor temperature near the body. High temperature together with a raised heart rate is treated as an indication of heat stress.

3. Heart-Rate Sensing

An optical sensor such as the MAX30102 measures pulse from changes in reflected light [6]. The signal is sensitive to movement, so the firmware uses averaging over a short window before the value is accepted.

4. Motion and Fall Sensing

A MEMS inertial sensor measures acceleration and rotation. A fall is suspected when a sudden high acceleration is followed by a period with almost no movement [8].

5. Location

A GPS module supplies latitude and longitude, which are attached to every alert so that rescue can be directed to the worker.

6. Data Processing

The ESP32 samples each sensor periodically, filters the readings, and compares them with configured limits. The basic process is: Sensor Reading → Filtering → Limit Check → Packet Formation → Transmission. The limits used in an actual installation must be selected according to the relevant safety standards and are not universal values.

B. Control Algorithm & system Operation

1. Start the system.
2. Initialise the ESP32, sensors, GPS, buzzer, and display.
3. Connect to Wi-Fi or the LoRa gateway.
4. Read gas, temperature, heart-rate, and motion data and the GPS position.
5. Filter the readings.
6. Check critical conditions on the device. If a critical condition exists, activate the local alarm.
7. Send the data packet to the cloud.
8. Update the digital twin of the worker.
9. Run the AI module and calculate the risk score.
10. If the risk score is above the threshold, grade the risk and send alerts to the worker and the supervisor.
11. Record the incident in the log.
12. Wait for the next sampling interval and repeat from step 4. The thresholds used in an actual implementation should be selected carefully for the site and should not be treated as universal safety limits.

C. Visualization & emergency Monitoring

An important feature of the system is that the information does not remain only on the physical device. The cloud platform sends the data to a dashboard and a mobile application, where the supervisor can see:

1. Worker name and ID
2. Live gas, temperature, and heart-rate values
3. Location on a map
4. Risk level and alert status
5. Date and time of the latest update
6. Incident history

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When the system identifies a dangerous condition, an emergency notification is generated for the supervisor together with the worker's position.

D. Working Principal

The system starts when power is supplied to the ESP32. First, the controller initialises all connected sensors and the wireless connection. The sensors then measure gas level, temperature, heart rate, and motion, and the GPS module provides the position. The ESP32 filters these readings and checks them against the critical limits stored on the device. If a critical condition is found, the buzzer and LED are activated immediately. The readings are then sent to the cloud, where the digital twin of the worker is updated. The AI module analyses the twin and calculates a risk score. If the score crosses the threshold, an alert is sent to the worker and the supervisor and the incident is recorded. After completing one measurement cycle, the system starts the next cycle automatically. The overall operation can be represented as: Sensing → processing → Twin Update → AI Decision → Alert → Continuous Monitoring.

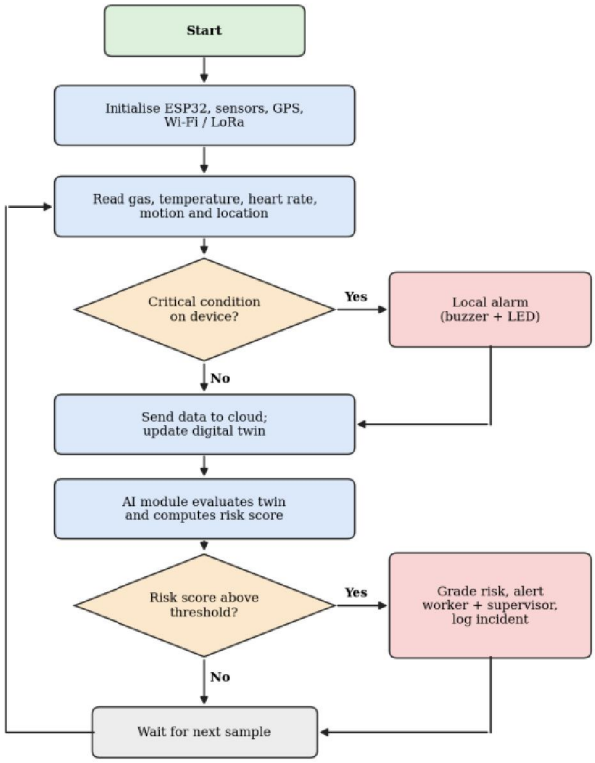


Fig. 3: Flowchart of System

V. DISCUSSION & EXPERIMENTAL OBSERVATION

The proposed system brings together three main functions: collection of data about the worker and surroundings, creation of a live digital twin, and prediction of risk. A single measurement rarely describes a dangerous situation, so combining several signals is useful. For example, a moderate gas level together with a rising heart rate and temperature may be more serious than any one of them alone. The digital twin makes it possible to compare a worker with his or her own history, and the cloud makes it possible to alert a supervisor who is not at the place of the incident. The local alarm and rule check on the device give a second layer of protection when the network fails. At the same time, the system has

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practical limitations. Low-cost gas and optical heart-rate sensors have limited accuracy and need calibration. Movement and sensor placement affect the readings, and connectivity may be poor inside tunnels or closed structures. Monitoring of health-related data raises privacy questions, so data should be collected only for safety, protected in transmission and storage, and used with the consent of the workers. In places with explosive atmospheres, the enclosure and electronics must also meet the required certification. For this reason, the prototype should be validated against reference instruments before any claim about its reliability is made.

VI. CONCLUSION

The AI Digital Twin Safety Badge combines IoT sensing, embedded processing, a cloud digital twin, and machine-learning risk prediction in one low-cost wearable. By following the state of each worker continuously and analysing it for developing danger, the system aims to change industrial safety from inspection after the event to prevention before it. The architecture is modular and can be extended with more sensors and better models. Testing of the prototype against reference instruments and in realistic conditions is the next step towards deployment.

Future Scope: The system can be improved in several directions. Edge AI can run a small model on the badge or on a nearby gateway to reduce delay, and future 6G networks may allow faster and more reliable links. Augmented-reality helmets can show the status of the twin and the hazard zones to the worker. Drones can be sent automatically to the location of an emergency. Tamper-resistant records, such as blockchain-based logs, can keep the incident history reliable. Federated learning can improve the models across several sites without sharing the raw data of workers.

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