International Journal of Multidisciplinary and Innovative Research

ISSN(print): 3050-6883, ISSN(online): 3050-6891

Volume 03 Issue 07 July 2026

DOI: 10.58806/ijmir.2026.v3i7n12

Page No: 619-625

Industrial Hazard Identification and Automated Safety Control Systems: A Comprehensive Review of Industry 4.0 Technologies, Artificial Intelligence, and Future Safety Paradigms

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ABSTRACT

Industrial environments are characterized by complex interactions among human operators, machinery, materials, and information systems, creating diverse safety challenges. Conventional safety management approaches predominantly rely on periodic inspections, manual monitoring, and reactive intervention strategies, which often fail to provide timely hazard detection and rapid emergency response. The emergence of Industry 4.0 has fundamentally transformed industrial safety management through the integration of cyber-physical systems (CPS), the Industrial Internet of Things (IIoT), artificial intelligence (AI), machine learning (ML), digital twins, and automated control technologies.

This review presents a comprehensive analysis of industrial hazard identification and automated safety control systems by synthesizing research published between 2013 and 2026. The study examines industrial hazards, enabling technologies, communication architectures, intelligent analytics methods, and automated response mechanisms. Furthermore, it explores the role of Safety 4.0 and Industry 5.0 paradigms in promoting human-centric, sustainable, and resilient industrial operations. Key challenges related to interoperability, cybersecurity, data quality, scalability, ethical concerns, and workforce adaptation are critically evaluated. Finally, future research opportunities, including explainable artificial intelligence, digital twins, immersive technologies, and autonomous safety systems, are discussed.

KEYWORDS: Industrial safety, hazard identification, automated safety control, Industry 4.0, Industrial Internet of Things, cyber-physical systems, machine learning, digital twin, Safety 4.0, Industry 5.0.

ARTICLE DETAILS

Published On:
25 July 2026

Available on:
https://ijmir.com

1. INTRODUCTION

Industrial sectors such as manufacturing, automotive production, chemical processing, oil and gas, mining, and power generation play crucial roles in global economic development. However, these sectors operate under hazardous conditions involving complex processes, high-energy equipment, toxic substances, and human-machine interactions. Industrial accidents continue to result in fatalities, injuries, environmental degradation, operational disruptions, and significant financial losses [6].

Traditional safety management approaches primarily focus on compliance-based frameworks, periodic inspections, and post-incident investigations. Although these approaches have contributed to reducing workplace accidents, they remain largely reactive and often fail to identify emerging hazards in real time [7], [8]. The increasing complexity of industrial systems further challenges conventional safety management practices.

The fourth industrial revolution, commonly referred to as Industry 4.0, has introduced advanced digital technologies capable of transforming industrial safety from reactive risk management to proactive and predictive safety assurance [3]. Industry 4.0 integrates cyber-physical systems, cloud computing, IIoT, artificial intelligence, and advanced analytics to create intelligent and interconnected industrial environments [1], [2], [4].

Cyber-physical systems establish a bidirectional relationship between physical assets and computational intelligence, enabling continuous monitoring and autonomous decision-making [1], [2]. IIoT platforms facilitate real-time data collection from distributed sensors and industrial devices [5]. Machine learning algorithms support anomaly detection, predictive maintenance, and hazard forecasting [10–12]. Digital twins enable virtual simulations of industrial processes for proactive risk assessment and emergency planning [16].

Recent studies have demonstrated that Industry 4.0 technologies significantly enhance occupational safety, operational efficiency, and system resilience [7], [8], [22]. Furthermore, the emergence of Industry 5.0 emphasizes human-centric, sustainable, and resilient manufacturing systems that integrate human expertise with intelligent automation [17].

This review aims to synthesize current knowledge regarding industrial hazard identification and automated safety control systems by addressing the following objectives:

1. To classify major industrial hazards and associated risks.
2. To review Industry 4.0 technologies supporting hazard identification.
3. To examine machine learning and artificial intelligence applications in industrial safety.
4. To evaluate automated safety control mechanisms.
5. To identify implementation challenges and research gaps.
6. To discuss future directions toward Safety 4.0 and Industry 5.0.

2. METHODOLOGY

This study adopts a narrative review approach to synthesize existing knowledge related to industrial hazard identification and automated safety control systems. The literature selection process involved identifying relevant publications from scientific databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. The search focused on peer-reviewed journal articles, conference papers, and review studies published between 2013 and 2026. The following keywords were used individually and in combination:

1. Industrial hazard identification
2. Automated safety control
3. Industrial safety management
4. Industry 4.0
5. Industrial Internet of Things
6. Cyber-physical systems
7. Machine learning for industrial safety
8. Digital twin
9. Safety 4.0
10. Industry 5.0

The selected literature was categorized into five thematic areas:

1. Industrial hazards and risk assessment.
2. Industry 4.0 enabling technologies.
3. Artificial intelligence and predictive analytics.
4. Automated safety control systems.
5. Human-centric safety and future paradigms.

3. INDUSTRIAL HAZARDS AND RISK ASSESSMENT

Industrial hazards can be categorized into physical, chemical, electrical, mechanical, environmental, and human-factor hazards [6].

3.1 Physical and Mechanical Hazards

Physical hazards include excessive noise, vibration, temperature extremes, radiation exposure, and moving machinery. Mechanical hazards arise from rotating equipment, conveyor systems, robotic operations, and high-pressure systems. These hazards frequently cause injuries such as fractures, burns, lacerations, and amputations.

Condition monitoring technologies, including vibration analysis and acoustic monitoring, play essential roles in identifying abnormal equipment behavior before catastrophic failures occur [12].

3.2 Chemical and Environmental Hazards

Chemical hazards involve exposure to toxic gases, hazardous chemicals, combustible materials, and airborne contaminants. Industrial incidents involving gas leaks, explosions, and chemical spills may have severe consequences for workers and surrounding communities [6]. Environmental hazards include air pollution, waste generation, and accidental release of hazardous substances. Emerging Industry 4.0 technologies facilitate continuous environmental monitoring and risk mitigation through intelligent sensing and predictive analytics [18].

3.3 Electrical Hazards
Electrical hazards include electric shocks, arc flashes, short circuits, overload conditions, and insulation failures. Automated monitoring systems employing current, voltage, and thermal sensors can detect electrical abnormalities and initiate protective actions.

3.4 Human-Factor Hazards
Human errors remain a leading cause of industrial accidents. Factors contributing to unsafe behavior include fatigue, stress, inadequate training, cognitive overload, and poor ergonomic design [13], [14]. The integration of ergonomic principles into smart manufacturing environments is essential for reducing workplace injuries and improving human-machine collaboration [14].

3.5 Risk Assessment Techniques
Traditional risk assessment methodologies continue to play important roles in industrial safety management. Common approaches include:

1. Hazard and Operability Studies (HAZOP)
2. Failure Mode and Effects Analysis (FMEA)
3. Fault Tree Analysis (FTA)
4. Event Tree Analysis (ETA)
5. Layer of Protection Analysis (LOPA)

These methods support systematic identification, evaluation, and mitigation of industrial risks [6].

4. INDUSTRY 4.0 TECHNOLOGIES FOR HAZARD IDENTIFICATION

4.1 Cyber-Physical Systems
Cyber-physical systems integrate sensing, computation, communication, and control capabilities to create intelligent industrial environments [1], [2]. Lee et al. [1] proposed a five-level CPS architecture consisting of connection, conversion, cyber, cognition, and configuration layers. This architecture enables real-time monitoring, predictive analytics, and autonomous control.

Monostori [2] emphasized that cyber-physical production systems provide adaptive and decentralized decision-making capabilities, enhancing flexibility and resilience. Oks et al. [9] further highlighted the role of CPS in enabling self-aware and self-optimizing industrial systems capable of supporting advanced safety functions.

4.2 Industrial Internet of Things
IIoT technologies facilitate seamless connectivity among industrial devices, sensors, actuators, and cloud platforms [4], [5]. Smart factories leverage IIoT infrastructures to collect real-time data regarding equipment conditions, environmental parameters, and worker activities [4]. Software-defined IIoT architectures improve network flexibility, scalability, and interoperability by separating control functions from physical infrastructure [5].

4.3 Sensor Technologies
Sensors constitute the foundation of industrial hazard identification systems. Common sensor categories include:

1. Gas sensors
2. Temperature sensors
3. Humidity sensors
4. Smoke detectors
5. Flame sensors
6. Vibration sensors
7. Acoustic sensors
8. Current and voltage sensors
9. Optical sensors
10. Vision-based systems

The integration of heterogeneous sensors enables comprehensive monitoring of industrial environments and supports accurate hazard identification [11].

4.4 Communication Infrastructure
Reliable communication networks are essential for real-time industrial safety applications. Common industrial communication protocols include:

1. MQTT
2. OPC UA
3. Modbus

4. PROFIBUS
5. EtherNet/IP
6. CAN Bus

Wireless communication technologies, including Wi-Fi, Zigbee, Bluetooth Low Energy, LoRaWAN, and 5G, facilitate remote monitoring and distributed sensing [5], [11].

5. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING FOR INDUSTRIAL SAFETY

5.1 Predictive Analytics

Machine learning algorithms can identify hidden patterns within industrial datasets and predict hazardous events before they occur [12]. Predictive analytics applications include:

1. Equipment failure prediction
2. Remaining useful life estimation
3. Process anomaly detection
4. Hazard forecasting
5. Predictive maintenance

Common machine learning algorithms include support vector machines, random forests, neural networks, and gradient boosting techniques [12].

5.2 Anomaly Detection

Anomaly detection enables early identification of abnormal system behavior that may indicate hazardous conditions [23]. Deep learning approaches, particularly convolutional neural networks, have demonstrated significant potential for detecting anomalies in industrial IoT environments [24-30]. Machine learning-based alarm forecasting systems can reduce false alarms and improve operational awareness [23-29].

5.3 Industrial Cybersecurity

The increasing connectivity of industrial systems introduces substantial cybersecurity challenges [10]. Machine learning techniques can identify malicious network activities, detect cyberattacks, and improve industrial control system security [10]. However, AI-based cybersecurity systems require continuous model updating to address evolving threats.

6. Automated Safety Control Systems

Automated safety control systems reduce response times and minimize dependence on human intervention. A typical industrial safety control architecture consists of four layers:

1. Data acquisition layer
2. Communication layer
3. Data processing and analytics layer
4. Control and response layer

Industrial controllers, including PLCs, SCADA systems, and DCSs, execute automated safety actions based on predefined rules or AI-generated recommendations.

Typical control actions include:

1. Emergency shutdown
2. Alarm activation
3. Ventilation control
4. Fire suppression
5. Equipment isolation
6. Access restriction
7. Notification of emergency personnel

Edge computing enhances system responsiveness by enabling local data processing and decision-making [12].

7. DIGITAL TWINS AND SAFETY 4.0

Digital twins are virtual representations of physical systems that continuously synchronize with real-world operational data [16].

Digital twin technologies enable:

1. Real-time system visualization
2. Hazard simulation
3. Predictive maintenance

4. Process optimization
5. Emergency response planning

The integration of digital twins with AI and IIoT technologies creates intelligent safety ecosystems capable of predicting hazardous events before they occur [16]. Safety 4.0 extends Industry 4.0 principles to occupational health and safety management through the integration of intelligent monitoring, predictive analytics, and automated decision-making [32-33].

8. HUMAN-CENTRIC SAFETY AND INDUSTRY 5.0

While Industry 4.0 focuses primarily on technological advancement, Industry 5.0 emphasizes human-centricity, sustainability, and resilience [17]. Human-centric industrial safety systems integrate human expertise with intelligent automation to improve worker well-being and productivity. Emerging technologies supporting human-centric safety include:

1. Wearable devices
2. Augmented reality systems
3. Virtual reality training platforms
4. Collaborative robots
5. Smart personal protective equipment

Immersive technologies enhance safety training effectiveness and improve hazard awareness among workers [27, 33]. Ergonomic considerations remain critical for reducing cognitive workload and preventing occupational injuries [14].

9. CHALLENGES AND RESEARCH GAPS

Despite significant progress, several challenges hinder the widespread adoption of intelligent industrial safety systems.

9.1 Interoperability

The integration of heterogeneous devices, communication protocols, and software platforms remains challenging [5], [9].

9.2 Data Quality and Reliability

Sensor inaccuracies, communication delays, missing data, and environmental interference can negatively affect safety performance [12].

9.3 Cybersecurity

Increasing connectivity expands the attack surface for cyber threats targeting industrial systems [10].

9.4 Scalability

Large-scale deployment requires substantial computational resources, communication bandwidth, and data management capabilities [15].

9.5 Workforce Adaptation

Successful implementation depends on employee acceptance, digital literacy, and continuous training [17], [21, 29].

9.6 Ethical and Regulatory Issues

AI-based safety systems raise concerns regarding transparency, accountability, privacy, and regulatory compliance. Current safety standards and regulations require further adaptation to accommodate autonomous and intelligent industrial systems.

10. FUTURE RESEARCH DIRECTIONS

Future industrial safety research should focus on the following areas:

1. Explainable artificial intelligence for transparent safety decisions [19]
2. Federated learning for privacy-preserving analytics [10]
3. Blockchain-enabled industrial cybersecurity [10]
4. Integration of digital twins with real-time hazard prediction [16]
5. Autonomous robots for emergency response [28-33]
6. Advanced wearable technologies for worker monitoring [21]
7. 6G-enabled industrial communication networks [11]
8. Human-centric Safety 5.0 frameworks [17]

The convergence of CPS, IIoT, AI, digital twins, and immersive technologies is expected to create intelligent safety ecosystems capable of autonomous hazard identification and response [19], [22].

CONCLUSION

Industrial hazard identification and automated safety control systems have evolved significantly with the emergence of Industry 4.0 technologies [1–5]. The integration of cyber-physical systems, IIoT, artificial intelligence, digital twins, and automated control mechanisms has transformed industrial safety from reactive incident management to predictive and autonomous risk mitigation [7], [12], [16].

Current evidence demonstrates that intelligent safety systems improve hazard detection accuracy, reduce response times, enhance workforce protection, and increase operational resilience [7], [8], [22-27]. However, challenges related to interoperability, cybersecurity, data quality, scalability, workforce adaptation, and regulatory compliance continue to limit widespread implementation [9], [10], [15].

Future research should prioritize the development of explainable, secure, scalable, and human-centric safety systems aligned with the principles of Industry 5.0 [17], [19]. Such advancements will contribute to safer, more sustainable, and resilient industrial environments [22-29].

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