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SURVEY

Industrial Internet of Things for Safety Management Applications: A Survey

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ABSTRACT Industrial Internet of Things (IIoT) aims to achieve higher operational and management efficiencies by bridging machinery, equipment, human resources, and all other actors involved in an industrial environment. This bridging enables data flow over an often complex and heterogeneous communication network. It enables timely decision-making, which affects various aspects of the organization such as business, operations, maintenance, safety, stock, and logistics. Despite the plethora of works in the domain of IIoT dealing with the above aspects, very few works deal with safety in industries. Industrial safety, especially whenever it is intertwined with the safety of humans, is a critical domain and holds much scope for improvement in the context of IIoT-based solutions for industrial safety management. Through this survey, we provide a comprehensive overview of the safety issues prevalent in the industries. Subsequently, we classify and provide an in-depth analysis of the safety aspects in various application areas of IIoT such as healthcare, transportation, manufacturing, and mining. Finally, we examine the research gaps in various domains and recommend future research directions. We discuss diverse forms of technologies, prototypes, systems, models, methods, and applications to ensure the safety of individuals and the risks associated with them. The primary aim of this work is to analyze and synthesize the existing researches and acknowledge the applicability of these research works towards safety management using IIoT.

INDEX TERMS Industrial safety, Industrial Internet of Things (IIoT), safety management, risks, hazards.

I. INTRODUCTION

The proliferation of the Internet and network-connected devices across all spheres of life in the modern-day world and the rising demand for a formal relatable paradigm led to the emergence of Internet of Things (IoT) [1]. The end-point and the intermediate nodes in this rapidly increasing, dense, and complex network of devices – both regular and low-powered – are increasingly becoming smart, intelligent, and almost autonomous. These interconnected smart devices interact and communicate to transfer data to the central servers through the Internet and make use of the various technologies associated with the Internet [1]. Eventually, these technologies and paradigms started finding practical and beneficial adoption in industries.

Industrial Internet of Things (IIoT) platforms render networked integration of smart devices, machinery, and other infrastructure in the industrial context [2]. Additionally, in industries, IIoT enables the integration of information technologies (IT), and operational technologies (OT) [2]. IIoT offers the foundation for conceptualizing an industrial environment as a network of digitally connected entities comprised of various actors – workers, supervisors, planners, engineers, machinery, software, computers, and others. This digital transformation of industrial organizations results in a simplified and scalable solution for making timely and

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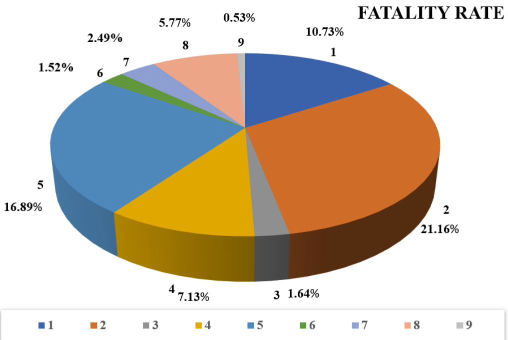
well-informed decisions, thereby making these organizations faster and smarter [3]. The interconnections between industrial infrastructure using IIoT have enabled the seamless flow of data from the source of data generation to the end-users. Operations such as data acquisition, data and information exchange, data processing, data storage, development of new services, management, and analytics have been simplified and been made highly traceable and timely through the incorporation of IIoT [2], [3]. Further, various IIoT applications such as IIoT "as a service" using the multi-access edge computing [4], Artificial Intelligence (AI) applications at the edge [6], and task offloading [5] are also developed. Certain IoT applications are designed for solving the problems associated with network discovery [7], formulate the interconnection within the network [8], and security issues [9].

One of the most prominent, yet highly critical, roles in the industry, which can be accentuated with IIoT in light of the technological advancements and benefits it offers, is industrial safety management. Therefore, the prospect of having an intelligent and timely unified information acquisition and management system, which the IIoT paradigm naturally offers, is highly desirable for industrial domains such as safety management. For example, in underground mines and high voltage switchgear installations, the fatality rate of workers is typically high [10] owing to the highly hazardous nature of the work involved. A failure to comply with work-specific Standard Operating Procedures (SOPs) to the dot in these safety-critical domains often proves fatal. Further, as an example, Fig. 1 illustrates the data[1] for the fatality rates across various industries in the world, released by the U.S. Bureau of Labor Statistics.



1. Agriculture, fishery, and hunting, 2. Construction, 3. Mining 4. Manufacturing, 5. Transportation and Warehousing, 6. Real estate and leasing, 7. Healthcare, 8. Retail trade, 9. Educational services

FIGURE 1. **Fatality rates and their causes across various industries in the year 2020.**

The statistics in Fig. 1 show scope for improvement of safety in many industrial areas, and several suggestions are made in this direction in the subsequent sections of this manuscript. IIoT technologies promise direct benefits to this end for ensuring safety monitoring and enforcement. Commonly available wearable smart IoT devices can be conveniently reused to provide unparalleled safety levels to workers on a factory floor or under hazardous working conditions. As discussed earlier, IIoT supports the synchronization of IT and OT, while improving levels of automation in industrial processes. Further, such systems enhance traceability of events as the sensed data from the machines and other intelligent devices are stored on central servers, providing a history of workers' access to the machines and the operational status of machines. Such records and historical data from industrial equipment can also generate information relevant to their condition monitoring and predictive maintenance. Timely insights into machine health also reduce the scope for mishaps owing to malfunctioning or poorly maintained equipment and machinery in industries. Further, robots have been an essential part of industrial automation for the past few years. However, with the evolution of IoT-based technologies and Industry 4.0, the field of robotics has witnessed a significant boost. These changes have the potential to upgrade the safety of individuals across diverse industry verticals [11] by removing humans from the direct line of hazards. Table 1 shows some of the common workplace hazard sources,[2] its scope of automation, and possible IoT-based solutions for the same.

A. MOTIVATION

In the existing research works, the authors mentioned that the application of connected technologies in the industrial environment, termed as IIoT with the conventional industrial processes projects significant improvement in the industrial efficiency and production [2], [3], [11]. On the other hand, safety acts as the keystone in the upgradation of industrial efficiency and product quality. In case of any accident/incident at the workplace due to deviation from the safety protocol affects the entire unit physically and mentally. Additionally, it causes damage to the factory infrastructure and machinery, which disrupts the production processes. Further, the consequences are loss of precious production times and efficiency on the factory floor, resulting in capital losses for the business owners, besides losing workers' confidence in their equipment. Therefore, any form of breach in the industrial safety protocols and SOPs may prove disastrous for the industries.

The safety of the working personnel typically acts as one of the uncompromising factors of concerns in modern industries. The number of risks and hazards present in the different units on the factory floor is quite high as shown in Table 1. Although various safety management measures and SOPs generally exist in industries, the use of smart devices further improves the safety of machines and workers, in addition to bringing event traceability. These smart devices form the basis for deploying IIoT networks in industrial

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[1] https://www.bls.gov/news.release/cfoi.t04.htm

[2] https://www.opensourcedworkplace.com/news/25-types-of-hazards-in-the-workplace-and-how-to-prepare

TABLE 1. A comprehensive list of hazard types, their possible sources, and possible automation measures in industrial environments.

No.	Hazard source	Examples of sources	Automated detection	Possible solutions
1	Hazardous liquids	Acids in cleaning products, disinfectants, glues, paints, pesticides, petroleum products, and solvents	✓	RFID tracing of containers
2	Dangerous gases	Natural gas, liquefied petroleum gas, autogas, Carbon Monoxide, medical gas, and Methane	✓	Gas sensors
3	Radiation	Low-frequency radiation from induction furnaces, microwave radiation, infrared radiation, ionizing radiation	✓	Radiation sensors
4	Ergonomic fails	Discomfort from workplace settings	×	-
5	Spread of diseases	Infectious diseases, outbreaks, epidemics	Partially	Worker temperature and oxygen-level checks
6	Office stress	Anxiety, indifference, fatigue, lack of sleep, social withdrawals, and resort to vices	×	-
7	Sociological constraints	Miscommunication, gossiping, bullying, harassment, discrimination, disagreements	×	-
8	Workplace violence	Threat of physical violence, bullying, intimidation, and disruptive behavior	✓	Sound level sensors
9	Noise pollution	Increased noise levels, explosions	✓	Sound level sensors
10	Fire hazard	Flammable liquids, gases, improper storage of flammable products	✓	Fire and gas sensors
11	Faulty electricity	Faulty wiring, damaged gadgets and outlets, overloading	✓	Power sensors, electrical discharge detectors, line continuity sensors
12	Inadequate lighting	Poor lighting, prolonged staring at computers/terminals	✓	Luxmeters, light switches
13	Poor air quality and ventilation	Unequal ventilation, malfunctioning air filters and air circulators, malfunctioning air conditioners	✓	Air flow sensors, air quality sensors
14	Temperature extremes	Loss of body heat and numbing of extremeties in sub-zero work environments	✓	Ambient temperature sensors, wearables
15	Confined spaces	Pits, trenches, sewers, drainages, tanks, chambers, tunnels, underground pathways, unventilated rooms, and small work areas	×	-
16	Working at height	Roof cladding, steelworkers on top of buildings, demolition squads, highrise cleaners	✓	Altimeters, wearables
17	Elevators and forklifts	Installation and repair of elevators, workers in the vicinity of forklifts	✓	Proximity sensors, robots
18	Poor construction	Shoddy construction, unstable structures	Partial	Tilt sensors, seismic sensors, humidity sensors, cameras
19	Dangerous machines	Sharp edges, machines with repetitive motion, use of chemicals, high-voltage installations	✓	Condition monitoring of machines, fences, curtains
20	Defective workplace tools	Faulty tools, damaged insulation of tools	Partial	Camera-based tool inspection
21	Emergency preparedness	Contingency plans in cases of fires, earthquakes, explosions, obstruction mapping, bottleneck identification	×	-
22	Poor sanitation	Unclean workplaces, unhygenic toilets	×	-
23	Biological hazards	Waterborne diseases, parasitic worms	×	Biosensors
24	Waste management	Overflowing bins, stagnant water sources, improper disposal of wastes	✓	Smart bins

work environments. With the integration of advanced technologies and smart devices, the traditional industrial framework[3] is transformed to an IIoT-compliant one [3]. Further, this technological augmentation leads to improved operational efficiency, operation time, quality of products, and safety of individuals. In addition to this, other impacts of the industrial transformation are better utilization of assets and improved working conditions. The above-mentioned factors strongly motivated us to survey the risks involved and IoT-based safety management techniques used across various industries.

B. SHORTLISTING CRITERIA

The following survey has explored multiple sources – journals, conferences, books, book chapters, web-pages and blogs – for developing its structure and subsequently its contents. The search parameters for selecting the papers were tuned to be as close to the topic of this survey as possible, with the publication year range lying majorly between 2018 to present day. Some of the relevant keywords chosen were – Industry 4.0 safety, Industrial safety, IIoT, Industrial IoT, safety management, safety in factories, safety in industries, safety in healthcare, safety in transportation, safety in logistics, mine safety, and others. The contents of this survey has been developed from journal (both regular and survey) and conference articles. Fig. 2 outlines the distribution of the selected paper types used in this survey. Similarly, Fig. 3 shows the relative distribution of the journal and conference

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[3] Traditional industrial framework is the infrastructure with automation among the processes, networks, and business models. However, the incorporation of these advanced technologies lead to the digital transformation, which results in the improvement of both the quality and the quantity of products.

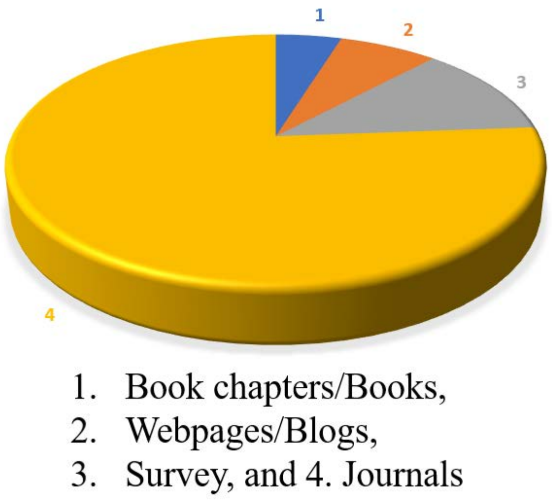

FIGURE 2. Overview of book chapters, web-pages, survey, and journal papers selected for this survey.

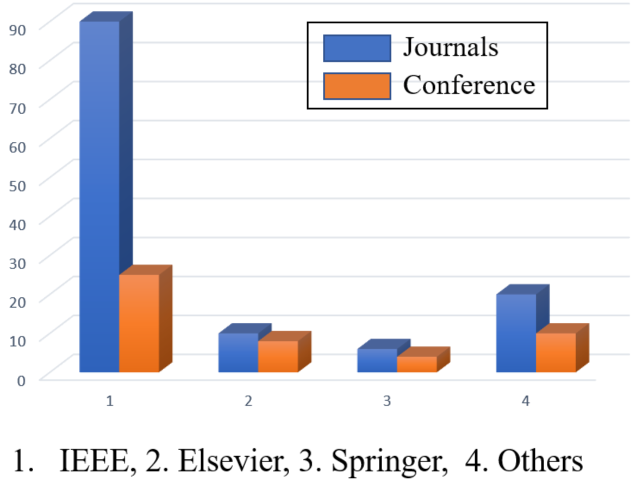

FIGURE 3. Overview of publishers selected for this survey.

papers across various publishers that have been primarily used in this survey. Once the specific industries were shortlisted, we used word-clouds to identify the relevant keywords and associated safety-specific issues in each of these chosen domains.

C. CONTRIBUTION

In this work, we provide a synthesized survey of the issues pertaining to safety in industries, the various sources of hazards, and the current important role of IIoT and future possibilities of such technologies in alleviating some of these issues in industries. Fig. 5 outlines the various industries according to their services. We categorize the industries which are almost similar in terms of their function and operation. In Fig. 5, we represent them under various groupings of *High Economic Implications*, *Time Critical*, and *Hazard Critical*, which are indicated by three contrasting colors. Some industries are more time critical than others, whereas some are more hazard critical. However, those industries that lie at the intersection of these three parameters are of importance to us and this survey. Specifically, in this survey, we focus on the industries that have high stakes in adopting safety and safety management solutions. These selected industries have high economic (cost) implications, have time-critical operational workflows, and deal with hazardous substances, materials, and environments – *healthcare*, *transportation*, *manufacturing*, and *mining* [13].

We provide an outline of the systems, models, prototypes, and applications developed across the various industrial verticals from the perspective of safety management. These research works are aimed at provisioning safety of workers, communication, environmental, and energy consumption aspects. In healthcare, for instance, various types of on-body and off-body sensor nodes are used to measure the physiological parameters of patients. The communication of the physiological data, channel conditions, accurate diagnosis of the patient's disease, and proper medications play an important role in the healthcare industry. On the other hand, the safety of workers in hazardous zones, communication with the remote end, maintaining proper safety standards in the factory floor, and providing preliminary safety-related information, are essential requirements to be addressed in the fields of manufacturing, mining, and road transportation. Therefore, we study and analyze the limitations of the existing researches for different IIoT application verticals. Based on the analysis of these limitations, we provide future research directions.

We summarize the researches with regard to their applications in the respective industrial sectors. We discuss the Service Oriented Architecture (SOA)-based IIoT infrastructure, which comprises four layers – (a) sensor-equipped device, (b) intermediate device, (c) processing, and (d) interface. Additionally, we discuss another unique safety infrastructure, Safety-as-a-Service, applicable across diverse industries [14]–[16]. Finally, we present the future research challenges in the industries for IIoT adoption and compliance. The specific *contributions* of this work are as follows:

- We review how technologies are used to provide safety to the people and systems with respect to the diverse application areas of IIoT such as *healthcare*, *mining*, *transportation*, and *manufacturing*. Thereafter, we discuss the existing researches related to IIoT, undergone in the aforementioned fields.
- The overview of the generalized layered safety management infrastructure of IIoT is briefly discussed in this paper. We also discuss a safety-related infrastructure, named Safe-aaS, to be applicable across diverse industrial verticals for provisioning customized safety-related decisions to the end-users.
- We present the future research directions, based on which the existing prototypes, systems, and models, can be extended to improve the safety, system efficiency, cost of products, and product quality.

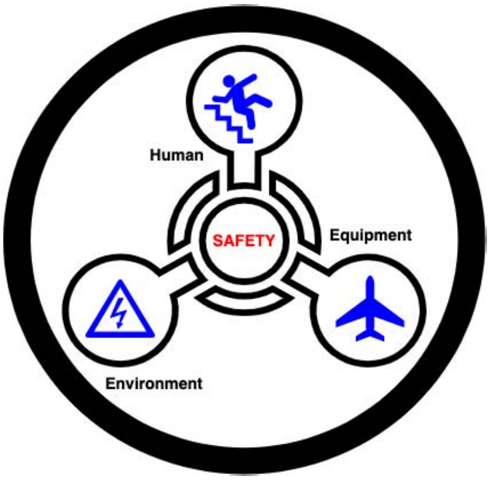

FIGURE 4. The safety trifecta: the three crucial industrial safety components that can be used to assess risks.

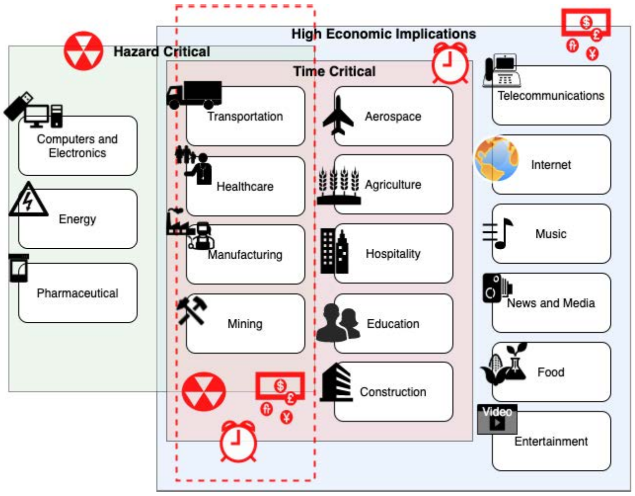

FIGURE 5. Types of industries and their groupings based on the nature of their work and criticality related to economic impact, time, and hazards.

The organization of the rest of this paper is as follows – Section II-A discuss the safety trifecta and the risks associated in the industries and section II-B provides an overview of the SOA-based layered IIoT architecture. Section III highlights the prior researches done in the domain of healthcare - the risks involved and the IoT-based solutions applied to improve the safety of patients. Further, Section IV depicts the research work undergone in the field of road transportation for enhancing the on-road safety of individuals and vehicles. Similarly, Sections V and VI also discusses the prior research works in the field of manufacturing and mining industries to improve the working conditions of workers on the factory floor and underground mines. We describe the future research directions in Section VII. Finally, Section VIII summarizes the research works.

II. SAFETY MANAGEMENT IN INDUSTRIES AND IDENTIFYING THE RISKS ASSOCIATED

A. THE SAFETY TRIFECTA: PARAMETERS FOR IDENTIFYING INDUSTRIAL SAFETY RISKS

As per IEC standards, "Safety is defined as the freedom from unacceptable risk of physical injury" [12]. The co-dependence of machines, the environment, and individuals in industry forms an integral part of industrial operations and dictates safety in industries. These safety policies aim to minimize industrial hazards, near misses, fatalities, and accidents.

Further, a near-zero risk work environment is challenging to attain in most industries, but maintaining safety standards significantly minimizes the hazards caused. We identify a trifecta – Human, Environment, and Equipment – each of which needs proper investigation or audit individually to define and determine safety hazards in industries completely. We limit the scope of this survey to only four industries and analyze the safety issues and IIoT solutions for each based on the identified safety trifecta in Fig. 4. This limitation was imposed to majorly focus only on the verticals which satisfy the criteria of high economical impact, time criticality, and hazard criticality. The primary industrial verticals of relevance to this survey are – *healthcare*, *transportation*, *manufacturing*, and *mining* [13]. We use word clouds in Figs. 8, 10, 12, and 14 to identify repetitive keywords in domain-specific safety and incident reports for each of the four chosen verticals. Each of the keywords highlighted in the word cloud for the verticals highlight specific terms relevant to that vertical and also helps identify some of the relevant safety threats and points of interest in that vertical. Larger is the text size in the generated word cloud, more is its occurrence in the safety and incident report. This approach helps us identify the key points to investigate under each of the chosen verticals. Further, in the latter parts of this manuscript, we provide the summary and future research directions for each of these application areas.

B. SAFETY MANAGEMENT USING IIoT - AN OVERVIEW

Safety is an essential aspect of concern in many application domains. Given that layered architectures are a common way to structure automation systems [122], Service Oriented Architecture (SOA) is a promising approach, which can be seamlessly deployed and scaled across multiple application domains. On the other hand, Machine Learning also play an important role in IIoT applications for real-time control and management of industries [153]. IEC61499 standard is also used for the model-based design of complex industrial systems [160]. An SOA-based IIoT infrastructure is described as a combination of various layers such as sensor-equipped device, intermediate device, processing, and interface layer [154]–[156]. Depending on the clients' requests, services are provided by the service provider through a Web portal. This approach is in line with cloud-based software solutions that are becoming popular in industrial systems as well. Fig. 6 illustrates the four layers of the IIoT architecture:

- *Sensor-equipped device layer*: This layer constitutes heterogeneous types of physical sensor nodes, which are either deployed at any particular geographical location or machines are equipped with sensor nodes, as illustrated in Fig.6. Generally, the sensor nodes deployed at a particular geographical location are of two types – scalar and camera. Some of the machines may also have either inbuilt or externally placed sensor nodes. These sensor nodes sense and transmit data to the cloud/intermediate device layer, depending upon the time-critical nature of the sensed data. Further, the safety information is processed and transmitted to the workers. In IIoT environment, robots and humans work together on the factory floor to improve efficiency and productivity in industries [121].

- *Intermediate device layer*: This layer comprises heterogeneous data concentrators, which gather and store the data transmitted by the sensor nodes for a brief period. This layer may consist of edge/fog nodes, which primarily process the time-critical data with reduced latencies [4], [5]. Thereafter, the primarily processed data are transmitted to the networking layer. As a result, the amount of bandwidth required reduces. For example, gateways, routers, and switches act as intermediate devices.
- *Processing layer*: In the processing layer, various operations such as storage, complex analytics, and processing of these sensor data are performed. These data are delivered to the clients, as per their request. Further, the processed data provides feedback information such as the machine's health, probability of fault occurrence, and predictive maintenance required to maintain the safety of both the machines and the users.
- *Interface layer*: This layer acts as an interface between the clients and the IIoT platform. The customers register and select specific services, mention the time duration of chosen services, and make payments [4] to the IIoT infrastructure provider via this layer. During registration, the end-users provide their details.

Safety-as-a-Service Infrastructure: In traditional industries, the safety of machines and working personnel were extended only with the help of hardware circuits. However, the development and integration of advanced technologies such as intelligent sensors, programmable logic controllers (PLCs), and complex analytics have significantly improved safety in various industries.

Further, the functional assessment of safety for these automated industrial systems is performed through qualitative and quantitative analysis of the individual hardware and software systems. The safety of personnel at the workplace is upgraded by adopting proper safety culture, cooperation, and flow of information among them. Moreover, efficient leaders at the workplace significantly influence the motivation, policies, and concerns of safety. A good safety leader helps to improve the safety behavior of other workers, which results in the reduction of the rate of accidents and incidents. There exists a relation between safety leadership, culture, climate, behavior, and the overall performance of an organization [157]–[160]. The provision of prior information based on events that have already occurred influences the safety and performance of organizations. For example, various lagging safety indicators such as lost-time frequencies, the severity of lost-time accidents, property damage expenses, and workers' compensation losses act as safety performance measures [161]. Similarly, considering the electrical safety of an organization, the evaluation of formal training requirements of the workers is based on the analysis of the job hazards assigned to them. In addition to this, to identify the training requirements, the proper differentiation among qualified, unqualified, and competent persons is necessary [162]. Although different research problems were identified and systems were designed, no common platform conveys customized safety-related information to the end-users/customers. Considering these issues, a unique Service Oriented Architecture (SOA)-based infrastructure, termed as Safety-as-a-Service (Safe-aaS), was proposed for provisioning safety-related information as services to the clients on a pay-per-use basis [14]–[16], [163].

Safe-aaS is a unique five-layered platform, which provides customized safety-related decisions dynamically to the end-users. The Safe-aaS platform provides these decisions to multiple end-users simultaneously, founded on the concept of decision virtualization. The Safe-aaS platform is usable across diverse industries. Considering road transportation as the application scenario, the theoretical modeling of the Safe-aaS platform was done. Safe-aaS architecture is founded on the concept of decision virtualization, using which the same decision is virtualized and provided to multiple end-users simultaneously. However, the end-users get an illusion that the decision is generated only to serve his/her requests. Fig. 7 demonstrates the five layers of Safe-aaS which are – device, edge, decision, decision virtualization, and application. The device layer comprises heterogeneous types of static and mobile sensor nodes. The static sensor nodes are deployed at a particular geographical location, while the mobile sensor nodes are placed in the vehicles. The vehicles may possess inbuilt sensor nodes or sensor nodes are externally placed into them. These sensor nodes sense and transmit the data to the edge layer or cloud, based on the time-sensitive nature of data. The time-critical data are primarily processed in the edge layer and transmitted to the decision layer, for further processing. In the decision layer, multiple processed data are combined to generate a decision. Additionally, this decision layer provides storage for a short time. Further, the logical mapping among the decision parameters requested by the end-users and the generated decisions are done in the decision virtualization layer. The application layer acts as the interface between the end-users and the infrastructure. The four main actors of Safe-aaS are – end-users, sensor owners, vehicle owners, and safety service providers (SSPs). The end-users register to this infrastructure through a Web portal and select certain decision parameters, as illustrated in

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[4] Payment is optional, depending upon the type of service.

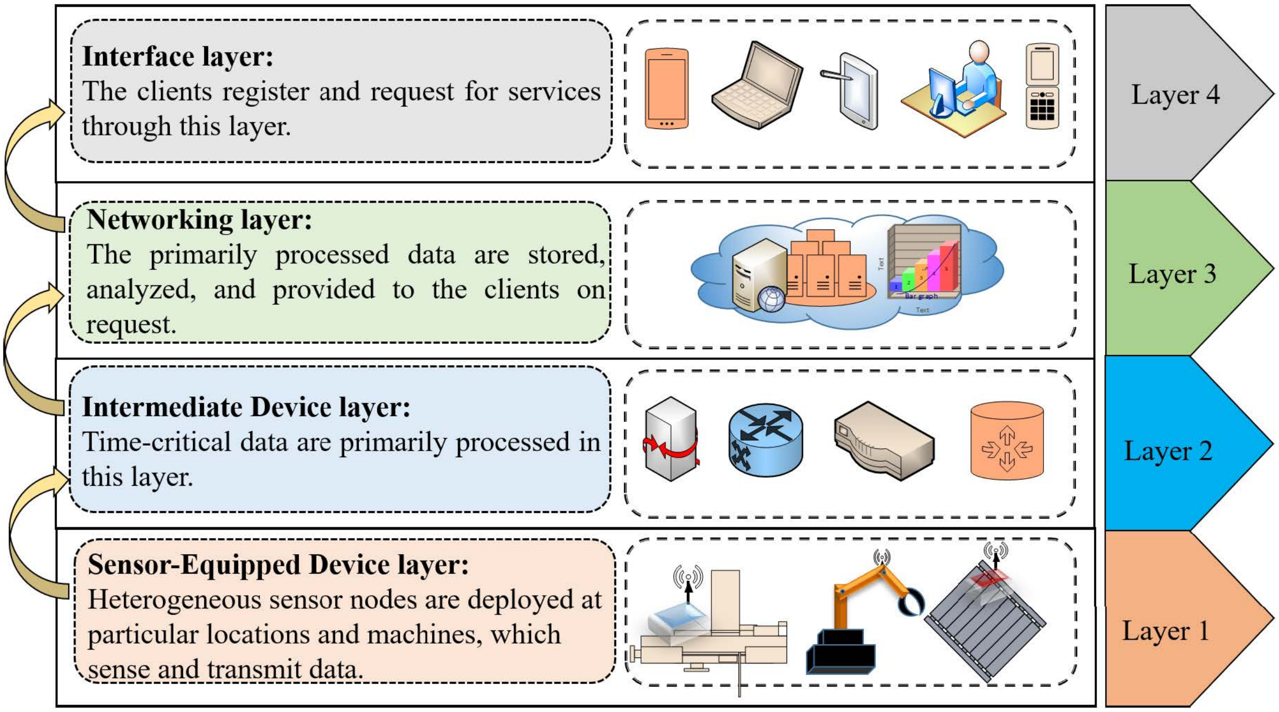

FIGURE 6. Layered architecture for safety management using IIoT.

Fig. 7. For example, the decision parameters in the industrial scenario are the downtime of machines, appropriate safety measures to be taken by workers in different zones, and predictive maintenance of machines. Similarly, the decision parameters in the road transportation scenario are the number and depth of potholes, presence of sharp turnings, presence of speed breakers, permissible weight to be carried by the heavy vehicles, and weather conditions. Based on the decision parameters selected by the end-users, safety-related decisions are provided to them. However, the end-users remain entirely unaware of the back-end process of decision generation. On the other hand, the sensor and vehicle owner rent their sensor nodes to the Safe-aaS infrastructure. An SSP is the centralized entity, who administers the entire infrastructure, handles the registration process of end-users, and manages the other financial issues.

III. HEALTHCARE INDUSTRIES

With the introduction of IoT, healthcare industries are undergoing a major transformation. The adoption of IoT-based technologies at the hardware and software levels has immensely benefited the healthcare industry, and paved way towards the development of Healthcare IoT (H-IoT) systems [17]. Although the primary concern of a majority of technological innovations in healthcare aims to improve the safety of patients and caregivers, a good number of solutions aim to provide safety for auxiliary healthcare operations. These auxiliary healthcare operations are responsible for the proper functioning of the healthcare industry.

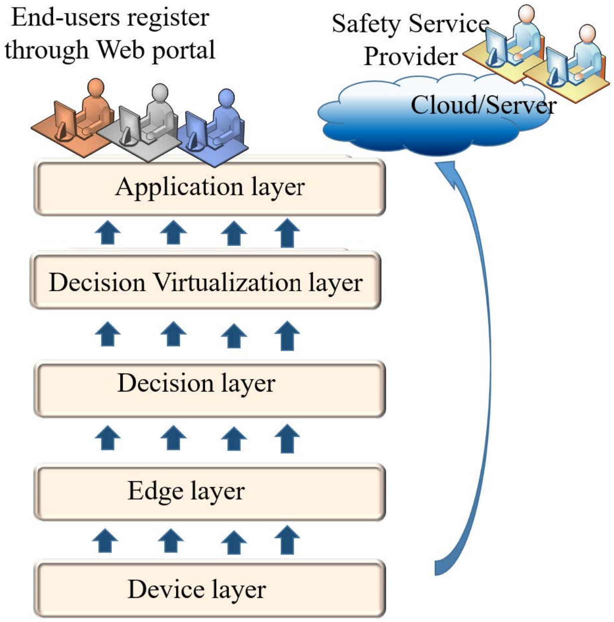

FIGURE 7. Safety-as-a-service infrastructure.

For example, the primary role of hospitals is to treat patients, for which there are doctors, nurses, and other staff, which are the direct actors in this environment. However, many more actors are involved in some way or the other during a patient's treatment in a hospital, such as technicians, maintenance staff, porters, ambulance crews, paramedics, customer-care operators, pharmacists, radiologists, and others. We parse multiple safety and incident

FIGURE 8. Word cloud of healthcare industry safety related incident reports and guidelines.

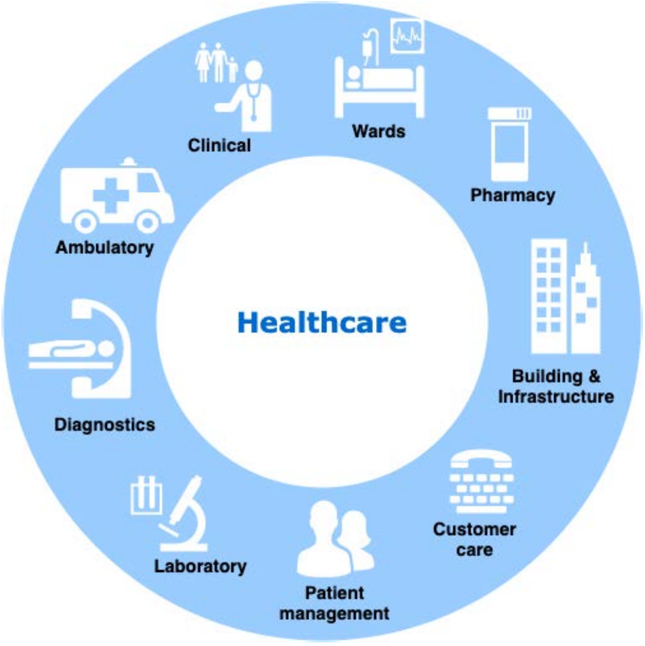

FIGURE 9. Crucial sub-domains of the healthcare industry.

reports[5] in the healthcare domain. Based on these parsed reports [18]–[21] culminating in a gross word count of more than 21, 000 words, we use a word cloud generator to highlight recurring and pertinent safety-related keywords to proceed further in this domain. It is with this rationale we use the safety trifecta to identify and assess the risks under all three categories of this industry.

A. IDENTIFYING THE RISKS

Fig. 9 shows some of the crucial aspects of the healthcare industry. These are often found together in a large multispecialty hospital, but often, some of these components can be found alone. Irrespective of whether they are together or alone, the safety trifecta holds. Considering this, we holistically identify the major stakeholders/actors in this industry. In a healthcare environment, the following risks from auxiliary sources, identified against our safety trifecta are important:

1) **Humans**: Medical staff (Doctors, Nurses, Paramedics, Therapists), Technicians (equipment, laboratory, testing), Porters, Catering, Security, Drivers, Pharmacists, Maintenance, Cleaners, and others.
2) **Equipment**: Electrical (ECG machines, ultrasound machines), Radioactive (X-rays, CT Scan), Thermal (massagers), Vehicles (ambulances, electric trolleys/carts).
3) **Environment**: Building, Ward, Lifts, Lobby, Ambulance, Incinerators, Waste disposal, and others.

Considering the various actors identified against our safety trifecta, we can identify the following risk/hazards in the healthcare industry:

- Exposure to infections and bio-hazards to the medical staff. Also, considering the hospital to be a closed environment, the risk of infection spread is high if hazards are not identified and timely precautions are not taken.
- Exposure to radiations from diagnostic equipment and specialty treatments is always a cause of concern.
- Fire hazards in buildings and infrastructure are always a concern from a regular safety perspective. However, burns occurring due to specialized treatment/therapy equipment may also occur.
- Chemical hazards from laboratory chemicals and other sources are always a risk in the healthcare industry.
- Workplace accidents owing to a fast-moving and rapidly changing work floor are quite common.
- Quality of foods and medicines, especially those stored in temperature-controlled enclosures, are also a potential cause of hazard if the enclosures exhibit excursions from ideal storage temperature.
- Proper waste segregation, disposal, and overall management are critical in the healthcare industry. Any deviations or violations pose a significant threat to the health of humans in that environment.

B. MITIGATING THE PRIMARY RISKS

The advancement in mobile computing platforms has enhanced the development of mobile healthcare (m-health) applications, which assist in the real-time monitoring of patients, even using complex sensors such as Electroencephalograms (EEGs) [22]. Further, the introduction of networked computing paradigms such as Artificial Intelligence (AI) [23], fog/edge computing [23], [24], and Software Defined Networks (SDN) [25] has led to the transformation at each level in H-IoT systems. In H-IoT systems, advanced learning mechanisms assist in various healthcare applications such as continuous monitoring and analysis of physiological data of patients suffering from chronic diseases, identification of skin diseases, and prevention of epidemics. The security and privacy of stored and monitored patient data is another essential aspect of concern in intelligent healthcare. IoT technologies such as blockchains [26] and other privacy preserving algorithms [27] for healthcare systems play a crucial role in securing patient information.

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[5] https://www.hse.gov.uk/statistics/

TABLE 2. **IoT solutions relevant to various application aspects in the healthcare industry.**

Application	EF	NP	DP	DC	NL	M	DA	HRI	PI
Routing protocol [66]	✓	×	C	×	×	×	×	×	×
Node placement [69]	✓	✓	C	×	✓	×	×	×	×
Channel variation [67]	×	×	C	✓	×	×	×	×	×
Communication [68]	×	✓	C	✓	×	×	×	×	×
Data transmission [33]	✓	×	C/F	×	✓	×	×	×	×
Data classification [65]	×	×	×	×	×	×	SVM	×	×
Patients' safety [47], [50], [51], [61], [62], [64]	×	×	×	×	×	✓	×	✓	×
Critical patient care [55], [56], [60]	×	×	×	×	×	×	×	×	✓

Legend: Energy Efficiency (EF), Node Placement (NP), Data Processing (DP): Cloud (C)/Fog (F), Data Communication (DC), Network Lifetime (NL), Mobility of patient (M), Data Analytics (DA): Support Vector Machine (SVM), Health-risks identification (HRI), Patient Identification (PI): RFID tags or Bar codes

The dependability of communication systems is an essential aspect of concern across diverse industries to maintain safety levels. In the context of IoT and industrial IoT systems, communication systems also indicate sensing units and gateway devices, or summarily, any electronic device talking to a remote system or any other device over a network – wired or wireless. In healthcare, a dependable communication system helps the healthcare providers make appropriate decisions to mitigate concerns, diagnose, and understand issues related to a patient's symptoms [28]. These communication systems [29] are deeply embedded in applications used for talking to diagnostic equipment [30], remote consulting with experts and specialists through live video streaming, ambulatory healthcare, on-body monitoring systems, wearables, ward-based patient monitoring, and other such roles. The variations in the channel quality affect communication in the wireless body area networks (WBANs). As the channel quality fluctuates, the quality of service (QoS) of the network tends to degrade. Therefore, the number of data packets successfully delivered to the other end of the channel (such as a cloud) varies.

Additionally, the physiological data of patients that are under continuous monitoring are time-critical. Any delay in delivery and drop of data packets may be interpreted by an automated IoT-based backend monitoring system or a remote monitoring system as a degradation of the patient's health condition. This communication system behavior can often lead to false alerts or even cause missed alerts during actual medical episodes. If there were no dependable communication and if we could not detect connection and/or data loss, it might lead to incorrect diagnosis are false conclusions about the state of the patient. This may impact on the health and safety of a patient. Therefore, such safety-critical data is necessary to be transmitted reliably and possibly in a deterministic manner. The reason behind the introduction of safety profiles in industrial communications is the increase in the reliability of networks (e.g., by heartbeat messages, transaction numbers, and improved CRCs). Further, this ensures that the communication failures are noticed, and proper safety measures can be taken well in time. In healthcare devices, the communication-related problem for transmitting patient's physiological data can be solved by using reliable IoT communication technologies [31] and dedicated channels to transmit health data [32]. If dedicated channels are not possible, the local processing of safety-critical data and actions is one of the possible solutions to this problem [32], [33]. For example, in case of a patient undergoing cardiac arrest, the sensed data can be locally processed using an intelligent pacemaker, which is much more reliable and prompt than transmitting it over a network and waiting for a medical opinion. Therefore, safety management in terms of the health conditions of a patient is essential.

At the time of writing this paper, the ongoing COVID-19 pandemic has also highlighted the need for IoT-based solutions for keeping checks on the spread of this highly infectious pandemic and also promulgated the feasibility of healthcare IoT systems and their widespread adoption, thereby bringing a sudden paradigm change in the healthcare industry. The safety-critical nature of this pandemic highlighted the need for ensuring the critical safety of healthcare workers (be in whatever role) and forced establishments and governments to approach healthcare from an altogether new approach. COVID-19 has created a health crisis throughout the world. Therefore, faster detection of positive COVID cases [34] and segmentation of the affected areas [35], may minimize the rate of spread of the disease. Similarly, Lee and An [36] proposed a public warning system using deep learning methods for spreading additional information regarding COVID. On the other hand, various mobile applications are developed which provides information of the affected persons. However, the privacy of the mass public and patients are violated. Tahir *et al.* [37] developed a blockchain-based mechanism, which ensure privacy preserving of COVID-19 positive patients. Interestingly, the need for physical distancing due to the pandemic and physical interaction between a patient and a doctor was optimally bridged by IoT-based healthcare systems. These systems enabled doctors to examine patients remotely [30]. Additionally, hospitals were armed with the ability to monitor the flow of patients and determine contamination zones concerning the spread of communicable diseases [38], strict privacy-preservation anti-infodemics were pursued [39] and many other significantly impactful developments [40] took place in the healthcare industry using IoT. All of these solutions and many more are helping to mitigate the primary risks that are patient-centric, in the healthcare industry.

C. MITIGATING THE AUXILIARY RISKS

The Healthcare industry comprises many stakeholders, each with its unique role to play within the healthcare ecosystem. Interestingly, most of these stakeholders do not directly have a role to play in a patient's treatment. Critical operations such as building and infrastructure maintenance [41], waste disposal and management [42], human resources [43], pharmacy [44], diagnostics, technical, equipment maintenance [45], laboratories [46], and others play an auxiliary role in this industry but are a crucial component of the healthcare industry. The safety aspects following the hazards identified using the safety trifecta outline factors such as fires, chemical spills, gas leaks, workplace accidents, faulty equipment, liquid leaks, improper waste disposal, infections, and contaminations as some of the major auxiliary incidents in the healthcare industry.

The safety of patients from any form of accident is an inevitable aspect of concern in hospitals. There were approximately 1100 cases of hospital fires recorded in the USA between the years 2012 to 2014. Post-incident evacuation procedures in this context were analyzed and protocols specified in [47]. IoT-based fire detection systems [48], ionizing radiation monitoring [49], Virtual reality (VR)-based fire safety training for staff [50], Smart Emergency Medical Services (SEMS) [51], and others [52] are some of the useful roles IoT plays in enhancing the safety of auxiliary operations in a healthcare industry. Radio Frequency Identification Devices (RFIDs) and bar codes are critical in healthcare asset management and logistics [53]. In hospitals and clinics, the medical staff is often overloaded and work under stress, resulting in human errors. The low-cost and low-power applications of RFID technologies for monitoring and identifying patients have recently become one of the most popular applications in healthcare systems. Human-based systems and processes may be prone to certain intermittent malfunctions and false triggering that might impact the provisioning of appropriate medicines, misreported stocks, and even cause miscoordination among the nurses and doctors, and discontinued activities of nurses during busy schedules [54]–[56]. These human errors pose a threat to the patients' safety and may degrade their health conditions. To avoid human errors and improve the safety of patients, RFID tags and bar codes are integrated, and Near Field Communication (NFC) technologies are used with equipment, medicines, food, and other consumables to enhance traceability and help with their status tracking. Various IoT-based solutions are already in use in the healthcare industry that can track patients within a hospital [57], track medicines and their usage [58], and perform other critical tasks [59] that are indispensable from a safety perspective. Table 2 outlines some of the IoT-specific solutions which are of high relevance while addressing the various challenges in the healthcare industry.

FIGURE 10. Word cloud of transportation industry safety related incident reports.

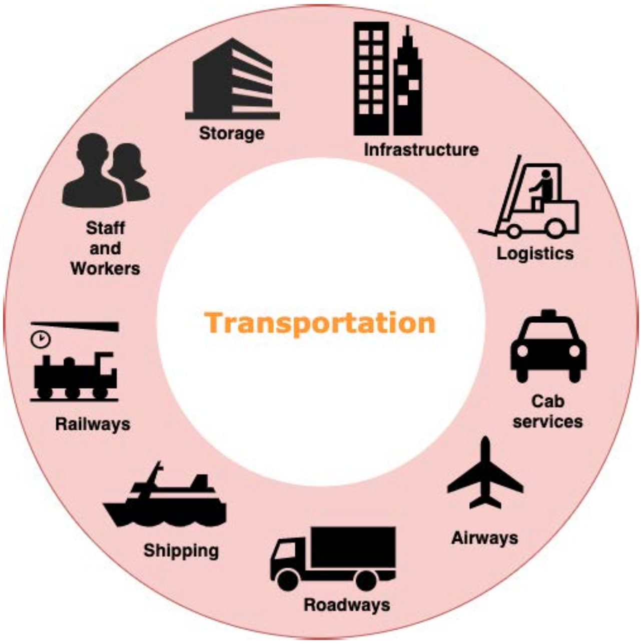

FIGURE 11. Crucial sub-domains of the transportation industry.

IV. TRANSPORTATION INDUSTRIES

In the past few years, the rate of on-road vehicles and the casualties caused due to accidents has increased significantly. As per the report of World Health Organization (WHO) in the year 2021 on road safety [70], the number of causalities due to vehicle crashes is around 1.3 million and 50 million are injured every year. These reports also reveal that road traffic injuries is the leading cause of deaths for children and young adults within the age 5-29 years. Therefore, the safety of vehicles and drivers has evolved as an issue of significant concern, which underlines the importance of safety and safety management in the transportation industry. Specific safety standards of on-road vehicles are managed and monitored by the U. S. National Highway Traffic Safety Administration (NHTSA). The NHTSA also undertakes the evaluation of the reliability of automotive electronic components and their safety in the US. However, transportation is a global industry. Most countries, especially the developing ones, do not have stringent safety guidelines, checks, or procedures to ensure safe driving practices, driver fatigue, driving conditions, and

TABLE 3. Some IIoT-based road safety applications for the transportation industry.

Application	Work done	Future Research Directions
ECG-based Safety Scheme for detecting drowsiness of drivers (as in [74])	Proposed an electrocardiogram genetic algorithm-based support vector machine (ECG GA-SVM) to alert the drivers while driving and improves their on-road safety.	SVM-based algorithms may be applied to check the road parameters, which causes accidents, and analyze them to improve safety of drivers.
Tool for analysis of crash data (as in [93])	Proposed a simple and efficient tool for analysis of automobile crash data. Assists transportation engineers to obtain information from responses	The tool may be applied to analyze the other road-safety related information
Safety-as-a-Service for Road Transportation (as in [16])	Proposed the Safety-as-a-Service (Safe-aaS) platform for providing safety-related decisions to registered end-users Using the concept of decision virtualization, customized safety-related decisions are simultaneously provided to multiple end-users	Real-life implementation of Safe-aaS Privacy and security issues in Safe-aaS Presence of misbehaving and malicious nodes in Safe-aaS
Integration of safety applications (as in [77]–[79])	Various sensors are used to measure safe inter-vehicular distance and safe speed. Authors evaluated the preventive and active safety measures. Developed a driver-support system in three levels – perception, decision, and action level. Integrated a warning manager with the system to interface with the driver	The observations of driver may be integrated for autonomous planning. Additionally, AI and ML techniques may be used to model human-behavior. The system may be further extended to support real-time scenarios
Used smart phones for safe driving (as in [97])	Three-axis accelerometer of smart phones to record and analyze driver behaviors. Road conditions such as potholes, bumps, and rough and uneven road are detected	Smart sensor-based technologies may be integrated to develop ITS The system model may be improved in terms of accuracy, processing, and sensitivity
Safety issues during lane change for manually driven vehicles (as in [82])	Studied the lane change characteristics of manually driven vehicles in automated vehicle platooning environment	Inter-vehicular distance between the vehicles in the platoon may be considered. Performance of the vehicles may be analyzed in real-time to obtain realistic results
Assessment of road safety from past data (as in [95])	Studied the traffic accident data of the year 2003-2007 and forecasted the data for 2008-2010 using one-variable, first order, grey model	Reliability and robustness of the algorithm may be improved. The error percentage may be reduced in the predicted model
Assessment of road safety threats using simulation (as in [72])	Authors modeled the driver inputs as random variables and used Monte Carlo sampling to predict the future threat scenarios on-road	The iterative-sampling process may be analyzed further. Based on the visual data collected and past data of accidents occurred in the road, this model may be used to predict real-time safety informations and warnings
Detection of urban road manhole covers (as in [99])	Proposed algorithm for automated detection of manhole covers using mobile laser scanning (MLS) data Multi-layer feature generation and random forest model was used to detect the manhole covers	MLS mechanism can be applied to detect and find the depth of potholes, cracks on road, and obstruction on road
Deceleration-based surrogate safety measure (SSM) (as in [73])	Proposed a SSM which consider the driving behavior during acceleration and deceleration. The authors focused on the rear-end collisions during car-following solutions	Based on the data obtained from trajectory of vehicles, the driving behavior of the driver can be predicted and warning can be given for the driver's safety.

other critical factors associated with the transportation industry. We parse multiple safety and incident reports[6][7] in the transportation and logistics domain. Based on these parsed reports [71] culminating in a gross word count of more than 31, 000 words, we use a word cloud generator to highlight recurring and pertinent safety-related keywords to proceed further in this domain.

A. IDENTIFYING THE RISKS

Fig. 11 shows some of the crucial aspects/sub-domains of the transportation industry. Interestingly, the safety challenges associated with the transport industry also spill over to the other industries, as transportation is universal and is generally involved with other industries in some capacity or the other. Further, the various components of the transportation industry as denoted in Fig. 11 can be considered as standalone industries or can be considered as entirely different industries, depending on the combination of two or more of these components. For example, a large international supply chain and logistics company typically uses all of the components shown in the figure. Whereas a radio cab company only uses *cab services*, *infrastructure*, and *staff and workers* for their whole operation.

Considering all these, we holistically identify the major stakeholders/actors in this industry. In the transportation industry, the following risks identified against our safety trifecta are important:

1) **Humans**: Drivers/vehicle operators, passengers, support staff, maintenance staff, engineers, porters, delivery agents, and others.

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[6] https://www.hse.gov.uk/research/rrpdf/rr681.pdf

[7] https://blog.falcony.io/en/11-incidents-in-transportation

2) **Equipment**: Heavy vehicles, passenger vehicles, cranes, trolleys, aircraft, ships, boats, engines, coaches, fuel pumps, robots, and others.
3) **Environment**: Building, Garage, Lifts, Warehouses, Airports, Bus bays, Terminals, Docks, and others.

Considering the various actors identified against our safety trifecta, we can identify the following risk/hazards in the transportation industry:

- Collisions and accidents of mobile vehicles – ground, air, water.
- Fire hazard due to storage of fuels and unexpected fuel or gas leaks.
- Accidents caused by poorly maintained equipment, vehicles, or infrastructure are a huge safety hazard.
- Fire hazards in buildings and infrastructure are always a concern from a regular safety perspective. However, fires due to inflammable goods in storage or during transport also pose a good safety risk.
- Workplace accidents owing to a fast-moving and rapidly changing work floor are quite common.

B. MITIGATING THE RISKS

Road accident threat levels depend on the location and velocity of vehicles. Based on established methods of threat modeling of the driving environment and its assessment, the probability and time of road collisions can be estimated [72]. Innovative road vehicle safety features such as the Deceleration-based Safety Surrogate Measure (DSSM) have been proposed based on studies and modeling on real-life collisions occurring due to microscopic vehicle trajectory data [73]. Besides sudden deceleration of vehicles on high-speed roads, another common factor contributing to road accidents is driver drowsiness. Early warning systems paving the way for a much safer road transport industry include intelligent systems that detect driver drowsiness using complex AI tools to determine alertness levels using driver ECG data [74], smart glasses for fatigue detection [75], and others. Modeling and tracking of vehicle behavior on roads based on velocity data, GPS bearings, and compass headings [76] also present a viable way of addressing road safety excursions and speedy incidence reports in case of accidents. Various frameworks to analyze the preventive and active safety functions of road transportation are under development. These holistically integrate technical performance, human factors, and active safety functions [77]–[80]. Many works, such as the one looking into establishing and enhancing the communication facilities over the Vehicle-to-Everything (V2X) paradigm [81] also play an essential role in developing smart vehicle and intelligent transportation infrastructure.

With the advancement of IoT and allied technologies, autonomous vehicles and cyber-physical system-based driver assistance systems have emerged, improving drivers' and vehicles' on-road safety. Vehicle platooning is one of the most advantageous features of automated driving environments. However, the vehicle platooning feature affects the lane change behavior of manually driven vehicles (MVs), which leads to instability in the traffic flow. These lane change characteristics of MVs in the automated vehicle (AV) platooning environment and the other associated traffic safety issues can be avoided through the adoption of novel traffic operations [82]. Similarly, traffic telematics services are developed to improve the safety of on-road vehicles and drivers. These traffic services are essential for provisioning vehicle-to-vehicle and vehicle-to-infrastructure communication at a moderate data rate. Additionally, certain specific vehicular channel measurements and channel characteristics help to develop a dependable vehicular network. This results in a vehicular network with upgraded coverage, reliability, scalability, and minimum delay [83]. Therefore, with the adoption of improved traffic operation and vehicular communication, on-road safety is improved, while road congestion and rash driving can be avoided. Table 3 lists some of the IoT and IIoT-based applications focusing on extending or enhancing road safety of the transportation industry.

Similar to road safety, the various safety aspects of the airways [84], waterways [85], and railways [87] sub-sectors of the transportation industry are quite interesting. In the field of transportation, the operation and movement of both the humans and cargo depend upon their operation [86]. Typical IoT-based safety features that are designed for regular road-based transport are not always feasible in these sectors. Here, most of the time, the safety of the equipment/vehicle [88] goes hand-in-hand with the safety of the manifest (human or otherwise). This is not always true for IoT-based safety solutions for road-based transport, which are more human-centric and highly customizable. Additionally, vehicles, equipment, and parking infrastructure maintenance hold utmost importance in these domains (airways, waterways, and railways), especially considering the complex intertwining of vehicle, operator, and passenger safety.

The nature of cargo also plays a vital role in deciding safety features and precautions during its transportation. Radioactive materials, chemicals, and inflammable cargo are transported in special containers and vehicles. Special emphasis is put on vehicle path, velocity, and security in such cases. This industry is also prone to the effects of fires [89] and accidents due to equipment or vehicle malfunction. Predictive maintenance and diagnostics [90] play a crucial role in enhancing the safety of these vehicles. Many high-end global vehicle manufacturers now provide vehicles with in-built diagnostic and prognostic systems to reduce accidents or mishaps due to vehicle failures [91]. Although the size of this industry is massive, with significantly challenging aspects to be considered for enhancing safety, many promising IIoT solutions, such as digital twins [92], are already in place, and many more are being developed for seamless and effective safety management.

V. MANUFACTURING INDUSTRIES

Manufacturing industries deal with the production of goods through the transformation or forming of materials through

FIGURE 12. Word cloud of manufacturing industry related safety incident reports.

FIGURE 13. Crucial sub-domains of the manufacturing industry.

the use of labor, machines, and carefully laid-out processes. Safety in manufacturing and process industries has two essential aspects. One is the protection of workers from injuries caused by the operation of machines, which leads to the introduction of Safety Instrumented Systems (SISs) and all kinds of protection mechanisms. The other is related to electricity, which has been introduced into manufacturing and process industries at the end of the 19*th* century. In the modern-day industries, the need for integrated essential safety measures in the manufacturing industries, starting from the initial design phases to completing and transporting finished goods, is essential and can be easily achieved through various IIoT solutions. Some research works were undergone to analyze the applications of IoT- and cyber-physical system-based real-time advanced analytics, production logistics, and artificial intelligence in smart manufacturing environment [103]–[106]. We parse multiple safety and incident reports[8] [9] in the manufacturing domain. Based on these parsed reports [100]–[102] culminating in a gross word count of more than 17, 000 words, we use a word cloud generator to highlight recurring and pertinent safety-related keywords to proceed further in this domain.

A. IDENTIFYING THE RISKS

Fig. 13 shows some of the crucial aspects/sub-domains of the manufacturing industry. Some aspects of the safety challenges associated with this industry are shared with the healthcare and transportation industry. It is mainly due to the inclusion of similar operations such as logistics. The various components in Fig. 13 are the individual types of manufacturing industries, each with their somewhat similar operating processes and dependencies on raw input materials or the markets for which they output goods. Interestingly, each of these components/types of industries within the manufacturing industries has its ecosystem involving humans, equipment, and operational environments.

Considering all these, we holistically identify the major stakeholders/actors in this industry. In the manufacturing industry, the following risk factors/subjects identified against our safety trifecta are important:

1) **Humans**: Machine operators, instrumentation and control engineers, assemblers, fitters, woodworkers, welders, cutters, machinists, laborers, painters, material handlers, and others.
2) **Equipment**: Lathes, drills, milling machines, CNC machines, heavy vehicles, cranes, trolleys, aircraft, ships, boats, engines, coaches, fuel pumps, lasers, robots, and others.
3) **Environment**: Building, Garage, Lifts, Warehouses, Foundry, Mills, Workshops, Forge, Farms, Forests, Sea, Underground, Air-controlled environments, and others

Considering the various actors identified against our safety trifecta, we can identify the following risks/hazards in the manufacturing industry:

- Electrical arcing injuries, faulty equipments, fires in electrical installations, explosions caused by damaged electrical apparatus, electrocution, improper grounding, working on live circuits, and others.
- Fire hazard due to storage of fuels and unexpected fuel or gas leaks.
- Accidents caused by poorly maintained equipment, vehicles, or infrastructure are a huge safety hazard.
- Fire hazards in buildings and infrastructure are always a concern from a regular safety perspective. However, fires due to inflammable or explosive materials in storage or transport also pose a good safety risk.

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[8] https://www.hse.gov.uk/statistics/industry/manufacturing.pdf

[9] https://www.noviqu.com/posts/safety-incidents-in-manufacturing-you-shouldnt-overlook.html

- Workplace accidents owing to fast-moving, often hazardous, and rapidly changing environments are quite common.
- Involvement of human operators in risky, yet repetitive, tasks can cause loss of attention and cause safety lapses.

The different Key Performance Indicators (KPIs) of an organization, such as near-misses, injuries, fatalities, and lost work hours, create a long-term impact on the production process. Various industrial safety-related issues that the researchers address include process safety, electrical equipment in hazardous zones, electric shocks, safe work practices, safety designs, and ground fault protection techniques [107], [108], [110]. Additionally, hot or radioactive zones involving molten metals, laser cutters, and other such highly hazardous processes in smelters, foundries, forges, and mills are also substantial risk factors in their respective industries. These pose a threat to its human handlers and the equipment being used to do so, and its environment.

B. MITIGATING THE RISKS

Electrical safety is an essential aspect of concern at most workplaces associated with manufacturing. Electrification has brought a massive transformation in the various industrial fields such as manufacturing, process, textiles, power generation and distribution, communication, heating, lighting, and control systems. However, this has caused the exposure of workers to electrical and other hazards. It is worth noting that the emerging risks of electricity were a driving force for the foundation of standardization bodies and that safety regulations were among the first standards to be published (1889 in Austria, 1895 in Germany). Still, during the late 20th century, severe injuries and loss of lives due to electrocution is one of the leading reasons for fatalities at the workplace [108]. Further, the construction of power and communication transmission lines was marked as one of the most hazardous and was ranked fourth with respect to the number of fatalities [10]. The faults emerging at the High Voltage (HV) switchgear, control gear, assemblies, and overhead power lines (OPLs), are also risky and unpredictable. Typically, two types of short-circuit faults – bolted short circuit and arcing fault – occur in electrical installations. Only trained personnel are allowed to be in proximity to the HV switchgear, control gear, and assemblies to avoid accidents. Thus, adequate safety measures must be taken by the operators during the maintenance of switchgear, control gear, assemblies, and OPLs [10], [111]. The degree of risks of electrical injury at the workplace may vary primarily with the type of job the personnel is associated with. However, it was identified that the carpenters, electricians, painters, welders, porters, labourers, and other mostly in-field operatives predominantly suffer from fatal electrical injuries. These workers are exposed to electrical hazards through the use of common tools and appliances and unintentional proximity with the overhead power lines during their routine work [110]. Therefore, improving the safety of these workers, who form a significant part of the workforce, is necessary.

Cooperative operation between humans and robots acts as one of the key factors in the development of *smart factories*, is also purported to be a fundamental safety enabler shortly. This major transformation has minimized risks and improved the safety of individuals, infrastructure, equipment, and the environment. However, maintaining a safe distance between humans and robots is necessary to avoid collision and injuries [121]. In the process industries, any form of failure in the system may cause severe harm to the workers, destroy assets, and affect production. Safety Instrumented Systems (SISs) were developed to safeguard the workers from accidents, while applying various technical and non-technical protection layers. SISs comprise sensors, actuators, logic, and final elements (hardware parts), which assist the processes to return to the safe state on violation of the predetermined conditions. A classical application of such SISs is the operation of machines, which human operators effectively fence off. In modern manufacturing environments relying increasingly on collaborative robotics, rigid fencing is becoming increasingly difficult [11].

Interestingly, process failures may be caused due to the malfunction of the equipment in the system, process environment, maintenance, and type of equipment. Further, the operation and environmental conditions may fluctuate with time for the same laboratory setup. Therefore, considering that the values at specific points may result in ambiguity in the assessment of Safety Integrity Level (SIL) [119]. SIL becomes complex because of the uncertainty on the various reliability aspects of SIS parameters. Further, considering the failure rates of SIS components, the assessment of "confidence" of the SIL parameters is necessary. Based on the analysis of failure probability of SISs on demand, approaches such as fuzzy probabilistic methods for minimizing SIL uncertainties [118], and Funnel Risk Graph Method (FRGM)-based SIS evaluation for reducing analysis time [116] are quite practical and economical.

One of the key applications of IoT across diverse industrial applications is Machine-to-Machine (M2M) communication, which allows machines to communicate with minimum or no human intervention. Further, M2M communication enables these interconnected machines to communicate through sensors and actuators in the different manufacturing processes. Such industrial communication systems cannot be straightaway used for SISs, because of the inherent possibility of communication or network failures. Special safety communication profiles were introduced to act as protection mechanisms – extended checksums, message sequence numbers, or heartbeat messages to the communication protocols – to reduce the risk of undetected communication failures. Additionally, the energy consumption, reliability of equipment, safety of workers, and security, are also significant aspects of concern in the various process industries [115].

With the widespread adoption of Internet-based technologies in the manufacturing industries, the integration of smart

TABLE 4. Summary of the IIoT applications in manufacturing and process industries.

Application	[110]	[108]	[10]	[111]	[109]	[112]	[114]	[113]	[117]	[119]	[118]	[116]	[115]	[120]
Fault detection/Failures	×	×	×	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×
Safety of workers	✓	✓	×	✓	×	×	×	✓	✓	✓	✓	✓	×	×
Health management	×	×	×	×	×	×	×	✓	×	×	×	×	×	×
Process safety	×	✓	×	×	×	×	×	✓	✓	✓	×	×	✓	×
Fatality/Injuries	×	✓	✓	✓	×	×	×	×	×	×	×	✓	×	×
Records/Data	✓	✓	✓	×	×	✓	×	×	×	✓	×	✓	✓	×
Safety standards	✓	✓	×	✓	×	×	×	×	✓	✓	✓	✓	×	×
SIS and SIL	×	×	×	×	×	×	×	×	✓	✓	✓	✓	×	×
Reliability	×	×	×	×	✓	✓	✓	×	×	×	×	×	×	×
Cost effectiveness	×	×	×	×	✓	✓	✓	×	×	×	×	×	✓	✓
Environmental effects	×	×	×	×	×	×	✓	×	×	×	×	×	×	×
Blackouts	×	×	×	×	×	×	✓	×	×	×	×	×	✓	×
M2M model	×	×	×	×	×	×	×	×	×	×	×	×	✓	✓
M2M communication	×	×	×	×	×	×	×	×	×	×	×	×	×	✓

devices with the existing system has become popular. The concept of integration was first introduced in the mid 1970s. The primary objective behind the integration was to combine the computer-assisted manufacturing subsystems into a comprehensive form. To enable real-time data collection, processing, and transfer of information, special ''industrial networks'' had to be developed, which found popular adoption in the manufacturing industries, primarily starting from the late 1980s. The elementary objectives of industrial communication systems are to reliably and uniformly exchange information of the processes within a stipulated time. Moreover, the secure transfer of information is an essential part of distributed automation-based industrial systems. Further, the management of complexity and heterogeneity in industries is a challenge in future industrial communication. During the 1980s and 1990s, field buses were the only means for industrial communication. Around the year 2000, Real-time Ethernet (RTE) started to gain popularity over field buses, while industrial wireless networks came still later and are far less widely used. Various existing RTE approaches are available, which provide different mutually incompatible solutions. As most recent trend, IoT and CPS based on telecom mobile networks, in particular the evolving 5G infrastructure, are beginning to play a bigger role also in industrial automation. The digital transformation and the 5G infrastructure gradually started playing key roles in industrial automation. With the transformation in these manufacturing industries, the flow of information among the sensors, controllers, actuators, and other associated processes involves minimum or no human interaction. Therefore, the safety of personnel on the factory floor is improved with the digital transformation in the industries [123]–[126]. We provide in Table 4 a list of various specific IIoT solutions for manufacturing and process industries and also list how they fare against the various factors in their application domain.

VI. MINING INDUSTRIES

Mining typically deals with the extraction of minerals and other geological materials from the earth. Even though the mere act of taking out the minerals from the earth is commonly considered mining, in real life, technically, mining is a vast and diverse industry. Each of the aspects of the mining industry come with their own set of challenges. Fig. 15 shows the various essential components/stakeholders of a mining industry from the perspective of safety. Even the tasks preceding an actual mining operation, such as surveying, have their own set of safety hazards that need to be taken into account from a safety perspective before the task begins. As per the existing literature, there are two types of mining techniques – surface (open-cast) and underground. Any form of mining lifecycle comprises exploration, development, operation, decommissioning, and land rehabilitation. For a long time, the mining occupation were associated with strenuous physical efforts, which resulted in various health hazards, injuries, and diseases of the miners. We parse multiple safety and incident reports[10] in the mining domain. Based on these parsed reports [129], [130] culminating in a gross word count of more than 24, 000 words, we use a word cloud generator to highlight recurring and pertinent safety-related keywords to proceed further in this domain.

FIGURE 14. Word cloud of mining disaster related reports.

A. IDENTIFYING THE RISKS

In the existing literature, the researchers addressed various problems such as health issues of workers, explosions, and fires, related to underground mines [127]. Although several precautions are taken by the miners such as helmets, safety

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[10] https://www.icmm.com/en-gb/research/health-safety/benchmarking-2020-safety-data

TABLE 5. Applications of IIoT in enhancing safety of mining industry.

Application	Work done	Future Research Directions
Analysis of electric loaders to reduce diesel emissions (as in [136])	Proposed a cost-benefit model for electric load haul dump (eLHD) units in underground hard rock mining to lower the operating costs	With the help of eLHD units, relocation cost may be minimized The design of trailing cables may be improved, better ventilation for the workers, and underground battery-powered mining vehicles may be used.
Unmanned coal mining robot (as in [139])	Designed an unmanned robot to remotely perform various operations and assist the workers in the mines The authors developed a tele-operation system to remotely operate the robots using joystick modules	The robot may be modified to operate autonomously with minimum or no remote human intervention
Multiple input multiple output (MIMO) systems (as in [145])	Proposed the use of multiple input multiple output based system for communication in underground mines using K-factor analysis method	The channel capacity may be computed with the variation in the power transmitted and signal-to-noise ratio, for better system characteristics
Applications of RFID in mining services (as in [144])	Authors summarized the use of passive, active, semipassive, active LF, ZigBee compliant RFID tags, smart cards in underground mines for detection of buried objects, explosives, long range communication, tracking and monitoring of environmental parameters	Design of low-cost and efficient RFID tags, which may serve multiple applications and automatically identify the devices
Post-accident mining communications (as in [151])	Authors addressed the issues related with post-accident communications and proposed three approaches–enhanced leaky feeder, wireless-mesh, and medium frequency systems	Interoperability among the multiple systems may be added to improve the post-accident availability of systems Reliability, sustainability, and quality of service (QoS) of the various communication systems
Acoustic positioning for safety in mines (as in [150])	Proposed an acoustic positioning system for miners' safety in underground mines Authors used pulse compression with linear chirps for precise and accurate positioning	With the varying placement of the loud speakers, accuracy may be improved The measurement unit may be calibrated applying peak picking in the correlation signals
Measurement of incombustible content in underground mines (as in [133])	Designed a optical and dielectrometry-based real-time sensing module to measure the total incombustible content Based on optical reflection, the sensor determines the deposited dust content	The fabricated sensor prototype was tested in laboratory scale, therefore, for real-time wireless application in mines, the durability of these sensors may be further improved
Through-the-Earth (TTE) communication in mines (as in [134])	Authors proposed the TTE communication technology for underground mines The paper primarily aims at the control and propagation of radio signals between the antennas (transmit and receive), placed apart by earth or coal	The predictive analysis of the model can be done to compute the communication loss due to the electromagnetic field and interference effects
Communication in underground mines (as in [143], [144], [149])	Various RFID-based systems, which comprises of Passive, Active, and Semipassive–Low frequency (LF) and High frequency (HF) tags, are used in mines to detect explosives, track assets, and monitor environmental parameters Communication during emergency conditions in the underground mines are difficult due to propagation delay, noise, and channel variation	Design of low-cost and efficient RFID tags, which may serve multiple applications and automatically identify the devices A real-time system may be developed to predict the risk of an accident, by sensing and accessing the information

goggles, and torches, inside the mines, they suffer from different health hazards such as physical, chemical, ergonomic, biological, and psychosocial, as illustrated in Fig. 16 [127]. A significant technological revolution was observed in mines between 1950 and 1960. The microcomputer-based developments and applications for monitoring and communication in the underground mines revolutionized this industry during 1969 up to the mid of 1985 [128]. Further, in various underground mines such as coal mines and oil shale mines, diesel-engine and excavator operators and anyone working in their vicinity were highly exposed to dust particles and diesel particulate matter (DPM). As per the report of the International Agency for Research on Cancer, the diesel particulate matter (DPM) emitted by diesel engines are a Group I carcinogen [131]. This exposure of the underground miners to dust particles and particle-associated 1-nitropyrene (NP) caused severe health problems to a majority of them [132]. Additionally, the dust concentrations in the underground mines also fluctuate with the duration of the maintenance period. Coal dust explosions produced during mining were caused due to the deposition of float dust and inert rock dust applied to the roof, floor, and rib areas, in the underground mines. This float dust and rock dust ratio to the total deposited mass is known as total incombustible content (TIC). Further, TIC must be regulated up to 80% for safe working conditions of the miners. Fig. 16 lists some of the health hazards faced

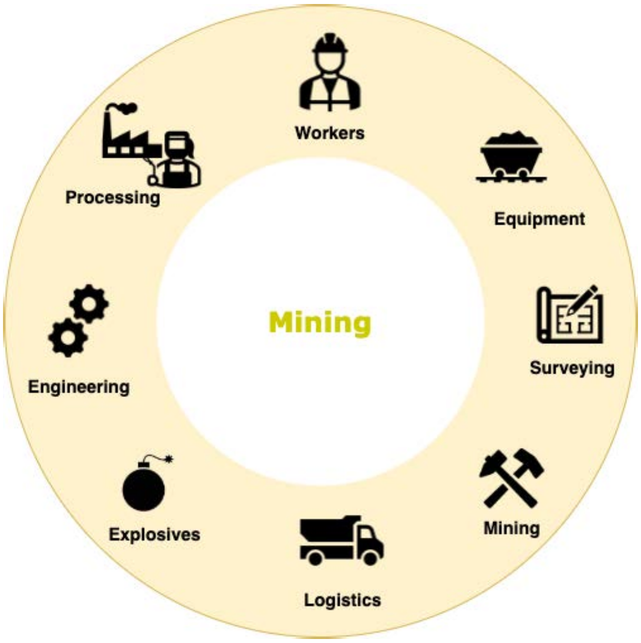

FIGURE 15. Crucial sub-domains of the mining industry.

by the human elements of a mining industry in their work environment.

Considering all these, we holistically identify the major stakeholders/actors in this industry. In the mining industry, the following risks factors/subjects identified against our safety trifecta are important:

1) **Humans**: Drivers/vehicle operators, miners, support staff, maintenance staff, engineers, porters, executives, scientists, workers, and others.
2) **Equipment**: Heavy vehicles, generators, drills, excavators, cranes, trolleys, engines, fuel pumps, conveyor belts, and others.
3) **Environment**: Open cast mines, Underground mines, Underground shafts, Forests, Hills, Building, Lifts, Warehouses, Foundry, Mills, Workshops, Forge, and others

Considering the various actors identified against our safety trifecta, we identify the following risks/hazards in the mining industry:

- Severe respiratory and health hazards due to particulate matter and gases.
- Fire hazard due to storage of fuels and unexpected fuel or gas leaks.
- Fire and accident hazard due to use and storage of explosives for mining operations.
- Accidents caused by poorly maintained equipment, vehicles, or infrastructure are a safety hazard.
- Flooding hazards in underground mines due to sub-surface water pockets are a major risk.
- Mine roof integrity and mine collapse are serious threats to mining operations.
- Workplace accidents owing to fast-moving, often hazardous, and rapidly changing environments are quite common.
- Involvement of human operators in risky, yet repetitive, tasks can cause loss of attention and cause safety lapses.

B. MITIGATING THE RISKS

Approaches for safety in the mining industry can range from solutions such as the opto-dielectrometry-based measurement of TIC of the deposited rock dust/float dust [133] to the use of unmanned rovers for the detection of harmful gases and extreme temperatures in the mines [135]. Further, the introduction of zero-emission vehicles and electric load haul dump units (eLHDs), not only helped with reducing particulates but also resulted in considerable savings in the cost of ventilation, fuel, and consumables in mines [136].

Mining is considered a high-risk operation. The information collected from individuals, previous victims of mining hazards and other incidents, can control those situations. Therefore, knowledge management and transfer of information to immediately act during any emergency is an essential aspect of concern in the mines [137]. In the underground mines, various useful information such as the miner's location, regular maintenance of the equipment, and information usage during an emergency exists. Special training is necessary for emergency management and response, which requires personnel to timely recognize an emergency and apply the collected information [138]. Organizations such as KAIST, Hydraumatics Co., and Korea Coal Corporation jointly developed a teleoperated robot for application in the underground mines, remotely operated by personnel. The designed robot comprises cameras, laser scanners, and other sensors to perform shoveling and breaking operations similar to humans at a remote location. The feasibility of these developed robots in assisting workers was tested in an active coal mine [139]. The application of autonomous vehicles plays an essential role in improving the safety of miners and production in underground mines. With the use of autonomous vehicles, the operator can be remotely placed in a safe location, while the machine operates in the dusty, noisy, and hazardous zones [140].

Advanced technologies and distinct automation techniques introduced for various mining applications were categorized into three different types – lower level, mid-level, and full automation. Lower level automation involves warning systems and technologies; mid-level comprises removing operator or system control performed by an operator from a certain distance, and full automation allows the operator to perform a remote operation. However, automation in the mining industry is not without its risks and set of challenges, especially considering the involvement of humans on some level [142]. AI-based safety measurement and risk assessment of mines [141], and other similar modeling tools play a crucial role in planning and strategizing mine operations and its safety. The use of remote isolation systems for complex systems improves workplace safety standards through remote switching and racking of circuit breakers [117]. Some interesting uses of IIoT for safety operations in the mining industry are listed in Table 5.

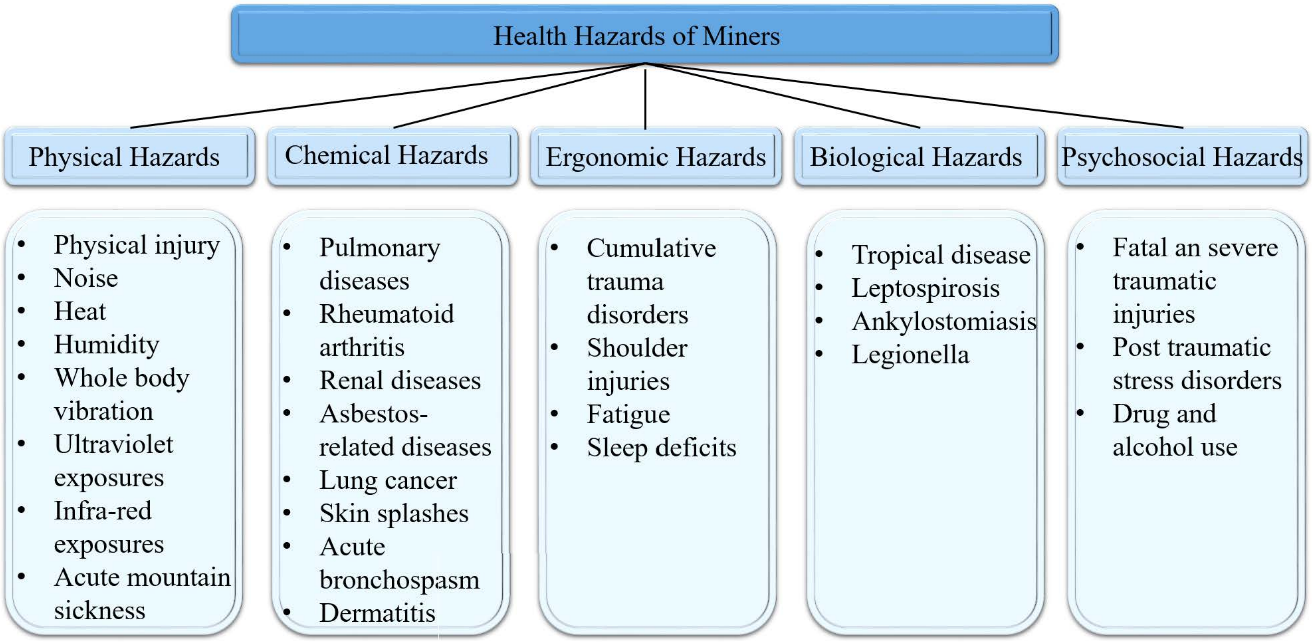

FIGURE 16. Health hazards faced by the human elements of a mining industry in their work environments.

Existing literature indicates that emergency response during any mining operation is complex, especially in underground mines, compared to other working environments. Moreover, the environment inside these underground mines fluctuates dynamically. Therefore, communication during each of these mining stages at such adverse conditions is crucial. There exist four types of underground communication systems – wired, radio, carrier current, and hybrid. Further, radio communication in underground mines is categorized as – through-the-earth (TTE) systems, in-mine systems, wireless networks, and ultra-wideband systems. However, each of these communication systems has different problems associated with them, which are quite challenging to resolve [143]. TTE wireless communication enhances the probability of miners' rescue during any emergency. These TTE systems utilize single or multi-turn loops of conductors for the transmission antennae. Similarly, to improve the working environment for miners and initiate rescues during any emergency, improved communication performance is necessary. Interestingly, patch antennas showed improved channel capacities because of higher antenna gain [145]. Other IoT-based communication technologies in mines include 4G-5G hybrid networking [146], LoRA [147], and LoRAWAN [148].

The typical challenges in establishing communication (especially during emergencies) in mines include path loss due to signal absorption, and geometric spreading, extensive multipath propagation and fading, rapid variation in the channels, significant propagation delay, and noise [149]. Despite the various technological safety measures, the safety of miners inside the underground mines requires further improvement. Underground mining operations are immensely hazardous and are often followed by severe injuries and death.

In the event of an underground incident, poor visibility leads to difficulty in identifying the miners in the regions near the various underground mining machines. Acoustic positioning systems have been advantageous in such scenarios [150]. Further, the Mine Improvement and New Emergency Response (MINER) Act of 2006 has brought significant changes to mining operations. The three communication approaches which emerged during this period were – enhanced leaky feeder, wireless-mesh, and medium-frequency (MF) systems [151]. In the case of enhanced leaky feeders, coaxial-type cables were designed for communication to leak a portion of its transmission signal through holes to the metallic shield within their proximity. Discrete nodes were utilized to form a network in wireless mesh systems. Additionally, communication signals are transmitted from one node to another. On the other hand, MF systems were primarily used for alternative communication during an emergency. These systems used ultra-high frequency range from 300–3000 kHz. Mine hazard monitoring and prediction systems [151], smart safety helmets [152], and hybrid Mine Hazard Alert Systems (MHAS) are some more of the promises IIoT holds for enhancing safety in mines.

Synthesis: IIoT have resulted in the inter-connectivity among the devices, machines, and network to develop intelligent and autonomous industrial units. The timely decision generation from the data generated from these devices is essential to ensure safety of individuals. In this paper, we acquire and analyze the research gaps, risks involved, and various applications developed to improve the safety of individuals. Further, based on the high economic (cost) implications, critical hazards involved, time-critical operations, and deal with hazardous substances, we select - transportation, healthcare, manufacturing, and mining industries. We categorize the risks involved across these industries under three safety trifecta - humans, equipment, and environment. We also discuss how to minimize these risks involved and improve the safety of individuals. Finally, we discuss the SOA-based four-layered IIoT infrastructure for the industries.

VII. FUTURE RESEARCH DIRECTIONS

As discussed in Section I, connectivity, communication, and safety of workers, are the various issues in the different application domains of IIoT. In this paper, we discussed the existing research works in the different application domains of IIoT, which immediately addressed the challenges around safety and provided solutions. Further, we observed the research lacunae in the different fields from the data integration, data security and privacy, standardization, hardware implementation, and personnel awareness, based on the synthesis observed from the previous research works. Considering the existing works and the research trends, we forecast the following towards safety management using IIoT:

(a)

1) *Data Integration*: Practically, in an IIoT network, heterogeneous sensor nodes are present. Therefore, huge volumes, variety, and velocity of data are generated from them. Further, the frequency at which the data are produced, vary from one sensor node to another. In addition to this, the data may be present in structured, semi-structured, or unstructured format, making the integration of data from various sources quite difficult. The data is then transferred to the cloud or edge nodes, where these massive sensed data are processed, and meaningful information is extracted from the data. Efficient management of this huge volume of data requests in real-time is quite challenging. Further, the communication and integration of the data is a complex task due to interoperability issues. There is a need for a common platform that can assist the development and integration of services.
2) *Data Security and Privacy*: In IIoT, the devices are interconnected, and they interact with the external world. Due to this interconnectivity between the machines, machine-to-human, and human-to-human modes, security of the information and the data are the significant aspects of IIoT [2]. For example – the physiological data of any patient are highly personal and sensitive. The Health Insurance Portability and Accountability Act (HIPAA) ensures the privacy of the health information of any patient. Therefore, similar mandatory security and privacy schemes need to be designed for IIoT systems.
3) *Lack of Standardization*: As multiple organizations are involved in IIoT, a common standard platform is necessary. In order to retain customers' trust, large automation supplier firms often prefer to develop customized solutions of their own. Due to lack of standardization, device and semantic level interoperability persists. Additionally, security and privacy aspects of the generated data and system exist. Therefore, a common standard is necessary to be analyzed and designed.
4) *Implementation*: In Section II-A, research works in the different application aspects of IIoT were discussed. The researches involve both theoretical and prototype development aspects. More focus should be put on converting academic research to practical and feasible industrial solutions – industrial upscaling or the safety-related services, distributed supply chain, communication in underground mines, health and safety hazards of workers, risks related to the diagnosis of a patient, and privacy of health data.
5) *Awareness of Personnel*: The technologies emerging in the context of IIoT are advanced and complex. Therefore, the existing personnel need appropriate training to acquire comprehensive knowledge of the transformed system. This applies in particular to the user interfaces of *intelligent* devices which may be *headless*, *direct*, or *indirect*. *Headless* devices show no indication of the device status. The device with *direct* user interface may be operated with minimum or no human intervention. *Indirect* type user-interface may obtain data through another device, present on the same network. Thus, to get acquainted with the transformed systems, the new users should be aware of the new technologies, acquire proper training, and follow safety measures. Researches may involve the development of virtual reality technologies to train the personnel.

VIII. CONCLUSION

IIoT integrates smart and intelligent devices with the existing industrial systems. As a result, various industrial sectors have undergone a considerable transformation. The safety of workers is one of the essential aspects of concern. Any form of violation of the industrial safety protocols may result in the damage or loss of property and human lives. Such incidents are also detrimental to the workforce's morale and impede the standard work processes in the industry. IIoT helps to attain these safety goals and implement them to improve the overall workplace safety. We primarily focus on the industries with high safety management levels, risk of incurring substantial economic losses, and possessing time-sensitive workflows. Considering these aspects, we selected the following industries – healthcare, transportation, manufacturing, and mining, to survey the existing research works. Further, we identified the risks involved, explored the research lacuna in mitigating these risks, and provided future research directions to fill the gap.

There are various risks involved in the healthcare industries such as exposure to infections, improper waste disposal, fire hazards, storage of food and medicines, equipment failure, and chemical hazards in the laboratories. Real-time monitoring and appropriate communication system help to maintain the safety levels of a patient. Moreover, certain other auxiliary factors such as medical waste disposal and management, medical equipment maintenance, and infrastructure management play essential roles in the healthcare industry. Mobile healthcare (m-health) constitutes healthcare applications with the integration of advanced sensors and technologies. The use of RFID tags and bar codes helped in the management of the assets and improved tracking of the status of medicines given to the patients.

Similarly, the diverse form of risks/hazards in the transportation industry includes collisions and accidents, fire hazards, and workplace accidents due to rapid movements on the factory floor. The safety standards of on-road vehicles are monitored, drowsiness of the drivers are detected, vehicular channel measurements, and provision of real-time information to the end-users may reduce the rate of accidents. Certain real-time assistance systems were also developed for providing safety-related information to the drivers, tools were designed for analysis of crash data, and learning-based models were proposed to upgrade the on-road safety of drivers and pedestrians. Further, the nature of cargo such as radioactive, inflammable, and chemical, acts as one of the critical factors in deciding the safety of the vehicles categorized under logistics. Various IIoT solutions such as digital twins are being developed to improve safety management in the transportation industry.

In the manufacturing industry, the risks involved include the different accidents and incidents on the factory floor due to hazardous environments, involvement of human operators, and fire hazards. Electrical safety forms an essential aspect of concern at the workplace because electrification has brought a massive transformation across the diverse manufacturing industries. Different types of automation techniques are introduced, SISs are developed, and industrial communication systems are designed to provide real-time data to the workers and upgrade their safety. With the development of smart factories, humans and robots collaboratively work on the factory floor. Additionally, the integration of smart devices, real-time data collection, processing, and transfer of information in the manufacturing industries has lead to the development of ‘‘industrial networks’’. Further, the digital transformation and 5G/B5G infrastructure are projected to play essential roles in industrial automation.

On the other hand, in the mining industries, the underground miners also suffer from various health hazards, injuries, and diseases, depending on their workplace locations and environments. Various factors such as fires, flooding, roof collapse in underground mines, and workplace accidents are the risks involved in the mining industry. Additionally, coal dust, silica dust, and other powdered materials also possess threat to the health of the miners. To avoid the adverse effects of dust and other pollutants in underground mines, zero-emission vehicles are introduced, emergency management and response training are given, and communication systems are developed. Further, the use of autonomous vehicles has resulted in the improvement of the safety of miners. Communication inside the underground mines is another essential aspect of concern. Different underground communication systems such as wired, radio, current, and hybrid, exist. However, for the evacuation of miners during an emergency, improved communication performance is necessary.

An SOA-based four-layered IIoT infrastructure – sensor-equipped device, intermediate device, processing, and interface, was developed for provisioning seamless safety information to the workers across diverse industries. In this platform, heterogeneous types of sensor nodes are deployed at various geographical locations or machines in the device layer. These sensor nodes sense and transmit data to the intermediate device layer, which comprises edge/fog nodes. Further, complex analysis and processing of the data are performed in the processing layer. The customers register, select services, and make payments through the interface layer. Another similar infrastructure, Safety-as-a-Service (Safe-aaS) platform, was discussed, which provides a customized, safety-related decision to the end-users. Further, several challenges exist in integrating heterogeneous data generated from the sensor nodes, security and privacy of the generated data, lack of a standard platform, and implementation of the theoretical and prototypes developed in the industrial scenario, are quite difficult. Additionally, proper training and awareness of the workers are also necessary. IIoT can be employed to minimize hazards and risks caused to the personnel across diverse industries, and upgrade their safety. The evolution of 5G/B5G and beyond technologies will gear up automation across the diverse industrial sectors. To summarize, the interconnectivity and communication among the units in the industry is always advantageous and productive, in terms of safety. IIoT significantly enhances these capabilities of the industries, thereby enhancing the safety in its environment and promotes seamless management.

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