

Exploring the Opportunities of AI & IoT in Confined Spaces

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Abstract— Confined spaces may present uncertain or unpredictable conditions, such as fluctuating atmospheric conditions or unexpected hazards. It often lack adequate ventilation, natural light, and space for movement. Managing stress and enhancing physical well-being in confined space work is essential for the overall health and well-being of workers. The unique challenges posed by confined spaces, such as limited connectivity, sensor placement and data processing require specialized AI and IoT solutions. The convergence of AI & IoT has brought the vision of a smarter world into reality with a massive amount of data and numerous services. We discuss the various AI and IoT technologies used in confined spaces, including computer vision, sensor networks and machine learning. To interchange data, IoT resources using the internet makes use of multiple interconnected technologies like Wireless Sensor Network (WSN), LoRa WAN and Zigbee. We also identify the key challenges and limitations of AI and IoT in confined spaces including data quality and sensor calibration. Finally, we provide insights of case-studies and potential applications of AI and IoT in confined spaces.

Index Terms— Artificial Intelligence, IoT, WSN, LoRa WAN, Zigbee, sensor calibration.

I. INTRODUCTION

Confined spaces which is prone to hazardous atmosphere and restricted access leads to difficult rescue operations in emergency situations. There is a huge lapse on the lack of awareness of safety standards practices in confined spaces. Poor planning, inadequate training, equipment failure and reckless attitude of rescue teams have exacted the ultimate penalty – death of rescuer. Around 48,000 people die at work in India annually, according to a study by the International Labour Organization. The 21st century has witnessed a revolutionary convergence of two transformative technologies: AI and the IoT. The evolution of AI has enabled machines to learn, reason, and adapt while the proliferation of IoT has connected a vast array of devices, sensors and systems generating an unprecedented amount of data. IoT consists of self-adjustable intelligent nodes that are interconnected with each other in a global and dynamic infrastructure of the network. The Internet of Things (IoT) has emerged as a revolutionary technology with significant research attention and wide-ranging applications across various domains. IoT is considered a crucial part of the future Internet, comprising billions of intelligent communicating 'things' that extend the boundaries of the physical world with virtual components [1].

Over the years, there is a rise in sensor implementation, because of advances in cloud and sensor technology, storage and processing capacity and reduced sensor manufacturing cost. As per the definition of IoT, it allows things and people to get connected with anything, at any time and any location by making use of any service and any network/path. As the complexity of Internet of Things (IoT) systems increases, a large variety of tools and technologies for IoT management are making their way into both research setups and the market. IoT management arrangements must consider the asset confinements of implanted gadgets, as well as their heterogeneity and network dynamics.[2]AI emerged alongside the development of the digital computer more than 80 years ago during the second world war. Key developments in AI's evolution include the emergence of machine learning algorithms, computational intelligence, and natural language processing [3]. Five aspects of the past decade are highlighted: self-learning and self-coding algorithms, Recurrent Neural Networks (RNN) algorithms Reinforcement learning, pre-trained models, and other typical deep learning algorithms, which represent the significant progress of this field [4]. The importance of Trustworthy of AI has been discussed in various sectors like health care, banking, autonomous systems and IoT. TAI unite the ways of building trust by addressing the principles of robustness & safety, privacy and data governance, transparency, Societal and Environmental wellbeing [5]. In this paper, we discuss about the computer vision technologies, Sensor Networks and Machine Learning algorithms along with current applications and challenges of Artificial Intelligence and IoT in confined spaces.

II. CHALLENGES OF CONFINED SPACES

Confined spaces present numerous challenges that significantly impact worker safety and health. These environments are characterized by limited access, poor ventilation, and the potential for hazardous conditions, making them particularly dangerous.

A. Safety Hazards

- Toxic Gases and Poor Ventilation: Confined spaces often contain toxic gases, and inadequate ventilation can exacerbate these risks, leading to potential asphyxiation or poisoning [26].
- Occupant Load Determination: Accurately assessing the number of workers that can safely occupy a confined space is complex, influenced by factors like exit size and internal structures.

B. Monitoring and Technology Challenges

- Remote Monitoring Limitations: Current systems rely on A/V cameras, which may not detect internal health issues like heart rate changes during emergencies
- Data Management Issues: Integrating data from wireless sensors and Building Information Modelling (BIM) poses significant challenges due to the volume and complexity of data.

C. Psychological and Physiological Effects

- Circadian Disruption: Prolonged exposure to static lighting in confined spaces can lead to sleep disorders and cognitive decline, affecting overall worker performance and well-being.

Challenges in confined spaces include lack of oxygen, temperature extremes, incomplete sensor data, communication failures, and the need for real-time monitoring. These factors contribute to hazardous environments, increasing risks for workers and complicating effective safety management.

III. SENSOR NETWORKS

Sensor networks play a crucial role in monitoring and ensuring safety in confined spaces such as tunnels and underground mines. These environments pose unique challenges, including harsh conditions, limited communication, and the need for real-time data transmission. Sensor networks are also being deployed in confined spaces that require a higher density of nodes and are close enough to be wired. These operate at a scale, where stretchable wiring can be used to expand a network to cover large areas, such as strain gauges for aircraft structural monitoring or on robots [9].

Wireless sensor networks have been proposed for a multitude of locations- dependent applications. APIT is a novel localization algorithm which is range free and performs best when an irregular radio pattern and random node placement are considered and low communication overhead [8]. WSNs are deployed to monitor environmental parameters such as temperature, humidity, gas concentration, and air quality. These networks consist of nodes equipped with sensors and communication modules, enabling data transmission to a central system for analysis and decision making. A mixed network topology combining wireless and wired networks

with IoT sensors are used in underground mining. These networks are essential for monitoring conditions in confined spaces like tunnels, addressing challenges posed by irregular distributions and high-power needs [10].

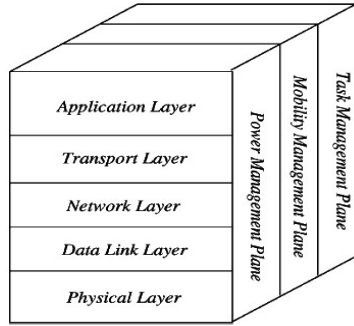


Fig. 1. Wireless Sensor Network Architecture

A. Application Layer

The application layer is liable for traffic management and offers software for numerous applications that convert the data in a clear form to find positive information. Sensor networks arranged in numerous applications in different fields.

B. Transport Layer

The function of the transport layer is to deliver congestion avoidance and reliability where a lot of protocols intended to offer this function are either practical on the upstream. These protocols use dissimilar mechanisms for loss recognition and loss recovery.

C. Network Layer

The main function of the network layer is routing, it has a lot of tasks based on the application, The main tasks are in the power conserving, partial memory, buffers, and sensor don't have a universal ID and have to be self-organized.

D. Data Link Layer

The data link layer is liable for multiplexing data frame detection, data streams, MAC, & error control, confirm the reliability of point–point (or) point– multipoint.

IV. TYPES OF SENSOR NETWORKS USED IN CONFINED SPACES

This section explores the various types of sensor networks employed in these settings, highlighting their characteristics, applications, and the challenges they address.

A. LoRa WAN

LoRa has revolutionized IoT by enabling data communication over a long range while using very little power. LoRa-based multi-hop network specifically designed for monitoring underground mining environments, emphasizing energy efficiency and sporadic data traffic. It does not detail other types of sensor networks used in confined spaces like tunnels [11].

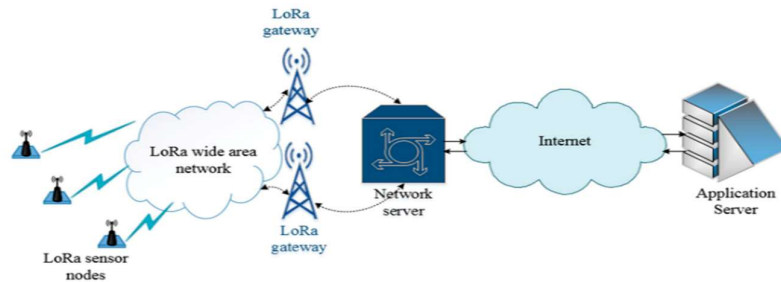


Fig. 2. LoRa WAN Architecture

The sensors used in underground mines are categorized based on applications, including environmental monitoring (gas, dust, temperature), safety (fire detection), and production management. It discusses both wired and wireless communication technologies suitable for these confined spaces [12]. The mesh networking protocol is an on-demand routing protocol. It discovers and maintains routes only when data needs to be sent, effectively reducing power consumption. Wide-Area Positioning System Based on Long Range Mesh (LoRaWAPS), is a low-cost and low-power outdoor positioning system with multi-anchor wireless mesh networking and multi-dimensional data fusion. Tags are used to track the locations of goods or persons. The tag is portable and has long battery life. It is equipped with a large-capacity battery that can last for several years with a single charge. The tag weighs less than 100 g. LoRa technology enables wireless communication and ranges between tags and positioning anchors [17].

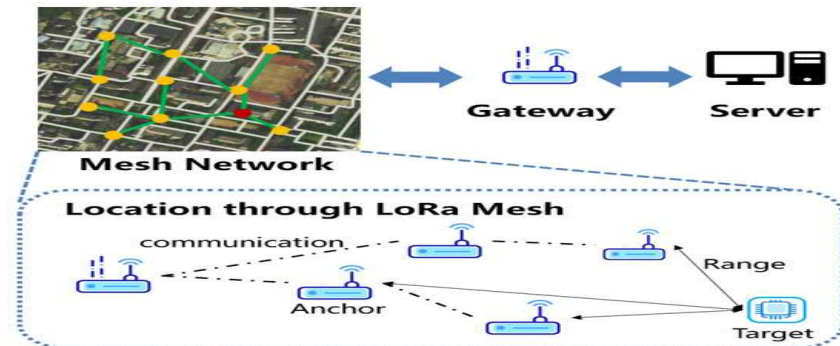


Fig. 3. Wide-Area Positioning System Based on Long Range Mesh (LoRaWAPS)

B. ZigBee

ZigBee technology, specifically incorporating an accelerometer (ADXL335) for vibration measurement and a dust sensor (PMSA003A) for dust density monitoring in underground mines. These sensors were installed in confined spaces, such as tunnels, to monitor environmental conditions and ensure worker safety. The ZigBee network facilitated data transmission despite the challenges of connecting to external networks in such environments, allowing for real-time monitoring of dust and vibration levels [13]. Intelligent environmental monitoring system utilizing ZigBee technology can monitor parameters such as temperature, humidity, and electrical consumption, making it suitable for smart industrial environments, including mining, where real-time data transmission and monitoring are critical for safety and efficiency. The use of a three-axis accelerometer for bridge inclination monitoring, which alerts administrators via text messages in the event of an earthquake or inclination, showcasing advancements in safety monitoring systems for infrastructure.[16]. A real-time indoor air quality monitoring device that utilizes the Internet of Things (IoT) technology is designed for use in enclosed spaces such as offices and homes, highlighting the importance of monitoring air quality in environments where people spend significant amounts of time. Environmental data is collected from various sensor nodes. Monitoring devices are equipped with low-cost sensors that measure various air pollutants, including particulate matter (PM2.5), ground-level ozone (O3), carbon monoxide (CO), sulphur dioxide (SO2), and nitrogen dioxide (NO2).

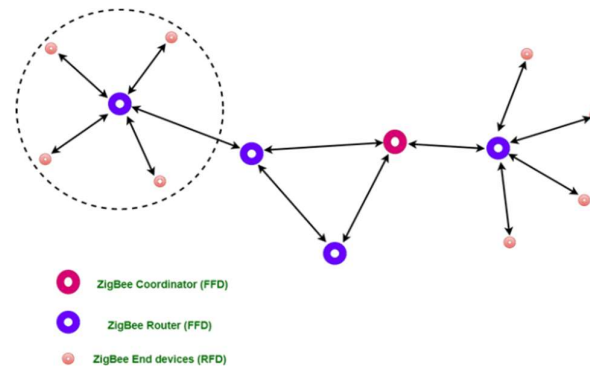


Fig. 4. ZigBee Network Topology

There is a lack of exploration into the integration of advanced data analytics or machine learning techniques for real-time data processing and predictive analysis, which could enhance the system's capability to anticipate environmental changes and improve decision-making processes.

V. MACHINE LEARNING

The effectiveness of machine learning classification algorithms in analyzing data from sensor networks and computer vision is pivotal for making accurate predictions and informed decisions. Analysis of sensor networks and computer vision data within constrained environments poses particular challenges based on resource limitations, including limited processing capability, memory, and power. Efficient machine learning (ML) classification is crucial in overcoming such challenges with high accuracy and performance. This section discusses some of the approaches and algorithms suggested in recent literature in order to achieve efficient ML classification in such an environment.

The paper titled "Machine Learning-Enhanced Wireless Sensor Networks for Real-Time Environmental Monitoring" discusses a framework that integrates machine learning with Wireless Sensor Networks (WSNs) to improve data processing and anomaly detection for environmental monitoring. It highlights a 40% improvement in anomaly detection accuracy, a 35% reduction in data redundancy, and a 25% increase in energy efficiency. This framework is particularly beneficial for applications like wildlife tracking, pollution control, and smart agriculture, addressing challenges in timely and accurate data transmission [14].

Implementation of Wireless Sensor Networks (WSNs) enhanced by Machine Learning (ML) techniques for various applications, including environmental monitoring indicate significant accuracy in training and testing data, showcasing the potential of ML to optimize Wireless Sensor Networks performance in real-time. Several ML models, including Random Forest and XG Boost, demonstrating their effectiveness in analyzing sensor data highlights how ML improves data processing, energy efficiency, and predictive modelling within WSNs [15].

VI. COMPUTER VISION

Computer vision is a field of AI that include methods for acquiring, processing, analyzing, and understanding digital images. Computer vision systems use artificial intelligence (AI) technology to mimic the capabilities of the human brain that are responsible for object recognition and object classification. Machine learning (ML) algorithms identify common patterns in these images or videos and apply that knowledge to identify unknown images accurately.

Object recognition can be considered as a popular modern neural network architectures and performs comparative analysis in relation to some of the problems to be solved [6]. Sensor based remote healthcare monitoring is a timely approach which is light-weight, self-supervised, negative sample-free approach to detect anomalous events [7].

A. Computer Vision in Confined Spaces

Computer Vision SLAM techniques using LiDAR, wheel odometry, and IMU data for navigation in confined spaces, address challenges like few geometric features. It does not cover computer vision applications, algorithms, or comparative analyses in confined versus open environments [18]. Absolute localization in feature-poor industrial confined spaces use visual inertial odometry and GPU-based point cloud registrations, The integration of 3D registrations with VIO estimates using an EKF is a critical aspect of the proposed system. The EKF is a well-established technique in robotics for fusing different sensor data.[19]

The paper "A Surveillance Technology for Virtual Security Space Based on Computer Vision" discusses various aspects of surveillance technology and its applications in enhancing safety in industrial environments. The paper builds on the advancements in computer vision technology, which have significantly improved the ability to analyze and interpret visual data. This includes techniques for image processing, object detection, and spatial analysis, which are essential for developing effective surveillance systems [20].

Micro aerial vehicles is a key focus and are increasingly being utilized in various fields due to their ability to maneuver in tight spaces. MAVs can significantly improve inspection processes in confined areas, where traditional methods may fail. The integration of laser range finders for localization technology allows for precise distance measurements, which is essential for navigating and mapping confined spaces. The literature indicates that combining MAVs with laser range finders can enhance the accuracy of inspection [21]A novel path following method that integrates prediction lookup and interpolation algorithms is designed to enhance the efficiency of the robot's movement along a desired path, which is particularly important in confined spaces where maneuverability is limited [22]. Prediction lookup algorithm can efficiently identifies points on the

desired path that correspond to the robot's joints, which is critical for ensuring that the robot can follow the path accurately without collisions.

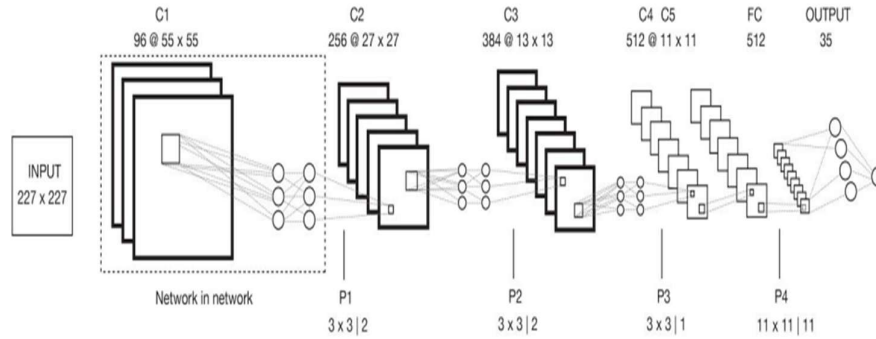


Fig. 5. Illustration of the architecture of Deep CNN Model [23]

A Case Study at MIT Campus" presents a significant advancement in the field of indoor space recognition through the use of Deep Convolutional Neural Networks (DCNN). DCNNs in object and scene recognition, highlights their ability to learn complex features from images. This is crucial for recognizing and interpreting indoor spaces effectively, as traditional methods may struggle with the variability in indoor environments [23]. The use of CAM techniques allows and visualize which parts of the images contribute most to the model's decision. Several computer vision models, including YOLOv8l, RT-De Tr, and Faster R-CNN, to determine their efficacy in detecting unsafe behaviors and hazardous areas [24]. Among these, YOLOv8l demonstrates superior performance, achieving a mean Average Precision (mAP-50) score of 0.919. This indicates that YOLOv8l is highly effective in detecting unsafe behaviors and ensuring compliance with safety protocols, particularly in monitoring personal protective equipment (PPE) usage. The use of 3D point cloud descriptors is a key focus which allows for the extraction of local geometric features from a known map, which can be matched with features visible in the robot's field of view. This approach highlights the importance of geometric features in improving localization accuracy. The integration of a visual inertial odometry estimate with a motion-filtered 3D registration using an Extended Kalman Filter is another significant aspect. EKF has been widely used in robotics for state estimation [25].

VII. COMPARISON OF KEY APPROACHES

TABLE. I

Approach	Key features
Computer Vision SLAM technique	Address challenged like few geometric features
Visual inertial odometry and GPU-based point cloud registrations	The EKF is a well-established technique in robotics for fusing different sensor data
MAV (Micro Aerial Vehicle) with Localization Technology	Improve inspection processes in confined spaces with laser range finders
Prediction lookup algorithm	Identifies points on the desired path, which is critical for ensuring that the robot can follow the path accurately without collisions
YOLOv8l	Highly effective in detecting unsafe behaviors and ensuring compliance with safety protocols.

VIII. INDUSTRY -SPECIFIC CASE STUDIES

The integration of AI and IoT in confined spaces has been successfully applied in various industries, each with its unique challenges and requirements. This section presents case studies from different industries, highlighting the practical applications and benefits of AI and IoT in confined spaces.

A. Construction Industry

The construction industry is one of the most hazardous sectors, with confined spaces such as construction sites, tunnels, and buildings posing significant safety risks. AI and IoT have been widely adopted in the construction industry to enhance safety, improve efficiency, and reduce costs [27]. AI and IoT were used to monitor safety conditions on a construction site. IoT sensors were deployed to track parameters such as dust levels, noise, and

temperature, while AI algorithms analyzed this data to detect potential hazards and recommend corrective actions. The system also monitored the health and well-being of workers, enabling early detection of fatigue and stress.

B. Manufacturing Industry

The manufacturing industry has also benefited significantly from the integration of AI and IoT in confined spaces. Manufacturing plants often involve complex processes and hazardous environments, making AI and IoT essential for enhancing safety and efficiency. Sensors were deployed to track parameters such as temperature, humidity, and air quality, while AI algorithms analysed this data to optimize the production process and reduce waste. The system also monitored the condition of machinery, enabling predictive maintenance and reducing downtime [28].

C. Mining Industry

Mining environments are often hazardous, with risks such as gas leaks, rockfalls, and equipment failures. AI and IoT can be used to enhance safety, improve efficiency, and reduce costs in mining operations.[29]

D. Health Care Industry

Hospitals and healthcare facilities often involve complex environments where patient safety and well-being are critical. AI and IoT can be used to monitor patient conditions, detect potential risks, and improve the quality of care. [30]

IX. LIMITATIONS OF CASE STUDIES

- AI and IoT for safety monitoring and predictive maintenance requires high implementation costs, data privacy concerns, and limited connectivity.
- High computational demands, data security risks, and integration challenges for process optimization and quality control.
- Data privacy concerns, high implementation costs, and limited interoperability in health care industry.

X. CONCLUSION

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) in confined spaces, enhanced by technologies such as computer vision and wireless sensor networks, presents a transformative opportunity for various industries. These technologies enable real-time monitoring and analysis, improving safety, efficiency, and operational effectiveness in environments where traditional methods may fall short. 5G Networks and beyond are expected to enable faster, more reliable, and more secure communication in confined spaces. Computer vision facilitates object recognition, allowing for enhanced situational awareness and automated decision-making in confined spaces. Meanwhile, wireless sensor networks provide seamless communication and data collection, enabling remote monitoring and management of conditions in real-time. Together, these technologies empower organizations to optimize resource usage, mitigate risks, and respond swiftly to changing conditions.

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