International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Iot-Based Safety Solutions for Underground Tunneling: Constraints and Mitigation Strategies

Mr. Ratan L. Sharma

Strata worldwide, Chhattisgarh, India

Abstract

Underground tunneling plays a vital role in the development of modern infrastructure, enabling the construction of transportation networks, sewage systems, subways, and utility corridors in densely populated urban areas where surface space is limited. Despite its significance, tunneling operations are inherently dangerous and complex due to a combination of factors such as confined working spaces, limited visibility, fluctuating atmospheric conditions, geological instability, and the operation of heavy machinery. These conditions pose significant safety risks, including the potential for gas leaks, toxic fume accumulation, tunnel collapses, equipment malfunctions, and human error, all of which can lead to accidents, injuries, or even fatalities.

To mitigate these risks, the integration of advanced technologies like the Internet of Things (IoT) offers a promising and transformative approach to enhancing underground tunneling safety. By leveraging a network of interconnected smart devices—such as sensors, wearable technologies, and automated control systems—IoT enables real-time environmental monitoring, predictive maintenance of machinery, location tracking of personnel, and rapid emergency response capabilities. This interconnected framework facilitates continuous data collection and intelligent decision-making, helping operators to detect and respond to hazards before they escalate into critical incidents.

However, the successful deployment of IoT in underground environments is challenged by a range of technical and operational constraints. These include the difficulty of maintaining reliable wireless communication networks in enclosed and signal-degrading conditions, ensuring the durability and accuracy of sensors exposed to dust, moisture, and vibration, managing power consumption for devices with limited access to power sources, and safeguarding the integrity and confidentiality of sensitive data transmitted through the network.

This paper aims to provide a comprehensive analysis of how IoT technologies are currently being applied to improve tunneling safety. It identifies the main limitations that hinder widespread implementation and proposes practical and innovative solutions to address these challenges. The goal is to support the development of a resilient, efficient, and scalable IoT framework that can be effectively integrated into underground tunneling projects to protect human lives and optimize operational performance.

Keywords: Mining, Tunneling safety, Underground project, IoT-based safety solutions, Tunneling operations.

1. INTRODUCTION

Tunneling operations are among the most hazardous tasks in civil engineering and construction due to a combination of complex environmental, geological, and mechanical factors. These operations typically occur in confined and poorly ventilated spaces, where limited visibility and restricted access increase the difficulty of both routine tasks and emergency response efforts. The underground setting also brings unique risks such as the presence of toxic or flammable gases, reduced oxygen levels, excessive humidity, and constant exposure to dust and noise. Additionally, the structural integrity of the tunnel itself can be compromised by ground movement, water ingress, or substandard excavation practices, posing serious threats to both personnel and equipment.

Given these conditions, ensuring the safety and well-being of workers, as well as the protection of costly machinery and materials, is not only a regulatory necessity but a fundamental operational priority. Traditional safety monitoring methods, such as periodic manual inspections and stand-alone alarm systems, are often inadequate in rapidly evolving underground environments.

In recent years, the emergence of the Internet of Things (IoT) has introduced a paradigm shift in how safety is managed in tunneling projects. By integrating a network of interconnected smart devices—including gas detectors, vibration and temperature sensors, surveillance cameras, wearable health monitors, and automated control systems—IoT enables continuous, real-time data acquisition from every critical point of the tunnel. This information can be transmitted to centralized monitoring hubs where advanced analytics and AI-driven algorithms interpret the data to support immediate, informed decision-making. The result is a more responsive, adaptive, and intelligent approach to identifying risks, predicting equipment failure, and coordinating emergency responses.

However, the application of IoT in subterranean environments is not without significant hurdles. Challenges such as signal degradation due to rock and soil density, physical wear and tear on sensors, limited power supply options, and cybersecurity vulnerabilities can compromise the effectiveness of IoT systems underground. Furthermore, integrating diverse hardware and software platforms within the confined and hazardous setting of a tunnel adds complexity to deployment and maintenance.

This paper addresses these issues by exploring the current state of IoT applications in tunneling safety. It examines the specific technical and operational limitations encountered in underground settings and proposes a set of practical and scalable solutions. These include the use of ruggedized IoT hardware, energy-efficient communication protocols, edge computing, and AI-based analytics—each aimed at overcoming existing barriers and optimizing the use of IoT for safer tunneling operations.

2. Applications of IoT in Tunneling Safety

The integration of Internet of Things (IoT) technologies in tunneling safety systems has brought about a significant transformation in how underground construction projects are monitored and managed. By enabling real-time communication between physical devices and centralized control platforms, IoT enhances the ability to detect hazards early, respond quickly to emergencies, and maintain continuous oversight of working conditions. Below are the key applications of IoT in tunneling safety:

2.1 Environmental Monitoring

Environmental monitoring is one of the most critical components of ensuring safety in underground tunneling operations. The enclosed nature of tunnels makes them particularly vulnerable to hazardous atmospheric conditions, including the accumulation of toxic gases, insufficient oxygen levels, and high concentrations of dust particles. These conditions not only pose serious health risks to workers but can also lead to catastrophic incidents such as explosions, fires, or suffocation.

IoT-based environmental monitoring systems offer a proactive solution to these challenges by deploying a network of interconnected, real-time sensors throughout the tunnel. These sensors are capable of continuously measuring key atmospheric parameters and transmitting the data wirelessly to a centralized monitoring system for analysis and alert generation.

The main parameters monitored by IoT environmental sensors include:

- **Gas Concentrations**: IoT gas sensors detect dangerous levels of flammable and toxic gases such as **methane (CH_4)**, **carbon monoxide (CO)**, **hydrogen sulfide (H_2S)**, and others that may be released during excavation or from surrounding geology. Early detection of these gases can prevent explosions, poisoning, or fire outbreaks.
- **Oxygen Levels**: Maintaining adequate oxygen concentration is vital in underground environments. Oxygen deficiency can lead to dizziness, unconsciousness, and even death. IoT oxygen sensors ensure that the air quality remains within safe thresholds and can trigger ventilation systems when needed.
- **Temperature and Humidity**: Fluctuations in temperature and humidity can affect both worker comfort and equipment performance. High humidity may lead to corrosion of machinery and reduced visibility, while extreme temperatures can cause thermal stress. IoT sensors allow continuous tracking and climate control to maintain a safe and efficient working environment.
- **Dust and Particulate Matter**: Drilling and blasting activities in tunnels generate high levels of airborne particulate matter, which poses respiratory risks and can impair visibility. IoT-enabled dust sensors measure **PM2.5 and PM10** levels and enable the activation of dust suppression systems like misting or ventilation units when necessary.

The real-time data collected by these sensors can be visualized through dashboards, integrated with alarm systems, and used in conjunction with predictive analytics to forecast hazardous conditions before they escalate. Some advanced systems also incorporate AI algorithms to identify trends or anomalies in environmental conditions, allowing safety managers to take preventive action in advance.

By automating environmental monitoring, IoT not only reduces the dependency on manual inspections—which are often limited and delayed—but also enables a continuous feedback loop for maintaining safe working conditions. This significantly enhances the overall risk management strategy in tunneling projects, improving both worker safety and operational reliability.

The data collected is transmitted in real-time to control centers, where threshold breaches can trigger automated alerts, ventilation adjustments, or evacuation procedures. This reduces the risk of worker exposure to toxic environments and ensures regulatory compliance.

2.2 Structural Health Monitoring (SHM)

Structural Health Monitoring (SHM) is a critical application of IoT technology in underground tunneling, aimed at ensuring the long-term stability and integrity of tunnel structures. Given the constant exposure of tunnels to dynamic loads, geological stresses, and environmental factors such as water ingress and ground movement, early detection of structural abnormalities is essential to prevent progressive deterioration, structural failure, or collapse.

IoT-enabled SHM systems use a distributed network of embedded and surface-mounted sensors to collect real-time data on the physical state of tunnel infrastructure. These smart sensors are typically integrated into the tunnel lining, walls, and supporting structures during or after construction, and continuously monitor a variety of mechanical and geotechnical parameters. The key monitored variables include:

- **Vibrations and Seismic Activity**: Accelerometers and geophones detect ground vibrations caused by nearby construction, blasting, or seismic events. Sudden spikes in vibration intensity may indicate geological disturbances or weakening of the tunnel structure, prompting immediate investigation or mitigation measures.
- **Crack Propagation in Tunnel Linings**: Strain gauges, ultrasonic sensors, and fiber optic sensors are used to monitor the initiation and growth of cracks in concrete or segmental linings. By analyzing the rate and direction of crack propagation, engineers can assess the severity and progression of structural damage, and plan timely reinforcement or repairs.
- **Displacement, Stress, and Strain in Tunnel Walls**: Linear Variable Differential Transformers (LVDTs), extensometers, and fiber Bragg grating (FBG) sensors measure changes in stress distribution, strain levels, and deformation of tunnel segments. These parameters help in identifying areas under abnormal load conditions, which may be precursors to buckling or shear failure.

The real-time data gathered by SHM sensors is transmitted to a central monitoring system via secure IoT communication protocols. This system often includes advanced analytics platforms powered by machine learning and artificial intelligence, which can detect anomalies, recognize failure patterns, and trigger automated alerts when safety thresholds are breached. In some cases, predictive models can also estimate the remaining useful life of structural components, enabling predictive maintenance strategies.

Implementing IoT-based SHM not only enhances safety but also reduces operational costs by minimizing the need for manual inspections and preventing unscheduled maintenance. It enables continuous, long-term surveillance of structural health with high spatial and temporal resolution, which is especially valuable for large and complex tunneling projects that span years of construction and operation.

Moreover, SHM data can be archived and used for forensic analysis in case of failures, or as a historical record to inform the design of future tunneling projects under similar geological conditions. By providing accurate and actionable insights, IoT-based SHM serves as a cornerstone of proactive risk management in tunnel engineering.

2.3 Worker Health and Safety Monitoring

Human safety remains the most critical concern in any underground tunneling operation. Workers are exposed to a variety of physical, environmental, and psychological stressors, including long working hours, poor air quality, excessive noise, extreme temperatures, and the risk of accidents. Ensuring the continuous health monitoring and location tracking of personnel is vital for preventing injuries, managing fatigue, and enabling timely response during emergencies. IoT-based wearable technologies are revolutionizing how worker safety is managed in real time.

Modern wearable IoT devices—such as **smart helmets**, **sensor-embedded vests**, **biometric wristbands**, and **location-enabled ID tags**—are increasingly being deployed on tunneling sites. These devices are equipped with a range of sensors that continuously monitor workers' physiological and environmental data, including:

- **Heart Rate, Body Temperature, and Fatigue Levels**: Biometric sensors embedded in wristbands or chest patches track vital signs and physical strain. Abnormal readings can indicate dehydration, heat stress, overexertion, or early signs of medical emergencies such as cardiac events. Some advanced systems use algorithms to assess fatigue based on prolonged physical activity and heart rate variability, helping supervisors adjust shift schedules or assign breaks as needed.

- **Real-Time Location Tracking (RTLS)**: Using technologies like GPS (where available), Ultra-Wideband (UWB), Bluetooth Low Energy (BLE), and RFID, IoT wearables enable precise indoor and underground location tracking of workers. This enhances operational oversight and enables quick location of personnel in case of tunnel collapse, fire, or gas leakage. It also assists in enforcing geofencing rules by alerting when workers enter restricted or hazardous zones.
- **Exposure to Harmful Gases or Loud Noise**: Integrated gas sensors in helmets or vests can detect the presence of hazardous gases such as methane or carbon monoxide in a worker's immediate environment. Similarly, sound-level sensors help monitor exposure to harmful noise levels, which can lead to long-term hearing damage. Alerts can be automatically sent to safety managers when predefined thresholds are exceeded.

In emergency situations such as tunnel fires, cave-ins, or gas leaks, these wearable IoT devices become life-saving tools. The real-time data they provide allows emergency response teams to quickly identify the number and location of trapped or incapacitated workers. Supervisors can remotely access health metrics to prioritize medical attention for those in critical condition, significantly improving the efficiency and effectiveness of rescue operations.

Beyond safety, the data collected from wearables can also be analyzed to improve workforce productivity, optimize shift rotations, and reduce absenteeism by identifying early signs of health deterioration. In many projects, these systems are integrated with centralized dashboards and cloud platforms that allow safety managers to monitor the health status of the entire workforce from a single interface.

By transforming workers into connected nodes within the broader IoT network, wearable technologies offer a proactive, data-driven approach to occupational health and safety in tunneling environments. This not only strengthens compliance with safety regulations but also fosters a culture of prevention and accountability across tunneling operations.

2.4 Equipment and Machinery Monitoring

The efficiency and safety of underground tunneling operations heavily depend on the reliable performance of specialized heavy machinery, including **Tunnel Boring Machines (TBMs)**, **drilling rigs**, **conveyor belts**, **ventilation systems**, and **hydraulic supports**. These machines operate in extreme and demanding environments, where failures can not only cause significant delays and financial losses but also lead to serious safety hazards for workers in confined underground spaces.

IoT technologies have revolutionized the way this critical equipment is monitored and maintained. By embedding **smart sensors** and control modules into machinery, IoT-based equipment monitoring systems enable real-time data collection, analysis, and intelligent decision-making. Key applications include:

- **Predictive Maintenance**: Sensors measuring **vibration**, **temperature**, **oil pressure**, **load levels**, and **motor currents** can detect early signs of wear or malfunction. By continuously monitoring these parameters, IoT systems can predict when components are likely to fail, allowing maintenance teams to perform timely repairs or replacements before breakdowns occur. This shift from reactive to predictive maintenance significantly reduces unplanned downtime and extends the life of machinery.
- **Real-Time Fault Detection and Performance Monitoring**: IoT devices allow operators to continuously monitor operational parameters such as drilling speed, cutter head torque, hydraulic pressure, and power consumption. Any deviation from normal operating ranges can immediately trigger alerts, allowing for corrective actions before minor issues escalate into major failures. In the

case of ventilation systems, sensors monitor airflow rates, fan speed, and gas levels to ensure continuous air circulation and worker safety.

- **Remote Diagnostics and Usage Analytics**: IoT-connected equipment can transmit real-time operational data to centralized control rooms or cloud platforms. Engineers and technicians can remotely diagnose issues, track usage patterns, and optimize machine performance using analytics and machine learning models. This remote visibility is especially valuable for large-scale tunneling projects where machines are distributed across multiple sites or hard-to-access areas within a tunnel.

The benefits of IoT-based equipment monitoring extend beyond safety and reliability. These systems also contribute to **cost efficiency** by reducing manual inspections, optimizing energy use, and minimizing emergency repairs. Moreover, historical data collected from machine sensors can be used to identify recurring issues, optimize maintenance schedules, and improve equipment design in future projects.

In addition, the integration of equipment monitoring with other IoT subsystems—such as worker safety and structural health monitoring—enables a **holistic view** of tunnel operations. For instance, if a TBM sensor detects excessive vibration near a specific section, correlated data from structural sensors and worker tracking devices can help determine if an evacuation is necessary, or if tunnel support needs reinforcement.

Overall, IoT-enabled equipment and machinery monitoring not only enhances the operational efficiency of tunneling projects but also plays a critical role in ensuring safe working conditions by proactively identifying and mitigating mechanical risks.

2.5 Automated Emergency Response Systems

Underground tunneling environments are particularly vulnerable to sudden hazards such as fires, gas leaks, flooding, or structural collapses, which can escalate rapidly and pose severe threats to worker safety and infrastructure integrity. Traditional emergency response mechanisms, often reliant on manual detection and intervention, are frequently too slow or ineffective in such dynamic and confined settings. The integration of IoT technology into emergency response frameworks offers a transformative solution by enabling automated, rapid, and coordinated reactions to dangerous events.

IoT-enabled automated emergency response systems use interconnected sensors, control units, and communication devices strategically deployed throughout the tunnel to detect hazardous conditions instantly and execute predefined safety protocols without human delay. Key automated functions include:

- **Activating Alarms and Public Address Systems**: Upon detecting anomalies such as high gas concentrations, smoke, abnormal temperature spikes, or structural instability, IoT sensors trigger loud alarms and voice-based public address announcements. These alerts promptly notify workers and supervisors of the danger, ensuring swift evacuation or protective actions.
- **Controlling Ventilation to Clear Gases or Smoke**: Smart ventilation systems, integrated with gas detectors and air quality sensors, automatically adjust airflow patterns to remove toxic or combustible gases and dissipate smoke from fire incidents. This dynamic control of ventilation reduces the risk of asphyxiation, explosions, and further damage, while maintaining breathable air for safe evacuation and rescue operations.
- **Illuminating Escape Routes Using Smart Lighting**: Visibility is often severely compromised during emergencies in tunnels due to power outages, smoke, or dust. IoT-controlled smart lighting systems activate emergency lighting and guide illuminated pathways toward safe exits. Some

systems can dynamically adjust lighting intensity or direct personnel away from hazardous zones by illuminating alternate routes, significantly improving evacuation efficiency.

- **Sending Emergency Alerts to Rescue Teams and Operators**: Automated systems communicate real-time hazard data and worker location information to on-site safety managers and external rescue teams via wireless networks and cloud platforms. This ensures that emergency responders have immediate situational awareness, enabling them to deploy resources more effectively and coordinate rescue efforts with precision.

These automated response capabilities enhance the speed, accuracy, and coordination of emergency management in underground tunnels, which is critical when every second counts. By minimizing human reaction times and errors, IoT-enabled emergency systems not only increase the likelihood of successful evacuations and rescues but also help mitigate damage to infrastructure and equipment.

Moreover, such systems can be integrated with broader safety management platforms that leverage AI and predictive analytics to anticipate potential hazards before they fully develop, allowing preventive measures to be enacted proactively.

In summary, the deployment of automated emergency response systems within an IoT framework significantly elevates the resilience of tunneling operations against unforeseen incidents, safeguarding both human life and project assets.

2.6 Data Integration and Predictive Analytics

One of the most powerful advantages of IoT frameworks in underground tunneling safety is the ability to collect, integrate, and analyze vast amounts of data generated by diverse sensor networks monitoring environmental conditions, structural health, worker safety, and equipment performance. These data streams, often heterogeneous and high-volume, are centralized in advanced IoT platforms that facilitate comprehensive situational awareness and informed decision-making.

By leveraging **machine learning (ML)** and **artificial intelligence (AI)** algorithms, these platforms transform raw sensor data into actionable insights, enabling a shift from traditional reactive safety management to a more dynamic, predictive approach. Key capabilities include:

- **Predicting Potential Safety Incidents Before They Occur**: ML models analyze historical and real-time data to identify subtle patterns and precursors indicative of emerging hazards. For instance, gradual increases in micro-vibrations detected by structural sensors combined with shifts in worker location data could signal potential tunnel wall instability. Predictive analytics can forecast such incidents, allowing safety managers to intervene proactively, preventing accidents or failures.
- **Identifying Trends and Anomalies in Worker Behavior or Environmental Conditions**: AI algorithms continuously monitor data streams to detect abnormal deviations from established norms. Examples include unusual fatigue patterns in workers indicated by biometric sensors, sudden spikes in gas concentrations, or irregular equipment performance metrics. Early detection of these anomalies can trigger immediate safety checks or operational adjustments to mitigate risk.
- **Supporting Real-Time Decision-Making and Long-Term Planning**: Integrated IoT platforms offer intuitive dashboards and alert systems that empower supervisors to make informed decisions quickly during active operations. Simultaneously, aggregated historical data supports strategic planning, such as optimizing ventilation schedules, refining maintenance protocols, and designing safer tunnel layouts for future projects.

The synergy of data integration and predictive analytics in IoT systems fundamentally enhances the reliability, responsiveness, and resilience of tunneling safety management. By enabling continuous learning and adaptation, these systems reduce downtime, prevent injuries, and optimize resource allocation, ultimately leading to safer and more efficient tunneling environments.

Furthermore, the continuous feedback loop created by IoT data facilitates iterative improvements in safety protocols and engineering practices, fostering innovation in underground construction technologies.

Summary:

IoT technologies are redefining safety standards in tunneling projects by creating a comprehensive, interconnected system that enables real-time monitoring, predictive insights, and automated responses. These applications collectively improve situational awareness, enhance operational efficiency, and significantly reduce the risk of accidents in challenging underground environments.

3. Limitations of IoT Framework in Underground Tunneling

While the Internet of Things (IoT) offers significant advancements in enhancing safety and operational efficiency in underground tunneling, its deployment in such challenging environments comes with a unique set of limitations and constraints. Understanding these limitations is crucial for developing more robust, reliable, and scalable IoT frameworks tailored for underground conditions.

3.1 Network Connectivity and Communication Challenges

Reliable communication is the backbone of any IoT system, especially in underground tunneling operations where real-time monitoring and rapid response are critical for safety. However, the underground environment presents substantial obstacles to establishing and maintaining robust wireless communication networks.

One of the primary challenges is the **physical barrier posed by thick layers of rock, soil, and concrete**, which severely attenuate or block radio frequency (RF) signals commonly used in cellular or Wi-Fi networks. Unlike surface environments, where signal propagation is relatively unobstructed, tunnels create confined and complex propagation paths. This leads to several specific issues:

- **High Latency and Intermittent Connectivity**: Due to poor signal strength and frequent signal loss, IoT devices underground often experience delays in transmitting data to surface control centers or cloud platforms. This latency can impair real-time monitoring and decision-making, potentially compromising timely hazard detection or emergency response.
- **Signal Attenuation and Multipath Interference**: The tunnel's narrow and irregular geometry causes RF signals to reflect and scatter multiple times before reaching their destination, resulting in multipath interference. This phenomenon causes fluctuations in signal strength and quality, increasing packet loss and reducing overall communication reliability.
- **Specialized Networking Solutions Required**: To overcome these inherent challenges, tunneling projects typically deploy **dedicated communication infrastructures** such as:
- **Leaky feeder cables**, which are coaxial cables with perforations that allow radio signals to leak in and out along their length, providing continuous coverage throughout the tunnel.
- **Underground Wi-Fi systems** specifically designed for confined spaces with repeaters to extend coverage.
- **Mesh networks** that enable IoT devices to communicate with each other and relay data dynamically, creating resilient, self-healing networks.

  While these solutions improve connectivity, they come with their own drawbacks. The installation of leaky feeders and Wi-Fi access points requires significant upfront capital and ongoing maintenance efforts in harsh, often inaccessible underground conditions. Additionally, these systems may be susceptible to physical damage during tunneling activities, requiring robust design and frequent inspections.

In summary, ensuring seamless, low-latency, and reliable communication in underground tunnels remains a formidable technical challenge. Addressing these issues is critical to enabling the full potential of IoT frameworks in enhancing tunneling safety.

3.2 Sensor Robustness and Durability

The underground tunneling environment is one of the most physically demanding settings for deploying IoT sensors and devices. These environments expose equipment to a harsh combination of factors including **high humidity**, pervasive **dust and particulate matter**, constant **vibrations**, frequent **temperature fluctuations**, and unexpected **mechanical shocks** caused by heavy machinery and blasting activities. These conditions significantly challenge the durability and reliable functioning of IoT sensors, which are critical for accurate data collection and safety monitoring.

Key issues related to sensor robustness and durability include:

- **Sensor Degradation or Failure Due to Corrosion, Wear, or Contamination**: Moisture and dust particles can penetrate sensor housings, leading to corrosion of metal components, clogging of sensor apertures, or contamination of sensitive surfaces. Over time, this degradation can cause permanent damage or intermittent faults, reducing sensor lifespan and compromising data quality.
- **Reduced Sensor Accuracy and Increased Maintenance Requirements**: Continuous exposure to vibration and mechanical shocks can cause misalignment or loosening of sensor elements, resulting in drift or inaccurate measurements. For example, vibration sensors may produce noisy data if not properly isolated, and gas sensors may become less sensitive if their membranes are fouled by dust. As a result, frequent calibration and maintenance become necessary, increasing operational costs and downtime.
- **Challenges in Protecting Sensitive Electronics Without Compromising Sensor Responsiveness**:

To enhance durability, sensors often require protective enclosures or coatings. However, these protective measures can interfere with sensor sensitivity and responsiveness—for instance, thick housings may reduce the accuracy of gas or temperature sensors, and coatings might slow response times. Balancing protection and performance is a critical design challenge.

To address these durability challenges, it is essential to select sensors specifically engineered for industrial or mining environments, employing ruggedized designs with corrosion-resistant materials, dust-proof seals, and shock-absorbing mounts. Additionally, implementing remote diagnostics to monitor sensor health can preempt failures by signaling when recalibration or replacement is needed.

In summary, ensuring sensor robustness and longevity in underground tunneling is vital for maintaining continuous, accurate safety monitoring. Failure to address these durability issues can lead to data gaps, false alarms, or undetected hazards, undermining the overall effectiveness of IoT safety frameworks.

3.3 Power Supply and Energy Constraints

A critical challenge for implementing IoT frameworks in underground tunneling is ensuring a reliable and continuous power supply for the vast network of sensors, communication devices, and wearable technology. Unlike surface environments where power infrastructure is readily accessible, underground tunnels often lack direct connections to electrical grids, making consistent energy provisioning highly complex.

Key issues associated with power supply and energy constraints include:

- **Dependence on Battery-Powered Devices with Limited Lifespans**: Most IoT sensors and devices deployed underground rely on batteries as their primary power source. However, batteries have finite energy storage capacities and limited operational lifespans, requiring regular replacement or recharging. Given the logistical difficulties and safety concerns in accessing sensor locations deep within tunnels, frequent battery maintenance is impractical and costly.
- **Difficulty in Deploying Energy Harvesting Techniques**: Common renewable energy harvesting methods, such as solar panels, are ineffective in underground tunnels due to the absence of natural light. Alternative energy harvesting options such as thermal gradients, vibrations, or airflow energy are often minimal or inconsistent in tunnels, limiting their practical utility for powering IoT devices.
- **Challenges in Designing Energy-Efficient Communication Protocols**: Wireless communication, especially continuous or frequent data transmission, consumes significant power. Designing communication protocols that optimize energy consumption without compromising data quality or latency is essential. Strategies such as low-power wide-area networks (LPWAN), duty cycling (periodic device sleep modes), data aggregation, and edge computing can help reduce power demands but require careful implementation.

  To mitigate these energy constraints, research and development are focusing on:
- **Ultra-Low-Power Sensor Technologies** that minimize energy usage.
- **Energy-Efficient Networking Protocols** tailored for underground applications.
- **Hybrid Power Solutions** combining batteries with limited energy harvesting sources where feasible.
- **Remote Power Management Systems** that enable adaptive power usage based on operational priorities.

In summary, overcoming power supply and energy constraints is vital to ensuring the continuous and reliable operation of IoT devices in underground tunneling environments. Without effective solutions, power limitations can result in data loss, monitoring gaps, and reduced overall system efficacy, jeopardizing safety outcomes.

3.4 Data Security and Privacy Concerns

The deployment of IoT frameworks in underground tunneling environments introduces significant cybersecurity challenges that must be addressed to safeguard safety-critical systems. The interconnected nature of IoT devices—ranging from sensors and wearables to control units—creates multiple potential entry points for malicious actors. Unauthorized access or data manipulation could not only compromise the integrity of safety monitoring but also endanger human lives by disrupting emergency response mechanisms.

Key data security and privacy concerns include:

- **Vulnerability to Network Intrusions**: IoT networks underground can be susceptible to cyberattacks such as hacking, malware injection, or denial-of-service (DoS) attacks. Intruders gaining access to the network might alter sensor readings, disable alarms, or interfere with control commands, thereby masking hazards or triggering false alarms. This vulnerability undermines trust in automated safety systems and may cause catastrophic failures if undetected.
- **Challenges in Secure Data Transmission and Storage**: Ensuring the confidentiality and integrity of data transmitted from underground IoT devices to surface control centers or cloud servers is challenging. The underground environment's constrained communication infrastructure can limit the implementation of robust encryption protocols, increasing the risk of interception or tampering

during data transfer. Furthermore, secure storage of sensitive operational and personnel data requires effective encryption and access controls, which can be difficult to maintain consistently in distributed systems.

- **Resource Constraints on Edge Devices**: Many IoT sensors and wearable devices have limited computational power, memory, and energy resources, which restrict the complexity of security algorithms they can support. Implementing comprehensive authentication mechanisms, strong encryption, and secure firmware updates on resource-constrained devices is technically challenging. This limitation can lead to weaker security postures or vulnerabilities if outdated or insecure protocols are used.

To address these concerns, tunneling IoT systems must incorporate **multi-layered cybersecurity strategies** that balance security with operational feasibility, such as:

- Lightweight encryption and authentication protocols tailored for low-power devices.
- Secure key management and regular software patching.
- Network segmentation and anomaly detection to isolate and identify suspicious activity.
- Employee training and strict access controls to prevent insider threats.

In conclusion, addressing data security and privacy concerns is essential to maintain the reliability and safety of IoT-enabled underground tunneling operations. Failure to implement robust cybersecurity measures risks severe operational disruptions and potential harm to personnel.

3.5 Data Management and Integration Complexity

The implementation of IoT frameworks in underground tunneling environments results in the continuous generation of massive volumes of data from a wide variety of sources. These include environmental sensors, structural health monitoring devices, wearable technologies for workers, and heavy machinery monitoring systems. While this wealth of data holds the promise of comprehensive insights into tunnel safety, it also introduces significant challenges in data management and integration.

Key issues related to data complexity include:

- **Difficulties in Real-Time Data Aggregation and Analysis**: Real-time safety monitoring demands rapid collection, transmission, and processing of diverse data streams. However, the sheer volume and velocity of data can overwhelm traditional data handling systems, leading to bottlenecks in aggregation and delays in analysis. This latency can undermine the effectiveness of early warning systems and automated responses critical for worker safety.
- **Challenges in Integrating Heterogeneous Data Formats and Protocols**: IoT devices deployed in tunneling operations often come from multiple vendors and utilize different communication protocols, data standards, and formats. This heterogeneity complicates the seamless integration of sensor outputs into unified platforms necessary for comprehensive safety management. Incompatibilities can result in fragmented datasets, loss of data fidelity, or increased system complexity.
- **Risk of Data Overload Causing Delays or False Alarms**: Without well-designed analytics frameworks, the high volume of incoming data can lead to information overload, where critical signals may be buried within noise. Inadequate filtering or improper threshold settings can cause frequent false alarms or missed detections, eroding user trust and potentially causing complacency. Conversely, overloaded systems may experience processing delays that reduce situational awareness. To address these challenges, advanced data management strategies are essential, such as:

- Employing scalable cloud-based or edge computing platforms capable of handling large-scale, heterogeneous data.
- Implementing standardized data formats and communication protocols to enhance interoperability.
- Utilizing intelligent data filtering, fusion, and prioritization algorithms to extract actionable insights while minimizing noise.
- Leveraging machine learning models to differentiate between normal variations and genuine anomalies, reducing false positives.

  In summary, effective management and integration of diverse IoT data streams are critical for transforming raw data into timely, accurate, and actionable safety intelligence. Overcoming data complexity ensures that IoT frameworks can fulfill their potential in enhancing underground tunneling safety.

3.6 Cost and Implementation Barriers

The adoption of IoT frameworks for underground tunneling safety, while promising substantial benefits, faces significant financial and operational hurdles. Deploying a comprehensive IoT system in the challenging underground environment demands considerable upfront investment and ongoing resources, which can impede widespread implementation.

Key cost and implementation challenges include:

- **High Installation and Maintenance Costs**: The remote and physically demanding nature of tunneling sites increases both the complexity and expense of installing IoT devices and supporting infrastructure. Specialized equipment must often be ruggedized to withstand harsh environmental factors such as moisture, dust, and vibration. Furthermore, routine maintenance, calibration, and repairs are more labor-intensive and costly due to difficult accessibility, sometimes requiring halting operations or deploying specialized personnel for equipment servicing.
- **Need for Specialized Technical Expertise**: Designing, installing, and managing an underground IoT system requires multidisciplinary expertise spanning sensor technology, networking, data analytics, and cybersecurity. Recruiting or training personnel with these specialized skills adds to implementation expenses. Additionally, troubleshooting system faults in a subterranean setting demands experience with both IoT hardware and the unique challenges of underground environments, further increasing operational overhead.
- **Resistance from Stakeholders Due to Perceived Complexity or Reliability Concerns**: The novelty of IoT technologies in tunneling projects can lead to skepticism among operators, engineers, and management teams. Concerns about system complexity, potential failures, and integration with existing workflows may cause resistance to adoption. This hesitancy can slow decision-making processes and delay investments, particularly when the return on investment is perceived as uncertain or long-term.

Despite these barriers, the long-term benefits of IoT frameworks—such as improved safety, reduced downtime, and optimized maintenance—can justify the initial costs. To facilitate adoption, phased implementation approaches, pilot projects, and cost-benefit analyses can demonstrate tangible value and build stakeholder confidence.

In summary, addressing cost and implementation challenges through strategic planning, capacity building, and clear communication is essential for the successful deployment of IoT safety frameworks in underground tunneling.

Summary:
The integration of Internet of Things (IoT) technologies into underground tunneling operations offers significant potential to enhance safety through real-time monitoring, predictive analytics, and automated emergency responses. However, several critical limitations must be addressed to fully harness these benefits. Challenges related to unreliable network connectivity, sensor robustness under harsh conditions, constrained power supply, data security vulnerabilities, complex data management, and substantial cost and implementation barriers currently hinder seamless deployment. Developing tailored, environment-specific solutions—such as resilient communication infrastructures, ruggedized sensors, energy-efficient protocols, robust cybersecurity measures, advanced data integration platforms, and cost-effective implementation strategies—is essential. By overcoming these obstacles, IoT frameworks can transform subterranean construction environments into safer, more efficient, and more resilient workspaces, ultimately safeguarding workers and optimizing operational performance.

4. Proposed Solutions and Strategies

Successfully implementing IoT frameworks in underground tunneling environments requires more than just technology—it demands an integrated, strategic approach tailored to the unique constraints of subterranean operations. These environments are characterized by harsh physical conditions, limited connectivity, energy constraints, and high safety demands. As such, addressing the multifaceted challenges identified earlier—including unreliable communication, sensor fragility, limited power availability, complex data management, and cybersecurity vulnerabilities—necessitates a combination of **robust engineering**, **intelligent system design**, and **emerging digital technologies**.

The following solutions offer a pathway toward overcoming these limitations by enhancing the reliability, resilience, and scalability of IoT systems used in underground tunnel safety monitoring. By focusing on key areas such as **low-power networking**, **ruggedized hardware**, **efficient power utilization**, **localized data processing**, and **secure, intelligent analytics**, these strategies aim to transform IoT from a theoretical safety enhancement into a practical, real-world solution for the tunneling industry.

4.1 Use of Low-Power Wide Area Networks (LPWANs)

Establishing reliable and energy-efficient communication in underground tunnels remains one of the most significant barriers to the effective deployment of IoT systems. Traditional wireless communication technologies such as Wi-Fi, Bluetooth, or cellular (4G/5G) networks often suffer from high energy consumption and limited penetration through soil, rock, and concrete. To address these limitations, **Low-Power Wide Area Networks (LPWANs)**—particularly **LoRaWAN (Long Range Wide Area Network)** and **Narrowband IoT (NB-IoT)**—are emerging as ideal solutions for subterranean applications.

LPWAN technologies are designed to **transmit small packets of data over long distances** while using very little power, making them well-suited for underground environments where energy resources are scarce and data transmission requirements are relatively low-frequency and lightweight. These networks can cover several kilometers above ground and maintain acceptable performance even in **non-line-of-sight conditions**, which is essential for navigating the curved, segmented, and enclosed structure of tunnels.

- **LoRaWAN** offers a star-of-stars network topology with excellent range and minimal infrastructure, making it suitable for rapidly expanding networks of environmental sensors and wearables.

- **NB-IoT**, operating over licensed spectrum bands, offers better security and integration with existing telecom infrastructure, which is advantageous for critical safety applications requiring Quality of Service (QoS) assurances.

Additionally, LPWANs support **deep indoor and underground penetration**, which outperforms many high-frequency alternatives that degrade quickly in enclosed environments. Their **low data rates**, typically sufficient for transmitting environmental readings or status updates, help reduce **network congestion** and prolong **battery life** of devices—often up to several years with proper optimization.

To enhance coverage and fault tolerance, LPWAN deployments can be integrated with **mesh networking architectures**, enabling devices to relay data through neighboring nodes, thus extending the network beyond the range of a single gateway. This **redundant, self-healing communication model** ensures reliability even in the event of localized signal blockages or infrastructure damage.

In summary, LPWAN technologies provide a practical, scalable, and cost-effective foundation for underground IoT communications. Their deployment enables robust, low-maintenance connectivity, which is critical for ensuring continuous safety monitoring and operational efficiency in tunneling projects.

4.2 Ruggedized Sensor Design

Underground tunneling environments present some of the harshest conditions for electronic equipment, characterized by high humidity, dust, water seepage, chemical exposure, mechanical shocks, and constant vibration. In such settings, the reliability and accuracy of sensor data are directly tied to the physical resilience of the hardware. Therefore, the **design and deployment of ruggedized sensors** is a critical strategy to ensure uninterrupted and dependable IoT-based safety monitoring.

Sensors deployed in tunnels must be **built to withstand extreme environmental stressors**. Devices rated at **IP68 or higher** are specifically designed for this purpose. These sensors are fully protected against dust ingress and can operate reliably even when submerged in water. Additionally, protective housings constructed from **corrosion-resistant materials** such as stainless steel, specialized polymers, or industrial-grade aluminum protect internal electronics from damage caused by abrasive particles, humidity, and chemical agents often present in tunnel atmospheres.

Another essential feature is the integration of **shock-absorbing and vibration-dampening mechanisms**. Sensors mounted on tunnel walls or machinery are frequently exposed to vibrations from drilling, blasting, and moving equipment. Without proper isolation, such vibrations can cause sensor misalignment or fatigue, leading to inaccurate data or device failure. Ruggedized designs help maintain calibration and prolong the service life of critical monitoring components.

Furthermore, the inclusion of **self-diagnostic and health-monitoring capabilities** adds another layer of resilience. Sensors equipped with these features can continuously assess their own performance—detecting anomalies such as signal drift, battery degradation, or physical damage—and send alerts when maintenance or recalibration is needed. This facilitates a **predictive maintenance model**, where issues can be addressed before they lead to system downtime or inaccurate readings.

By minimizing unplanned failures and ensuring consistent performance in extreme environments, ruggedized sensors play a pivotal role in the **reliability and scalability** of underground IoT systems. Their deployment not only enhances data integrity but also **reduces maintenance frequency and operational disruptions**, making them a cornerstone of any robust tunneling safety framework.

4.3 Energy Harvesting and Efficient Power Management

Power availability is a persistent challenge in underground tunneling environments, where access to conventional energy sources is limited and frequent battery replacement is logistically difficult, costly, and potentially hazardous. Ensuring continuous operation of IoT devices over long durations demands innovative approaches to power generation and energy efficiency. **Energy harvesting**, combined with **intelligent power management**, provides a viable path toward self-sustaining IoT systems.

Energy harvesting involves converting ambient environmental energy into usable electrical power to support low-power sensors and devices. Two of the most promising techniques for tunnel environments include:

- **Vibration-Based Energy Harvesting**: Tunneling operations generate significant mechanical vibrations from sources such as tunnel boring machines (TBMs), ventilation systems, and drilling equipment. Piezoelectric or electromagnetic harvesters can capture this kinetic energy and convert it into electricity to power nearby sensors. These systems are ideal for locations with frequent mechanical activity, effectively turning the operational dynamics of the tunnel into a renewable energy source.
- **Thermoelectric Generators (TEGs)**: Underground tunnels often have stable but uneven temperature distributions, particularly near hot equipment or ventilation outlets. TEGs exploit **temperature gradients** between hot and cold surfaces to generate electricity via the Seebeck effect. This technique is especially effective in areas where consistent thermal differences are present, offering a steady, maintenance-free power source for stationary sensor nodes.

  To complement energy harvesting, IoT systems must incorporate **energy-efficient hardware and software design** strategies, including:

- **Adaptive Duty Cycling**: Devices alternate between active and sleep states based on predefined conditions or sensor thresholds, significantly reducing energy usage during idle periods without compromising data collection.
- **Low-Power Communication Protocols**: Protocols such as LoRa, Zigbee, and BLE (Bluetooth Low Energy) are optimized for minimal transmission energy while maintaining reliable data links. Data compression and aggregation can further reduce the volume of transmissions, saving power.
- **Smart Power Management Algorithms**: Devices can dynamically adjust their sensing frequency or communication intervals based on battery levels, energy harvesting rates, or operational priorities—maximizing uptime and minimizing unnecessary consumption.

The **hybrid approach** of combining energy harvesting with intelligent energy management not only reduces dependence on manual battery replacement but also **extends device lifespans** and **enhances system resilience**. This strategy is essential for enabling large-scale, low-maintenance IoT deployments in remote and hazardous underground locations, supporting continuous safety monitoring and predictive maintenance.

4.4 Edge Computing Integration

In traditional IoT architectures, data collected from sensors is typically transmitted to centralized servers or cloud platforms for processing. However, in underground tunneling environments, this model is often impractical due to **limited bandwidth, high latency, and unreliable connectivity**. These constraints can compromise the speed and reliability of safety-critical applications that require real-time responses. **Edge computing**—the practice of processing data at or near the source of generation—offers a transformative solution to these challenges.

By deploying **edge devices** within the tunnel network, computational tasks such as data filtering, preprocessing, and analytics can be performed locally. This reduces the volume of raw data that must be transmitted to surface-level or remote control centers, thereby **alleviating network load and mitigating latency**. In environments where communication links may be intermittent or degraded, this local processing ensures that essential safety functions remain operational without depending entirely on cloud-based infrastructure.

Key benefits of edge computing integration in tunneling operations include:

- **Real-Time Analytics and Immediate Response**: Edge devices can run lightweight machine learning models or rule-based systems to detect anomalies—such as rising gas levels, structural shifts, or equipment malfunctions—within milliseconds. These insights can trigger **automated safety actions**, such as alerts, ventilation activation, or equipment shutdowns, without waiting for external server input.
- **Increased Resilience and Fault Tolerance**: Edge computing supports **distributed architecture**, where multiple nodes can operate independently or in collaboration. This design prevents **single points of failure**, ensuring that if one node or network segment fails, others can continue functioning and maintaining critical safety monitoring.
- **Efficient Resource Usage**: By preprocessing and aggregating data locally, only **relevant or anomalous data** needs to be sent over limited underground communication channels. This conserves bandwidth and reduces the energy consumption of transmission modules, thereby supporting overall system efficiency and longevity.
- **Scalability and Modularity**: Edge computing frameworks are inherently scalable. Additional edge nodes can be deployed in high-risk or high-traffic zones of the tunnel without overloading the central infrastructure. This modular approach allows for incremental expansion and more precise, location-specific monitoring.

The integration of edge computing is thus a **cornerstone of intelligent, responsive, and scalable** underground IoT frameworks. It enables **fast, autonomous decision-making** in environments where time is critical and connectivity cannot always be guaranteed. As tunneling projects become more complex and data-driven, edge computing will play an increasingly vital role in ensuring safety and operational continuity.

4.5 Blockchain and AI for Security and Analytics

As underground tunneling operations become increasingly reliant on data-driven decision-making and interconnected IoT ecosystems, concerns about **data integrity, cybersecurity, and real-time analytics** grow more pressing. To address these challenges, the convergence of **blockchain technology** and **artificial intelligence (AI)** offers a powerful and complementary solution that enhances both the **security** and **intelligence** of tunneling safety systems.

Blockchain for Data Integrity and Security

Blockchain is a **decentralized, distributed ledger technology** designed to record transactions and data in an immutable, tamper-resistant format. In the context of underground IoT systems, blockchain can be used to:

- **Secure Sensor Data**: Every data point generated by environmental sensors, structural monitors, or wearable devices can be time-stamped and cryptographically recorded on a blockchain ledger. This ensures that once data is collected, it cannot be altered or deleted without consensus, thereby **preventing unauthorized manipulation**.
- **Enable Transparent System Logs**: Blockchain maintains a clear, auditable history of all device actions and transactions. This is particularly valuable for forensic investigations following incidents,

where the integrity of historical data must be guaranteed.

- **Decentralize Trust**: By eliminating reliance on a central authority, blockchain strengthens the security posture of IoT networks, making them more resilient against cyberattacks, insider threats, and single points of failure.

AI for Predictive Analytics and Autonomous Decision-Making

Artificial intelligence enhances the analytical capabilities of IoT frameworks by enabling **real-time data interpretation**, **anomaly detection**, and **risk prediction**. Key applications of AI in tunneling safety include:

- **Pattern Recognition and Anomaly Detection**: Machine learning models can analyze vast, multi-modal datasets from sensors and wearables to recognize normal operational patterns and flag deviations that might indicate equipment failure, structural stress, gas buildup, or unsafe worker conditions.
- **Predictive Maintenance and Risk Forecasting**: AI can forecast equipment breakdowns or structural failures before they occur by identifying early warning signs, reducing downtime and enhancing worker safety through proactive maintenance schedules.
- **Adaptive System Behavior**: AI algorithms can continuously learn from operational data, allowing the safety system to evolve in response to changing tunnel conditions or work patterns. For instance, it can dynamically adjust alert thresholds or recommend workflow adjustments during peak risk periods.

Synergistic Benefits

When combined, blockchain and AI enable **secure, autonomous, and intelligent safety systems**:

- Blockchain ensures that the data AI models use is authentic and tamper-proof.
- AI, in turn, transforms this secure data into actionable insights in real time.
- Together, they support **automated decision-making** while maintaining **data trustworthiness**, a critical requirement in high-risk environments like tunnels.

This fusion of technologies also supports compliance with **regulatory standards** and **audit requirements** by providing transparent data records and explainable AI decisions. As tunneling projects grow in scale and complexity, this integration will become increasingly essential for achieving **end-to-end digital trust, operational safety, and system intelligence**.

5. Case Studies and Implementations

The integration of IoT frameworks into underground tunneling projects has transitioned from conceptual experimentation to practical, large-scale deployment. Across the globe, infrastructure development authorities have adopted IoT-based safety and monitoring systems to address the unique challenges of tunneling operations—such as confined workspaces, environmental hazards, and structural uncertainties. These real-world implementations provide **tangible evidence** of how IoT technologies can be tailored to meet diverse geotechnical and operational demands.

By examining a selection of notable case studies—including projects in the United Kingdom, India, and China—we can observe how different IoT configurations have been employed to support real-time environmental monitoring, structural health assessment, equipment diagnostics, and worker safety tracking. These implementations underscore the **flexibility, effectiveness, and scalability** of IoT solutions in enhancing both safety and productivity in subterranean construction and transport infrastructure projects.

Furthermore, the success of these deployments demonstrates that with the right technological and strategic alignment, IoT frameworks can **transform traditional tunneling operations** into intelligent, responsive, and resilient systems. The following case studies provide deeper insight into how specific IoT tools and methodologies have been applied in varied tunnel environments, offering lessons for future projects worldwide.

5.1 London Crossrail Project (UK)

The **London Crossrail Project**, now known as the **Elizabeth Line**, represents one of the most ambitious and technologically advanced transportation infrastructure projects in Europe. Designed to increase rail capacity and reduce congestion across London, the project involved the construction of over 42 kilometers of new tunnels beneath a densely populated urban landscape—posing significant engineering and safety challenges. To address these, the project embraced **cutting-edge IoT technologies** as a central component of its safety and monitoring strategy.

The Crossrail team deployed a comprehensive suite of **IoT-enabled sensors and data analytics tools** to ensure continuous real-time insight into tunnel conditions throughout the construction and operational phases. Key components of the IoT implementation included:

- **Embedded Strain Gauges and Displacement Sensors**: These were installed directly into the tunnel linings to continuously measure stress, strain, and deformation. The data enabled engineers to detect subtle structural movements that might indicate material fatigue, uneven ground settlement, or risk of collapse—allowing for immediate corrective actions before issues escalated.
- **Air Quality Monitoring Sensors**: Specialized environmental sensors were strategically positioned to measure concentrations of gases such as **carbon dioxide (CO_2)**, **oxygen (O_2)**, and other pollutants. These readings helped ensure safe atmospheric conditions for construction crews and machinery operators, especially in confined areas where ventilation is limited.
- **Integrated Data Visualization Platforms**: Sensor data was fed into cloud-based dashboards that provided project engineers and site managers with a real-time visual interface for tunnel health and safety parameters. These platforms facilitated **predictive maintenance planning**, anomaly detection, and **rapid decision-making** in response to emerging risks.

The Crossrail project demonstrated how a **robust, well-integrated IoT framework** could drastically improve both **risk mitigation and operational efficiency** in large-scale tunneling endeavors. It enabled a shift from reactive to proactive management by providing **early-warning systems**, automating data collection, and reducing reliance on manual inspections. The result was not only improved safety outcomes but also minimized delays and cost overruns—setting a benchmark for future smart infrastructure initiatives around the world.

5.2 Delhi Metro Phase III (India)

The **Delhi Metro Phase III** project marked a major expansion of one of the largest and busiest rapid transit systems in Asia. Constructed under densely populated urban areas and geologically diverse zones, the project faced significant tunneling challenges, including **soil instability, groundwater ingress**, and the need to protect nearby structures. In response, the Delhi Metro Rail Corporation (DMRC) adopted **IoT-based safety solutions** to enhance situational awareness, improve construction precision, and safeguard human lives.

The deployment of **IoT technologies** during Phase III construction exemplified how real-time data integration could transform traditional tunneling practices into a highly responsive and data-driven operation. Key features of the implementation included:

- **Sensor-Equipped Tunnel Boring Machines (TBMs)**: Advanced sensor arrays were integrated into TBMs to monitor key parameters such as **internal temperature, pressure, rotational torque, vibration levels**, and **cutting head wear**. This information was critical for ensuring optimal TBM performance and minimizing risks associated with mechanical failure or geological anomalies. The ability to detect deviations early enabled predictive maintenance and operational adjustments to prevent accidents or equipment breakdowns.
- **Wearable Tracking Devices for Workers**: To enhance human safety, all tunnel personnel were equipped with **wearable devices**—such as RFID badges and GPS-based trackers (adapted for underground use)—that enabled **real-time location monitoring**. These wearables also monitored environmental exposure and movement patterns, allowing safety officers to quickly locate individuals during emergencies, ensure safe distancing near hazardous zones, and monitor compliance with work protocols.
- **Centralized Monitoring and Alert System**: All sensor data was relayed to a **central control room**, where integrated dashboards visualized system health, environmental metrics, and worker locations. The system was capable of generating **automated alerts** in response to anomalies, such as unsafe gas concentrations, unusual TBM behavior, or unauthorized worker movement into restricted zones. This facilitated **real-time risk mitigation** and ensured rapid coordination of emergency responses.

The Delhi Metro's implementation emphasized the **holistic nature of IoT-based safety frameworks**—where equipment monitoring, environmental sensing, and human factors are all part of an interconnected ecosystem. In the context of a **congested urban environment**, this approach proved especially valuable, offering heightened operational transparency and reducing the risk of accidents in one of the most challenging construction scenarios in India.

The project set a precedent for **smart tunneling initiatives** in other developing nations, demonstrating that with strategic integration, IoT solutions can be both scalable and effective—even within cost-sensitive and resource-constrained infrastructure programs.

5.3 Shanghai Metro (China)

The **Shanghai Metro** stands as one of the world's largest and busiest urban transit networks, with thousands of kilometers of underground tunnels carrying millions of passengers daily. Given this extensive scale and high usage, maintaining the safety and reliability of the system's infrastructure is a continuous challenge. To address these demands, the Shanghai Metro has implemented an advanced **IoT-driven predictive maintenance framework** focused on proactive infrastructure health monitoring and operational efficiency.

Key elements of the Shanghai Metro's IoT implementation include:

- **Embedded Smart Sensors**: A network of IoT-enabled sensors has been installed within the tunnel walls and along rail systems to continuously monitor critical parameters such as **temperature variations, vibration signatures, and material fatigue**. These sensors detect micro-level structural changes and mechanical stresses that are early indicators of wear or potential failure.
- **AI-Powered Analytics Platforms**: The collected sensor data is processed using sophisticated **artificial intelligence (AI) algorithms** capable of identifying subtle trends and anomalies. These platforms predict the likelihood of component failures or structural weaknesses before they manifest into critical issues, allowing maintenance teams to intervene at the optimal time.
- **Centralized Maintenance Dashboard**: Sensor data streams are integrated into a centralized, user-friendly dashboard that provides maintenance engineers with real-time insights into infrastructure

health. The system generates **predictive alerts** and recommends scheduling of repair activities based on data-driven risk assessments, thereby optimizing resource allocation and minimizing unnecessary interventions.

This data-centric approach to maintenance has demonstrated several significant benefits:

- It **extends the lifespan** of tunnel and rail infrastructure by facilitating timely and targeted repairs.
- It **minimizes unplanned service disruptions**, thus maintaining high reliability and passenger satisfaction.
- It **enhances overall commuter safety** by proactively identifying and mitigating risks associated with aging infrastructure.

The Shanghai Metro case exemplifies how the convergence of IoT and AI can revolutionize underground transit system management, shifting from reactive maintenance to intelligent, predictive strategies—thereby safeguarding critical infrastructure and supporting the demands of urban mobility at scale.

Summary of Impact

The real-world implementations of IoT frameworks in underground tunneling projects underscore the transformative potential of these technologies when thoughtfully adapted to the unique environmental and operational challenges of subterranean construction. Across diverse contexts—from metropolitan rail expansions to large-scale infrastructure developments—IoT solutions have demonstrated a marked ability to **enhance worker safety, reduce unplanned downtime, and improve overall decision-making** through continuous, real-time monitoring and predictive analytics.

These case studies also reveal that the successful deployment of IoT in tunneling environments requires more than just technological innovation; it demands **close collaboration between multidisciplinary teams**, including civil engineers, data scientists, IT specialists, and safety professionals. Such cross-functional partnerships are essential for designing resilient IoT ecosystems that can withstand harsh underground conditions, integrate diverse data streams, and deliver actionable insights.

Ultimately, these implementations highlight a new paradigm in tunneling safety management—one that leverages **intelligent, connected technologies** to anticipate risks, automate responses, and optimize maintenance schedules. This shift not only protects human lives and infrastructure assets but also promotes greater operational efficiency and cost-effectiveness, setting a strong precedent for future smart tunneling projects worldwide.

6. Conclusion

The integration of Internet of Things (IoT) frameworks into underground tunneling operations heralds a new era in construction safety and efficiency. By enabling real-time monitoring, predictive maintenance, and automated emergency responses, IoT technologies offer unprecedented opportunities to safeguard workers, optimize equipment use, and mitigate risks inherent to subterranean environments. While challenges related to **network connectivity**, **energy supply**, **sensor durability**, and **data security** remain significant hurdles, continuous advancements in low-power communication technologies, ruggedized sensor design, edge computing, and artificial intelligence are rapidly bridging these gaps.

Moreover, the strategic and thoughtful deployment of IoT solutions—tailored to the specific geological and operational contexts of tunneling projects—can maximize their impact. Coupling these technological innovations with rigorous cybersecurity protocols ensures that safety-critical data remains protected against evolving cyber threats. Collectively, these developments position IoT as a cornerstone for transforming underground tunneling safety from a traditionally reactive practice into a **smart, proactive discipline**.

As the tunneling industry continues to evolve, embracing IoT-driven frameworks will be essential for meeting the increasing demands of urban infrastructure development while prioritizing the health and safety of workers and the integrity of critical underground assets.

7. Future Work

While significant progress has been made in applying IoT frameworks to underground tunneling safety, several key areas warrant further research and development to fully realize the technology's potential:

Development of Universal Standards:

The underground tunneling industry currently faces a significant gap due to the absence of standardized protocols and frameworks specifically designed for IoT deployments in subterranean environments. This lack of uniformity hampers interoperability among diverse sensors, communication devices, and data platforms, leading to fragmented systems that are costly and complex to integrate. Developing universal standards tailored to the unique challenges of underground tunneling—including rugged environmental conditions, communication constraints, and stringent safety requirements—will be essential. Such standards should encompass sensor specifications, communication protocols, data formats, and cybersecurity measures to ensure seamless integration, reliable performance, and compliance with regulatory frameworks. Establishing these universal guidelines will not only accelerate IoT adoption across tunneling projects globally but also foster innovation and collaboration among technology providers, operators, and regulators.

Large-Scale Field Trials of Hybrid Communication Systems:

Connectivity remains one of the most critical challenges in underground tunneling due to the complex and obstructive nature of subterranean environments. To overcome this, further extensive field trials are needed to evaluate and optimize hybrid communication systems that integrate multiple networking technologies—such as Low-Power Wide Area Networks (LPWAN), mesh networks, leaky feeder cables, and wired infrastructures. These large-scale trials will provide invaluable data on network performance under real-world conditions, helping to identify the most effective combinations and configurations tailored to different geological formations and tunnel lengths. Moreover, such testing will assess the long-term reliability, scalability, and maintenance requirements of these hybrid networks, ensuring they can deliver consistent, low-latency, and energy-efficient communication. Balancing technical performance with economic feasibility will be crucial, and these trials will inform cost-effective deployment strategies that can be adopted widely across the tunneling industry.

AI-Driven Adaptive Safety Systems:

The dynamic and hazardous nature of underground tunneling environments necessitates safety systems that can respond swiftly and intelligently to changing conditions. Advancing artificial intelligence (AI) capabilities to create adaptive, context-aware safety systems offers a promising path forward. Future research should focus on developing sophisticated machine learning models capable of continuously interpreting multi-source sensor data—including environmental, structural, and biometric inputs—to detect subtle patterns indicative of emerging risks. These AI-driven systems would not only predict potential hazards with greater accuracy but also autonomously initiate appropriate safety measures, such as triggering alarms, adjusting ventilation, or initiating evacuation protocols, without requiring human intervention. By enabling real-time, proactive decision-making, AI-based adaptive safety frameworks have the potential to drastically reduce incident response times, minimize human error, and enhance overall tunnel safety.

Human-Centric Design of Wearables and Interfaces:

For IoT wearables to effectively enhance safety in underground tunneling, their design must prioritize the needs, comfort, and workflows of tunnel workers. Future research should emphasize human-centric design principles that focus on ergonomic form factors, ensuring devices are lightweight, non-intrusive, and comfortable for extended use in physically demanding and confined environments. Additionally, developing intuitive and user-friendly interfaces is essential so that workers can easily understand alerts and interact with devices without distraction or confusion. Seamless integration of wearables with existing operational workflows and safety protocols will further encourage adoption and consistent usage. By involving end-users in the design and testing phases, these efforts will help bridge the gap between technological capabilities and practical usability, ensuring that wearables contribute positively to both safety and productivity underground.

Addressing the critical challenges facing IoT implementation in underground tunneling requires a concerted effort that transcends individual disciplines. Interdisciplinary research involving experts from fields such as engineering, computer science, data analytics, materials science, and human factors is vital to develop holistic solutions that consider the technical, environmental, and human dimensions of tunneling safety. Furthermore, close collaboration between academia, industry stakeholders, technology developers, and regulatory authorities is essential to ensure that innovations are not only scientifically sound but also practically viable and compliant with safety standards.

Such multi-stakeholder cooperation fosters the sharing of knowledge, resources, and best practices, accelerating the translation of research findings into real-world applications. It also facilitates the creation of standardized frameworks, regulatory guidelines, and certification processes that support widespread adoption and scalability of IoT technologies in subterranean settings. By leveraging diverse expertise and aligning objectives, this collaborative approach will enable the design, development, and deployment of next-generation smart tunneling systems that are inherently safer, more resilient, and capable of adapting to the complex and evolving challenges posed by underground environments. Ultimately, these advances will contribute to transforming underground tunneling from a high-risk activity into a more predictable, efficient, and secure operation.

References

1. A. Chaudhuri, “The trace kernel bandwidth criterion for support vector data description,” Pattern Recognit., vol. 111, Mar. 2021, Art. no. 107662, doi: 10.1016/j.patcog.2020.107662.
2. A. Janusz, M. Grzegorowski, M. Michalak, Ł. Wróbel, M. Sikora, and D. Ślęzak, "Predicting seismic events in coal mines based on underground sensor measurements," Engineering Applications of Artificial Intelligence, vol. 64, pp. 83-94, 2017/09/01/ 2017, doi: https://doi.org/10.1016/j.engappai.2017.06.002.
3. A. TohidiFar, M. Mousavi, and A. Alvanchi, "A hybrid BIM and BN-based model to improve the resiliency of hospitals' utility systems in disasters," International Journal of Disaster Risk Reduction, vol. 57, p. 102176, 2021/04/15/ 2021, doi: https://doi.org/10.1016/j.ijdrr.2021.102176.
4. A. Tubis, S. Werbińska-Wojciechowska, and A. Wroblewski, "Risk Assessment Methods in Mining Industry—A Systematic Review," Applied Sciences, vol. 10, no. 15, 2020, doi: 10.3390/app10155172.

5. B. Xiao, J. Zhao, D. Li, Z. Zhao, W. Xi, and D. Zhou, “The monitoring and analysis of land subsidence in Kunming (China) supported by time series InSAR,” Sustainability, vol. 14, no. 19, Sep. 2022, Art. no. 12387, doi: 10.3390/su141912387.
6. BayesFusion. "GeNIe Modeler: Complete Modeling Freedom." https://www.bayesfusion.com/genie/ (accessed 20 July 2022.
7. BayesFusion. "SMILE: Structural Modeling, Inference, and Learning Engine." https://www.bayesfusion.com/smile/ (accessed 20 July 2022.
8. C. Zhou and L. Y. Ding, "Safety barrier warning system for underground construction sites using Internet-of-Things technologies," Automation in Construction, vol. 83, pp. 372-389, 2017/11/01/ 2017, doi: https://doi.org/10.1016/j.autcon.2017.07.005.
9. D. Ślęzak et al., "A framework for learning and embedding multi-sensor forecasting models into a decision support system: A case study of methane concentration in coal mines," Information Sciences, vol. 451-452, pp. 112- 133, 2018/07/01/ 2018, doi: https://doi.org/10.1016/j.ins.2018.04.026.
10. F. Souza, T. Offermans, R. Barendse, G. Postma, and J. Jansen, “Contextual mixture of experts: Integrating knowledge into predictive modeling,” IEEE Trans. Ind. Informat., vol. 19, no. 8, pp. 9048–9059, Aug. 2023, doi: 10.1109/TII.2022.3224973.
11. F. Tang, Z. Md. Fadlullah, B. Mao, and N. Kato, “An intelligent traffic load prediction-based adaptive channel assignment algorithm in SDN-IoT: A deep learning approach,” IEEE Internet Things J., vol. 5, no. 6, pp. 5141–5154, Dec. 2018, doi: 10.1109/JIOT.2018.2838574.
12. G. Mei, N. Xu, J. Qin, B. Wang, and P. Qi, “A survey of Internet of Things (IoT) for Geohazard prevention: Applications, technologies, and challenges,” IEEE Internet Things J., vol. 7, no. 5, pp. 4371–4386, May 2020, doi: 10.1109/JIOT.2019.2952593.
13. Global Mining Guidelines Group (GMG), "Underground Mine Communications Infrastructure Guidelines Part III: General Guidelines," in Underground Mine Communications Infrastructure guideline suite: Global Mining Guidelines Group (GMG), 2019. [20] P. Lyu, N. Chen, S. Mao, and M. Li, "LSTM based encoder-decoder for short-term predictions of gas concentration using multisensor fusion," Process Safety and Environmental Protection, vol. 137, pp. 93-105, 2020/05/01/ 2020, doi: https://doi.org/10.1016/j.psep.2020.02.021.
14. H. Dui, S. Chen, Y. Zhou, and S. Wu, “Maintenance analysis of transportation networks by the traffic transfer principle considering node idle capacity,” Rel. Eng. Syst. Saf., vol. 221, May 2022, Art. no. 108386, doi: 10.1016/j.ress.2022.108386.
15. H. Dui, S. Zhang, M. Liu, X. Dong, and G. Bai, “IoT-enabled real-time traffic monitoring and control management for intelligent transportation systems,” IEEE Internet Things J., early access, Jan. 9, 2023, doi: 10.1109/JIOT.2024.3351908.
16. H. Dui, X. Dong, and J. Tao, “Reliability evaluation and prediction method with small samples,” Int. J. Math. Eng. Manag. Sci., vol. 8, no. 4, pp. 560–580, Aug. 2023, doi: 10.33889/IJMEMS.2023.8.4.032.
17. H. Dui, X. Dong, L. Chen, and Y. Wang, “IoT-enabled fault prediction and maintenance for smart charging piles,” IEEE Internet Things J., vol. 10, no. 23, pp. 21061–21075, Dec. 2023, doi: 10.1109/JIOT.2023.3285206.
18. H. Jang and E. Topal, "Transformation of the Australian mining industry and future prospects," Mining Technology, vol. 129, no. 3, pp. 120-134, 2020/07/02 2020, doi:

10.1080/25726668.2020.1786298.
19. J. Rusek, K. Tajduś, K. Firek, and A. Jędrzejczyk, "Score-based Bayesian belief network structure learning in damage risk modelling of mining areas building development," Journal of Cleaner Production, vol. 296, p. 126528, 2021/05/10/ 2021, doi: https://doi.org/10.1016/j.jclepro.2021.126528.
20. J. Louis et al. Integrating IoT into operational workflows for real-time and automated decision-making in repetitive construction operations Automat. Constr. (2018)
21. K. Le Son, M. Fouladirad, and A. Barros, "Remaining useful lifetime estimation and noisy gamma deterioration process," Rel. Eng. Syst. Saf., vol. 149, pp. 76–87, May 2016, doi: 10.1016/j.ress.2015.12.016.
22. K. Sakil Ahmed, J. Sharmin, and M. Ahmed Ansary, "Numerical investigation of tunneling induced surface movement: A case study of MRT line 1, Dhaka," Undergr. Space, vol. 12, pp. 116–136, Oct. 2023, doi: 10.1016/j.undsp.2023.02.008.
23. K. Elbaz et al. Cutter-disc consumption during earth pressure balance tunnelling in mixed strata Proc. Inst. Civil Eng.-Geotech. Eng. (2018)
24. L. Chang, L. Zhang, and X. Xu, "Causality-based multi-model ensemble learning for safety assessment in metro tunnel construction," Rel. Eng. Syst. Saf., vol. 234, Jun. 2023, Art. no. 109168, doi: 10.1016/j.ress.2023.109168.
25. L. Feng and L. Zhang, "Enhanced prediction intervals of tunnel-induced settlement using the genetic algorithm and neural network," Rel. Eng. Syst. Saf., vol. 223, Jul. 2022, Art. no. 108439, doi: 10.1016/j.ress.2022.108439.
26. L. Xing and B. W. Johnson, "Reliability theory and practice for unmanned aerial vehicles," IEEE Internet Things J., vol. 10, no. 4, pp. 3548–3566, Feb. 2023, doi: 10.1109/JIOT.2022.3218491.
27. L. Xing, "Cascading failures in Internet of Things: Review and perspectives on reliability and resilience," IEEE Internet Things J., vol. 8, no. 1, pp. 44–64, Jan. 2021, doi: 10.1109/JIOT.2020.3018687.
28. L. Xing, "Reliability in Internet of Things: Current status and future perspectives," IEEE Internet Things J., vol. 7, no. 8, pp. 6704–6721, Aug. 2020, doi: 10.1109/JIOT.2020.2993216.
29. L. Xing, M. Tannous, V. M. Vokkarane, H. Wang, and J. Guo, "Reliability modeling of mesh storage area networks for Internet of Things," IEEE Internet Things J., vol. 4, no. 6, pp. 2047–2057, Dec. 2017, doi: 10.1109/JIOT.2017.2749375.
30. M. Kozielski, M. Sikora, and Ł. Wróbel, "Data on methane concentration collected by underground coal mine sensors," Data in Brief, vol. 39, p. 107457, 2021/12/01/ 2021, doi: https://doi.org/10.1016/j.dib.2021.107457.
31. M. Li, D. Wang, and H. Shan, "Risk assessment of mine ignition sources using fuzzy Bayesian network," Process Safety and Environmental Protection, vol. 125, pp. 297-306, 2019/05/01/ 2019, doi: https://doi.org/10.1016/j.psep.2019.03.029.
32. M. Li, H. Wang, D. Wang, Z. Shao, and S. He, "Risk assessment of gas explosion in coal mines based on fuzzy AHP and bayesian network," Process Safety and Environmental Protection, vol. 135, pp. 207-218, 2020/03/01/ 2020, doi: https://doi.org/10.1016/j.psep.2020.01.003.
33. M. S. Abdalzaher, M. S. Soliman, S. M. El-Hady, A. Benslimane, and M. Elwekeil, "A deep learning model for earthquake parameters observation in IoT system-based earthquake early warning," IEEE Internet Things J., vol. 9, no. 11, pp. 8412–8424, Jun. 2022, doi:

10.1109/JIOT.2021.3114420.
34. M. You, S. Li, D. Li, and S. Xu, "Applications of artificial intelligence for coal mine gas risk assessment," Safety Science, vol. 143, p. 105420, 2021/11/01/ 2021, doi: https://doi.org/10.1016/j.ssci.2021.105420. [9] X. Tong, W. Fang, S. Yuan, J. Ma, and Y. Bai, "Application of Bayesian approach to the assessment of mine gas explosion," Journal of Loss Prevention in the Process Industries, vol. 54, pp. 238-245, 2018/07/01/ 2018, doi: https://doi.org/10.1016/j.jlp.2018.04.003.
35. N. Li, X. Feng, and R. Jimenez, "Predicting rock burst hazard with incomplete data using Bayesian networks," Tunnelling and Underground Space Technology, vol. 61, pp. 61-70, 2017/01/01/ 2017, doi: https://doi.org/10.1016/j.tust.2016.09.010.
36. P. Dey, S. K. Chaulya, and S. Kumar, "Hybrid CNN-LSTM and IoT-based coal mine hazards monitoring and prediction system," Process Safety and Environmental Protection, vol. 152, pp. 249-263, 2021/08/01/ 2021, doi: https://doi.org/10.1016/j.psep.2021.06.005.
37. P. Wen, Y. Li, S. Chen, and S. Zhao, “Remaining useful life prediction of IIoT-enabled complex industrial systems with hybrid fusion of multiple information sources,” IEEE Internet Things J., vol. 8, no. 11, pp. 9045–9058, Jun. 2021, doi: 10.1109/JIOT.2021.3055977.
38. P. Zhang, R.-P. Chen, T. Dai, Z.-T. Wang, and K. Wu, "An AIoT-based system for real-time monitoring of tunnel construction," Tunnelling and Underground Space Technology, vol. 109, p. 103766, 2021/03/01/ 2021, doi: https://doi.org/10.1016/j.tust.2020.103766.
39. P. Jayawardana et al. Dual in-filled trenches for vibration mitigation and their predictions using artificial neural network Soil Dyn. Earthq. Eng. (2019)
40. R. Moradi, S. Cofre-Martel, E. Lopez Droguett, M. Modarres, and K. M. Groth, "Integration of deep learning and Bayesian networks for condition and operation risk monitoring of complex engineering systems," Reliability Engineering & System Safety, vol. 222, p. 108433, 2022/06/01/ 2022, doi: https://doi.org/10.1016/j.ress.2022.108433.
41. R. Kanan et al. An IoT-based autonomous system for workers' safety in construction sites with real-time alarming, monitoring, and positioning strategies Automat. Constr. (2018)
42. R. Navon Research in automated measurement of project performance indicators Automat. Constr. (2007)
43. R.P. Chen et al., Prediction of maximum surface settlement caused by EPB shield tunneling with ANN methods Soils Found.(2019)
44. S. He, Y. Lu, and M. Li, "Probabilistic risk analysis for coal mine gas overrun based on FAHP and BN: a case study," Environmental Science and Pollution Research, vol. 29, no. 19, pp. 28458-28468, 2022/04/01 2022, doi: 10.1007/s11356-021-18474-3.
45. S. R. Pokhrel, L. Pan, N. Kumar, R. Doss, and H. L. Vu, “Multipath TCP meets transfer learning: A novel edge-based learning for industrial IoT,” IEEE Internet Things J., vol. 8, no. 13, pp. 10299–10307, Jul. 2021, doi: 10.1109/JIOT.2021.3056466.
46. S. Wu, “Survey on prediction algorithms in smart homes,” IEEE Internet Things J., vol. 4, no. 3, pp. 636–644, Jun. 2017, doi: 10.1109/JIOT.2017.2668061.
47. S. Zhang, Q. Zhai, and Y. Li, “Degradation modeling and RUL prediction with Wiener process considering measurable and unobservable external impacts,” Rel. Eng. Syst. Saf., vol. 231, Mar. 2023, Art. no. 109021, doi: 10.1016/j.ress.2022.109021.

48. S. Freitag et al. Recurrent neural networks and proper orthogonal decomposition with interval data for real-time predictions of mechanised tunnelling processes Comput. Struct. (2018)
49. S. Mahdevari et al. A support vector regression model for predicting tunnel boring machine penetration rates Int. J. Rock Mech. Min. (2014)
50. T. Porselvi, C. S. Sai Ganesh, B. Janaki, K. Priyadarshini, and S. Shajitha Begam, "IoT Based Coal Mine Safety and Health Monitoring System using LoRaWAN," in 2021 3rd International Conference on Signal Processing and Communication (ICPSC), 13-14 May 2021 2021, pp. 49-53, doi: 10.1109/ICSPC51351.2021.9451673.
51. T. Xiahou, Z. Zeng, and Y. Liu, "Remaining useful life prediction by fusing expert knowledge and condition monitoring information," IEEE Trans. Ind. Informat., vol. 17, no. 4, pp. 2653–2663, Apr. 2021, doi: 10.1109/TII.2020.2998102.
52. T. Yan, Y. Lei, N. Li, B. Wang, and W. Wang, "Degradation modeling and remaining useful life prediction for dependent competing failure processes," Rel. Eng. Syst. Saf., vol. 212, Aug. 2021, Art. no. 107638, doi: 10.1016/j.ress.2021.107638.
53. W. McKinney, Python for data analysis: Data wrangling with Pandas, NumPy, and IPython. O'Reilly Media, Inc., 2012.
54. W.-C. Hung, Y.-A. Chen, and C. Hwang, "IoT technology and big data processing for monitoring and analysing land subsidence in central Taiwan," in Proc. Int. Assoc. Hydrol. Sci., 2020, pp. 103–109, doi: 10.5194/piahs-382-103-2020.
55. X. Chen, "Distributed computation offloading and trajectory optimization in multi-UAV-enabled edge computing," IEEE Internet Things J., vol. 9, no. 20, pp. 20096–20110, Oct. 2022, doi: 10.1109/JIOT.2022.3175050.\
56. X. Qin, "Application of high-resolution PS-InSAR in deformation characteristics probe of urban rail transit," Acta Geod. Cartogr. Sin, vol. 45, no. 6, pp. 713–721, Jun. 2016, doi: 10.11947/j.AGCS.2016.20150440.
57. X. Wu, H. Liu, L. Zhang, M. J. Skibniewski, Q. Deng, and J. Teng, "A dynamic Bayesian network based approach to safety decision support in tunnel construction," Reliability Engineering & System Safety, vol. 134, pp. 157- 168, 2015/02/01/ 2015, doi: https://doi.org/10.1016/j.ress.2014.10.021.
58. X.J. Gao et al. Recurrent neural networks for real-time prediction of TBM operating parameters Automat. Constr. (2019)
59. Y. Kawamoto, R. Sasazawa, B. Mao, and N. Kato, "Multilayer virtual cell-based resource allocation in low-power wide-area networks," IEEE Internet Things J., vol. 6, no. 6, pp. 10665–10674, Dec. 2019, doi: 10.1109/JIOT.2019.2940600.
60. Y. Tan, J. Wang, J. Liu, and N. Kato, "Blockchain-assisted distributed and lightweight authentication service for industrial unmanned aerial vehicles," IEEE Internet Things J., vol. 9, no. 18, pp. 16928–16940, Sep. 2022, doi: 10.1109/JIOT.2022.3142251.
61. Y. Wu, M. Chen, K. Wang, and G. Fu, "A dynamic information platform for underground coal mine safety based on internet of things," Safety Science, vol. 113, pp. 9-18, 2019/03/01/ 2019, doi: https://doi.org/10.1016/j.ssci.2018.11.003.
62. Y.F. Jin et al. A single-objective EPR based model for creep index of soft clays considering L2 regularization Eng. Geol. (2019)
63. Z. Wu, T. Wang, Y. Wang, R. Wang, and D. Ge, "Deep learning for the detection and phase unwrapping of mining-induced deformation in large-scale interferograms," IEEE Trans. Geosci.

Remote Sens., vol. 60, pp. 1–18, 2022, doi: 10.1109/TGRS.2021.3121907.