Journal of Advanced Research in Computational Thinking and Data Science 5, Issue 1 (2025) 50-59

KARYA ILHAM PUBLISHING
CONNECTING MINDS, BRIDGING IDEAS, INSPIRING READERS

International Journal of Advanced Research in Computational Thinking and Data Science

Journal homepage:
https://karyailham.com.my/index.php/ctds/index
ISSN: 3030-5225

Enabling Smart and Sustainable Solutions: Applications of Wireless Sensor Networks in the Era of IoT

Ehtesham Ali[1,*], Habiba Ashraf[2], Syed Muzzamil Ali Shah[3], Muhammad Abdullah[4], Qadri Waseem[5] Muhammad Faizan[5], Muhammad Aleem[5,] Muhammad Adil[6]

[1] Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Pekan, Pahang, Malaysia
[2] Department of Zoology, Lahore College for Women University, Lahore, Pakistan
[3] HITEC University Taxila Pakistan
[4] Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Malaysia
[5] Faculty Of Computing Universiti Malaysia Pahang Al-Sultan Abdullah 26600 Pekan, Pahang, Malaysia
[6] Aquila's Global Tech Haripur Pakistan

ARTICLE INFO

Article history:
Received 19 January 2025
Received in revised form 9 February 2025
Accepted 2 March 2025
Available online 5 March 2025

Keywords:
Wireless Sensor Networks; IoT; applications; environmental healthcare; agriculture; industrial automation; smart cities; disaster management; sustainability

ABSTRACT

Wireless Sensor Networks (WSNs) have emerged as a powerful technology that enables the seamless integration of various applications on the Internet of Things (IoT) ecosystem. With the advancement in sensing, communication, and computing technologies, WSNs offer a wide range of opportunities to address real-world challenges and contribute to the development of smart and sustainable solutions. This paper explores the applications of WSNs in different domains, highlighting their potential in enhancing efficiency, improving decision-making processes, and promoting sustainability. We present a comprehensive overview of notable applications in areas such as environmental monitoring, healthcare, agriculture, industrial automation, smart cities, and disaster management. Furthermore, we discuss the key challenges and future directions for the effective deployment and utilization of WSNs in these applications. Through this exploration, we aim to provide valuable insights into the potential of WSNs in enabling smart and sustainable solutions for a better- connected world.

1. Introduction

The rapid rise of wireless sensor networks (WSNs) has revolutionized the way we interact with our environment and leverage the power of the Internet of Things (IoT). WSNs consist of a large number of spatially distributed autonomous sensors that collaborate to collect and transmit data wirelessly. These networks find applications in diverse domains, including environmental monitoring, healthcare, agriculture, industrial automation, smart cities, and disaster management. By seamlesslyintegrating sensing, communication, and computing capabilities, WSNs provide a versatile platform for gathering valuable information, enabling real-time decision- making, and optimizing resource utilization [2]. In this introduction, we emphasize the transformative nature of

* *Corresponding author.*
E-mail address: ehteshamali23@gmail.com

https://doi.org/10.37934/ctds.5.1.5059a

wireless sensor networks in our everyday lives. We highlight the key components of WSNs, which are autonomous sensors that collect data and communicate wirelessly on the inter- net. These sensors are distributed across different locations, enabling comprehensive coverage and data collection. Also, these sensors have expanded on the broad range of domains where WSNs are employed, showcasing their versatility and applicability [3]. Furthermore, WSNs have a great significance in the context of the Internet of Things (IoT), which refers to the interconnection of various devices and systems through the Internet. WSNs play a pivotal role in the IoT ecosystem by providing a means to collect and transmit data from physical environments to digital platforms [4]. This enables seamless integration and analysis of data, leading to improved decision- making and enhanced efficiency in various applications. The primary objectives of WSNs include collecting valuable information, enabling real-time decision-making, and optimizing resource utilization. These objectives are achieved through the integration of sensing, communication, and computing capabilities within WSNs. The sensors collect data from the environment, communicate wirelessly to transmit the data and utilize computing resources for processing and analysis as mentioned by Bogena *et al.,* [1]. By establishing the context and significance of WSNs in the introduction, we set the stage for the subsequent sections of the paper, which delve into the specific applications of WSNs in different domains.

2. Application Of Wireless Sensor Networks (WSNS)

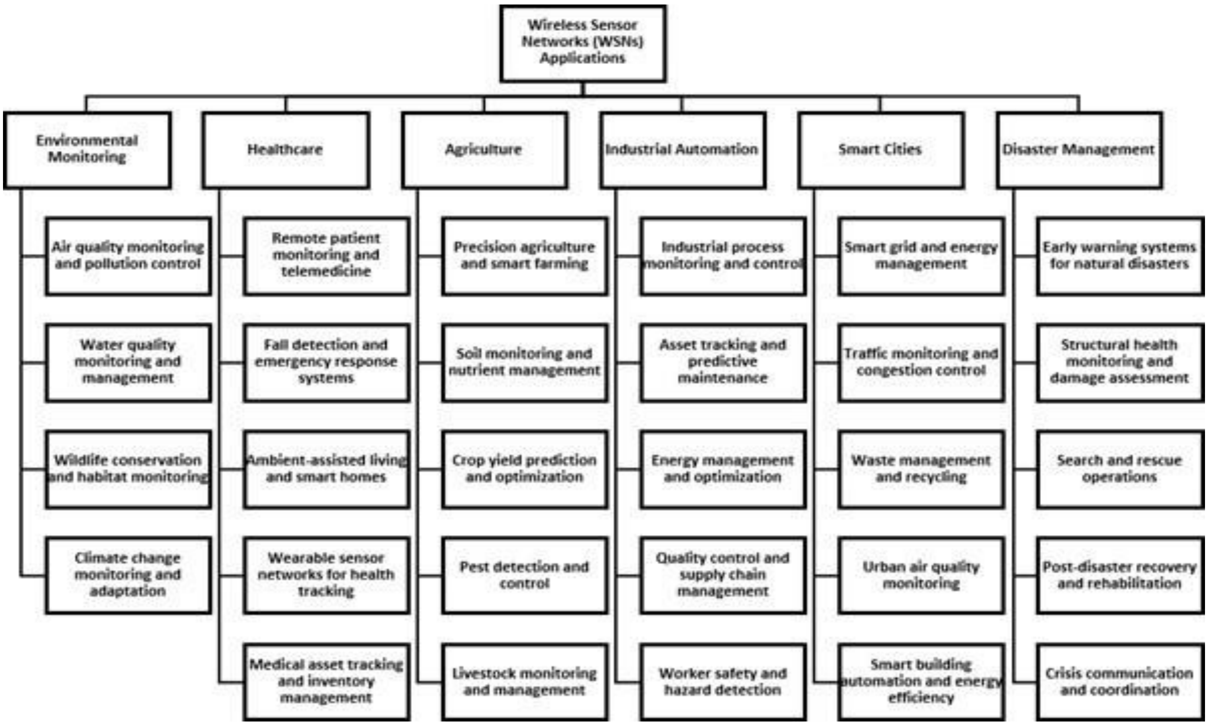

Fig. 1. Application-based classification of Wireless Sensor Networks (WSNs)

2.1 Environmental Monitoring

Environmental monitoring involves the data collection, data analysis, and data interpretation related to the environment. This collected data helps to assess the current condition of natural resources, to track the changes over time, and to make decisions about the management and conservation of resources. Some of the applications for environmental monitoring in various sub sectors include:

2.1.1 Air quality monitoring and pollution control:

Wireless Sensor Networks (WSNs) equipped with air quality sensors are crucial in monitoring pollutant levels in the atmosphere. They can detect and measure various pollutants like particulate matter, carbon monoxide, nitrogen dioxide, and ozone. By deploying sensor nodes in urban areas or near pollution sources, WSNs contribute to various important air quality and control applications like pollution control, urban planning, and public health initiatives [5].

2.1.2 Water quality monitoring and management:

Wireless Sensor Networks (WSNs) play a great role in the continuous monitoring of water bodies such as rivers, lakes, and oceans. By employing sensors to measure parameters like pH, dis- solved oxygen, temperature, and turbidity, WSNs can assess water quality and detect potential sources of contamination.

2.1.3 Wildlife conservation and habitat monitoring:

Tracking and monitoring wildlife, particularly endangered species like tigers, is crucial for ecological preservation. However, traditional methods involving sedation to record vital signs often harm animals and their habitats. Hence, WNS has emerged as a trend to secure and improve wildlife creatures [6].

2.1.4 Climate change monitoring and adaptation:

Wireless Sensor Networks (WSNs) are utilized in climate change monitoring by collecting data on various environmental parameters such as temperature, humidity, rainfall patterns, and atmospheric conditions.

2.1 Healthcare
2.2.1 Wireless sensor networks (WSNs) play a transformative role in healthcare:

Applications such as remote patient monitoring, fall detection, ambient-assisted living, health tracking, and medical asset tracking are various utilizations for the same. WNS's potential game-changing effects on patient care and healthcare administration have improved the medical industry a lot.

2.2.2 Remote patient monitoring and telemedicine:

Wireless sensor networks (WSNs) have been utilized in enabling remote patient monitoring through wearable sensors and medical devices. This allows continuous monitoring and transmission of vital signs to healthcare professionals, facilitating timely intervention and personalized care. WSNs are particularly beneficial for patients with chronic conditions or those in remote areas, as they enable remote consultations and telemedicine services [7].

2.2.3 Fall detection and emergency response systems:

Emergency incidents can occur unpredictably, posing challenges for complications or even fatalities. Wireless Sensor Networks (WSNs) can detect falls among vulnerable individuals, triggering alerts to caregivers or emergency response systems so that they can respond in advance before any fetal incidents happen.

2.2.4 Ambient-assisted living and smart homes:

Wireless Sensor Networks (WSNs) integrated with smart home technologies enable ambient-assisted living for the elderly and individuals with disabilities. Sensor nodes monitor daily activities, detect anomalies, and provide necessary assistance or alerts. This promotes independence, improves the quality of life, and ensures a safe living environment.

2.2.5 Wearable sensor networks for health tracking:

Wireless Sensor Networks (WSNs) in the form of wearable devices collect and transmit data on physical activity, sleep patterns, and overall health. These devices facilitate the monitoring of fitness goals, track progress, and provide feedback, encouraging healthier lifestyles and preventive healthcare. Wearable technology has significantly impacted remote patient management and healthcare delivery by enabling real-time data collection, enhancing accuracy, and informing decision- making [8].

2.2.6 Medical asset tracking and inventory management:

Wireless Sensor Networks (WSNs) are valuable for tracking medical assets in healthcare facilities, including equipment, medication, and supplies. By attaching sensor nodes to these assets, real-time tracking becomes possible, optimizing inventory management, reducing costs, and ensuring availability.

2.3. Agriculture
2.3.1 Precision agriculture and smart farming:

Wireless Sensor Networks (WSNs) play an important role in precision agriculture by monitoring soil moisture, temperature, and nutrient levels. Sensor nodes deployed in fields provide real- time data that helps farmers optimize irrigation, fertilizer application, and crop management practices. This promotes efficient resource utilization, improves yields, and fosters sustainable farming practices [9].

2.3.1 Soil monitoring and nutrient management:

Wireless Sensor Networks (WSNs) are instrumental in soil monitoring, collecting data on soil moisture, pH levels, and nutrient content. This data empowers farmers to make informed decisions regarding irrigation, fertilization, and soil management, optimizing crop growth while minimizing the environmental impact.

Crop yield prediction and optimization: Crop yield prediction and optimization using Wireless Sensor Networks (WSNs) involve deploying sensor nodes in agricultural fields to collect data on environmental parameters. This data is used to develop predictive models for estimating crop yield based on current conditions.

2.3.2 Pest detection and control:

Wireless Sensor Networks (WSNs) with sensors are capable of detecting pest activity in agricultural fields. By monitoring environmental factors such as temperature, humidity, and pest behavior, WSNs enable early detection of pests [10].

2.3.3 Livestock monitoring and management:

Wireless Sensor Networks (WSNs) play a key role in monitoring the health and behavior of livestock animals. Sensor nodes attached to animals collect data on parameters like body temperature, activity levels, and feeding patterns. This data aids in early disease detection, optimizing feeding strategies, and ensuring animal welfare. The Internet of Things (IoT) has the potential to transform agriculture by providing real-time data on crop and livestock conditions.

2.4 Industrial Automation

2.4.1 Industrial process monitoring and control:

WSNs enable real-time monitoring of industrial processes by collecting data on parameters like temperature, pressure, and flow rates. This data aids in process optimization, predictive maintenance, and ensuring safe and efficient operations [11].

2.4.2 Asset tracking and predictive maintenance:

WSNs can track and monitor industrial assets, such as machinery and equipment. Sensor nodes attached to these assets collect data on performance, enabling predictive maintenance and reducing costly downtime.

2.4.3 Energy management and optimization:

WSNs help optimize energy usage in industrial settings by monitoring energy consumption patterns, identifying energy wastage, and suggesting energy-saving measures. This contributes to cost reduction and promotes sustainable energy practices.

2.4.4 Quality control and supply chain management:

WSNs aid in quality control by monitoring product parameters and ensuring compliance with standards. Additionally, WSNs can track and monitor goods throughout the supply chain, providing real-time visibility and improving logistics efficiency [12].

2.4.5 Worker safety and hazard detection:

WSNs enhance worker safety in industrial environments by monitoring factors such as temperature, humidity, gas levels, and noise. Sensor nodes detect hazardous conditions and send alerts, enabling timely interventions and preventing accidents.

2.5 Smart Cities

2.5.1 Smart grid and energy management:

WSNs play a crucial role in smart grid systems by monitoring energy distribution, managing power usage, and optimizing grid operations. This enables efficient energy management, load balancing, and integration of renewable energy sources.

2.5.2 Traffic monitoring and congestion:

WSNs provide real-time traffic data through sensors deployed in road networks. This data aids in traffic management, congestion control, and optimization of transportation systems for im- proved efficiency and reduced travel time]. Waste management and recycling: WSNs assist in waste management by monitoring waste levels in containers and optimizing waste collection routes. This reduces costs, minimizes environmental impact, and promotes recycling and sustainable waste management practices [13].

2.5.3 Urban air quality monitoring:

WSNs equipped with air quality sensors monitor pollution levels in urban areas. This data helps in assessing air quality, identifying pollution sources, and implementing measures to improve urban air quality and public health. Smart building automation and energy efficiency: WSNs integrated with building automation systems enable efficient control of lighting, heating, ventilation, and air conditioning (HVAC) systems. This promotes energy efficiency, occupant comfort, and cost savings in buildings [14].

2.6 Disaster Management

2.6.1 Early warning systems for natural disasters:

WSNs facilitate the early detection and warning of natural disasters such as earthquakes, tsunamis, and floods. Sensor nodes deployed in high-risk areas detect seismic activity, water levels, and other relevant parameters, providing timely alerts to authorities and residents.

2.6.2 Structural health monitoring and damage assessment:

WSNs monitor the health and integrity of structures such as bridges and buildings. Sensor nodes measure factors like vibrations, strain, and temperature, aiding in structural health monitoring, damage assessment, and maintenance planning.

2.6.3 Search and rescue operations:

WSNs play a crucial role in search and rescue operations during disasters. Sensor nodes equipped with location-tracking capabilities aid in locating survivors, assessing risks, and coordinating rescue efforts in challenging environments.

2.6.4 Post-disaster recovery and rehabilitation:

WSNs assist in post-disaster recovery by collecting data on factors like environmental conditions, infrastructure damage, and resource needs. This information helps in planning and implementing effective rehabilitation strategies, ensuring a speedy recovery [15].

2.6.5 Crisis communication and coordination:

Crisis communication and coordination using Wireless Sensor Networks (WSNs) involve using sensor nodes for real-time data col- lection and communication during crises. WSNs enable situational awareness, efficient communication among responders, and timely decision-making. They facilitate monitoring of environmental conditions, exchange of critical information, resource allocation, and coordination of rescue efforts. WSNs also aid in the early detection of crises and issuing warnings. Overall, WSNs enhance crisis response and management by enabling effective communication and coordination among emergency responders.

2.7 Challenges and Issues

Various types of challenges and issues among wireless sensor networks in the Era of IoT include [16]:

*2.7.1 Design based challenges***:**
2.7.1.1 Scalability:

Scalability maintains the rules we define. It keeps the WNS working and management effective and efficient even when networks get bigger or complex. Scalability ensures a road system of network flows to work smoothly, no matter how complex the networks flow on it. In simple words, WNS should be scalable. As the networks expand, the devices get closer to each other, hence the management can become more complicated and tough to handle the issues and complexities WNS must keep the communication efficient even when there is more demand.

2.7.1.2 Fault Tolerance:

Wireless sensor networks and their nodes (SNs) are mostly deployed in harsh setups, which is more prone to frequent hardware issues and failures. Therefore, to ensure network functions properly, all protocols must swiftly detect and should be resilient to these failures, even in the face of high-node dropout rates caused by various unknown factors.

2.7.1.3 Affordable Production:

As many WSNs' and their nodes are treated as disposable. However, cost-effective production is vital for network viability and existence. Keeping sensor nodes feasible is important to compete with conventional methods of data collection [17].

2.7.1.4 Hardware Constraints:

Each sensor node and its Net- work requires hardware components such as transmitters, sensors, power sources and processors. Moreover, more features enhance functionality but also, they increase power consumption and cost. Hence, there should be a controlled balancing of added functionality via hardware with low-power demands and cost [18].

2.7.1.5 Optimizing Energy:

Energy constraints are always a challenge. Saving energy in comparison with maintaining the topology of the networks is key to energy optimization.

2.7.1.6 Effective Communication:

All WNS nodes communicate using optical, radio or infrared methods. Effective and optimal communication channels have to be chosen based on reliability and interference.

2.7.1.7 Power Management:

Minimizing the power resources, an efficient energy utilization is important. There should be a balance to maintain tasks such as data compression for radio transmission efficiently while not ignoring the computation costs.

2.7.2 Interoperability

Interoperability is a key concern in the IoT landscape. The presence of interoperability issues among IoT platforms can lead to economic threats. Effective solutions are needed to address these challenges and ensure seamless communication among diverse IoT systems. This situation can result in inefficiencies and increased costs. Establishing standards and protocols for interoperability is essential to unlock new opportunities, enhance efficiency, and drive innovation in the IoT ecosystem [19].

2.7.3 Security and Privacy:

Wireless Sensor Networks (WSNs) are tailored for specific applications, adapting their protocols to meet application requirements and environmental conditions. These protocols are designed to efficiently complete tasks using minimal network information. This approach is necessary due to the limited processing power and energy resources of the network nodes. Security and privacy are paramount concerns in WSNs. The protection of user data is of utmost priority. However, there’s a noticeable gap in this domain, possibly due to the lack of well-defined security standards. It the solutions are feasible; it will help to enhance their reliability for various applications.

2.7.4 Protocols:

Wireless Sensor Networks (WSNs) are crafted to suit applications. The protocols within WSNs are customized to meet the unique demands of the application and the environment where the events take place. These protocols are ingeniously designed to make the most of minimal network information to accomplish their tasks. This strategic approach is vital due to the constrained processing capability and energy resources of the nodes within the network [20].

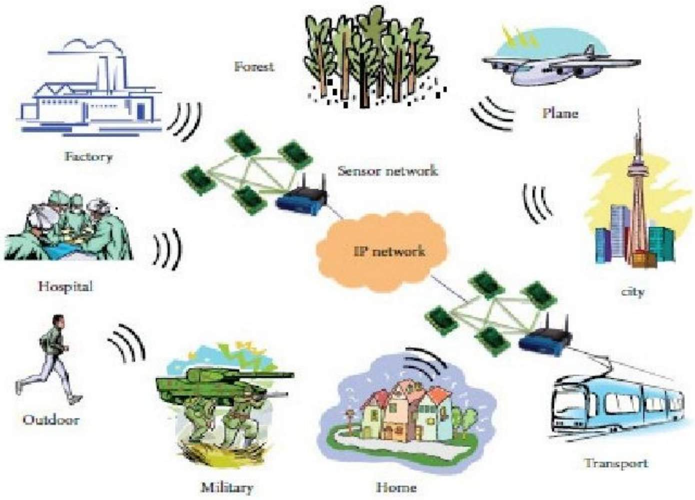

Fig. 2. Wireless Sensor Network Overview

3. Discussion

In the field of wireless sensor networks (WSNs) and their common issues, there's a range of programming methods and techniques devised to tackle the challenges at hand. These methods primarily delve into the nitty-gritty of low- level system intricacies. Yet, there's an equally vital aspect to consider—simplifying the design and implementation of WSNs, moving beyond the complexities of technical details. This is where high-level procedures (HLB) come into play, offering a streamlined approach to address these challenges.

In the realm of WSNs, certain pivotal issues need attention to ensure their efficiency and effectiveness. One such issue is interoperability, which ensures that devices from different manufacturers can seamlessly work together. Moreover, it's crucial to establish robust security and privacy measures to safeguard the sensitive data transmitted within the network. Additionally, well-defined protocols act as guidelines governing how devices communicate and share information effectively.

By addressing these challenges and striking a balance between low-level technicalities and broader procedural approaches, the evolution of WSNs holds the promise of enhancing their utility across various domains.

4. Conclusion

Wireless Sensor Networks have a profound impact on various domains, playing a crucial role in shaping smart and sustainable solutions in the era of IoT. By harnessing the power of WSNs, we can address critical challenges, enhance operational efficiency, and promote sustainable practices. However, deploying WSNs in real-world applications also presents several challenges, such as network scalability, energy efficiency, data management, and security. Addressing these challenges will pave the way for wider adoption and effective utilization of WSNs, further fueling innovation and advancements in the field. Researchers, industry professionals, and policymakers must collaborate and develop robust solutions to leverage the full potential of WSNs in shaping a better-connected world.

References

[1] Bogena, Heye R., Johan A. Huisman, C. Oberdörster, and Harry Vereecken. "Evaluation of a low-cost soil water content sensor for wireless network applications." *Journal of Hydrology* 344, no. 1-2 (2007): 32-42. https://doi.org/10.1016/j.jhydrol.2007.06.032

[2] Lin, Jen-Yung, Huan-Liang Tsai, and Wei-Hong Lyu. "An integrated wireless multi-sensor system for monitoring the water quality of aquaculture." *Sensors* 21, no. 24 (2021): 8179. https://doi.org/10.3390/s21248179

[3] Simbeye, Daudi S., and Shi Feng Yang. "Water quality monitoring and control for aquaculture based on wireless sensor networks." *Journal of networks* 9, no. 4 (2014): 840. https://doi.org/10.4304/jnw.9.4.840-849
[4] Tan, Yen Kheng, and Sanjib Kumar Panda. "Review of energy harvesting technologies for sustainable wsn, sustainable wireless sensor network." *and Yen Kheng Tan (Editor-in-Chief), Available at: http://www. intechopen. com/articles/show/title/review-of-energyharvesting-technologies-for-sustainable-wsn* (2011). https://doi.org/10.5772/13062
[5] Zhang, Qing Song. "Environment pollution analysis on smart cities using wireless sensor networks." *Strategic Planning for Energy and the Environment* (2023): 239-262. https://doi.org/10.13052/spee1048-5236.42112
[6] Ndagi, Abubakar, and Csaba Zoltan Kertesz. "Automatic Water Distribution System Using Wireless Sensor Network." In *2023 27th International Conference on Information Technology (IT)*, pp. 1-4. IEEE, 2023. https://doi.org/10.1109/IT57431.2023.10078653
[7] Polasi, Phani Kumar, S. Aishwarya, P. Kruthika, and Mohammed Kaif Momin. "An IoT-based duplex mode Remote Health Monitoring System." In *2023 International Conference on Recent Advances in Electrical, Electronics, Ubiquitous Communication, and Computational Intelligence (RAEEUCCI)*, pp. 1-5. IEEE, 2023. https://doi.org/10.1109/RAEEUCCI57140.2023.10134141
[8] Mendes, Lucas F., Paulo AC Aguilar, and Carla IM Bezerra. "Software Architecture for IoT-based Indoor Positioning Systems for Ambient Assisted Living." In *2023 IEEE 20th International Conference on Software Architecture (ICSA)*, pp. 93-104. IEEE, 2023. https://doi.org/10.1109/ICSA56044.2023.00017
[9] Bassine, Fatima Zahra, Terence Epule Epule, Ayoub Kechchour, and Abdelghani Chehbouni. "Recent applications of machine learning, remote sensing, and iot approaches in yield prediction: a critical review." *arXiv preprint arXiv:2306.04566* (2023).
[10] Sivadevuni, Sreeparnesh Sharma, and Sathish Kumar Ravichandran. "Tracking and Localization of Devices-An IoT Review." In *2023 International Conference on Inventive Computation Technologies (ICICT)*, pp. 1321-1325. IEEE, 2023. https://doi.org/10.1109/ICICT57646.2023.10134278
[11] Mourtzis, Dimitris, John Angelopoulos, and Nikos Panopoulos. "Design and development of an IoT enabled platform for remote monitoring and predictive maintenance of industrial equipment." *Procedia Manufacturing* 54 (2021): 166-171. https://doi.org/10.1016/j.promfg.2021.07.025
[12] Paunikar, Shil Sudhir, and Anil Vanalkar. "Block Chain Scada Quality Control for in Industrial Automation." *International Journal for Research in Applied Science and Engineering Technology* 11, pp. 1171-1174. https://doi.org/10.22214/ijraset.2023.48705
[13] Epela, Bernard, Audace Manirabona, and Fulgence Nahayo. "iITLMA, an intelligent traffic light management algorithm based on wireless sensor networks." *Wireless Personal Communications* 131, no. 1 (2023): 1-11. https://doi.org/10.1007/s11277-023-10236-3
[14] Deng, Zhihang, Minshui Huang, Neng Wan, and Jianwei Zhang. "The current development of structural health monitoring for bridges: a review." *Buildings* 13, no. 6 (2023): 1360. https://doi.org/10.3390/buildings13061360
[15] Majid, Mamoona, Shaista Habib, Abdul Rehman Javed, Muhammad Rizwan, Gautam Srivastava, Thippa Reddy Gadekallu, and Jerry Chun-Wei Lin. "Applications of wireless sensor networks and internet of things frameworks in the industry revolution 4.0: A systematic literature review." *Sensors* 22, no. 6 (2022): 2087. https://doi.org/10.3390/s22062087
[16] Al-Thobhani, Nashwan Saeed Ghaleb, Amerah Alnamany, Maryam Mansour, and Eatmad Alhmati. *Wireless Body Area Networks for Healthcare*. No. 8874. EasyChair, 2022.
[17] Elangovan, Muniyandy, D. Surrya Prakash, and P. Sasidharan. "Monitoring of Workplace Safety Using IoT." In *Journal of Physics: Conference Series*, vol. 2115, no. 1, p. 012014. IOP Publishing, 2021. https://doi.org/10.1088/1742-6596/2115/1/012014
[18] Jamshed, Muhammad Ali, Kamran Ali, Qammer H. Abbasi, Muhammad Ali Imran, and Masood Ur-Rehman. "Challenges, applications, and future of wireless sensors in Internet of Things: A review." *IEEE Sensors Journal* 22, no. 6 (2022): 5482-5494. https://doi.org/10.1109/JSEN.2022.3148128
[19] Deng, Zhihang, Minshui Huang, Neng Wan, and Jianwei Zhang. "The current development of structural health monitoring for bridges: a review." *Buildings* 13, no. 6 (2023): 1360. https://doi.org/10.3390/buildings13061360
[20] Epela, Bernard, Audace Manirabona, and Fulgence Nahayo. "iITLMA, an intelligent traffic light management algorithm based on wireless sensor networks." *Wireless Personal Communications* 131, no. 1 (2023): 1-11. https://doi.org/10.1007/s11277-023-10236-3