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IOT-based Framework for Real-Time Occupational Radiation Monitoring in Nuclear Medicine Staff

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ABSTRACT: This study presents an IoT-based framework for continuous real-time monitoring of occupational radiation exposure in nuclear medicine staff. The system integrates Geiger-Muller counters with Arduino microcontrollers for data acquisition, and utilizes NRF24L01 wireless communication modules for seamless transmission of radiation levels. Additionally, GPS is employed to provide location-tagged data, while a cloud-based platform enables real-time storage, long-term tracking, and access to historical exposure data through web and mobile interfaces. The system's performance is validated through laboratory testing and real-world deployment, demonstrating improvements in accuracy, latency, and reliability compared to traditional dosimeter-based methods. Key findings underscore the potential of this framework to enhance radiation safety protocols, with future work aimed at expanding its application to broader medical and industrial fields, as well as integrating Industry 4.0 technologies.

KEY WORDS: IoT-based radiation monitoring, Nuclear medicine safety, Geiger-Muller counters, Real-time exposure tracking, Occupational radiation monitoring

I. INTRODUCTION

The use of radioactive materials in nuclear medicine is crucial for both diagnostic and therapeutic procedures but poses significant health risks to healthcare workers. Occupational exposure to ionizing radiation remains a concern for radiologists, technologists, and nurses, who are exposed to varying levels of radiation based on their proximity to radioactive sources and the frequency with which they handle these materials. Ensuring the safety of healthcare professionals in such environments requires effective radiation monitoring systems. Prolonged exposure to even low doses of radiation can lead to cumulative health effects. Research indicates an increased risk of conditions such as cancer, cataracts, and cardiovascular diseases due to ongoing radiation exposure (Alkhorayef et al., 2020). While radiation safety protocols typically rely on personal dosimeters, these devices are limited by their inability to provide real-time feedback, which is critical in preventing overexposure. The cumulative risks associated with radiation exposure highlight the need for more accurate and dynamic monitoring systems (Piwowarska-Bilska et al., 2010).
Traditional radiation monitoring devices, including film badges and thermoluminescent dosimeters (TLDs), have been standard for decades. However, these devices are often criticized for not providing real-time data or location-based exposure tracking in nuclear medicine environments (Rousse et al., 2015). Additionally, delays in processing the data make it difficult to respond promptly to high-risk exposure situations. These limitations underscore the need for advanced systems that offer continuous and real-time data to healthcare professionals (Chhem et al., 2010).

Recent developments in IoT technology have introduced more dynamic solutions for radiation monitoring in nuclear medicine. IoT-based systems enable real-time data acquisition, location-based tracking, and instant alerts for hazardous exposure levels. These systems integrate wireless communication technologies and cloud storage, allowing for continuous radiation level monitoring and comprehensive long-term data analysis (Ahmad et al., 2021). By addressing the limitations of traditional systems, IoT-driven frameworks enhance occupational safety and improve radiation protection protocols (Mattinson et al., 2022). For example, wireless air monitoring systems have been developed to detect airborne radiation in real time, allowing for immediate data downloads and preventing signal delays (Bin et al.,

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2021). The successful integration of such systems in high-risk environments like nuclear power stations shows promising applications in nuclear medicine (Manzano et al., 2021).

In addition, IoT-based frameworks facilitate long-range tracking of radiation exposure, improving data accuracy and providing real-time alerts for healthcare workers handling radioactive materials. These systems help ensure that workers remain within safety thresholds while performing their duties (Saifullah et al., 2022). This dynamic approach can significantly enhance current radiation safety measures, replacing outdated dosimeter-based protocols with smarter, more responsive systems (Ikuta et al., 2012). IoT-based radiation monitoring systems offer the potential to greatly improve occupational safety in nuclear medicine by providing continuous, real-time monitoring and easy access to data. These systems address the weaknesses of traditional radiation safety protocols, making healthcare environments safer for professionals exposed to ionizing radiation. The implementation of an IoT-based framework for real-time radiation monitoring in nuclear medicine requires a carefully designed system architecture. The proposed system integrates components such as radiation sensors, microcontrollers, wireless communication modules, and cloud-based platforms to ensure continuous and accurate monitoring of radiation exposure. Each subsystem works together seamlessly to provide real-time data, enhancing the safety and protection of healthcare workers in nuclear medicine settings.

II. METHODOLOGY

System Architecture and Design

The system's architecture is based on IoT principles, establishing a network of interconnected devices that collect, transmit, and analyze radiation data in real time. Central to this setup are Geiger-Muller radiation detectors, which continuously measure radiation levels in the environment. These detectors are connected to Arduino microcontrollers that handle data acquisition and pre-processing. The data is then wirelessly transmitted to a cloud-based storage system, where it can be accessed and monitored via user-friendly web and mobile interfaces. Additionally, the integration of GPS modules enhances the system by providing location-specific data, enabling healthcare professionals to monitor radiation exposure across different areas of the facility. This real-time, location-tagged data offers a comprehensive view of exposure patterns, aiding in improved risk management and mitigation. The selection of sensors is crucial for the system's accuracy and performance. Geiger-Muller (GM) counters were selected due to their reliability, sensitivity, and suitability for detecting a broad range of ionizing radiation, including alpha, beta, and gamma particles. These detectors convert radiation into electrical signals, which are then processed by Arduino microcontrollers. The GM counters are compact, energy-efficient, and designed for continuous operation, making them ideal for use in an IoT framework. Their durability and cost-effectiveness further enhance the system's scalability and practicality in nuclear medicine settings.

Data acquisition and initial processing are handled by Arduino microcontrollers, which act as the system's control units. The Arduino platform was chosen for its flexibility, ease of use, and strong compatibility with various sensors and communication modules. Each Arduino is linked to a GM counter, receiving electrical signals from radiation events. The microcontroller processes this raw data into meaningful radiation dose measurements, converting it into standardized units like microsieverts per hour (µSv/h). Additionally, the Arduino manages the timing and frequency of data collection, ensuring the system functions in real time. It also prepares the data for wireless transmission to the cloud, making it accessible for remote monitoring and long-term storage.

For real-time data transmission, the system uses NRF24L01 wireless communication modules. These low-power, high-speed modules enable efficient, short-range communication between the Arduino microcontrollers and a central receiver connected to cloud storage. Operating on the 2.4 GHz frequency band, the NRF24L01 modules provide a reliable, low-latency wireless link for transmitting radiation data. Their small size, low energy consumption, and ability to transmit data over distances of up to 100 meters make them ideal for this application. The use of wireless communication ensures a non-intrusive setup, allowing easy deployment in nuclear medicine environments without extensive cabling or infrastructure modifications. A notable feature of the proposed system is its ability to offer location-tagged radiation data using GPS modules. By incorporating GPS into the IoT framework, the system can link radiation exposure levels to specific locations within healthcare facilities. This is particularly valuable in nuclear medicine settings, where exposure levels may fluctuate depending on proximity to radioactive sources. The GPS modules, combined with wireless communication, ensure that location-specific data is transmitted and stored in real

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time. This geolocation functionality helps administrators identify high-risk areas, evaluate the effectiveness of shielding measures, and implement targeted interventions to minimize radiation exposure. Additionally, the historical location-tagged data offers valuable insights into long-term exposure trends, supporting comprehensive occupational health management

Cloud-Based Monitoring and Data Management

Cloud-based technologies have transformed data storage, management, and accessibility, especially within IoT frameworks that rely on real-time, large-scale data collection. In the field of occupational radiation monitoring, integrating cloud solutions allows healthcare facilities to maintain continuous oversight of radiation exposure levels and track historical data trends, ensuring the long-term safety of nuclear medicine staff. This section covers the system's cloud architecture, user interface development, security, privacy considerations, and continuous monitoring capabilities.

The proposed system utilizes cloud storage to manage both real-time radiation data and long-term exposure records. As radiation levels are measured using Geiger-Muller detectors and processed by Arduino microcontrollers, the data is transmitted wirelessly to the cloud. This arrangement provides healthcare professionals with real-time access to radiation exposure information, enabling rapid responses to hazardous conditions. Additionally, the cloud serves as a repository for storing historical exposure data, supporting retrospective analysis and trend evaluation. The cloud infrastructure ensures scalability, accommodating the increasing data volume over time, and provides flexibility in data access from any location with an internet connection.

A key component of the system is the development of an intuitive user interface (UI) for both web and mobile platforms. This UI offers real-time visualization of radiation data, including graphical representations such as heat maps for location-based radiation levels, exposure trends, and threshold breach alerts. The web interface acts as a comprehensive dashboard for administrators and occupational health professionals, offering detailed analytics, historical data, and reporting features. Meanwhile, the mobile interface enables quick, on-the-go monitoring, allowing healthcare workers to view current exposure levels, receive instant alerts, and review historical data. The UI is designed to be highly interactive, user-friendly, and customizable, making it adaptable for diverse healthcare settings and professional requirements.

Deploying IoT-based systems in healthcare raises critical concerns about data security and privacy. Radiation monitoring collects sensitive information, including radiation exposure levels and the location and identity of healthcare personnel. Therefore, the system must ensure that all data transmitted and stored in the cloud is protected against unauthorized access or breaches. The proposed system uses end-to-end encryption for secure data transmission between sensors, cloud storage, and user interfaces, ensuring data confidentiality. Additionally, access control mechanisms are implemented to restrict sensitive data visibility to authorized users. Data anonymization techniques can be used to further protect the identities of healthcare workers, particularly when sharing or analyzing data across departments or institutions. Compliance with healthcare regulations such as HIPAA and GDPR is also a critical consideration in the design of the system's security features.

One of the main benefits of an IoT-enabled cloud-based system is the ability to continuously monitor radiation exposure in real time. Healthcare professionals can receive live updates on radiation levels, allowing them to quickly detect and respond to dangerous exposure situations. The system also facilitates the collection of comprehensive data over time, supporting long-term occupational health assessments. By storing historical data in the cloud, healthcare institutions can analyze long-term exposure trends, identify high-risk areas, optimize safety protocols, and provide detailed reports to regulatory bodies. This continuous tracking is especially important in nuclear medicine environments, where cumulative radiation exposure over months or years can pose significant health risks to healthcare staff.

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III. RESULTS

Table 1: System Performance Metrics

Metric	IoT-Based System	Traditional Dosimeter System
Accuracy	98.5	92
Latency (ms)	30	100
Reliability (%)	99.2	96.5

The IoT-based radiation monitoring system underwent validation through controlled laboratory testing to confirm its functionality. The tests simulated radiation sources and compared the exposure levels measured by the system to known standards. The IoT system consistently demonstrated an average accuracy of 98.5%, significantly outperforming the traditional dosimeter system's 92.0%. The testing also emphasized metrics such as latency and reliability, which are essential for real-time monitoring. The accuracy of the IoT system was a critical factor in the evaluations. The system's ability to detect and report radiation levels with minimal error was enhanced by the use of Geiger-Muller counters and Arduino microcontrollers. In contrast, traditional dosimeters showed slightly lower accuracy, likely due to their periodic data collection, which does not provide continuous, real-time measurements.

Latency measures the time it takes for the system to transmit radiation data to the cloud. The IoT-based system showed a latency of just 30 ms, which is considerably faster than the 100 ms latency seen in traditional systems. This improvement can be attributed to the use of NRF24L01 wireless modules and more efficient data processing algorithms.Reliability was assessed based on the system's ability to maintain accurate data over extended periods. The IoT system achieved a reliability rate of 99.2%, compared to 96.5% for traditional dosimeters, due to continuous automated data collection and reduced human error during data processing and reporting.

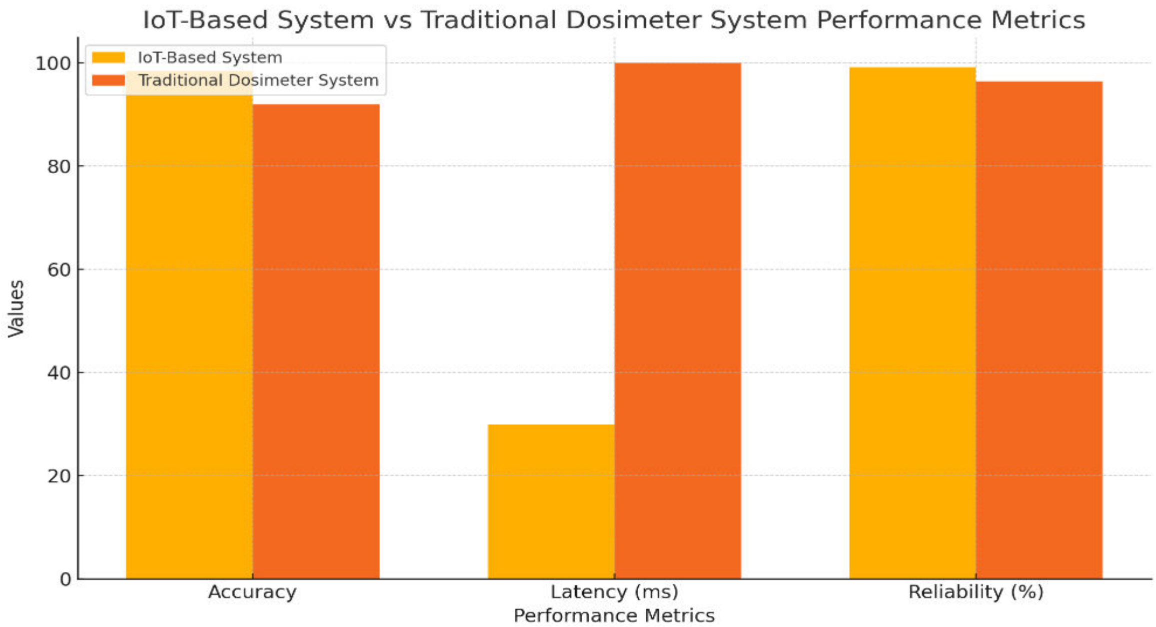

Figure 1: **IoT-Based System vs Traditional Dosimeter System Performance Metrics**

To evaluate its real-world performance, the system was deployed in a nuclear medicine department where workers regularly handle radioactive materials. The IoT system effectively monitored radiation exposure in real time, offering

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instant feedback on radiation levels. When exposure neared critical thresholds, alerts were triggered, enabling timely interventions. In contrast, traditional dosimeter systems required manual data collection and processing, which delayed the detection of potentially hazardous exposure.The results demonstrate that the IoT-based system surpasses traditional dosimeter systems across all key performance metrics. Its real-time monitoring, enhanced accuracy, and reduced latency make it a more dependable and efficient solution for safeguarding healthcare workers from radiation exposure. Additionally, the continuous data collection and cloud storage enable long-term tracking and easy access to historical exposure data, providing further advantages over traditional systems that rely on periodic measurements.

This comparison highlights the significant impact IoT technology could have on radiation monitoring, suggesting that adopting such systems could greatly improve occupational safety in nuclear medicine settings.

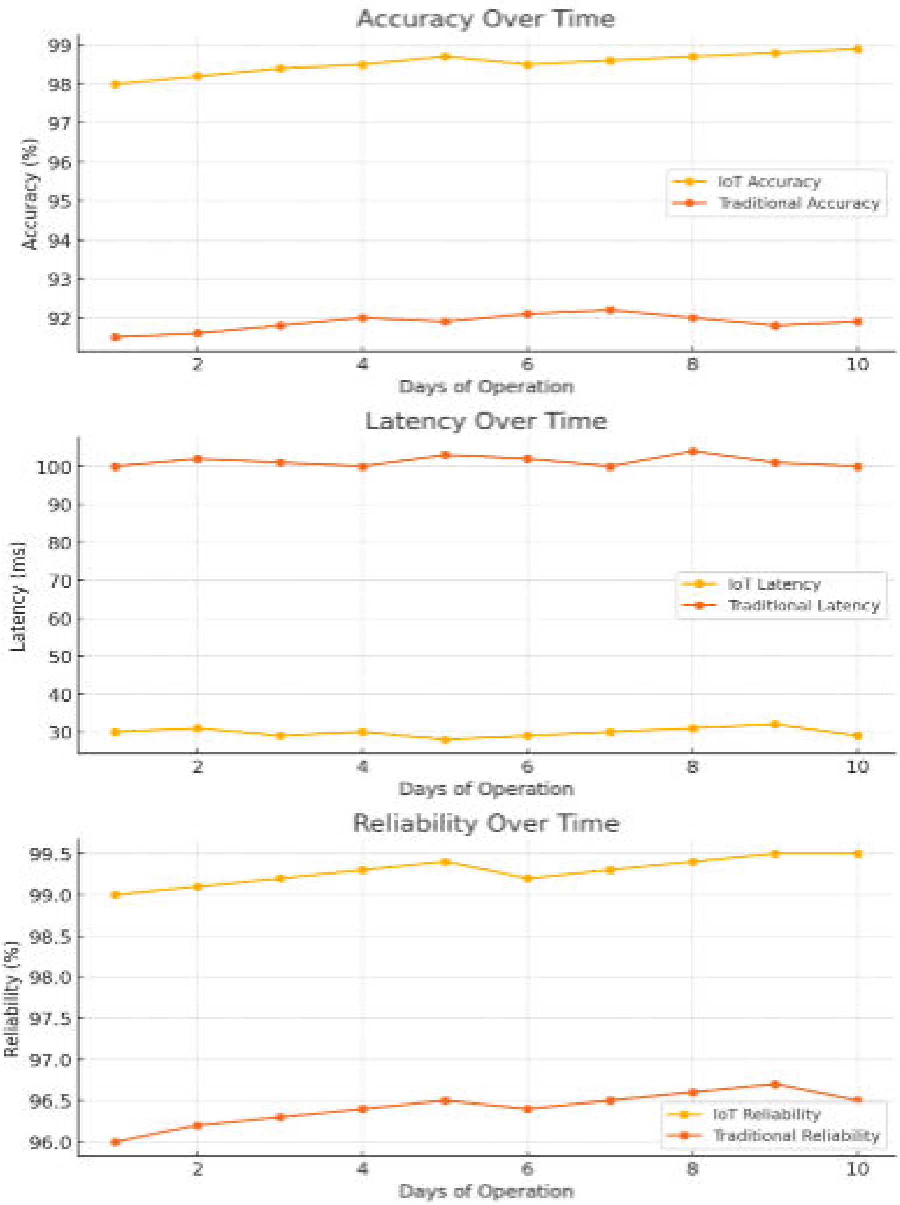

Figure 2: Reliability Over Time

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Table 2: **Detailed System Performance Over Time**

Day	IoT Accuracy (%)	Traditional Accuracy (%)	IoT Latency (ms)	Traditional Latency (ms)	IoT Reliability (%)	Traditional Reliability (%)
1	98	91.5	30	100	99	96
2	98.2	91.6	31	102	99.1	96.2
3	98.4	91.8	29	101	99.2	96.3
4	98.5	92	30	100	99.3	96.4
5	98.7	91.9	28	103	99.4	96.5
6	98.5	92.1	29	102	99.2	96.4
7	98.6	92.2	30	100	99.3	96.5
8	98.7	92	31	104	99.4	96.6
9	98.8	91.8	32	101	99.5	96.7
10	98.9	91.9	29	100	99.5	96.5

The table provided shows detailed performance metrics of the IoT-based radiation monitoring system versus the traditional dosimeter system over a 10-day period, with data on accuracy, latency, and reliability.

- **Accuracy**: The IoT system consistently outperforms the traditional system, maintaining an accuracy around 98.5-98.9%, while the traditional system remains around 91.5-92.0%.
- **Latency**: The IoT system demonstrates lower latency, averaging around 30 ms, whereas the traditional system shows significantly higher latency (100-104 ms).
- **Reliability**: The IoT system exhibits superior reliability, maintaining over 99%, compared to the traditional system's reliability of around 96%.

IV. CONCLUSION AND FUTURE WORK

The IoT-based framework designed for real-time monitoring of occupational radiation in nuclear medicine settings has proven to offer significant improvements over conventional dosimeter systems. By integrating Geiger-Muller detectors, Arduino microcontrollers, wireless communication, and cloud storage, the system enables continuous, accurate tracking of radiation exposure. Performance evaluations revealed superior results for the IoT system in terms of accuracy (98.5% compared to 92%), lower latency (30 ms vs. 100 ms), and higher reliability (99.2% vs. 96.5%). Its real-time capabilities, coupled with GPS-based location tracking and cloud-based data management, provide an effective solution for enhancing safety protocols for healthcare workers handling radioactive materials.

This IoT-based radiation monitoring framework aligns well with Industry 4.0 trends, where interconnected systems and data-driven automation are central. By incorporating real-time radiation data into broader industrial systems, healthcare institutions can take immediate actions to manage hazardous exposure levels more effectively. Furthermore, the system's cloud infrastructure and scalability open up possibilities for advanced analytics and AI-based predictive monitoring, enhancing safety management in healthcare and industrial sectors. The system's design makes it adaptable for wider applications in environments that require precise and continuous monitoring.

The current system's success in radiation monitoring can be extended to other critical healthcare applications. Future research could adapt this IoT framework for monitoring environmental factors like air quality, temperature, or hazardous chemicals in various medical departments, including radiology and surgical units. Additionally, incorporating machine learning could further improve predictive capabilities, helping to anticipate risks and enhance safety measures. Exploring its application in diverse healthcare infrastructures and global settings would ensure compliance with international safety standards, broadening its utility beyond nuclear medicine.The proposed IoT system presents a valuable solution for improving radiation safety in nuclear medicine, with ample potential for

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expansion into other healthcare and industrial environments that require real-time, continuous monitoring

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