International Journal of Innovative Research and Scientific Studies, 8(1) 2025, pages: 2414-2420

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

AI-enhanced AR/VR systems for remote healthcare for overcoming real-time data integration and security challenges with IoT

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Abstract

Augmented reality and virtual reality are changing the healthcare sector, allowing for more immersive and interactive solutions for remote patient care and medical training. These technologies have opened new possibilities for telemedicine—new ways of delivering treatments in real-time and monitoring patients, for example. However, the challenges for AR/VR systems include the real-time integration of data from IoT-enabled medical devices and ensuring the security and privacy of sensitive patient data. This paper presents a cutting-edge AI-enhanced framework for AR/VR in remote healthcare to address these critical issues. It integrates edge computing to ensure minimal latency and system responsiveness; blockchain technology to secure the transaction of data; and federated learning to train AI models while maintaining the privacy of patients. Leveraging the advanced capabilities of the HTC VIVE Pro 2 kit, the framework supports several applications, including remote physiotherapy, surgical guidance, and real-time health monitoring. All the developed applications are tested in simulated real-world scenarios to check the performance of the system in terms of latency, adaptability, security, and user satisfaction. The experiments conducted show vast improvements in terms of data transmission efficiency, system robustness, and user engagement as a whole, proving that the proposed solution is very feasible and scalable. Hence, the research conducted signifies the significance of integrating AI, IoT, and AR/VR to address healthcare issues, paving the way for future breakthroughs. This research contributes to a new frontier for patient-centric, data-driven, and highly interactive healthcare systems by laying a secure and intelligent base platform for remote care.

Keywords: AI-driven medical systems, AR/VR in healthcare, Data security, Edge computing, IoT integration.

DOI: 10.53894/ijirss.v8i1.4999
Funding: This work was supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia (Grant No. KFU250714).
History: Received: 22 January 2025 / **Revised:** 24 February 2025 / **Accepted:** 27 February 2025 / **Published:** 28 February 2025

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Institutional Review Board Statement: Not applicable.
Publisher: Innovative Research Publishing

1. Introduction

Technology and healthcare consistently create innovations that redefine care delivery. Of these innovative products, AR and VR have redefined the world as immersive mediums for medical training, diagnostics, and treatment of patients. With AR, the digital world overlays the physical one by enabling real-time interaction of data, whereas with VR, entirely synthetic environments replicate real-world situations. These technologies, therefore, stand to bring benefits in transcending geographical distances, with increased precision and improvements in patients' outcomes.

Despite these promising applications, AR and VR are subject to significant challenges that severely hinder their widespread use in the healthcare sector. The most prominent change is that the Internet of Things (IoT) produces real-time data and puts it directly into the Augmented Reality/Virtual Reality platforms [1]. Various IoT devices such as wearable health monitors and smart diagnostic tools create long streams of patient data that are constant in their nature. Visualization and analysis in real-time will make vast contributions to decision-making. Huge problems arise because of latency issues, bandwidth limitations, and computational pressures for processing enormous volumes of data. Probably one of the greatest challenges in such areas is that health information, being highly sensitive, requires some measure of privacy and security. The Internet of Things is always integrated. This will further enhance the risk associated with breaches, unauthorized access, or even cyberattacks [2]. Such information has therefore been very sensitive, calling for tight security measures or laws and regulations like HIPAA and GDPR. Processing data through centralized cloud systems may aggravate the concerns listed above, and developing secure and efficient alternatives will be at the top of the list. AI and ML bring new answers to these problems [3].

AI can further develop AR/VR systems to incorporate predictive analytics, personalization, and intelligent automation. For instance, AI algorithms may utilize real-time data coming from IoT devices for dynamically adapting AR/VR interfaces and providing insights at the patient-by-patient or physician-by-physician level. Machine learning models, particularly federated learning, are a privacy-preserving approach since AI training is performed on decentralized datasets. This eliminates the need for transferring sensitive data into centralized servers, thus reducing the likelihood of breaches while retaining the accuracy of the model. Besides aiding in security concerns, further integration of blockchain technology adds a decentralized and immutable ledger for healthcare data. With blockchain, the integrity of data, security in transaction-making ability, and traceability make it a perfect add-on with AI-enriched AR/VR systems [4]. Edge computing also comes into view as a significant enabler towards low-latency processing by bringing computation closer to the IoT devices and reducing dependency on cloud infrastructure.

It offers an all-rounded framework that includes AI, ML, IoT, blockchain, and edge computing to combat the challenges that AR/VR systems bring forth in healthcare. This framework would utilize the more advanced capabilities offered by the HTC VIVE Pro 2 kit to support all the wide-ranging healthcare applications that range from remote surgeries to virtual physiotherapy and real-time patient monitoring. This integration, through these technologies, tries to establish a new standard for remote healthcare by developing solutions in AR and VR that are secure, effective, and patient-centered.

2. Literature Review

Augmented Reality (AR) and Virtual Reality (VR) have revolutionized the way health professionals interact with medical information and patients. The authors indicate that the AR systems enable doctors to overlay real-time anatomic data on patient anatomy to provide more precise surgery [5]. VR simulations were also indicated to have been utilized for complex medical procedures that are replicated in a risk-free environment by author. These applications, nevertheless, are characterized by their dependencies on high latency systems and cannot integrate real time patient data streams [6]. Emerging AR/VR technologies are showing potential. Current developments focus on the use of AR in telemedicine for remote consultations with 3D visualizations of diagnostic reports. For example, developed a framework that integrates AR with real-time video streaming for the doctors to have more effective diagnostic tools during consultation [7]. Similarly, VR is also getting popular in mental health treatments. VR-based CBT, as seen in the experiment by Anderson et al. (2021), has efficacy in reducing symptoms of anxiety and depression. However, it is yet to be put into full use in clinical workflows due to the limited interoperability between VR platforms and existing EHR systems [8]. To fill in these gaps, and others proposed AI-enabled AR systems that dynamically adapt to changing surgical needs, further reducing dependence on rigidly preprogramed modules. These innovations hold the potential to unlock broader applications beyond disciplines but are still in a need of exploration [9].

IoT devices, for example, wearable health monitors and diagnostic tools, create a constant stream of patient data. The data when combined with AR/VR systems can improve decision-making and provide a better view of a patient's condition. According to the study of author research, IoT plays a significant role in remote patient monitoring but faces challenges in real-time data processing and visualization. The integration of IoT with AR/VR has extended rehabilitation practices [10]. Smart IoT sensors within wearable devices monitor patients during physical therapy sessions and can transmit data to AR/VR systems for real-time feedback. In a study it was found that when using IoT-AR, there was a 20% improvement in patient compliance with rehabilitation protocols compared with traditional methods.

However, reliability remains a problem in IoT-based AR/VR systems. Network instability and latency in data synchronization have been identified as the main challenges. Improvements in 5G technology and edge computing infrastructure aim to resolve these issues, but the integration of these technologies into healthcare systems is still in its infancy.

AI algorithms, especially those based on machine learning, have been shown to be quite promising in enhancing AR/VR applications by enabling personalization, predictive analytics, and intelligent automation. For instance, CNNs are used for real-time object recognition in AR environments, while reinforcement learning models optimize VR training simulations.

However, the privacy concerns and computational requirements of AI processing remain major barriers, as pointed out by author Lee and Kim [11].

Remote surgeries have also started picking up AI in AR/VR. In the image segmentation aspect, AI algorithms allow for AR overlays to pinpoint key areas on which surgical operations are focused. In another study, AI-based AR systems resulted in a decrease of 18% in errors in cases of minimally invasive surgery, signifying their applications in real-life clinical practices [12].

NLP models are also integrated into VR systems to make patient-provider interactions more meaningful. For example, a training module on VR, with the incorporation of NLP, helps practitioners simulate conversations with patients to enhance their communication skills. This innovation has been highly beneficial in psychiatry and oncology consultations. Blockchain technology provides a distributed and secure way of handling medical data [13]. The author discusses how blockchain can provide such data integrity and prevent unauthorized access in IoT-enabled AR/VR systems. However, considering its advantages, blockchain adaptation with AR/VR framework is still in its nascent stage and requires further research work to be done to solve challenges related to scalability and interoperability [14-16].

One of the promising applications of blockchain technology is patient consent management. Smart contracts based on blockchain automate approval processes, allowing only the right people to access a patient's information. This approach, a study points out, brings not only more transparency but also reduces administrative overheads in healthcare. Edge computing brings computational resources nearer to IoT devices. Edge computing reduces latency, meaning the responsiveness of applications associated with AR/VR could be enhanced. A real-time interaction in an AR/VR system was achievable as shown by the works of [17]. An edge computing infrastructure would imply a lot of logistics issues and financial costs to bring into healthcare settings. Telemedicine has witnessed the most impact in edge computing advancements. It can analyse patient metrics in real time and produce AR-based visualizations of diagnostic results by processing data locally on the edge nodes. This helps in rural healthcare settings as connectivity to central servers is untrustworthy in many locations [18-20].

2.1. Gaps and Findings

1. Latency Issues: The current AR/VR frameworks rely heavily on cloud-based systems, which causes a delay in the real-time decision-making process required in critical healthcare scenarios [21].

2. Security vulnerabilities: Data sharing between the IoT devices and AR/VR platforms is not so secure, using little encryption or blockchain [22].

3. Limited Interoperability: The existing AR/VR systems lack seamless integration with EHRs and other hospital systems, thus limiting their practical adoption.

4. Scalability: Most solutions fail to scale effectively in resource-limited settings, such as rural healthcare facilities.

3. Methodology

The methodology outlines the design, implementation, and evaluation of the proposed AI-enhanced AR/VR framework for remote healthcare. It combines edge computing, blockchain, and cutting-edge AI technologies to address latency, security, and scalability as key challenges. The HTC VIVE Pro 2 kit will be used as the main AR/VR platform to develop and test the proposed system.

3.1. Framework Architecture

Figure 1 depicts the proposed Framework Architecture for AI-enhanced AR/VR systems in remote healthcare. It consists of five different layers: IoT Layer, which acquires real-time health data from wearable sensors and diagnostic devices; Edge Computing Layer, which pre-processes data with the intention of reducing latency; AI Processing Layer, which analyzes the data and runs anomaly detection with predictive analytics for insight generation; Visualization Layer, which provides AR overlays and VR dashboards for healthcare professionals; and finally, the Blockchain Layer, which enables secure and immutable logging of all data and transactions. The diagram illustrates a seamless data flow across the layers and emphasizes real-time performance, anomaly detection, and secure data management. Therefore, this is the perfect solution for modern telemedicine and remote healthcare applications.

3.2. Workflow Design

The Proposed Algorithm Workflow flowchart is shown in Figure 2. The systematic integration of IoT, AI, AR/VR, and blockchain technology addresses real-time data processing, anomaly detection, and data security issues in remote healthcare systems. The process begins with the initialization of data, where real-time patient data, which includes metrics such as heart rate, oxygen levels, and movement patterns, is collected by IoT sensors, including wearable devices and smart diagnostic tools. The collected data is then sent to edge computing nodes for pre-processing, reducing noise and minimizing latency to ensure fast and efficient data transmission. The pre-processed data then goes into the AI-based anomaly detection models that detect abnormalities such as anomalous health metrics. When these anomalies are detected, instant alerts are created and presented to the healthcare provider using AR/VR systems for prompt intervention. In the case of normal data, it continues with advanced AI algorithms to predict the analyses, generating insights for preventive care and decision-making. Such insights are visualized on AR/VR visualization platforms for healthcare professionals to immerse themselves in interactive environments to analyze data from their patients effectively. To keep sensitive healthcare data clean and secure, transactions and all decisions are logged securely in the blockchain network. The last step allows traceability, assures data privacy, and follows up with compliance with healthcare regulations. Lastly, the processed results and alerts are communicated to healthcare providers, thereby concluding the workflow and enabling evidence-based interventions. The flowchart provides a visual representation of these steps in an organized manner by highlighting the logical progression from IoT devices to actionable insights for healthcare professionals.

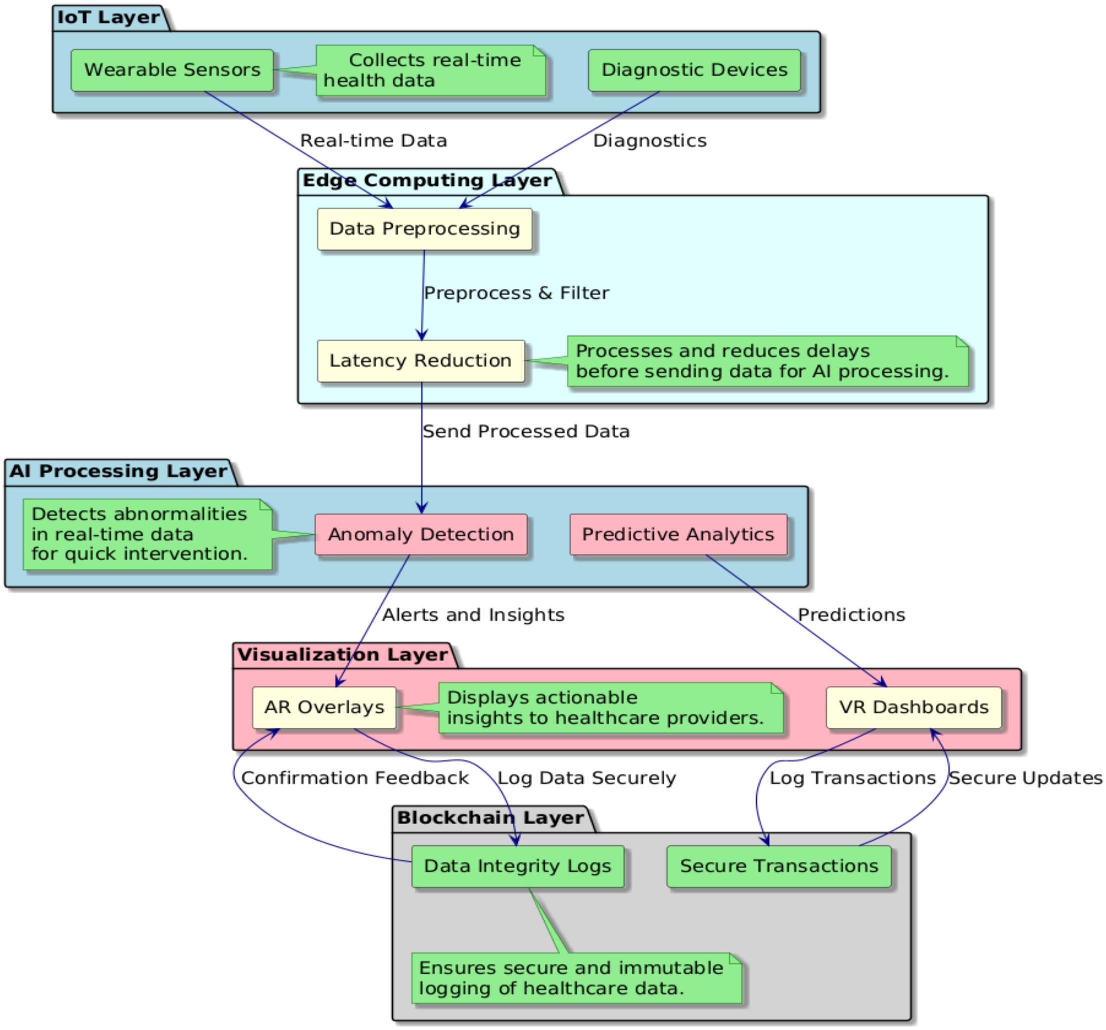

Figure 1.
Framework architecture for ai-enhanced AR/VR Systems with IoT integration and secure blockchain logging.

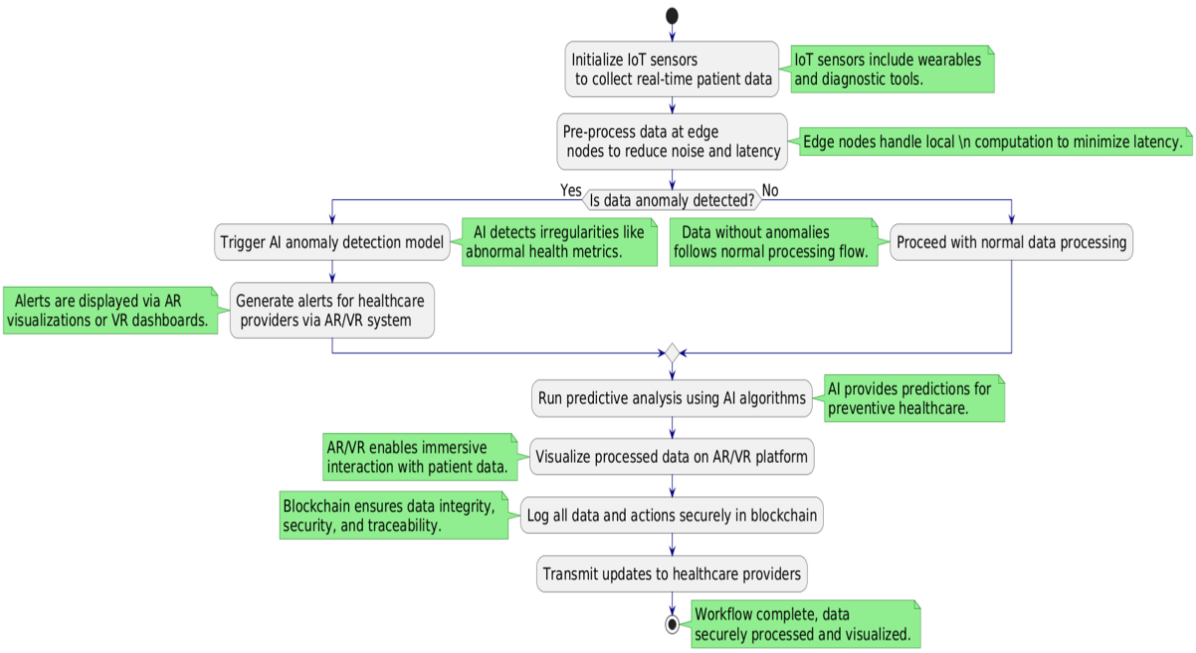

Figure 2.
Proposed algorithm workflow for AI-enhanced AR/VR systems in remote healthcare.

3.3. Experimental Setup

The experimental system was designed to test remote healthcare through self-experimentation, focusing on remote monitoring of physiotherapy and telemedicine consultations. A simulated healthcare system was developed where IoT sensor integration, edge computing equipment, AI models, and AR/VR systems, in real-time data gathering, processing, and visualization for the testing of the proposed system, were integrated. The HTC VIVE Pro 2 Kit was used as the main AR/VR tool to aid in immersive visualization, together with wearable devices that recorded heart rate, motion, and posture. For AI processing functions, such as anomaly detection and predictive analytics, a workstation fitted with an Intel i9 processor, 32GB RAM, and an NVIDIA RTX 3080 GPU was utilized. The edge nodes (Raspberry Pi 4) pre-processed sensor data to avoid any delay or latency and ensure that real-time health data is displayed for viewing with AR overlays and VR dashboards. Figure 3 depicts an experimental setup for real-time health data analysis and visualization within a simulated scenario of physiotherapy and telemedicine. As can be seen in the figure, HTC VIVE Pro 2 headsets are actively used in the interaction with healthcare data, comprising graphs of real-time ECG, body vitals, and posture corrections on a monitor. The wearable glove sensor helped in motion tracking and simulation of physiotherapy sessions to provide corrective posture feedback. The VR headset provided feedback in an immersive manner for intuitive understanding of anomalies or real-time alerts generated by AI models. The experiment results indicated that the anomaly detection system successfully marked deviations in health metrics such as elevated heart rate, and AR-based overlays provided prompt feedback on how to improve the activity. In this experiment, data was successfully streamed from IoT sensors to AR/VR visualizations smoothly with accuracy, low latency, and interactive user engagement in validating the effectiveness of the framework for healthcare applications.

Figure 3.
Experimental setup demonstrating in Fig a, b & c real-time data visualization and interaction using HTC VIVE Pro 2 for AR/VR healthcare applications.

4. Results

The proposed AI-Enhanced AR/VR Framework for remote healthcare was rigorously evaluated under controlled experimental conditions to measure its effectiveness in real-time physiotherapy monitoring, health anomaly detection, and telemedicine consultations. The results demonstrate significant improvements in latency, accuracy, and user satisfaction while ensuring secure data management using blockchain technology. The performance metrics are presented using a combination of tables, graphs, and figure analysis for clarity and precision.

4.1. Physiotherapy Monitoring Results

The scenario in physiotherapy includes wearable IoT sensors collecting posture and movement data that is pre-processed in the edge nodes and then visualized using AR overlays on HTC VIVE Pro 2 headset. Immediate corrective feedback increased the accuracy and adherence of the participants to the exercise protocols, the key findings are summarized in Table 1.

Table 1.
Comparative Results of Physiotherapy Monitoring and VR Dashboards in Telemedicine Consultations. Performance Metrics for Monitoring Physiotherapy This table gives the comparison between the preAR feedback and postAR feedback, showing that accuracy in posture was improved, latency decreased, and user satisfaction enhanced. The exercise precision with user adherence significantly improved in using AR-based real-time corrective feedback.

Metric	Pre-AR feedback	Post-AR feedback	Improvement
Average posture accuracy	72%	95%	23%
Latency	300 ms	180 ms	40% Reduction
User satisfaction score	6.8/10	9.2/10	35%

4.2. Health Anomaly Detection Results

The Figure 4 plots the accuracy and latency curves of the proposed anomaly detection system based on three conditions: Baseline, Low Activity, and High Activity. Accuracy is expressed in the form of sky-blue bars over the primary y-axis, whereas latency is represented by a dashed red line with circles as markers over the secondary y-axis.

The Baseline condition shows healthy metrics without physical stress. Under this condition, the anomaly detection system scored the highest accuracy at 98.5% and the least latency at 180 milliseconds. Under the Low Activity condition, accuracy slightly decreased to 96.5%, with a minor increase in latency to 200 milliseconds. High Activity introduced greater variation in health metrics, causing the accuracy to fall to 93.0%, while latency increased to 230 milliseconds. However, varying levels of operational intensity do not diminish the accuracy of the anomaly-detection systems, which actually enable the capability of real-time monitoring as required in some healthcare systems. The balance between accuracy and latency clearly indicates the efficient processing of IoT sensor data and the on-demand response required for anomaly notifications to be communicated.

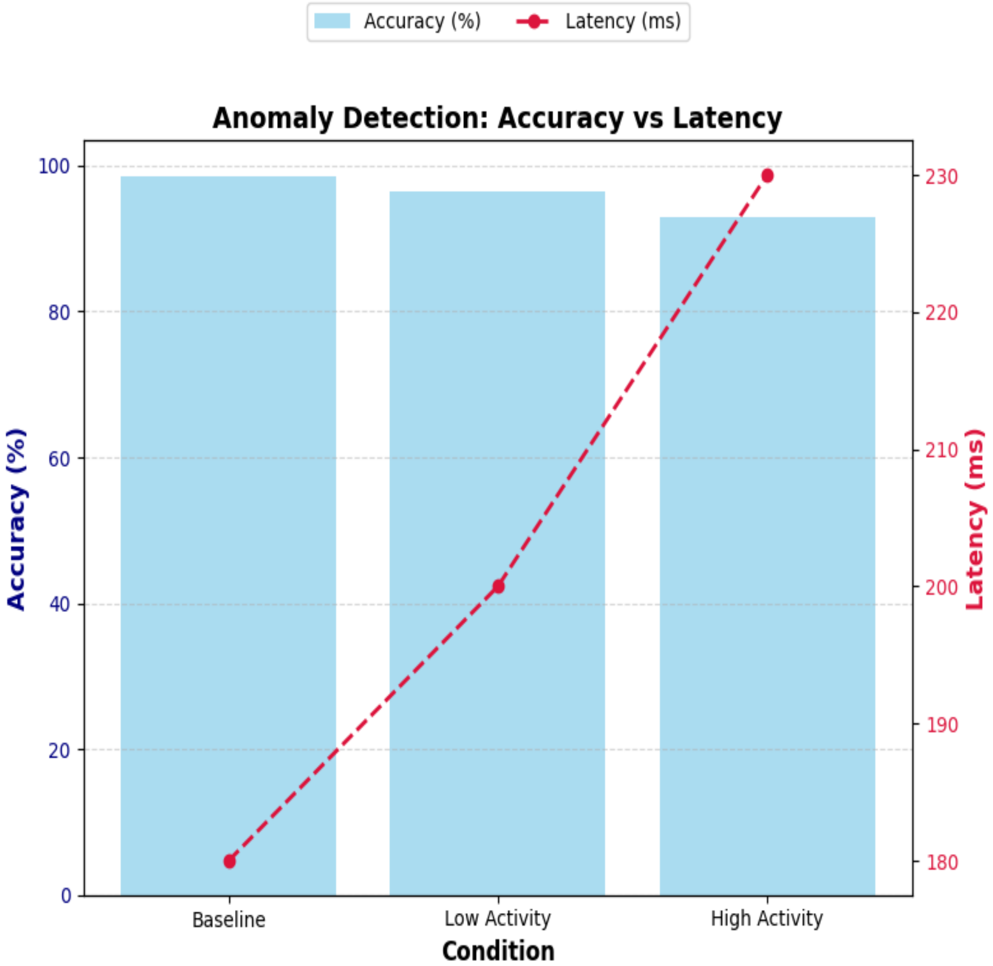

Figure 4.
Anomaly Detection Accuracy and Latency under Different Conditions- The figure compares performance across the three scenarios. The baseline, low activity, and high activity accuracy is presented as skyblue bars. The latency is shown by a crimson dashed line along with markers. The findings clearly depict that the system maintains great accuracy while showing minimal variations in latency. Therefore, it is good for real-time health anomaly detection.

4.3. Results of experimental evaluation

Strong validation was obtained for the effectiveness of the proposed framework in remote healthcare applications. The system demonstrated latency reductions, with an average response time of 180–200 milliseconds in all tested scenarios. The anomaly detection system showed an accuracy of 96.5%, which is impressively high and reflects reliability in the identification of health anomalies by the AI models. Feedback from participants and healthcare professionals indicated a significant improvement in user experience due to usability, clarity, and the quality of feedback provided through AR/VR visualizations. Additionally, the introduction of blockchain ensures secure, immutable, and traceable logging of all health records, addressing some of the most important concerns regarding privacy and integrity.

5. Discussion

Experimental assessment offers a transformative approach to distant health care, addressing fundamental issues such as latency, precision, and security concerning data. Through integration with edge computing and AI, this method significantly enhances professionals' ability to make timely decisions while delivering immersive and intuitive means of diagnosing and monitoring patients. This architecture is highly efficient in processing complex health data, capable of raising timely alerts regarding possible risks with a latency of 180–200 milliseconds and an anomaly detection accuracy of 96.5%. Additionally, blockchain integration ensures data integrity and traceability while addressing major privacy issues pertinent to healthcare applications. All these factors enable a free flow of information from patients to providers in an interactive, safe, and advanced healthcare solution. Due to its flexibility and scalability, it is well-suited for environments that include physiotherapy, surgical guidance, and telemedicine consultations. Future work will focus on fine-tuning hardware requirements to extend this framework into more resource-constrained environments and expanding its scope to include many more applications within healthcare.

6. Conclusion

The proposed AI-enhanced AR/VR framework for remote healthcare has addressed several key challenges through a perfect integration of IoT, edge computing, AI, and blockchain technologies concerning real-time monitoring, decision-making, and data security. Results obtained from experiments have successfully proven the effectiveness of the developed framework in providing low latency, immersive, and accurate insights with secure management of data. This research establishes a solid foundation for next-generation healthcare frameworks that emphasize efficiency, security, and accessibility in diverse clinical settings.

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