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Integrating Big Data and Edge Computing for Enhancing AI Efficiency in Real-Time Applications

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Abstract
Integrating Big Data and Edge Computing is revolutionizing the efficiency of artificial intelligence (AI) systems, particularly in applications requiring real-time responses. This study explores the synergistic role of these technologies in two critical sectors: autonomous vehicles and healthcare. Using a case study approach, real-world datasets and simulation platforms were employed to evaluate improvements in latency, prediction accuracy, and system efficiency. Key findings reveal that Edge Computing reduces latency by 30%, with response times dropping from 150 ms to 105 ms in autonomous vehicles and from 200 ms to 140 ms in healthcare applications. Additionally, leveraging Big Data for AI training enhanced prediction accuracy by 15% for traffic pattern recognition and 12% for patient condition monitoring. Despite these advancements, challenges such as scalability, data security, and interoperability persist, necessitating robust infrastructure and end-to-end encryption solutions. This research highlights the transformative potential of combining Big Data and Edge Computing to optimize AI systems for real-time applications, offering insights into improving operational efficiency and predictive accuracy. The findings are expected to guide future developments in AI technologies, particularly in the context of expanding 5G networks and growing demand for real-time data processing.

Keywords: *Edge Computing, Big Data Integration, AI Efficiency, Real-Time Processing.*

I. INTRODUCTION

The revolution in information technology has ushered in substantial changes across various industry sectors, particularly with the advent of Artificial Intelligence. AI has evolved into a core element of digital transformation, offering solutions that enhance efficiency and enable large-scale data analysis and faster decision-making (Blinova et al., 2022). However, these advancements have introduced new challenges, such as the need for swift and secure real-time data processing, especially in sectors requiring rapid responses like transportation, healthcare, and manufacturing. In this context, Big Data and Edge Computing play a pivotal role as key solutions to address these challenges. These technologies significantly improve the performance of AI systems by enabling fast and efficient data processing (Hallioui et al., 2022).

Big Data, which refers to vast and diverse data volumes generated by various devices such as Internet of Things (IoT) sensors, social media platforms, and other digital devices, has become a critical pillar in data-driven innovation (Chahal et al., 2022). The exponential growth of data necessitates more efficient management and analysis techniques to yield valuable insights. Simultaneously, Edge Computing offers the capability to process data close to its source, reducing latency and enabling real-time responses. Edge Computing is increasingly relevant due to the growing demand for rapid data processing and responsive decision-making in applications such as autonomous vehicles and AI-based healthcare systems (Fawzy et al., 2022).

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Autonomous vehicles are one of the primary sectors that benefit significantly from the integration of Big Data and Edge Computing. These vehicles must respond swiftly to environmental changes, such as road and traffic conditions, to avoid accidents and ensure passenger safety (McEnroe et al., 2022). In this context, Edge Computing enables faster data processing within the vehicle itself, eliminating the need to send data to a distant data center. This reduces latency and allows the vehicle's AI system to make real-time decisions, which is critical in emergencies. Meanwhile, Big Data provides large data volumes necessary for training AI models to improve accuracy in traffic pattern recognition, risk prediction, and adaptation to various road conditions (Bathla et al., 2022). The combination of these technologies enhances the efficiency and safety of autonomous vehicles.

In the healthcare sector, Edge Computing also makes significant contributions to AI-dependent medical devices. Wearable IoT medical devices used by patients can collect vital data in real-time, and with the support of Edge Computing, this data can be processed quickly to provide early warnings to medical personnel (Syu et al., 2023). This is crucial in emergency medical situations, where time is vital in saving patients' lives. Big Data, in turn, plays a key role in predictive analysis that supports more accurate medical decision-making, such as predicting patient health conditions based on extensive medical history and real-time sensor data (Hartmann et al., 2022).

Despite the promising benefits of integrating Big Data and Edge Computing, technical and non-technical challenges persist. One primary challenge is the need for adequate infrastructure to support data processing at the network edge (Chavhan et al., 2022). This infrastructure requires substantial investments in both hardware and software, as data must be processed and stored across multiple distributed nodes. Additionally, data protection and privacy present another challenge. Processing data across numerous nodes increases the risk of data breaches and cyber-attacks. Data security has become a top priority, particularly in sectors like healthcare, which involves highly sensitive patient data (Chiaradonna et al., 2023). Hence, the development of more advanced security solutions is essential to mitigate these risks.

Beyond security challenges, managing complexity and ensuring interoperability among various devices and platforms also present obstacles (Albouq et al., 2022). Every device connected to the network, whether a sensor in an autonomous vehicle or a medical device in a hospital, must communicate seamlessly with other devices to ensure smooth data flow. Insufficient interoperability can lead to delays in data processing and reduce system efficiency. Therefore, better standards are needed to ensure compatibility and coordination among devices within the IoT ecosystem that supports AI (Abdelmaboud et al., 2022).

This study aims to explore how integrating Big Data and Edge Computing can enhance AI system efficiency in two major sectors: autonomous vehicles and healthcare. It examines how these technologies can reduce latency, improve predictive accuracy, and optimize AI system responses to various real-time scenarios. Additionally, the study identifies the key challenges faced in implementing these technologies and proposes practical solutions to address them.

Through a case study approach focusing on autonomous vehicles and healthcare, this study provides in-depth insights into how Big Data and Edge Computing can be applied to solve real-world problems. For instance, in autonomous vehicles, these technologies can be used to accelerate responses to sudden road condition changes, while in healthcare, they can help provide early warnings for patients in critical conditions. The findings of this study are expected to make a significant contribution to the future development of AI technology, especially in applications requiring real-time responses and efficient data processing.

II. LITERATURE REVIEW

Big Data and Edge Computing have become two fundamental pillars in supporting the development of AI systems (Stadnicka et al., 2022). Big Data provides vast, diverse, and rapidly generated volumes of data, while Edge Computing enables data processing to occur closer to its source, thereby reducing latency. Together, these technologies play a crucial role in enhancing the speed and accuracy of AI, particularly in applications requiring real-time responses, such as autonomous vehicles and healthcare (Khan et al., 2022).

Big Data Technology

Big Data refers to large, diverse, and quickly changing datasets (Berisha et al., 2022). In the AI context, Big Data serves as a primary resource for training AI models, enabling AI to recognize more complex patterns (Alahakoon et al., 2023). The three main characteristics of Big Data, known as the "3Vs" — Volume, Velocity, and Variety — highlight the importance of efficient data management in handling large-scale data (Milli & Milli, 2023).

Research by Awotunde et al. (2022) demonstrates the role of Big Data in prediction and analysis, particularly during the COVID-19 pandemic, where large volumes of data were used to analyze societal behaviors and predict virus spread (Awotunde et al., 2022). However, this study also highlights challenges in Big Data management, such as the need for adequate technological infrastructure to store and analyze data. Another challenge lies in data privacy and security, as large-scale data processing and storage make it increasingly vulnerable to cyber-attacks (Ogbuke et al., 2022).

To maximize Big Data’s potential in AI, companies, and organizations must develop more efficient data analysis systems to filter relevant data. Excessive data without effective filtering can lead to information overload and slow decision-making processes (Li et al., 2022). Consequently, Big Data requires sophisticated techniques for effective and secure data analysis.

Edge Computing Technology

Edge Computing is a paradigm where data processing is performed closer to the data source, such as on IoT devices or sensors, rather than sending it to distant data centers. This approach significantly reduces latency and supports applications that require real-time responses. In autonomous vehicles, Edge Computing plays an essential role in enabling vehicles to quickly and accurately respond to changing road conditions (Bajaj et al., 2022). A study by Sandu & Susnea (2021) found that Edge Computing can reduce latency by 30% in autonomous vehicles compared to cloud-based systems (Sandu & Susnea, 2021).

One of the main advantages of Edge Computing is the reduced load on data centers by processing some data at the network edge (Caiazza et al., 2022). In healthcare, Edge Computing allows medical devices to issue early warnings about changes in a patient's condition, enabling healthcare professionals to respond more promptly and accurately (Rajavel et al., 2022). Additionally, latency reduction helps increase AI system efficiency in time-sensitive applications, such as autonomous vehicles and medical devices (Unal et al., 2022).

However, challenges faced by Edge Computing include costly infrastructure and data security concerns. Since data processing occurs across distributed nodes, the risk of data breaches increases. Therefore, further efforts are needed to develop adequate infrastructure and security technologies to address these challenges (Fazeldehkordi & Grønli, 2022).

Integration of Big Data and Edge Computing for AI

The combination of Big Data and Edge Computing holds immense potential to optimize AI systems (Bourechak et al., 2023). Big Data provides extensive datasets for training AI models, while Edge Computing enables rapid data processing and reduces latency—critical factors for applications requiring real-time responses. For example, in autonomous vehicles, the integration of these technologies allows AI systems to respond more accurately and swiftly to changes in road conditions (Iftikhar et al., 2023).

A study by Zhu et al. (2022) found that using Big Data to train AI models in autonomous vehicles enhances prediction accuracy by up to 15%. Edge Computing enables local sensor data processing, allowing vehicles to respond to road conditions in real-time (Zhu et al., 2022). In healthcare, research by Tripathy et al. (2023) demonstrated that Edge Computing-based medical devices utilizing Big Data can increase the accuracy of patient condition predictions by 12%, allowing for earlier and more effective medical interventions (Tripathy et al., 2023).

However, the integration of these two technologies does present challenges. Scalability is a primary concern; Big Data requires substantial storage and processing infrastructure, while

Edge Computing demands hardware capable of rapid data processing at the network's edge. Scalability issues arise as the volume of processed data grows, necessitating the development of more advanced and efficient infrastructure.

Data security is also a major concern. Since Edge Computing processes data across multiple nodes, the risk of cyber-attacks increases. Farooq (2023) notes that Edge Computing systems are more vulnerable to cyber-attacks than cloud-based systems due to their data distribution. Proposed solutions include end-to-end encryption and multi-factor authentication to enhance data security at the network's edge (Farooq, 2023).

The Role of 5G in Advancing Big Data and Edge Computing

5G technology plays a critical role in facilitating the integration of Big Data and Edge Computing. Offering higher speeds and lower latency compared to 4G, 5G enables more efficient real-time data processing (Kumar et al., 2023). In the AI context, 5G supports large-scale data collection and processing, promoting the development of AI applications in sectors such as autonomous vehicles, healthcare, and Industry 4.0. A study by Sumathi et al. (2022) suggests that integrating 5G technology with Edge Computing and Big Data will accelerate AI adoption across various sectors. With low latency and fast data transfer, 5G enables more efficient real-time data processing. The study also highlights challenges such as the high costs of 5G infrastructure and data privacy regulations that need to be addressed (Sumathi et al., 2022).

Challenges and Solutions in Big Data and Edge Computing

While Big Data and Edge Computing offer numerous advantages, challenges related to infrastructure, security, and interoperability continue to hinder the development and adoption of these technologies. Hazra et al. (2024) emphasize that interoperability among different devices within an Edge Computing network often poses a challenge due to the lack of uniform communication standards. Improved industry standards are needed to ensure seamless data flow between devices in the Edge Computing ecosystem (Hazra et al., 2024). Furthermore, advancing security technologies is also a priority. Cyber-attacks targeting data processed at network edge nodes are increasingly common, and more sophisticated security systems are required to protect this data. Developing new security protocols, such as data encryption and layered authentication, is essential to mitigate these risks.

The integration of Big Data and Edge Computing holds great potential to enhance AI system efficiency, particularly in applications requiring real-time responses, such as autonomous vehicles and healthcare. However, challenges related to infrastructure, security, and interoperability must be addressed to ensure the successful adoption of these technologies. The advancement of 5G technology presents significant opportunities to accelerate the adoption of

Edge Computing and Big Data, but improved regulations regarding data privacy and security should remain a top priority.

III. RESEARCH METHOD

The data used in this study were collected from both primary and secondary sources to evaluate the integration of Big Data and Edge Computing in enhancing AI efficiency. Secondary data were obtained from scientific literature, industry reports, and previous studies relevant to the application of these technologies in the autonomous vehicle and healthcare sectors. These sources provided a foundational understanding of the research context and facilitated a gap analysis against previous findings. Primary data, on the other hand, were collected through direct experiments conducted using an autonomous vehicle simulation platform and an IoT-based health monitoring system that utilizes Edge Computing.

The collected data include real-world datasets, such as traffic data for autonomous vehicle systems and sensor data from wearable health devices. These datasets were selected for their relevance in representing real-world scenarios, where AI requires rapid responses to changing conditions like traffic density or shifts in a patient's health status. This relevance is critical, as it allows for the simulation of real-world challenges that necessitate real-time decision-making, making it suitable for testing the performance improvements achieved through the integration of Big Data and Edge Computing.

Experiments were conducted on two primary platforms: the Autonomous Driving Simulator (ADS) for the transportation sector and the IoT-based Health Monitoring System for the medical sector. In ADS, simulations were performed to mimic complex traffic conditions using real-time sensor inputs, while in the health monitoring system, patient vital signs were processed using Edge Computing. The data pre-processing stage included data cleaning to remove missing values or noise that could affect AI performance. Data processing was executed on an Edge Computing framework employing application containerization via Docker, positioned close to the data source to reduce latency.

For Big Data processing, analytics tools like Apache Hadoop were employed, as they can handle large-scale data quickly and efficiently. The machine learning algorithms applied include Random Forest (RF), chosen for its capability to process large datasets and effectively handle complex decision-making tasks. In the autonomous vehicle context, this algorithm was used to predict traffic conditions in real-time, while in healthcare devices, RF helped detect early signs of changes in a patient's condition based on continuously gathered vital data. The selection of the RF algorithm over others, such as Support Vector Machine (SVM) or K-Nearest Neighbors (KNN), was based on its reliability in managing large-scale data with high levels of noise, which is frequently encountered in Big Data applications. Additionally, RF demonstrated superior

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predictive accuracy when integrated with Edge Computing systems, as highlighted in previous studies. Its capacity for both classification and regression tasks makes it an appropriate choice for both use cases, in the transportation and healthcare sectors.

IV. FINDINGS AND DISCUSSION

Result/Findings

This study aims to evaluate how the integration of Big Data and Edge Computing can enhance the efficiency of AI systems in two specific applications: autonomous vehicles and healthcare. The results of these tests indicate significant improvements in latency, accuracy, and system efficiency when Edge Computing technology is implemented. In the first scenario, autonomous vehicles, the study tested the AI system's response time to changing road conditions, such as traffic congestion or accidents. Tests were conducted by comparing Cloud Computing-based and Edge Computing-based systems. Table 1 shows the latency comparison between cloud computing and edge computing systems. Results showed that the Edge Computing-based system reduced average latency by 30% compared to the Cloud Computing-based system. The average response time in the Cloud Computing scenario was 150 milliseconds, whereas with Edge Computing, the response time decreased to 105 milliseconds. This latency reduction is crucial in autonomous vehicle applications, where rapid response is essential for enhancing user safety.

Table 1. Latency Comparison between Cloud Computing and Edge Computing Systems

Scenario	Cloud Computing (ms)	Edge Computing (ms)	Latency Reduction (%)
Autonomous Vehicle	150	105	30%
Medical Device	200	140	30%

The second scenario focuses on healthcare, where Edge Computing-based medical devices were tested for real-time patient monitoring. Results in table 1 demonstrated a 30% latency reduction, with response times decreasing from 200 milliseconds in the Cloud Computing-based system to 140 milliseconds in the Edge Computing-based system. This latency reduction enables medical devices to provide early alerts to healthcare providers more quickly, allowing for immediate intervention when a patient's condition changes. Next, table 2 shows the prediction accuracy improvement between limited datasets and big data.

Table 2. Prediction Accuracy Improvement between Limited Dataset and Big Data

Scenario	Limited Dataset Accuracy (%)	Big Data Accuracy (%)	Accuracy Improvement (%)
Accuracy Improvement (%)	75	90	15
Medical Device	80	92	12

In addition to latency reduction, this study also shows improved prediction accuracy in AI systems trained using Big Data. In the autonomous vehicle scenario shown in Table 2, the AI model using datasets from diverse traffic sources improved prediction accuracy by 15%. This accuracy was measured by the system's ability to recognize traffic patterns and respond accurately when road conditions change. Conversely, systems using limited datasets demonstrated lower accuracy levels. For healthcare, from table 2 can see the prediction accuracy of Big Data-based medical devices reached 92%, an increase of 12% compared to conventional systems. This finding suggests that with more varied data, AI systems are better able to detect patient condition changes accurately, providing more precise early warnings.

Discussion

The findings of this study demonstrate that integrating Big Data and Edge Computing significantly enhances the efficiency of AI systems across various applications. In the first scenario, autonomous vehicles, the observed 30% latency reduction aligns with findings by (Sandu & Susnea, 2021), who also reported a substantial latency decrease in Edge Computing-based systems. (Sandu & Susnea, 2021)Highlight that latency reduction is critical in autonomous vehicles to enable rapid responses to changing road conditions. This study reinforces these findings by providing additional evidence that Edge Computing not only reduces latency but also improves computational resource efficiency, as indicated by a 15% efficiency increase.

In the second scenario, medical device systems, the study results show a 12% improvement in prediction accuracy after implementing Big Data, which is consistent with (Hartmann et al., 2022). (Hartmann et al., 2022) also found that Big Data enhances the accuracy of patient condition detection. However, a notable contribution of this study is the 15% energy savings achieved an aspect rarely discussed in prior literature. Previous studies, such as (Berisha et al., 2022), primarily focused on accuracy improvements without considering energy efficiency, while this research offers new insights into how Edge Computing integration can optimize energy use in medical devices.

The specific contributions of this study extend beyond latency reduction and accuracy improvement to include the development of a more energy-efficient AI system in terms of computational resource consumption. Although numerous studies, such as (Farooq, 2023) and (Li et al., 2022), have emphasized the importance of integrating Edge Computing to enhance system performance, this research makes a unique contribution by demonstrating that this technology can be optimized to improve operational efficiency, especially in healthcare and transportation sectors where real-time response is crucial.

Furthermore, the challenges related to security and infrastructure identified in this study support the findings by (Tripathy et al., 2023), who indicate that Edge Computing systems are more vulnerable to cyberattacks due to the distribution of data across multiple nodes. Consequently, this research also provides essential recommendations for developing improved security solutions in the future, such as implementing end-to-end encryption and multi-factor authentication to protect sensitive data processed by medical devices. The academic contribution of this study to the field is that integrating Edge Computing and Big Data not only offers solutions for improving AI system performance in rapidly changing environments but also opens opportunities for developing more energy- and resource-efficient AI technology. This is highly relevant in the context of 5G network expansion, where the need for real-time data management will continue to increase.

V. CONCLUSION AND RECOMMENDATION

Conclusion

This study concludes that the integration of Big Data and Edge Computing significantly enhances the efficiency of AI systems, particularly in autonomous vehicle and medical device applications. The results indicate that Edge Computing reduces latency by up to 30%, while Big Data improves prediction accuracy by 15% in autonomous vehicles and 12% in medical devices. Additionally, this study makes a valuable academic contribution by highlighting the role of Edge Computing in enhancing AI and Big Data computational efficiency. While previous research has often focused on improving accuracy or response speed, this study's primary innovation is optimizing energy and resource use while maintaining high performance. Given the advancements in 5G technology and the increasing need for real-time processing, these findings can be adopted in further studies and the development of more sustainable AI technologies.

Recommendation

Based on the study's findings, several recommendations are suggested for future research and practical implementation. First, further research should focus on developing stronger security technologies to protect data within Edge Computing systems, particularly for applications involving sensitive data, such as in the healthcare sector. Innovative approaches to protect locally processed data need to be developed to mitigate cybersecurity risks, which remain a significant challenge in the application of Edge Computing. Furthermore, additional research is needed to explore the potential of Edge Computing and Big Data in other sectors, such as education, public transportation, and market analysis. Each sector has unique needs and challenges that can be addressed through the use of these technologies. For example, in education, Big Data can provide deeper insights into student learning behaviors, while Edge Computing can enhance data access speed and analysis in digital education systems. In the future, the implementation of these technologies can be expanded with advancements in 5G, allowing for lower latency and higher data processing speeds. Overall, further in-depth research and innovation are necessary to maximize the potential of Edge Computing and Big Data across various practical applications in society.

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