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Real-Time Decision-Making in Autonomous Robots Using Edge Computing

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ABSTRACT

The autonomous robots are becoming more prevalent in the dynamic setting where quick perceiving, analyzing, and decision-making are necessary to ensure effectiveness in working. However, many traditional robotic systems used cloud computing to make sense of high sensor data volumes but cloud systems may create delays, bandwidth constraints, and various reliance on robust network connectivity. Such constraints have the potential to impact time-sensitive robotic applications like navigation, obstacle avoidance and real time control adversely. The emergence of edge computing has emerged as a potential solution to solving these challenges by potentially processing data closer to the robot or data source. This paper will examine how edge computing can enhance real time decisions in autonomous robotic systems. The study considers the design of edge-based robotic systems, the incorporation of artificial intelligence models of decision making, and the communication network to serve such systems. The paper also compares the functions of cloud-based and edge-based systems in regards to latency and response time, bandwidth and reliability of the system. The results suggest edge computing to be highly useful in the responsiveness and efficiency of autonomous robots. Thus, edge computing and robotic systems are a viable option that can be used to build intelligent and robust technologies of the autonomous kind.

Keywords: Autonomous robots, edge computing, real-time decision-making, artificial intelligence, cloud robotics

INTRODUCTION

1.1 Background of Autonomous Robotics

Autonomous robotics denotes a research field that involves the integration of robotics, artificial intelligence (AI), machine learning, and state-of-the-art technologies to allow machines to do things without human supervision. Self-directed robots will then be aimed at sensing the world around them to analyse information and make decisions based on intelligent algorithms [1]. Applications of these robots are becoming common in the field of manufacturing, transportation, healthcare, agriculture and the logistics industry. Contemporary robots use cameras, LiDAR, GPS, ultrasonic and various other sensors to capture data about the surrounding environment and carry out duties, including navigation, object identification, and manipulation [2]. With the further development of computers and artificial intelligence devices, robots are becoming smarter and can complete more difficult tasks in changing circumstances.

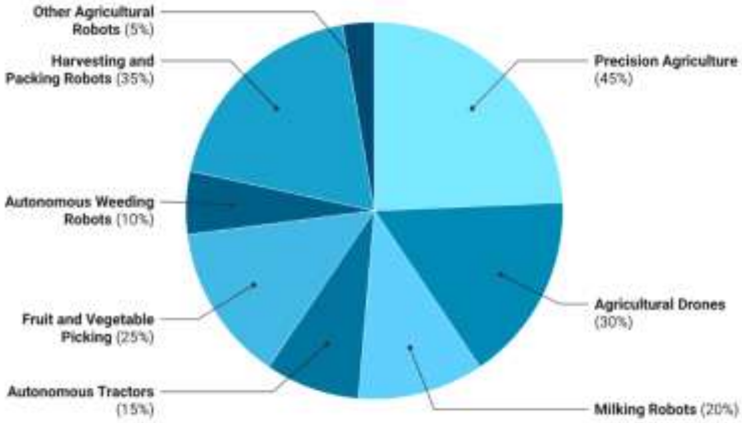

Figure 1: Adoption Rate of Robotics [3]

1.2 Importance of Real-Time Decision-Making in Robotic Systems

Making decisions in real-time is an argumentative requirement of autonomous robots in uncertain and highly dynamic settings. The robots have to manipulate a massive amount of sensory input and make prompt and safe judgments to aid in the efficient execution of tasks [4]. Indicatively, autonomous cars are expected to identify the presence of obstacles, interpret the environment, and modify their actions in milliseconds to avoid accidents. In the same way, industrial robots should also respond to the changes in the production settings and adjust instantly to ensure efficient operations. Lagging in decision-making can decrease the performance of the system, and this can also cause safety threats in operational areas, including healthcare and transportation.

1.3 Limitations of Cloud-Based Robotic Architectures

The services that could be provided by cloud computing to the robotic systems traditionally are strong computational power and large amounts of data storage. Use of cloud robotics that involves the transmission of data to remote servers to be processed and instructions followed on their analysis. The method has an opportunity to provide the next-level data processing and learning, as well as collaboration between the robots, but it has some drawbacks as well. The latency of the network, bandwidth limitations, and reliance on the stable internet connection can slow down the process of decision-making. This can be especially troublesome in an application where it is needed to respond promptly to information, such as autonomous driving and real-time navigation [5].

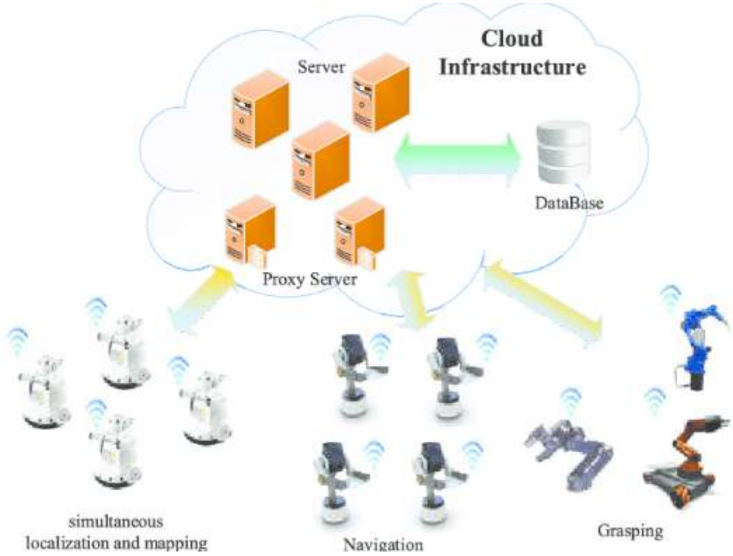

Figure 2: System Architecture of Cloud Robotics [6]

1.4 Emergence of Edge Computing in Robotics

Edge computing seems to be an option that can help to solve the shortcomings of the cloud-based robotic systems. The edge computing procedure deals with data locally to the place of its generation and eliminates the requirement of sending extensive information to remote cloud computers. Edge computing ensures that the latency can be significantly minimized and that the system will be more responsive by allowing local data processing. Use of edge devices like the local servers or gateways will be used to do computational jobs like computer vision, navigation, and sensor fusion [7]. The architecture enables the decision-making process of robots to be quicker and their functioning to be more efficient in real-time settings.

1.5 Problem Statement

Most autonomous systems, however, still make heavy use of centralized cloud infrastructures to process and make decisions despite the development of robotics and AI. Such dependence may cause latency, delay in communication and inefficiency of the operation. Hence, it is required to have distributed computing frameworks, in which a robot can be able to process information in one location and make timely decisions.

1.6 Significance of the Study

Combining edge computing and autonomous robotics can contribute greatly to the speed, reliability and efficiency of robots. The edge-enabled robots are able to handle data more efficiently in surroundings where they are operating, and hence have quicker responses with lower reliance on networks. Such a solution is especially handy in autonomous car applications, industrial robots, healthcare robots and emergency management.

1.7 Structure of the Paper

The rest of this paper will take the following structure. Section 2 provides the related literature in relation to robotics, AI, cloud computing, and edge computing. Section 3 entails the research objectives and purposes. Part 4 defines the system architecture. Section 5 is the methodology of the research. Section 6 gives the results and analysis, and at the end of this section, applications are made in Section 7. Section 8 addresses difficulties and perspectives, and Section 9 wraps up the study.

LITERATURE REVIEW

2.1 Evolution of Autonomous Robots

The technology of autonomous robot creation has advanced a lot during the last several decades. The first robots were less advanced rule-programmed machines used to do rather routine, repetitive work like on manufacturing assembly lines [8]. There was no ability to adapt to changes in the environment and these robots were based on preset instructions. Having improved computing technology and artificial intelligence, modern robots are more intelligent and can make their own decisions autonomously. Recent advances in robotics have brought in machine learning algorithms, better sensors, and perception systems which enable robots to understand what is around them and change their behaviour according to this knowledge. The modern autonomous robots combine perception, planning, and control systems to be used in dynamic settings like autonomous automobiles, service robots, and industrial automation systems [9]. These developments have progressed robotics to more intelligent systems and no longer the stiff programmed machines.

2.2 Artificial Intelligence in Robotic Decision-Making

Artificial intelligence is relevant in helping robots to make intelligent decisions. Machine learning, deep learning and reinforcement learning are some of the AI methods that enable robots to analyze sensory information and learn to perform better as time goes by. Machine learning systems provide pattern recognition and classification of objects based on visual or sensor data (perceived by the robot) to manipulate objects. Deep learning architectures (especially convolutional neural networks) are extensively applied in the computer vision problems of object detection and scene comprehension [10]. Reinforcement learning enables robots to know how to behave optimally by engaging in an interaction with the environment through rewards or penalties given to the behavior. Such AI-based techniques improve robot cognition, navigation, and decision-making, which can make the robots act independently in complicated settings [11].

2.3 Cloud Computing in Robotics

The establishment of contemporary robotic systems has been largely impacted by cloud computing. Cloud robotics provides access to robots to giant-scale computing facilities and shared information saved on remote computers. Robots can be used to do complicated tasks, including large-scale data analysis, machine learning training, and sharing knowledge, by leaving them to computational power in the cloud. Cloud robotics is also capable of sharing experiences and learning among the various robots, thus enhancing the overall functionality of the system. Researchers have brought to the fore the idea that cloud-based architectures are better in terms of scaling systems as well as offer access to powerful computing systems that are beyond what led to the limitations of onboard robotic hardware [5].

2.4 Limitations of Cloud-Based Robotic Systems

Although they are beneficial, cloud robotics has a number of limitations when used in real-time robotic systems. Network latency is one of the concerns that are significant as it arises when data needs to be sent between robots and cloud servers that are distant. This lag may have adverse effects in tasks of time sensitivity, like navigation and avoiding obstacles. The bandwidth can also be a factor that can limit the data that can be delivered effectively. Also, the cloud-based systems are susceptible to communication failure by virtue of their dependence on a constant internet connection. One of the main concerns with sending sensitive information to remote servers should be data privacy and security. These difficulties underscore the necessity to find some alternative computational models of autonomous robotics [12].

2.5 Edge Computing Concept

Edge computing has become a distributed computing paradigm that aims to handle the data near the source. Edge computing can be used instead of uploading all of the data to centralized cloud servers, with the benefit that data processing can be performed at the edge, in an edge device like a gateway, local server or an embedded processor. This will minimize the latency, response time and use less bandwidth over the network. Edge computing can be especially applicable in a real-time processing applications, such as the Internet of Things (IoT) systems, autonomous vehicles, and robotic systems [13].

2.6 Edge Computing in Robotics

Recent studies have discussed implementing a system of edge computing in robotic systems, which allows better handling of real-time decisions. Robotic architectures based on edge computing enable robots to analyze sensor data at the edge, or on adjacent edge servers, and eliminate cloud access communication delays. The research has shown that edge computing enhances robot adaptability, dependability, and performance in moving situations. Tasks that may be assisted by edge computing include object detection, navigation and simultaneous localization and mapping (SLAM), and they make the robots more efficient in the real world [14].

2.7 Research Gap

In spite of the fact that the use of cloud robotics and AI-based decision-making systems in robots, as well as research on applying edge computing in robots, has been studied before, very little has been done to combine the items of edge computing with real-time decision-making in fully autonomous robots that operate under dynamic conditions. The current research is either cloud robotics or AI-driven decision models, with little detailing on overall frameworks integrating edge computing and autonomous robotics to enable decision-making on low-latency and providing enhanced system performance.

Table 1: Research Gap

Area of Existing Research	Key Findings in Previous Studies	Identified Gap
Development of Autonomous Robots	Previous studies mainly focus on improving robotic hardware, sensor technologies, and navigation systems to enhance autonomy in robots.	Limited attention has been given to improving computational frameworks that support efficient real-time decision-making in complex environments.
Artificial Intelligence in Robotics	Machine learning, deep learning, and reinforcement learning are widely applied for perception, object recognition, and navigation in robotic systems.	Many AI-based robotic systems depend on centralized computing resources, which can restrict real-time responsiveness.
Cloud Robotics	Cloud-based robotic architectures provide large-scale computational power, shared data storage, and collaborative learning among robots.	Heavy reliance on cloud infrastructure introduces latency and communication delays that can affect time-sensitive robotic operations.
Communication Infrastructure in Robotic Systems	Research highlights the importance of network connectivity, IoT integration, and distributed robotic communication systems.	Network instability and bandwidth limitations can hinder reliable and continuous data transmission between robots and remote servers.
Edge Computing Technologies	Edge computing has been widely studied for reducing latency and enabling local data processing in distributed computing environments.	The application of edge computing specifically for robotic decision-making systems is still limited and requires further exploration.
Real-Time Robotic Decision Systems	Some frameworks have been proposed to improve real-time processing and control in robotic systems.	Few studies integrate edge computing with AI-driven decision-making models for fully autonomous robotic systems operating in dynamic environments.
Edge Computing in Robotics Applications	Emerging studies suggest that edge-enabled robotics can improve responsiveness and operational efficiency.	Comprehensive experimental validation and scalable architectures for edge-based autonomous robotic systems are still insufficient.

Objectives

- To analyze the role of edge computing in autonomous robotic systems.
- To examine architectures supporting edge-based robotic decision-making.
- To evaluate algorithms used for real-time robotic decision processes.
- To compare performance between cloud-based and edge-based robotic systems.
- To identify application areas of edge-enabled autonomous robots.

System Architecture / Conceptual Framework

A layered architecture is a common system design approach to autonomous robots that combines sensing, computation, communication, and control units. Sensors and perception of the environmental conditions form one part, processing facilitation units are at the center and process the data collected in the sensors, communication linkages and the actual implementation of tasks are through actuators make up the rest. All these parts combine so that robots can sense the world being around them, and understand and execute actions on their own. The current trends in robotic architecture are moving toward artificial intelligence and distributed computing system to work on massive quantities of data produced by sensors and allow making decisions in real-time in changing environments [2].

Edge computing has proven to be a suitable architecture for augmenting the computing power of the robot systems. With edge-enabled architecture, data processing is done nearer to the robot by using edge nodes or embedded processors instead of using centralized cloud servers. This decentralized method saves time on communication and allows performing computationally demanding tasks with significant latency. Edge nodes are a form of computing interface placed in between the robots and the cloud sphere when it is necessary to process sensor data in a local environment but still maintain the presence of remote servers to store the sensor data long-term or perform sophisticated analytics [15]. These architectures enhance system responsiveness and reliability, especially where the system needs quick decision-making.

The process of sensor data capture and processing is important in the operations of autonomous robots. In order to obtain real-time data regarding the environment, robots rely on various kinds of sensors, including cameras, LiDAR, GPS, and ultrasonic sensors. This information is computed using perception algorithms that provide meaningful information like object detection, obstacle identification, and mapping the environment [16]. The sensor data must be efficiently processed in order to provide the ability to see around and to make decisions during the solving of tasks by robots.

Artificial intelligence models based on edges also improve autonomy in the making of decisions by autonomous robots. The machine learning and deep learning models can be deployed on edge devices in order to accomplish tasks like visual recognition, navigation planning, and anomaly detection. Execution of AI models in edge devices will help to decrease the necessity to transfer massive amounts of sensor data to remote servers and will enable robots to react instantly to the changing environment. This is applied to support real-time applications, including autonomous vehicles, industrial robot, and service robots that need to operate in real-time and take immediate actions [17].

Another essential edge-enabled robotic system is the communication infrastructure. Such technologies as the Internet of Things (IoT), 5G networks, and high-speed Wi-Fi allow for reliable communication among the robots, edge nodes, and cloud servers. These technologies will provide an efficient exchange of data and will promote the work of collaborative robots in remote spaces [18]. The general data processing stage will normally start with the sensor data acquisition and then proceed with local data processing at the robot/edge node, AI-based decision making and lastly command execution using robot actuators. This unified architecture supports decision-making resulting in efficient, and low-latency autonomous robot systems.

METHODOLOGY

The research design used in this study is both experimental and system-based to appraise the aptitude of edge computing in ensuring that autonomous robotic systems can make real-time decisions. The study is aimed at the comparative examination between the traditional cloud-based processing and the edge-enabled architecture to investigate the enhancement of the responsiveness and efficiency of the system. Experimental evaluation experimentation is common in robotics research to evaluate the performance of the system in controlled experimental environments, as well as the interaction among sensors, algorithms, and computing infrastructure [19].

The experiment comprises the autonomous mobile robot with several sensors and an edge computing device built into it. The sensors that the robot uses to collect environmental data include the cameras, LiDAR, and the ultrasonic sensors. The sensors are used in conveying information that is needed when carrying out different tasks like environmental mapping, obstacle detection, and navigation. The sensor data that is collected can be either locally processed on the robot or framed by adjacent edge nodes in order to allow quicker computational reactions. Edge devices serve as processing intermediaries which minimize the requirement to ferry massive amounts of data to remote cloud computing servers, and enhance system efficiency and decrease latency.

The hardware that is involved in this system is a mobile robotic platform, sensor modules and an edge computing device like a GPU enabled embedded system. The software environment provides robotic control and data processing on the basis of such a platform like the Robot Operating System (ROS), which helps to communicate between components of a robot and provides an opportunity to integrate with artificial intelligence systems [20]. The algorithms include machine learning and computer vision that are used to carry out decision-making tasks such as object recognition, path planning, and obstacle avoidance.

Decision-making algorithms act upon the sensor data and accordingly decide on what to do to the robot in real time. The system performance is measured in terms of a number of metrics such as the latency, response time, the bandwidth utilisation, and energy consumption. Latency time is used to measure the delay between the collection of the information and the output of the decision, whereas the response time is used to determine how fast the robot responds to the environment. The utilization of bandwidth is a measure of how efficiently data can be transmitted and the amount of energy used is a measure of the cost of computation. Experimental results are examined with the help of a comparative assessment of edge-based and cloud-based processing models to identify the enhancement of real-time robotic performance.

RESULTS AND ANALYSIS

The findings of the experimental assessment point to the fact that the implementation of edge computing into autonomous robots allows enhancing the performance of real-time decision-making. The sensor data is processed by edge-based decision systems at the sensor node or by a set of edge nodes indicating that sensor data is processed locally reducing delays involved in transmitting data that may be of large amounts to remote cloud servers. Consequently, the robots are able to process the information provided by the environment more rapidly, and perform the right activities in a dynamic environment. Past studies within the field of edge computing and robotics indicate that the local processing improves the responsiveness of the system and enables robots to carry out delay-sensitive tasks (navigation, object detection, obstacle avoidance, etc.) more effectively [14].

Comparison of cloud-based and edge-based architectures shows that there exist observable performance differences. In cloud robotics architecture, sensor information has to be sent to central servers to be analyzed and robot instructions (sending decision commands) have to be sent to it. This result is the introduction of delays in communication and dependency on the network. Conversely, edge-enabled robots make the majority of computations near the robot and thereby greatly lessen the data transmission needs. Research has demonstrated that edge computing systems were capable of enhancing the compute efficiency and network bandwidth of robotic systems which required continuous processing of sensor data [14].

Measures of latency and response time provide even more points showing how beneficial edge decision-making can be. Latency is the delay of time between acquiring data and output of the decision and the response time is used to gauge the speed at which the robotic system will respond to changes in the environment. According to experimental data, edge computing can greatly minimize the latency relative to the cloud-based processing since there is a lower number of data packets to pass across the network. There is a shorter reaction time of robots now enabling them to respond better to obstacles, changes occurring in the environment, and task needs in real-time [20].

The edge-enabled robotic architectures also enhance system reliability as well as operational efficiency. Due to the high degree of localization of most computational processes, the robots have the ability to keep operating in such cases that the network connection to the remote cloud servers is weak or unattainable. This distributed processing functionality makes systems more resilient and can carry on running in a condition where the network infrastructure can be constrained. In general, the findings described above show that the application of edge computing into robotic architectures can improve the performance of these systems, the speed of making decisions, and the real-time performance of autonomous robots in more complicated environments.

Table 2: Performance Comparison of Cloud-Based and Edge-Based Robotic Decision Systems

Parameter	Cloud-Based Robotic System	Edge-Based Robotic System
Data Processing Location	Data processed on remote cloud servers	Data processed locally on edge devices or near the robot
Latency	Higher latency due to network communication delays	Lower latency because processing occurs close to the data source
Response Time	Slower response due to data transmission to cloud and back	Faster response enabling real-time decision-making
Bandwidth Usage	High bandwidth consumption due to continuous data transfer	Reduced bandwidth usage as most processing occurs locally
Network Dependency	Highly dependent on stable internet connectivity	Less dependent on continuous network connectivity
System Reliability	Performance may degrade during network disruptions	More reliable due to local processing capabilities
Operational Efficiency	May experience delays in time-critical tasks	Improved efficiency for dynamic and real-time environments
Real-Time Decision Capability	Limited in latency-sensitive applications	Highly suitable for real-time robotic operations

7. Applications of Edge-Enabled Autonomous Robots

It is a trend to use edge-enabled autonomous robots in any of the industries where timely information processing and quick decision-making are crucial. Autonomous vehicles are one of the most important spheres of their use. Self-driving vehicles send and receive traffic data in real-time; thus, self-driving cars require a great amount of sensor data in the form of cameras, radar, and LiDAR to identify obstacles, interpret the situation on the road, and take driving-related decisions. The use of edge computing allows these vehicles to process sensor data in the field and minimize the latency, as well as react more promptly to dynamic situations on the road [21].

Edge-enabled robotic systems also have the advantage to make best use of industrial automation and smart factories. The roles of robots are to assemble, test the quality and move materials in the factory. The edge computing facility is used to get production data sent to industrial robots and thereby enhance its operations by solving the problem of circularity and provide predictive maintenance and real-time monitoring on manufacturing processes [22].

Robotic surgery, patient monitoring and assistive robotics are only some of the applications in which edge-enabled robots are used in healthcare. They consist of systems that need decision-making that is precise and immediate so that the safety of patients and successful medical procedures could be obtained. With edge computing, medical robots are able to process medical sensors in real-time and respond, without having to fully utilize remote cloud infrastructure [23].

The robots are also useful in rescuing and disaster response where they operate with edges. Robots used in dangerous areas, including those wrecked in the building, or in the fire line, need to be able to perform an analysis of the environmental conditions as fast as possible to make it to a safe position and help the rescue teams. Correspondingly, smart agriculture involves autonomous robots with a sensor and edge computing capabilities to scan the conditions of the crops, identify plant diseases, and streamline the process of irrigation and fertilization. These applications establish the increase in the significance of edge computing in facilitating efficient and clever robotic systems.

CONCLUSION

In the autonomous robots, edge computing is critical towards enhancing real-time decision-making. At the same time, edge computing lowers the latency of processing data, as well as improves response time, and minimises reliance on cloud infrastructure that is deployed centrally. Combining edge-based architectures with artificial intelligence and more sophisticated sensors helps robots to perform effectively on different dynamic and time-sensitive environments. Examples of practical applications of this approach include autonomous vehicles, industrial automation, healthcare, disaster response and smart agriculture. Altogether, it is possible to state that edge-enabled robotic systems have better reliability, efficiency and scalability and can be regarded as a potential solution to a further generation of autonomous robotic systems.

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