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Edge Intelligence for Robotics: A Comprehensive Survey on Key Technologies, Trends, and Applications in Industrial Robots, UAVs, and Multirobot Systems

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Abstract

Edge computing (EC) is revolutionizing robotics by bringing computation closer to the data source, reducing latency and overcoming the limitations of cloud-based systems. This paradigm shift is essential as the number of connected devices and data volumes surge, especially with the advent of 5G networks. This paper provides a comprehensive survey of key technologies in edge computing for robotics, including industrial robots, UAVs, and multi-robot systems. We examine the integration of edge intelligence with AI, enabling real-time decision-making and enhanced processing efficiency while addressing challenges like mobility, security, and data privacy. Additionally, the paper explores case studies in autonomous navigation, industrial robotics, and UAV-based IoT applications, highlighting the benefits and challenges of implementing edge AI in diverse robotic systems. Through this survey, we aim to identify promising research directions and practical applications to accelerate the deployment of edge intelligence in robotics.

Keywords: Edge Computing (EC), Robotics, Edge Intelligence, Artificial Intelligence (AI), Unmanned Aerial Vehicles (UAV, Low Latency

Introduction:

The rapid expansion of network-connected devices, driven by advancements in technologies such as the Internet of Things (IoT) and 5G, has significantly transformed how data is processed and consumed. Traditional cloud computing models, which centralize data processing in remote servers, are increasingly facing limitations due to high latency, bandwidth congestion, and energy inefficiencies. These issues become particularly critical in robotics, where devices such as industrial robots, autonomous vehicles, and UAVs (unmanned aerial vehicles) require real-time decision-making capabilities and near-instantaneous responses to function effectively. In these cases, even slight delays in processing can lead to performance degradation or, worse, system failures, particularly in safety-critical applications like autonomous navigation, precision agriculture, and industrial automation.

Edge computing (EC) offers a compelling solution to these challenges by decentralizing data processing, bringing computation closer to the source of data generation, and reducing the reliance on distant cloud servers. By processing data locally, or at edge nodes, EC reduces latency, alleviates bandwidth pressure, and improves data privacy and security. This localized processing is especially crucial for robots and autonomous systems that need to act on sensor data in real-time for tasks such as obstacle avoidance, simultaneous localization and mapping (SLAM), and predictive maintenance in industrial settings. Furthermore, the fusion of artificial intelligence (AI) with edge computing—known as Edge AI—enables even more sophisticated data analytics directly on edge devices. This capability enhances the intelligence of robots and autonomous systems by allowing them to make faster, more informed decisions without needing to communicate continuously with centralized cloud resources.

Edge AI plays a pivotal role in advancing several critical applications in robotics, including UAV-based IoT services, industrial robotics, and multi-robot systems. For UAVs, Edge AI is essential for applications like autonomous navigation, formation control, and search-and-rescue operations, where low-latency decision-making can be the difference between success and failure. Similarly, in industrial robotics, where real-time processing is needed for tasks such as predictive maintenance and dynamic task scheduling, edge computing accelerates the transition towards intelligent manufacturing systems. The use of edge architectures also improves data security by limiting the transmission of sensitive data over large networks and enables more scalable, distributed robotic systems that can operate independently or in collaboration with other robots.

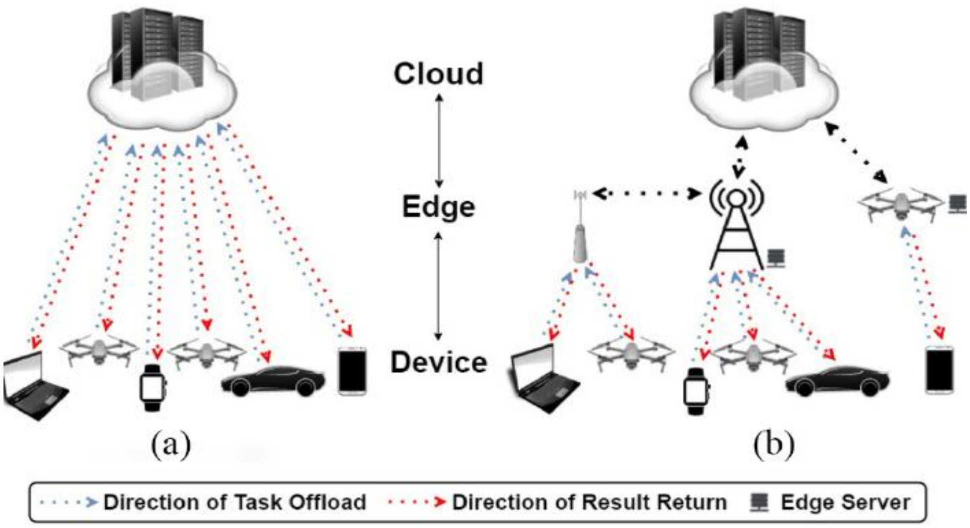

Fig. 1 Architecture of (a) cloud versus (b) edge computing. Source [5]

This paper provides an in-depth survey of the role of edge computing in advancing the field of robotics, with a particular focus on key technologies, real-world applications, and the challenges that come with this paradigm shift. I examine the integration of edge computing across diverse robotic platforms, including UAVs, industrial robots, and multi-robot systems, illustrating how edge architectures enhance operational efficiency, reduce latency, and address critical issues such as data security, privacy, and bandwidth management. Furthermore, we explore the convergence of edge computing with artificial intelligence (Edge AI), investigating its transformative potential in enabling real-time analytics and decision-making in robots, without relying heavily on cloud-based resources. This paper also discusses emerging research areas and the future direction of Edge AI in robotics, offering insights into how these technologies can lead to smarter, faster, and more autonomous robotic systems.

The Evolution and Importance of Edge Computing

The evolution of technology has significantly transformed the computing landscape, leading to the emergence of Edge Computing (EC) as a response to the limitations of Cloud Computing (CC). Initially, CC offered substantial advancements, such as on-demand services, scalability, and efficient data storage. However, the rapid increase in data generation resulted in challenges like undesirable latency, limited mobility support, and privacy concerns. In contrast, EC serves as a complementary solution that enhances geographical and latency-sensitive applications, allowing for local distributed data processing that improves service quality and enables real-time applications.

To enable the efficient functioning of EC, several key requirements must be addressed, including effective billing mechanisms, joint business models for management and deployment, and real-time application support. Furthermore, EC necessitates redundancy and fail-over capabilities to ensure high service availability, resource management for analyzing processing power, and scalable architectures that incorporate resource virtualization and security measures. Software solutions such as virtual machines and containers also play a crucial role in facilitating EC systems, along with emerging technologies like Software-Defined Networking (SDN) and Network Function Virtualization (NFV).

EC operates at the periphery of the network, providing distributed computation, storage, and networking capabilities that contrast with the centralized nature of CC. This paradigm extends the capabilities of CC by offering powerful computing resources closer to end users, thereby minimizing network traffic and latency while enhancing user experience. The four primary architectures within EC include Multi-access Edge Computing, Fog Computing, Cloudlet Computing, and Mobile Cloud Computing. Each architecture presents distinct characteristics, contributing to a flexible and efficient approach to data processing and resource management, which is vital for the advancement of autonomous systems and robotics.

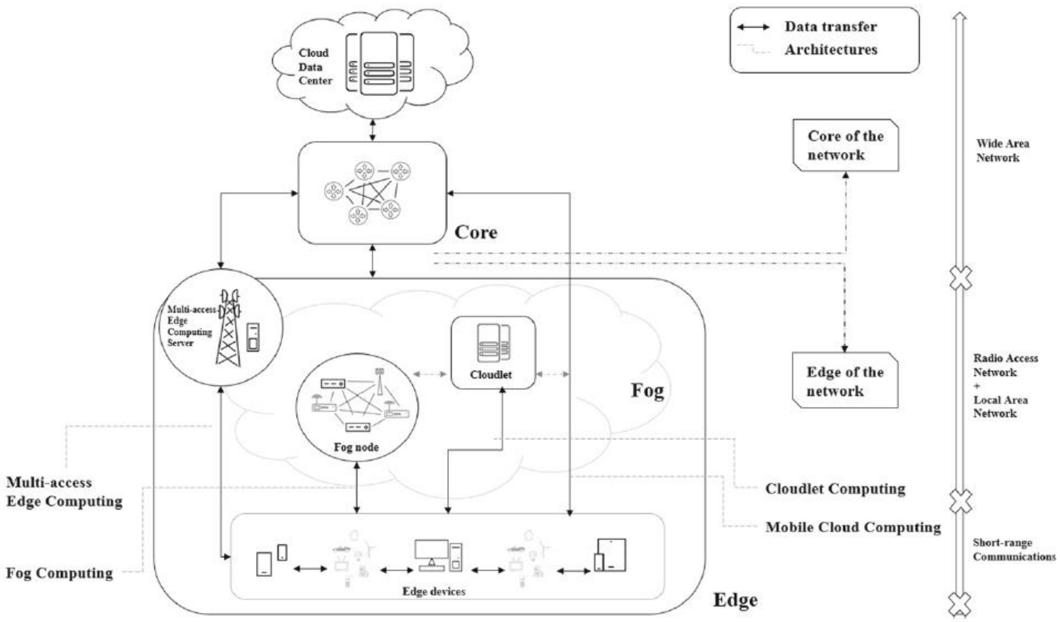

Fig. 2 Edge Computing Implementation Scenarios. Source [3]

Core Architectures of Edge Computing

This section analyzes the key Edge Computing (EC) architectures, including their definitions and unique properties. EC devices are computing, and network resources situated along the data path between sources and cloud data centers. These architectures can operate autonomously or within a Cloud framework. When functioning independently, data is processed locally at the network's edge, minimizing network overhead and enhancing security and privacy.

Multi-access Edge Computing, previously known as Mobile Edge Computing, refers to computing at the edge of a network. Its five major characteristics include operating on-premises, providing proximity, ensuring lower latency, enabling location awareness through low-level signaling, and utilizing network context information. These features enhance the initial EC architecture by incorporating wireless access and varied virtualization technologies.

Fog Computing is defined as a scenario where numerous heterogeneous devices communicate and collaborate to perform storage and processing tasks without third-party intervention. It emerged to address the vast number of IoT devices and big data, focusing on real-time, low-latency applications. The implementation possibilities are diverse, ranging from IoT to cloud services, but its boundaries are not clearly established.

Cloudlet Computing describes a "trusted, resource-rich computer" available for nearby mobile devices, providing computing and storage resources. Cloudlets emphasize flexibility, mobility, scalability, and elasticity and can operate independently of Cloud services. They function as "data centers in a box," offering low latency and high-performance computing through a high-bandwidth network.

Mobile Cloud Computing enables mobile devices to utilize data storage and processing capabilities beyond their local resources. This infrastructure moves computing power and data storage into the Cloud, benefiting a broader range of mobile subscribers. When mobile cloud computing integrates cloudlets, it shares properties with Cloudlet Computing, reinforcing their interrelated nature.

Use Cases of Edge Computing in Robotics

Edge Computing in UAV Systems

Edge computing significantly enhances Unmanned Aerial Vehicles (UAVs) by enabling AI-driven edge processing. This technology allows for real-time navigation, obstacle avoidance, and efficient energy management, critical for various applications. For example, in Search and Rescue (SAR) operations, UAVs can quickly analyze data and adapt to dynamic environments, improving response times. Similarly, in precision agriculture, UAVs equipped with edge computing can process data locally, optimizing crop monitoring and management. Additionally, drone delivery systems benefit from reduced latency, ensuring timely deliveries in urban settings.

Fig. 3 Typical Classification of UAVs. Source [5]

Industrial Robots and Edge Intelligence

In manufacturing, edge computing optimizes real-time data processing for industrial robots, enhancing automation, efficiency, and scalability. By processing data closer to the source, robots can make quicker decisions, improving production lines and reducing downtime. This is particularly beneficial in environments with variable conditions, where the ability to adapt swiftly to changes is crucial. The integration of edge intelligence allows for more flexible and responsive manufacturing systems, paving the way for smarter factories that leverage IoT devices and real-time analytics to streamline operations.

Multi-Robot Systems (MRs)

Multi-Robot Systems (MRs) utilize edge AI for simultaneous localization and mapping (SLAM), enabling collaborative robots to work efficiently in warehouses and industrial settings. By leveraging edge computing, these robots can process data locally, allowing them to share information in real time without relying on cloud resources. This capability enhances their ability to navigate complex environments, execute tasks simultaneously, and maintain fault tolerance—ensuring that operations continue smoothly even if one robot fails. The combination of edge AI and MRs represents a significant advancement in automated systems, making them more efficient and resilient.

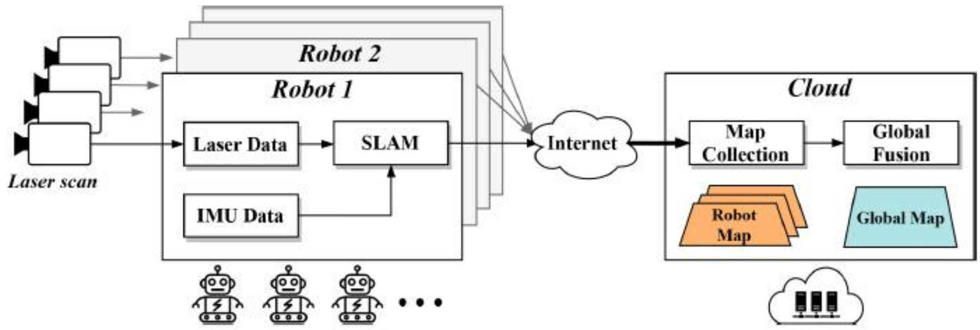

Fig. 4 Workflow of the Cloud-Based Multi-Robot SLAM Solution. Source [10]

Challenges and Opportunities in Edge Robotics

Despite significant advancements in Edge Computing (EC) technologies, numerous challenges persist that must be addressed to fully leverage the potential of edge robotics. This section explores key obstacles and future research directions within edge robotics, focusing on latency and bandwidth management, security and data privacy, scalability in multi-robot systems, and the integration of AI with edge computing.

Latency and Bandwidth Management

The need for real-time processing in edge robotics is critical, particularly for applications involving autonomous systems. Latency and bandwidth limitations can hinder the effectiveness of robotic operations, especially when high computational resources are required. Strategies such as computation offloading from end devices to edge nodes can enhance performance by aggregating external computing resources and optimizing storage capacity. By utilizing edge nodes to process data, mobile devices can extend their battery life and improve reliability. With the advent of 5G networks, which promise ultra-low latency and increased bandwidth, the potential for enhanced edge solutions is significant, yet the full impact of 5G on edge computing remains to be fully understood.

Security and Data Privacy

Security in heterogeneous edge environments poses unique challenges, as different devices and applications have varying security requirements. Lightweight security protocols may be necessary for devices with limited capabilities, while delay-sensitive networks, such as those used in autonomous vehicles, require robust security measures to prevent breaches. Frameworks for secure robotic operations must address these diverse needs, incorporating advanced credential management systems to protect data transmitted among numerous IoT devices. As the number of interconnected devices increases, so too does the potential for security vulnerabilities, necessitating ongoing research into secure communication protocols and data privacy strategies.

Scalability in Multi-Robot Systems

Scaling edge computing solutions for larger autonomous systems presents distinct challenges, particularly in the context of mobility and device heterogeneity. The growing number of mobile devices connected to the network edge leads to increased complexity in managing communications and ensuring consistent service quality. Disconnections between edge devices and the network can adversely affect parameters such as latency, bandwidth, and overall service performance. Future research should focus on developing global management architectures that facilitate seamless connections among multiple edge devices and support scalability as more robots are integrated into the system.

Integration of AI with Edge Computing

The integration of Artificial Intelligence (AI) with edge computing presents both challenges and opportunities. Edge devices often struggle with the computational demands of AI algorithms, particularly in real-time applications. However, opportunities for federated learning and distributed AI models can mitigate these challenges by enabling collaborative processing and decision-making across multiple edge nodes. This approach not only enhances the computational efficiency of edge devices but also ensures that data privacy is maintained, as sensitive information does not need to be centralized. Addressing AI computation challenges at the edge will be crucial for the successful deployment of intelligent robotic systems.

Conclusion

In conclusion, the advancement of edge robotics holds tremendous promise for enhancing the capabilities and efficiency of autonomous systems, yet it is accompanied by a set of significant challenges that require focused research and innovative solutions. Addressing latency and bandwidth management through strategies like computation offloading is essential to facilitate real-time processing, while robust security and data privacy frameworks must be developed to protect the integrity of diverse IoT environments. Furthermore, scalability in multi-robot systems necessitates the creation of comprehensive management architectures to ensure seamless connectivity among devices. Finally, the integration of AI with edge computing offers opportunities for federated learning and distributed models that can enhance computational efficiency while safeguarding sensitive data. By synthesizing efforts across these domains, we can unlock the full potential of edge robotics, fostering a new era of intelligent and reliable robotic systems that can adapt to the complexities of real-world applications.

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