Proceedings of the Indian National Science Academy (2024) 90:752–763
https://doi.org/10.1007/s43538-024-00264-3

RESEARCH PAPER

Cloud-integrated robotics: transforming healthcare and rehabilitation for individuals with disabilities

Ran Zhang[1,2] · Yan Zhou[1] · Junkai Zhang[1] · Juan Zhao[1]

Received: 15 November 2023 / Accepted: 11 February 2024 / Published online: 14 March 2024
© Indian National Science Academy 2024

Abstract
This paper explores the intersection of assistive technologies and cloud robotics, elucidating their transformative impact on healthcare, rehabilitation, and inclusivity for individuals with disabilities. By seamlessly integrating cloud computing and robotic systems, this convergence empowers personalized and data-driven interventions. The applications encompass a spectrum, ranging from cloud-connected prosthetics and robotic exoskeletons to communication devices and smart mobility aids. Benefits include real-time data analysis, remote customization, and adaptive learning, enhancing accessibility and collaboration among healthcare professionals. However, challenges such as data security and latency necessitate robust solutions. Looking ahead, the future promises enhanced personalization, cognitive interaction, and augmented reality integration, along with ethical considerations. This dynamic synergy augments user empowerment, redefines rehabilitation, and advances societal inclusion, advocating for a collaborative and ethical approach to reshape the landscape of assistive technologies through cloud robotics.

Keywords Assistive technologies · Cloud robotics · Rehabilitation · Personalized interventions · Data-driven · Healthcare

Introduction

The healthcare industry, being a perpetually changing and dynamic sector, is continuously seeking inventive solutions (Moradi et al. 2020). With the integration of state-of-the-art technologies into healthcare, patients will experience unparalleled access to tailored care, improved results, and more efficient medical services (Bolhassani and Oksuz 2021; Mohtasebi et al. 2023). Robotic systems have exerted significant socioeconomic influences on human lives over the recent decades (Pradel et al. 2022). Industrial robots, particularly robot manipulators, have found extensive deployment within factories to perform monotonous, repetitive, or hazardous tasks such as assembly, painting, packaging, and welding (Buerkle et al. 2023). These preprogrammed robots have exhibited remarkable success in industrial settings, capitalizing on their endurance, speed, and precision within structured factory environments (Mazzolai et al. 2022). However, the scope of these robots can be broadened or extended to operate within unstructured settings. This endeavour has led to the integration of robotic technologies with network technologies, fostering the emergence of networked robotics (Saeidi et al. 2022). Networked robotic systems denote a collection of robotic devices interconnected through wired and/or wireless communication networks. The applications of networked robotics can be categorized into teleoperated robots and multi-robot systems (Koul et al. 2022). In teleoperated scenarios, a human operator remotely controls or manipulates a robot by transmitting commands and receiving measurements via the communication network. Illustrative instances encompass remote control of planetary rovers and long-distance medical surgeries (Nacheri et al. 2021).

Conversely, multi-robot systems entail a collaborative team of networked robots that collectively execute tasks by exchanging sensory data and information through the communication network (Ramachandran et al. 2021). Examples include cooperative robot manipulators (Hu et al. 2020), squads of robots conducting search and rescue missions (Magid et al. 2019), and coordinated clusters

✉ Ran Zhang
zhangrantouming@163.com

[1] Department of Electrical Engineering, Hebei Institute of Mechanical and Electrical Technology, Xingtai 054000, Hebei, China

[2] Xingtai UAV Application Technology Innovation Center, Xingtai 054000, Hebei, China

of microsatellites operating in a desired formation (Grasso et al. 2021). Despite the benefits of networked robotics, akin to standalone robots, they encounter inherent physical constraints due to the robots' limited computing capacities for onboard computations (Croon et al. 2022). Access to information is further confined to the aggregate storage of the network. Recent advancements in wireless communications and cloud computing have paved the way to alleviate some of these constraints through the concept of cloud robotics, thereby enhancing the intelligence, efficiency, and cost-effectiveness of robotic networks (Hayyolalam et al. 2019; Mello et al. 2022). Challenges within the realm of networked robotics, especially within multi-robot systems, are manifold. This distributed system divides the tasks of sensing, actuation, communication, and computation among participating robots (Geihs 2020). Its successes span industrial applications, intelligent transportation systems, and security operations. However, the progress of networked robotics is hindered by the inherent constraints pertaining to resources, information, and communication within the existing framework. These constraints are elaborated upon in-depth within this Section (Wang et al. 2022a, b). Diankov and Kuffner (Diankov and Kuffner 2008) first proposed the concept of cloud robotics, which integrates the capability of cloud computing resources with robotics so that cloud robotics could offload CPU-heavy tasks to remote servers, and the robots can even turn to cloud-based services to expand their capabilities.

The convergence of cloud computing and robotics has paved the way for a paradigm shift in healthcare and rehabilitation, offering unprecedented opportunities to enhance the quality of care and support provided to individuals with disabilities (Aceto et al. 2020). This paper embarks on a comprehensive exploration of the transformative potential of cloud robotics in the context of physical therapy, rehabilitation, and assistive technologies. As traditional healthcare models continue to evolve, cloud robotics emerges as a cutting-edge approach that seamlessly integrates real-time data analysis, remote monitoring, and personalized interventions. The amalgamation of cloud computing's computational prowess and robotic systems' physical capabilities holds the promise of revolutionizing the delivery of therapeutic interventions, reshaping the landscape of healthcare services for those with disabilities.

The integration of various cutting-edge technologies represents a watershed moment in cloud-integrated robotics. IoT and WSNs provide a ubiquitous network infrastructure, facilitating seamless communication and data exchange among interconnected devices, thereby enabling real-time monitoring and control in robotics applications (Zandi et al. 2018; Pourghebleh et al. 2020). Smart electricity networks ensure efficient power management, which is crucial for sustaining the operation of robotic systems (Larijani and Dehghani 2024a, b; Anupong et al. 2023). Machine learning (ML), deep learning, and meta-heuristic algorithms contribute significantly by enabling robots to learn from data, optimize their performance, and autonomously adapt to dynamic environments, fostering increased efficiency and accuracy (Larijani and Dehghani 2024a, b; Abdul Samad et al. 2023; Rajput et al. 2022). Virtual human models serve as indispensable tools, allowing for simulation and analysis of human-robot interactions, essential for designing and optimizing assistive devices tailored to individual needs (Azizi et al. 2020). Saeidi et al. (Saeidi et al. 2023) analyzed the influential elements in the use of public transportation systems during a pandemic using the technological acceptance model (TAM) and the theory of planned behaviour (TPB). The amalgamation of these technologies within cloud-integrated robotics not only amplifies the capabilities of robotic systems but also paves the way for enhanced personalization, adaptability, and transformative advancements in healthcare, rehabilitation, and assistive technologies for individuals with disabilities (Pourghebleh et al. 2022).

The field of healthcare has seen remarkable strides in the integration of technology, and cloud robotics stands at the forefront of this revolution (Vairachilai et al. 2022). By leveraging the power of cloud resources, healthcare professionals can access an abundance of data, enabling data-driven decision-making and personalized treatment plans (Kamalov et al. 2023). This paper aims to delve into the myriad applications of cloud robotics, focusing on its impact on physical therapy and rehabilitation. Through cloud-enabled robotic devices, individuals can receive real-time feedback, engage in remote therapy sessions, and benefit from continuous monitoring—all contributing to a more holistic and patient-centric approach to care. Additionally, the accessibility and scalability offered by cloud robotics have the potential to bridge gaps in access to specialized care, particularly for those in remote or underserved areas.

The incorporation of cloud robotics into rehabilitation and assistive technologies holds the potential to redefine the boundaries of human capability and independence (Wang et al. 2023). Cloud-connected assistive devices can adapt and learn from users' movements, providing tailored support and promoting enhanced mobility. Moreover, the remote management and update capabilities of cloud robotics ensure that assistive technologies remain up-to-date and adaptable to evolving user needs (Alam 2021). However, the integration of cloud robotics into healthcare and rehabilitation is not without its challenges. Concerns related to data security, privacy, latency, and connectivity must be addressed to harness the potential benefits of this technology fully. Through this paper, insights into the current state, challenges, and future prospects of cloud

robotics in healthcare and rehabilitation are aimed to be provided, shedding light on its transformative role in improving the lives of individuals with disabilities.

Cloud robotics in healthcare

Cloud robotics has emerged as a game-changing technological paradigm within the healthcare sector, revolutionizing the way medical services are delivered, monitored, and personalized. At its core, cloud robotics involves the integration of cloud computing and robotic systems, enabling a synergistic relationship that amplifies the capabilities of both fields. In the context of healthcare, this convergence offers a range of applications, from telemedicine to surgical robotics and beyond (Afrin et al. 2021). Through cloud robotics, healthcare professionals can leverage the computational power and storage capacity of the cloud to process and analyze vast amounts of medical data in real time. This capability is particularly beneficial in diagnostic imaging, where high-resolution scans can be quickly processed and interpreted, leading to more accurate and timely diagnoses. Moreover, cloud robotics facilitates seamless collaboration among medical experts, enabling remote consultations and knowledge-sharing across geographical boundaries (Yang et al. 2020).

Jain and Doriya (Jain and Doriya 2022) proposed a robust framework in this article for healthcare robots to exchange healthcare data securely from the cloud. The framework encounters three objects: Healthcare Robots (HRs), Healthcare Admin (HA), and an Elliptic Curve Cryptography (ECS) module. The HR serves as the client of the cloud server and establishes a connection to it via the ECS module. The HA monitors and regulates robot activities inside the hospital by establishing access control lists (ACLs) for each robot and submitting them to the ECS. The ECS module performs security activities, including encryption, decryption, key management, and enforcing access control lists (ACLs). The system ensures the confidentiality and integrity of data through the use of Access Control Lists (ACLs) and a hash function. The HR department uploads sensor data files to the cloud for processing, and the cloud server handles the requests and returns the results to the HR department. The proposed methodology guarantees the confidentiality of sensitive data and demonstrates superior outcomes with less security burden. Implementing it in a healthcare setting with limited computational capacity is feasible.

One of the standout applications of cloud robotics in healthcare is telemedicine, which has gained prominence in recent years, especially in the wake of global health crises. Cloud robotics enables the remote operation of medical devices and robotic systems, allowing physicians to perform procedures or examinations on patients located in distant locations (Yu and Zhou 2021). This technology has proven invaluable for extending medical services to underserved or remote areas, improving access to specialized care, and reducing the need for patients to travel long distances for consultations (Hayyolalam et al. 2022). Additionally, cloud robotics contributes to the advancement of minimally invasive surgery by providing surgeons with real-time data and insights during procedures. The cloud's computational capabilities support intricate surgical manoeuvres and enhance precision, ultimately leading to improved patient outcomes and reduced recovery times (Masuda et al. 2020).

Cloud robotics also plays a pivotal role in remote patient monitoring, ushering in a new era of personalized healthcare. Wearable sensors and monitoring devices collect physiological data, which is then transmitted to the cloud for analysis. ML algorithms can process this data to identify patterns and anomalies, allowing healthcare providers to detect potential health issues at an early stage. Patients with chronic conditions can benefit from continuous monitoring, enabling timely interventions and adjustments to treatment plans (Dawarka and Bekaroo 2022). Furthermore, cloud robotics facilitates the creation of virtual health records that can be accessed and updated in real time by both patients and medical professionals. This seamless data sharing enhances care coordination and enables a holistic view of a patient's health history, leading to more informed decision-making (Dawarka and Bekaroo 2022).

While cloud robotics offers immense potential to revolutionize healthcare, several challenges must be addressed for its widespread adoption. Data security and privacy concerns are paramount, as sensitive medical information is transmitted and stored in the cloud (Singh et al. 2022). Robust encryption and stringent data governance frameworks are essential to safeguard patient confidentiality. Additionally, ensuring low-latency communication between robotic systems and the cloud is crucial, especially in time-sensitive medical procedures. Advances in 5G technology and edge computing are poised to address these challenges by minimizing latency and enhancing connectivity. In conclusion, cloud robotics promises to transform healthcare by providing innovative solutions that enhance diagnostic accuracy, extend medical services, enable remote monitoring, and facilitate collaboration among healthcare professionals, ultimately leading to improved patient care and outcomes. The challenges and requirements in cloud robotics revolve around several critical aspects.

Safety and security concerns

Robots may exchange resources across edge resources and cloud data centres thanks to multi-agent cloud robotics systems. As a result, these systems become vulnerable

to several communication levels (local, edge, and cloud) security risks. Compared to mobile cloud computing (MCC) and mobile edge computing (MEC), multi-agent cloud robotics has noticeably more potential data exposure points. Vulnerabilities within one robot can potentially compromise others' data due to the intelligent nature of these entities, making privacy and security risks more prominent. This risk is comparatively lower in MCC and MEC. Additionally, the random mobility of robots necessitates communication across diverse networks, leading to further security challenges. Hence, the selection of reliable resources is crucial for efficient resource allocation and service provisioning. Uncertain events like link failures, edge node shutdowns, power cuts, and interferences can hinder access to infrastructure services. Since multi-agent cloud robotic systems are dynamic, implementing proactive and reactive fault tolerance approaches to maintain system resilience becomes complex.

Comprehensive business model challenges

The dominant subscription-based business model in cloud computing is not well suited for edge infrastructure, primarily dealing with event-driven and localized demand. Robotic systems frequently demand dedicated resources to handle their intricate data streams, resulting in fluctuations in service needs. Developing a comprehensive business model for multi-agent cloud robotics that takes into account these numerous criteria presents complex issues that might interfere with the distribution of expenses and resources related to budgeting. These challenges are relatively more straightforward to handle with MCC and MEC.

Energy-delay optimization constraints

The execution of robotic applications is supported by computing resources distributed across hierarchical architecture layers. However, the realization of these settings suffers from limitations in energy resources. Executing a strategy with the remaining energy and resources poses a challenge. In multi-agent cloud robotic systems, robots serve as both producers and consumers of services, which substantially impacts application execution due to energy constraints. Therefore, it is crucial to choose appropriate resources and efficiently allocate them in order to provide services while staying within the energy limitations of the resources.

System-specific policy challenges

In multi-agent cloud robotics, the requirements for Quality of Service (QoS) change greatly between applications, which makes a consistent approach for resource allocation and service provisioning impractical. The diversity in application needs, such as stringent service delivery deadlines for robotic applications in smart hospitals compared to those in smart farms, requires tailored policies. For instance, robotic surgery demands higher accuracy while minimizing costs, which is crucial in smart factory maintenance. Since robotic systems are dynamic, creating system-specific regulations for effective resource management in this situation is difficult.

Trade-off between on-demand computation and communication

Multi-agent cloud robotics' offloading capability enables low-power or low-energy robots to access edge and cloud infrastructure for running compute-intensive applications. This requires smooth communication between local robots, the edge, and remote resources, adding to the communication time. Complications arise due to the uncertain mobility of robots and the resource heterogeneity across processing cores, networking standards, and energy consumption rates. Hence, on-demand computation and communication trade-offs need to be taken into account in resource allocation and service provisioning rules in multi-agent cloud robotics. On the other hand, because of the users' static movement patterns in MCC and MEC, the computation and communication trade-off frequently depends on predetermined rules.

Synchronized decision-making

Executing robotic applications in multi-agent cloud robotics involves computing infrastructure across various communication layers, requiring explicit synchronization of decision-making entities within this infrastructure. Interference between cloud, edge, and intelligent robots makes synchronization difficult to achieve. Therefore, unlike MCC and MEC, which depend on a single decision maker, resource management duties must be divided among several decision-making organizations in resource allocation and service delivery rules.

Cross-infrastructure interoperability

Heterogeneous computing resources from several service providers assist robots in their jobs in multi-agent cloud robotics. These resources, which are frequently held by different service providers (such as cloud infrastructure from Google or Amazon or edge infrastructure from cellular service providers), use different software systems to control fault tolerance, resource sharing, and privacy. Because MCC and MEC are associated with homogenous resource providers, support for cross-infrastructure and policy-driven

interoperability is therefore required for resource allocation and service provisioning policies, although it is not mandatory in these cases.

Dynamic robotic cooperation

Scenarios like earthquake disaster management and submarine cable maintenance necessitate collaborative work among multiple heterogeneous robots to achieve common goals. However, real-time interactions between robots, edge, or cloud resources are hampered when operating in unfavourable conditions with inadequate communication support. In order to overcome these obstacles, robotic collaboration frequently uses coordinated yet dispersed algorithms (federated learning, for example), which adds overhead to multi-agent cloud robotics in terms of resource management. Unlike MCC and MEC, which operate in simpler contexts, these concerns should be addressed by the policies regulating resource and service supply.

Complex data stream processing

To handle complex data streams from robot-embedded sensors, multi-agent cloud robotics requires modular applications with a variety of programming paradigms (e.g., map-reduce, distributed data flow). Global resources are burdened when extensive data processing is difficult for local and proximal resources due to resource and communication limits. Therefore, unlike MCC and MEC, which handle simpler batch or stream data from conventional smart devices and IoT sensors, resource allocation and service provisioning strategies in multi-agent cloud robotics need to define real-time data stream processing sites.

Real-time learning and autonomous action

Advanced ML and AI methods are necessary for robotic applications that require automatic, situation-aware operations in real-time. Although multi-agent cloud robotics uses edge infrastructure to assist in meeting real-time service needs, financial, structural, and maintenance issues prevent the installation of several resource-rich computer machines with lots of processing cores and GPUs. The implementation of compute-intensive ML and AI algorithms is hampered by these constraints. Because MCC and MEC deal with preset sets of events and actions, they do not always require the strict categorization and selection of resources that are suitable for robotic applications, which makes resource allocation and service provisioning in multi-agent cloud robotics necessary.

Cloud robotics in rehabilitation

Cloud robotics has emerged as a transformative force in the field of rehabilitation, offering innovative solutions to enhance the effectiveness and accessibility of therapeutic interventions. The integration of cloud computing with robotic systems has unlocked new possibilities for personalized, data-driven rehabilitation approaches. Cloud robotics in rehabilitation involves the utilization of cloud-based platforms to enhance the capabilities of robotic devices, enabling real-time data analysis, remote monitoring, and personalized treatment plans. This convergence of technology holds great promise for revolutionizing the rehabilitation process, addressing the unique needs of individuals with disabilities, and ultimately improving their quality of life (Liu et al. 2023).

One of the key advantages of cloud robotics in rehabilitation is its potential to provide remote and virtual therapy sessions. Through cloud-connected robotic devices, patients can engage in rehabilitation exercises and activities under the guidance of healthcare professionals, even when separated by physical distances (Khan et al. 2022). This is particularly valuable for patients who face challenges in accessing rehabilitation facilities due to geographical, transportation, or mobility constraints. Cloud robotics enables therapists to monitor patient's progress in real-time, adjust treatment plans based on data-driven insights, and offer timely feedback and guidance. This approach not only ensures continuity of care but also empowers patients to participate actively in their recovery process.

Moreover, cloud robotics facilitates the development of adaptive and intelligent rehabilitation devices. These devices can analyze users' movements, gather biomechanical data, and transmit this information to the cloud for in-depth analysis (Wang et al. 2022a, b). ML algorithms can then process the data to customize rehabilitation programs according to each individual's progress, limitations, and goals (Pignaton de Freitas et al. 2020). This personalized approach to rehabilitation enhances the efficiency of therapy, as it tailors' interventions to the specific needs and capabilities of each patient. Cloud robotics also enables the integration of gamification and virtual reality into rehabilitation exercises, making therapy sessions engaging, motivating, and enjoyable, which can contribute to better adherence and outcomes.

However, the implementation of cloud robotics in rehabilitation is not without challenges. Data security and privacy concerns are paramount, as sensitive patient information is transmitted and stored in the cloud. Establishing robust cybersecurity measures and

adhering to strict regulatory standards to protect patient confidentiality is imperative. Additionally, latency and connectivity issues can impact the real-time interaction between cloud-connected devices and patients, potentially affecting the quality of therapy. As technology continues to advance, solutions such as edge computing and improved network infrastructure may mitigate these challenges.

Dogmus et al. (Dogmus et al. 2019) proposed an innovative approach to address inquiries on rehabilitation robotics in basic terms using the formal ontology RehabRobo-Onto. In order to accomplish this, a new controlled natural language for rehabilitation robotics, known as RehabRobo-CNL, was created. In addition, they implemented translations of queries in RehabRobo-CNL into SPARQL queries, employing an innovative idea known as query description trees. Furthermore, they employed an automated reasoner to discover solutions to SPARQL queries. In order to enhance the accessibility of this method for professionals, an intelligent and interactive inquiry answering system called RehabRobo-inquiry was created. This system utilizes Semantic Web technologies and is made accessible using Amazon web services on the cloud. RehabRobo-Query assists users in formulating their inquiries using natural language and presents the answers in a legible way, maybe including hyperlinks to more comprehensive material. Effortless retrieval of information from RehabRobo-Onto using intricate natural language queries might assist engineers in generating novel designs for rehabilitation robots while also providing practitioners with better guidance for technology-based rehabilitation decision-making.

Gallego et al. (Gallego et al. 2020) developed the NAO therapist architecture, a robotic system designed to assist those suffering from Cerebral and Obstetric Brachial Palsy to enhance their condition. This is achieved through the independent engagement facilitated by a social robot. This project serves as a Proof of Concept to assess the feasibility of distributing the NAO therapist architecture among multiple computers in order to leverage the advantages of cloud computing and robotics as a service. This study aims to improve the NAO therapist architecture by integrating certain components of the design onto a cloud server. This novel architecture safeguards the source code against unauthorized duplication and facilitates the sharing of resources responsible for the platform's intelligence. The distributed design presents new challenges, such as the communication delay resulting from network connectivity. Subsequently, this issue has been assessed from both a technical standpoint and by surveying the patients who participated in the conducted tests.

Yuan et al. (Yuan et al. 2020) developed a communication strategy for the lower limb exoskeleton robot on a cloud platform. The Zigbee wireless communication protocol establishes a sensor network for gathering and consolidating users' physiological information and robot motion data. Additionally, Message Queuing Telemetry Transport (MQTT) is employed to transport the data to the cloud platform to preserve and process it. The cloud platform is ultimately remotely accessed to acquire the user's physiological data and the robot's movement using the HyperText Transfer Protocol (HTTP). The experiments demonstrate the efficacy and feasibility of the proposed communication strategy for displaying sensor data to users or clinicians on web pages.

Assistive technologies and cloud robotics

Assistive technologies, as outlined in Table 1, have revolutionized the lives of individuals with disabilities by providing tailored solutions that enhance their mobility, communication, and overall independence. The convergence of cloud robotics with assistive technologies heralds a new era of possibilities, augmenting their capabilities through seamless integration with cloud computing. This section explores the symbiotic relationship between assistive technologies and cloud robotics, shedding light on how their combined potential can elevate the quality of life for individuals facing diverse challenges. The fusion of assistive technologies and cloud robotics yields a spectrum of transformative applications. Cloud-connected prosthetics, equipped with sensors and real-time data exchange, offer users a heightened level of

Table 1 Applications of assistive technologies and cloud robotics

Application	Description
Cloud-connected prosthetics	Prosthetic limbs equipped with sensors and cloud connectivity for real-time adjustment and data sharing
Robotic exoskeletons	Cloud-enabled exoskeletons offer enhanced mobility, balance, and support for individuals with mobility impairments
Smart mobility aids	Wheelchairs and mobility devices with cloud connectivity, allowing remote monitoring and navigation assistance
Communication devices	Cloud-connected speech-generating devices for individuals with speech and communication challenges
Home automation and assistance	Cloud robotics controlling smart home devices, enabling greater independence and accessibility at home

control and adaptability. Robotic exoskeletons, enhanced by cloud integration, provide individuals with mobility impairments greater support and mobility options.

Meanwhile, smart mobility aids interfaced with cloud platforms enable remote monitoring and navigation assistance, fostering independence. Communication devices, enriched by cloud connectivity, empower those with speech impairments by facilitating efficient and intuitive communication. In the domain of home automation and assistance, cloud robotics offer a centralized means to control and manage smart home devices, enabling seamless living experiences.

The integration of cloud robotics augments assistive technologies with a plethora of advantages, as summarized in Table 2. Real-time data analysis empowers cloud-connected devices to monitor user interactions, enabling personalized adaptations that align with changing needs. Remote customization emerges as a key advantage, allowing caregivers and users to fine-tune assistive devices without geographical constraints. Adaptive learning and assistance become feasible, as cloud robotics can learn from user behaviours and adjust their functions over time, enhancing user experiences. Moreover, cloud-connected assistive technologies foster improved accessibility, bridging gaps and granting individuals with disabilities enhanced access to services, information, and social interactions. The collaborative potential of cloud robotics amplifies care coordination, enabling users, caregivers, and healthcare professionals to collaborate seamlessly for optimal outcomes.

While the integration of cloud robotics into assistive technologies holds immense promise, it is not devoid of challenges, as shown in Table 3. Data security and privacy concerns necessitate robust encryption and secure data storage protocols to protect sensitive user information. The imperative for low-latency communication between assistive devices and the cloud requires careful consideration to ensure real-time interactions. Adequate user training becomes pivotal to ensure that individuals can effectively utilize and maximize the potential of cloud-connected assistive technologies. Ethical and societal implications demand thoughtful examination, including issues related to data ownership, consent, and potential societal shifts. Lastly, the commitment to inclusivity is paramount, warranting that cloud-connected assistive technologies remain accessible and accommodating for individuals from diverse backgrounds and abilities.

Future research directions

The amalgamation of assistive technologies and cloud robotics has set a trajectory toward an exciting array of future possibilities, poised to redefine the landscape of disability support and rehabilitation. As technology continues to advance, several promising directions emerge, shaping the trajectory of research, innovation, and application in this domain.

Enhanced personalization and adaptability

Future developments will focus on refining the adaptability and personalization of cloud-connected assistive

Table 2 Benefits of integrating cloud robotics

Benefit	Description
Real-time data analysis	Cloud robotics enable continuous monitoring and analysis of user data for personalized adaptations
Remote customization	Assistive devices can be remotely adjusted and fine-tuned based on user preferences and needs
Adaptive learning and assistance	Cloud-connected devices can learn from user interactions and adapt to changing conditions over time
Enhanced accessibility	Cloud robotics provide individuals with disabilities increased access to services, information, and support
Improved collaboration	Cloud connectivity fosters collaboration among users, caregivers, and healthcare professionals for better care coordination

Table 3 Challenges and considerations

Challenge	Consideration
Data security and privacy	Robust encryption and secure data storage to safeguard sensitive information
Latency and connectivity	Ensuring low-latency communication between assistive devices and the cloud for real-time interaction
User training and acceptance	Adequate user training to ensure individuals can effectively utilize cloud-connected assistive technologies
Ethical and societal implications	Addressing ethical concerns related to data ownership, consent, and potential job displacement
Accessibility	Ensuring that cloud-connected assistive technologies are inclusive and accessible to diverse user groups

technologies. ML algorithms will gain prominence in deciphering user preferences, behaviours, and physiological signals, allowing devices to adjust and cater to individual needs autonomously. These advancements will empower users with a more intuitive and seamless interaction experience, enabling assistive devices to become an extension of their capabilities.

Cognitive and emotional interaction

Integrating cognitive and emotional interaction capabilities within cloud-connected assistive technologies holds immense potential. Natural language processing and emotional recognition algorithms could enable devices to interpret and respond to users' emotional states, fostering empathetic interactions. This could revolutionize communication devices and companionship robots, providing emotional support and enhancing the overall well-being of users.

Augmented reality and virtual reality integration

The integration of cloud robotics with augmented reality (AR) and virtual reality (VR) could reshape the rehabilitation landscape. Immersive AR and VR experiences could facilitate engaging and motivating therapy sessions, enhancing the effectiveness of physical rehabilitation exercises. Users could also benefit from remote therapy sessions conducted in virtual environments, further extending access to care.

Multi-modal interfaces

The evolution of multi-modal interfaces, encompassing gestures, voice commands, and brain-computer interfaces, will redefine how users interact with assistive technologies. Cloud robotics will play a pivotal role in processing these inputs and seamlessly translating them into actions, granting users greater control and autonomy over their devices.

Continual learning and shared knowledge

The cloud's capacity for data storage and processing will enable the aggregation and analysis of vast amounts of user data. Through collective insights gained from various users, assistive technologies could learn and evolve, continuously improving their functionalities and adapting to changing user needs. This shared knowledge could drive advancements and set new standards in the field.

Ethical and inclusive design

The future of cloud-connected assistive technologies demands ethical considerations that prioritize data privacy, security, and transparency. Strides will be taken to ensure inclusive design principles, ensuring that emerging technologies are accessible and useful for individuals with a wide range of abilities and backgrounds.

Tele-rehabilitation and remote monitoring

The integration of cloud robotics paves the way for expanded tele-rehabilitation services and remote monitoring capabilities. Cloud-connected assistive devices can facilitate virtual therapy sessions, enabling healthcare professionals to guide and monitor rehabilitation from a distance. Real-time data collection and analysis through cloud robotics could empower healthcare providers to make informed decisions and adjustments to treatment plans in real-time, enhancing patient outcomes and minimizing the need for frequent in-person visits.

Collaborative robotic networks

Future developments may see the emergence of collaborative robotic networks that work in tandem to provide comprehensive support. Cloud-connected robots could collaborate to assist users with complex tasks, such as transferring between surfaces or navigating challenging environments. These networks could optimize assistance based on user preferences and environmental factors, enhancing users' independence and safety.

Biofeedback and neurofeedback integration

Advancements in biofeedback and neurofeedback technologies could integrate seamlessly with cloud-connected assistive devices. By analyzing users' physiological signals, such as brain activity and muscle movements, cloud robotics could provide real-time feedback to users, facilitating more precise and effective control of assistive technologies. This could be particularly valuable for individuals with neurodegenerative conditions or severe motor impairments.

Global accessibility and outreach

Cloud-connected assistive technologies have the potential to bridge global accessibility gaps by providing cost-effective solutions to underserved regions. As cloud computing infrastructure becomes more widespread, cloud robotics

could offer access to cutting-edge assistive devices and therapies to individuals in remote or resource-constrained areas, democratizing access to rehabilitation and support.

Interdisciplinary collaboration

The future of assistive technologies and cloud robotics will likely involve interdisciplinary collaboration between engineers, healthcare professionals, ethicists, psychologists, and more. This collaboration will not only drive technical advancements but also ensure that devices are designed with users' physical, emotional, and psychological well-being in mind, fostering a holistic approach to disability support.

Ethical AI and transparent decision-making

As AI algorithms play an increasingly integral role in cloud-connected assistive technologies, ensuring ethical AI practices and transparent decision-making will be crucial. Research will focus on developing AI models that can explain their decisions and actions, enhancing user trust and accountability in these systems.

Long-term user engagement and behavioural insights

The integration of cloud robotics offers an opportunity to gather long-term behavioural insights from users. By analyzing patterns of device usage, movement, and interactions over extended periods, researchers and healthcare providers can gain deeper insights into users' progress, preferences, and challenges. This data-driven approach can inform the development of more effective rehabilitation strategies and assistive technologies that cater to individual user needs.

Remote training and skill acquisition

Cloud-connected assistive technologies can serve as platforms for remote training and skill acquisition. Users could receive personalized training and guidance through cloud robotics, acquiring new skills or adapting to changes in their abilities. This approach could be particularly valuable for users seeking to learn new activities or hobbies, fostering a sense of accomplishment and contributing to overall well-being.

Biomechanical optimization and ergonomics

Cloud robotics holds the potential to refine the biomechanical optimization of assistive devices. Through real-time data analysis and simulation, these devices could be fine-tuned to ensure optimal ergonomics and user comfort. This advancement could reduce the risk of strain, injury, and discomfort, promoting users' long-term engagement and utilization of assistive technologies.

Seamless integration with the healthcare ecosystem

The future envisions integrating cloud-connected assistive technologies into the broader healthcare ecosystem. Health records, treatment plans, and therapy progress could be stored and shared through secure cloud platforms, facilitating collaboration among healthcare professionals and ensuring continuity of care across various settings and providers.

Public awareness and societal acceptance

As cloud-connected assistive technologies become more prevalent, efforts to raise public awareness and promote societal acceptance will play a vital role. Education campaigns and advocacy initiatives can foster a more inclusive understanding of these technologies, reducing stigma and encouraging their adoption in various contexts.

User-centric design and co-creation

Future development will likely emphasize user-centric design and co-creation processes. Involving individuals with disabilities in the design, testing, and refinement of cloud-connected assistive technologies ensures that the devices meet their unique needs and preferences, resulting in more intuitive, effective, and user-friendly solutions.

Augmentation of cognitive abilities

Beyond physical assistance, cloud-connected assistive technologies could extend into augmenting cognitive abilities. Cloud robotics could support memory aids, cognitive training, and decision-making processes, aiding individuals with cognitive impairments in their daily lives.

Ethical and legal frameworks

The evolution of assistive technologies and cloud robotics calls for the development of robust ethical and legal frameworks. Regulations will need to address issues related to data privacy, informed consent, liability, and accessibility to ensure that these technologies are developed and deployed responsibly and equitably.

Summary

The integration of cloud robotics into assistive technologies opens up a transformative era marked by personalized empowerment, expanded rehabilitation horizons, and inclusive progress. These advancements, characterized by real-time data analysis, adaptive learning, and remote customization, represent a profound shift in empowering individuals with disabilities to reclaim autonomy and reshape their experiences. Cloud-connected devices transcend the traditional boundaries of rehabilitation, extending their influence across communication, mobility, and cognitive support. This convergence not only dismantles physical barriers but also fosters societal inclusion through equitable access and enhanced social integration. The commitment to ethical principles remains paramount in embracing this promising future. Safeguarding user rights, ensuring privacy, and cultivating responsible innovation are essential elements that demand continual attention. As this uncharted path is traversed, imperative collaborative endeavours among stakeholders are needed to chart the course for innovation, accessibility, and societal transformation.

Scopes for future study

The trajectory of cloud-integrated robotics within assistive technologies illuminates an expansive frontier ripe for comprehensive exploration and development. Future studies in this domain stand poised to revolutionize the landscape by fine-tuning the ethical framework governing these cutting-edge technologies. Central to this evolution is the emphasis on user-centric design paradigms prioritizing the needs, preferences, and safety of individuals interacting with these assistive systems. Concurrently, fortifying privacy-preserving mechanisms is critical to ensure data security and confidentiality in sensitive healthcare environments. Overcoming prevailing technological challenges, including minimizing latency, strengthening data security measures to withstand evolving threats, and optimizing connectivity for seamless operation, remains pivotal for the widespread integration and effectiveness of cloud-integrated assistive technologies.

Furthermore, directed research exploring the symbiosis of cloud robotics with burgeoning technologies like Artificial Intelligence (AI) and Augmented Reality (AR) holds the promise of unlocking unparalleled dimensions of innovation. This exploration is poised to usher in a new era where assistive technologies transcend conventional limitations, enabling enriched user experiences and expanded functionalities. The advancement trajectory in this field necessitates continuous collaboration and interdisciplinary research endeavours. Engaging a diverse consortium of stakeholders, from healthcare professionals, technologists, and policymakers to individuals with disabilities, is a cornerstone for catalyzing transformative solutions. By amalgamating the unparalleled capabilities of cloud robots with the visionary objectives of assistive technologies, a revolutionary path is embarked upon toward a future where inclusivity, empowerment, and technological strides converge to redefine opportunities and quality of life for people with disabilities.

Author contributions All authors contributed to the study's conception and design. Data collection, simulation and analysis were performed by " Ran ZHANG, Yan ZHOU, Junkai ZHANG and Juan ZHAO". The first draft of the manuscript was written by " Ran ZHANG ", and all authors commented on previous versions of the manuscript.

All authors have read and approved the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

References

Abdul Samad, S.R., et al.: Analysis of the performance impact of fine-tuned machine learning model for phishing URL detection. Electronics **12**(7), 1642 (2023)

Aceto, G., Persico, V., Pescapé, A.: Industry 4.0 and health: internet of things, big data, and cloud computing for healthcare 4.0. J. Industrial Inform. Integr. **18**, 100129 (2020)

Afrin, M., Jin, J., Rahman, A., Rahman, A., Wan, J., Hossain, E.: Resource allocation and service provisioning in multi-agent cloud robotics: a comprehensive survey. IEEE Commun. Surv. Tutorials **23**(2), 842–870 (2021)

Alam, T.: Cloud-based IoT applications and their roles in smart cities. Smart Cities. **4**(3), 1196–1219 (2021)

Anupong, W., et al.: Deep learning algorithms were used to generate photovoltaic renewable energy in saline water analysis via an oxidation process. Water Reuse. **13**(1), 68–81 (2023)

Azizi, S., Dadarkhah, A., Masouleh, A.A.: Multi-objective optimization method for posture prediction of symmetric static lifting using a three-dimensional human model. Annals Military Health Sci. Res., **18**, 2, (2020)

Bolhassani, M., Oksuz, I.: Semi-supervised segmentation of multi-vendor and multi-center cardiac MRI, in 2021 29th Signal processing and communications applications conference (SIU), IEEE, pp. 1–4. (2021)

Buerkle, A., et al.: Towards industrial robots as a service (IRaaS): flexibility, usability, safety and business models. Robot. Comput-Integ. Manuf. **81**, 102484 (2023)

Dawarka, V., Bekaroo, G.: Building and evaluating cloud robotic systems: a systematic review. Robot. Comput. Integr. Manuf. **73**, 102240 (2022)

De Croon, G., Dupeyroux, J., Fuller, S., Marshall, J.: Insect-inspired AI for autonomous robots. Sci. Rob. **7**(67), eabl6334 (2022)

Diankov, R., Kuffner, J.: Openrave: a planning architecture for autonomous robotics, Robotics Institute, Pittsburgh, PA, Tech. Rep. CMU-RI-TR-08-34, vol. 79, (2008)

Dogmus, Z., Erdem, E., Patoglu, V.: RehabRobo-Query: answering natural language queries about rehabilitation robotics ontology on the cloud. Semantic Web **10**(3), 605–629 (2019)

Gallego, A., Pulido, J.C., González, J.C., Fernández, F.: Design of a robotic as a service platform to perform rehabilitation therapies. In: Silva, M., Luís Lima, J., Reis, L., Sanfeliu, A., Tardioli, D. (eds.) Robot 2019: Fourth Iberian Robotics Conference. Springer, Cham (2020)

Geihs, K.: Engineering challenges ahead for robot teamwork in dynamic environments. Appl. Sci. **10**(4), 1368 (2020)

Grasso, M., Renga, A., Fasano, G., Graziano, M., Grassi, M., Moccia, A.: Design of an end-to-end demonstration mission of a formation-flying synthetic aperture radar (FF-SAR) based on microsatellites. Adv. Space Res. **67**(11), 3909–3923 (2021)

Hayyolalam, V., Pourghebleh, B., Kazem, A.A.P., Ghaffari, A.: Exploring the state-of-the-art service composition approaches in cloud manufacturing systems to enhance upcoming techniques. Int. J. Adv. Manuf. Technol. **105**, 1–4 (2019)

Hayyolalam, V., Pourghebleh, B., Chehrehzad, M.R., Pourhaji Kazem, A.A.: Single-objective service composition methods in cloud manufacturing systems: recent techniques, classification, and future trends. Concurr. Comput.: Pract. Exp. **34**(5), e6698 (2022)

Hu, B., Guan, Z.-H., Lewis, F.L., Chen, C.P.: Adaptive tracking control of cooperative robot manipulators with Markovian switched couplings. IEEE Trans. Industr. Electron. **68**(3), 2427–2436 (2020)

Jain, S., Doriya, R.: Security framework to healthcare robots for secure sharing of healthcare data from the cloud. Int. J. Inform. Technol. **14**(5), 2429–2439 (2022)

Kamalov, F., Pourghebleh, B., Gheisari, M., Liu, Y., Moussa, S.: Internet of medical things privacy and security: challenges, solutions, and future trends from a new perspective. Sustainability **15**(4), 3317 (2023)

Khan, W.A., Ahmad, F., Alanazi, S.A., Hasan, T., Naseem, S., Nisar, K.S.: Trust identification through cognitive correlates with emphasizing attention in cloud robotics. Egypt. Inf. J. **23**(2), 259–269 (2022)

Koul, N., Kumar, N., Sayeed, A., Verma, C., Raboca, M.S.: Data exchange techniques for the internet of robotic things: recent developments. IEEE Access (2022). https://doi.org/10.1109/ACCESS.2022.3209376

Larijani, A., Dehghani, F.: A computationally efficient method for increasing confidentiality in smart electricity networks, Electronics, vol. 13, no. 1, p. 170, [Online] (2024a). Available: https://www.mdpi.com/2079-9292/13/1/170

Larijani, A., Dehghani, F.: An efficient optimization approach for designing machine models based on combined algorithm, FinTech, vol. 3, no. 1, pp. 40–54, [Online] (2024b). Available: https://www.mdpi.com/2674-1032/3/1/3

Liu, J., Wang, D., Lin, Q., Deng, M.: Risk assessment based on FMEA combining DEA and cloud model: a case application in robot-assisted rehabilitation. Expert Syst. Appl. **214**, 119119 (2023)

Magid, E., et al.: Artificial intelligence based framework for robotic search and rescue operations conducted jointly by international teams, in Proceedings of 14th International Conference on Electromechanics and Robotics Zavalishin's Readings ER (ZR) 2019, Kursk, Russia, 17–20 April 2019, Springer, pp. 15–26. (2019)

Masuda, Y., Shepard, D.S., Nakamura, O., Toma, T.: Vision paper for enabling the internet of medical robotics things in open healthcare platform 2030, in Innovation in Medicine and Healthcare: Proceedings of 8th KES-InMed 2020, Springer, pp. 3–14. (2020)

Mazzolai, B., et al.: Roadmap on soft robotics: multifunctionality, adaptability and growth without borders. Multifunct. Mater. **5**(3), 032001 (2022)

Mello, R.C., Ribeiro, M.R., Frizera-Neto, A.: Introduction to cloud robotics. In: Implementing Cloud Robotics for Practical Applications: from Human-Robot Interaction to Autonomous Navigation, pp. 1–11. Springer (2022)

Mohtasebi, M., et al.: A wearable fluorescence imaging device for intraoperative identification of human brain tumors. IEEE J. Trans. Eng. Health Med. (2023). https://doi.org/10.1109/JTEHM.2023.3338564

Moradi, M.R., Kalhori, S.R.N., Saeedi, M.G., Zarkesh, M.R., Habibelahi, A., Panahi, A.H.: Designing a remote closed-loop automatic oxygen control in preterm infants. Iran. J. Pediatr. (2020). https://doi.org/10.21203/rs.2.19536/v1

Naceri, A., et al.: The vicarios virtual reality interface for remote robotic teleoperation: teleporting for intuitive tele-manipulation. J. Intell. Robot. Syst. **101**, 1–16 (2021)

Pignaton de Freitas, E., et al.: Ontological concepts for information sharing in cloud robotics. J. Ambient Intell. Humaniz. Comput. (2020). https://doi.org/10.1007/s12652-020-02150-4

Pourghebleh, B., Hayyolalam, V., Anvigh, A.A.: Service discovery in the internet of things: a review of current trends and research challenges. Wirel. Netw. **26**(7), 5371–5391 (2020)

Pourghebleh, B., Hekmati, N., Davoudnia, Z., Sadeghi, M.: A roadmap towards energy-efficient data fusion methods in the internet of things. Concurr. Comput.: Pract. Exp. (2022). https://doi.org/10.1002/cpe.6959

Pradel, M., de Fays, M., Seguineau, C.: Comparative life cycle assessment of intra-row and inter-row weeding practices using autonomous robot systems in French vineyards. Sci. Total Environ. **838**, 156441 (2022)

Rajput, S.P., et al.: Using machine learning architecture to optimize and model the treatment process for saline water level analysis. J. Water Reuse Desalin. (2022). https://doi.org/10.2166/wrd.2022.069

Ramachandran, R.K., Pierpaoli, P., Egerstedt, M., Sukhatme, G.S.: Resilient monitoring in heterogeneous multi-robot systems through network reconfiguration. IEEE Trans. Robot. **38**(1), 126–138 (2021)

Saeidi, H., et al.: Autonomous robotic laparoscopic surgery for intestinal anastomosis. Sci. Rob. **7**(62), eabj2908 (2022)

Saeidi, S., Enjedani, S., Alvandi Behineh, E., Tehranian, K., Jazayerifar, S.: Factors affecting public transportation use during pandemic an integrated approach of technology acceptance model and theory of planned behavior. Tehnički glasnik **18**, 1–12 (2023). https://doi.org/10.31803/tg-20230601145322

Singh, S., Pankaj, B., Nagarajan, K., Singh, N.P., Bala, V.: Blockchain with cloud for handling healthcare data: a privacy-friendly platform. Mater. Today: Proc. **62**, 5021–5026 (2022)

Vairachilai, S., Bostani, A., Mehbodniya, A., Webber, J.L., Hemakesavulu, O., Vijayakumar, P.: Body sensor 5 G networks utilising deep learning architectures for emotion detection based on EEG signal processing. Optik (2022). https://doi.org/10.1016/j.ijleo.2022.170469

Wang, X., Sun, Y., Ding, D.: Adaptive dynamic programming for networked control systems under communication constraints: a survey of trends and techniques. Int. J. Netw. Dynamics Intell. (2022a). https://doi.org/10.53941/ijndi0101008

Wang, Z., et al.: A design method for an intelligent manufacturing and service system for rehabilitation assistive devices and special groups. Adv. Eng. Inform. **51**, 101504 (2022b)

Wang, C., He, T., Zhou, H., Zhang, Z., Lee, C.: Artificial intelligence enhanced sensors-enabling technologies to next-generation healthcare and biomedical platform. Bioelectronic Med. **9**(1), 17 (2023)

Yang, G., et al.: Homecare robotic systems for healthcare 4.0: visions and enabling technologies. IEEE J. Biomedical Health Inf. **24**(9), 2535–2549 (2020)

Yu, H., Zhou, Z.: Optimization of IoT-based artificial intelligence assisted telemedicine health analysis system. IEEE Access. **9**, 85034–85048 (2021)

Yuan, Y., Cao, G.-Z., Zhu, A., Lyu, X., Wang, Y.: Communication scheme of a cloud platform for the lower limb exoskeleton rehabilitation robot, in 17th International Conference on Ubiquitous Robots (UR), 2020. IEEE, pp. 327–332. (2020)

Zandi, J., Afooshteh, A.N., Ghassemian, M.: Implementation and analysis of a novel low power and portable energy measurement tool for wireless sensor nodes, in Electrical Engineering (ICEE), Iranian Conference on, IEEE, pp. 1517–1522, (2018). https://doi.org/10.1109/ICEE.2018.8472439

Publisher's Note Springer nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.