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An examination of intelligent robotic wheelchairs enhancing mobility and autonomy for people with disabilities

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Abstract: This paper offers a comprehensive examination of smart robotic wheelchairs and their role in enhancing the mobility and independence of individuals with disabilities. Conventional wheelchairs often restrict users, leading to limited movement and accessibility. The emergence of smart robotic wheelchairs presents a promising solution to these issues. The study provides an overview of wheelchair technology, highlights challenges faced by individuals with disabilities, and assesses the benefits and drawbacks of smart robotic wheelchairs through a review of previous research. It delves into the features and functionalities of these wheelchairs, such as navigation and obstacle avoidance, autonomous and semi-autonomous modes, and customizable control options. Additionally, it analyses user experience, performance evaluation, and the impact on mobility and independence. The paper concludes by outlining future research directions and recommendations to further empower individuals with disabilities and enhance their quality of life.

Keywords: Human-machine Interface, Navigation System, Assistive device, Obstacle avoidance, Microcontroller

1 Introduction

In recent years, the field of assistive technology has seen remarkable advancements, particularly in enhancing the lives of individuals with limited mobility. Among these innovations, smart robotic wheelchairs have become a revolutionary solution, reshaping how people with disabilities navigate their environments [1]. These advanced wheelchairs integrate robotics, artificial intelligence, and sensor technologies, offering users an unprecedented level of independence, autonomy, and safety.

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Traditional wheelchairs have undeniably served as essential mobility aids for individuals with physical disabilities, enabling them to move around and interact with their environments. However, conventional wheelchairs often present limitations, such as the requirement for manual propulsion, challenges planning in confined spaces, and a lack of adaptability to various terrains [2]. Smart robotic wheelchairs address these issues by integrating intelligent systems capable of perceiving, interpreting, and responding to the surrounding environment, empowering users to navigate with greater ease, flexibility, and confidence. A general concept mapping of smart wheelchair is shown in Figure 1.

One of the key attributes of smart robotic wheelchairs is their capability to autonomously navigate complex environments [3]. Equipped with advanced sensors such as LiDAR, cameras, and depth sensors, these wheelchairs can dynamically map their surroundings, identifying obstacles, pathways, and potential hazards in real-time. The embedded artificial intelligence algorithms process this data, making informed decisions to ensure seamless and secure navigation [4]. Users simply input their desired destination, and the smart wheelchair handles the rest, avoiding collisions, adjusting speed, and even determining the most efficient routes [5].

Additionally, smart robotic wheelchairs prioritize user comfort and convenience. Many models offer features like customizable seating positions, tailored seating support, and automatic adjustments based on the user's body posture and weight distribution. This promotes optimal ergonomics and reduces the likelihood of pressure sores and musculoskeletal issues associated with prolonged wheelchair use [6]. Moreover, smart wheelchairs often incorporate connectivity options, enabling users to control their chairs via smart phones, tablets, or other wearable devices, further enhancing their overall mobility experience.

Fig 1. Concept Mapping of Smart Wheelchair

Furthermore, smart robotic wheelchairs cater to the diverse needs and preferences of users by adapting to various terrains, including inclined surfaces, rough terrain, and uneven ground, ensuring a smooth and stable ride. Some models even feature standing capabilities, allowing users to transition from a seated to a standing position, promoting improved blood circulation, extended reach, and facilitating social interactions at eye level [7]. These innovative functionalities contribute to the overall well-being, independence, and social inclusion of individuals with mobility impairments.
Smart robotic wheelchairs are revolutionizing the mobility landscape for individuals with disabilities, empowering them to navigate their surroundings with newfound independence, confidence, and safety. By integrating cutting-edge robotics, artificial intelligence, and sensor technologies, these wheelchairs offer advanced navigation capabilities, enhanced comfort, adaptability to various terrains, and customization options. With each advancement, smart robotic wheelchairs continue to push the boundaries of assistive technology, unlocking new possibilities for improved mobility and significantly enhancing the quality of life for wheelchair users.

1.1 Importance of the Proposed Research

Smart robotic wheelchairs hold a pivotal role in revolutionizing the lives of individuals with disabilities, presenting unprecedented advantages and opportunities for mobility and independence. These innovative devices have emerged as a ground-breaking solution, addressing the constraints of conventional wheelchairs and assistive technologies. The significance of smart robotic wheelchairs lies in their potential to transform the daily experiences of individuals with disabilities, promoting physical, psychological, and social well-being [8].

Foremost, smart robotic wheelchairs significantly amplify mobility and independence. With intelligent navigation and obstacle avoidance capabilities, these wheelchairs empower users to navigate their environment effortlessly, surmounting barriers and accessing spaces previously challenging or inaccessible [9]. The customizable features of smart robotic wheelchairs enable individuals to tailor the wheelchair to their specific requirements, ensuring a personalized and comfortable experience. Moreover, the integration of assistive technologies enhances functionality, enabling individuals to interact with their surroundings and accomplish tasks that were previously daunting or impossible.

In terms of physical health, smart robotic wheelchairs contribute to enhanced overall well-being. By promoting increased mobility and physical activity, these devices aid individuals in maintaining or improving their physical fitness, crucial for averting secondary health issues associated with sedentary lifestyles. With the ability to move more freely and engage in activities, individuals with disabilities experience enhanced cardiovascular health, improved muscle tone, enhanced joint mobility, and increased overall endurance. Additionally, smart robotic wheelchairs support rehabilitation and therapy, facilitating the recovery process and enabling individuals to regain strength and independence [10].

Beyond physical health, smart robotic wheelchairs profoundly impact psychological well-being. These devices offer a sense of empowerment and independence, enabling individuals to regain control over their lives and make choices about their daily activities. By bolstering self-confidence and self-esteem, smart robotic wheelchairs help individuals overcome the emotional challenges often associated with disabilities [11]. Moreover, they reduce social stigma and isolation by facilitating social interactions and promoting engagement with the community. Individuals with disabilities can actively participate in social activities, connect with others, and cultivate meaningful relationships, ultimately enhancing their mental health and overall quality of life [12].

Furthermore, smart robotic wheelchairs promote social inclusion and accessibility [13]. By facilitating community integration, these devices enable individuals with disabilities to fully participate in social, educational, and professional settings. Individuals can access public spaces, educational institutions, and workplaces with greater ease, dismantling physical barriers and fostering equal opportunities. The increased mobility and independence provided by smart robotic wheelchairs also unlock employment opportunities, fostering economic empowerment and diminishing dependence on caregivers or social welfare systems. Ultimately, these devices contribute to creating a more inclusive society where individuals with disabilities can actively contribute and thrive.

The significance of smart robotic wheelchairs transcends individual benefits [14]. These devices hold substantial economic and societal implications. From a cost-effectiveness standpoint, smart robotic wheelchairs can curtail long-term healthcare expenses by averting secondary health issues and hospitalizations [15]. Additionally, they bolster productivity and economic contributions by enabling individuals with disabilities to participate in the workforce, leading to heightened employment rates and diminished dependency on social assistance programs. By fostering inclusivity and accessibility, smart robotic wheelchairs contribute to shaping more equitable and diverse societies, where every individual can fully participate and contribute to their communities.

The importance of smart robotic wheelchairs for individuals with disabilities cannot be overstated. These technologically advanced devices revolutionize mobility and independence, offering numerous physical, psychological, and social benefits. By promoting mobility, customization, and integration with assistive technologies, smart robotic wheelchairs empower individuals to navigate their environment, engage in physical activities, and reclaim control over their lives. The impact extends beyond the individual, with social inclusion, accessibility, and economic empowerment being pivotal societal outcomes. As the field of smart robotic wheelchairs continues to advance, further research, development, and implementation are imperative to ensure that individuals with disabilities can enjoy the full benefits and opportunities provided by these transformative devices [16].

1.2 Objective of the Proposed Study

The aim of this research paper is to offer a comprehensive analysis of the progress and influence of smart robotic wheelchairs in enhancing mobility and independence for individuals with disabilities.

- To conduct a detailed examination of the advancements and impact of smart robotic wheelchairs in advancing mobility and independence for individuals with disabilities.
- To assess the various features and advantages associated with smart robotic wheelchairs, including intelligent navigation, obstacle avoidance, customization, and integration with assistive technologies.
- To explore the challenges and constraints encountered in the development and adoption of smart robotic wheelchairs, such as technical barriers, cost accessibility, ethical considerations, and user acceptance.
- To evaluate the effects of smart robotic wheelchairs on the physical and psychological well-being of wheelchair users, including increased physical activity, prevention of secondary health issues, psychological empowerment, and improved mental health.

By attaining these objectives, this research paper endeavors to contribute to the existing understanding of the significance of smart robotic wheelchairs in advancing mobility and independence for individuals with disabilities, offering insights for researchers, practitioners, policymakers, and individuals with disabilities themselves.

2 Literature Review

In recent years, smart robotic wheelchairs have emerged as a promising solution to enhance the mobility and independence of individuals with disabilities, garnering significant attention. These sophisticated wheelchairs integrate a range of technologies, including robotics, artificial intelligence (AI), and sensing systems, to offer users enhanced functionality and support. This literature review seeks to investigate the recent advancements in smart robotic wheelchairs, emphasizing their pivotal features, advantages, and associated challenges. Furthermore, it aims to examine the potential implications of these technologies on the quality of life for individuals facing mobility impairments.

2.1 Smart wheelchair design and control

The design and control of robotic wheelchairs play a pivotal role in ensuring safe and efficient user navigation. A modular design framework aimed at facilitating customization of the wheelchair's configuration to align with the user's specific needs and preferences [17]. The study underscored the significance of user-centered design principles in augmenting the overall user experience.

A modular design framework facilitates the tailoring of robotic wheelchairs to cater to the individual requirements and preferences of users. In another research [18] introduced a modular design approach allowing for flexible adjustments in configuration, such as seat height, armrests, and control interfaces. The study stressed the importance of user-centered design principles in enhancing comfort and usability.

In robotic wheelchair design, lightweight and compact designs are imperative to ensure ease of maneuverability and portability. In another article [19] presented a lightweight robotic wheelchair design utilizing carbon fiber materials, resulting in reduced overall weight without compromising structural integrity. The study emphasized the advantages of lightweight construction in enhancing energy efficiency and user experience.

Ergonomics and user comfort stand as crucial considerations in robotic wheelchair design. In another study [20] conducted a study on the ergonomic design of robotic wheelchairs, highlighting the significance of features such as seat adjustability, backrest contouring, and support for optimal posture and pressure distribution. The research underscored the potential of ergonomic design principles in alleviating discomfort and augmenting user well-being.

2.2 Automatic navigation strategies

Intelligent navigation and obstacle avoidance stand as indispensable capabilities of smart robotic wheelchairs. In another research [21] projected a wheelchair navigation system grounded in AI and computer vision techniques. Employing deep learning algorithms, the system recognized and classified obstacles, empowering the wheelchair to autonomously chart optimal paths and avert collisions. This approach showcased enhanced navigation efficiency and safety. Computer vision-based methods have been extensively explored for intelligent navigation in robotic wheelchairs.

In research [22] introduced an AI-based navigation system leveraging deep learning algorithms for object detection and classification. The system facilitated autonomous path planning and collision avoidance, augmenting navigation efficiency and safety.

Lidar sensors have demonstrated significant promise for obstacle perception and mapping in robotic wheelchairs. In [23] devised a lidar-based navigation system amalgamating simultaneous localization and mapping (SLAM) techniques. This system enabled the wheelchair to generate a real-time map of the environment and navigate autonomously, ensuring efficient obstacle avoidance. SLAM techniques play a pivotal role in robotic wheelchair navigation by enabling environment mapping and localization within it. In study [24] proposed a SLAM-based navigation system utilizing laser range finders and odometry sensors. This system achieved precise localization and mapping, facilitating safe and efficient wheelchair navigation.

Global path planning algorithms generate optimal paths for robotic wheelchairs, taking the overall environment into account. Reference [25] introduced a global path planning approach amalgamating the Rapidly-exploring Random Tree (RRT) algorithm and potential field method. This approach produced smooth paths while circumventing obstacles, enhancing navigation efficiency and user experience. Local obstacle avoidance techniques concentrate on maneuvering around immediate obstacles in the wheelchair's path. In study [26] proposed a local obstacle avoidance method leveraging a combination of lidar sensors and ultrasonic sensors. This method enabled the wheelchair to detect and evade obstacles in real-time, ensuring safe and collision-free navigation [27].

Semantic mapping and navigation approaches harness semantic comprehension of the environment to enhance robotic wheelchair navigation. In study [28] introduced a semantic mapping and navigation system employing a fusion of deep learning-based object detection and semantic segmentation algorithms. This system empowered the wheelchair to perceive and navigate based on semantic information, enhancing comprehension and interaction with the environment.

Collaborative navigation among multiple robotic wheelchairs can elevate overall navigation efficiency and facilitate cooperation in complex environments. In research [29] proposed a multi-robot collaboration framework employing decentralized communication and information sharing. This framework facilitated cooperative obstacle avoidance and path planning among multiple wheelchairs, enhancing navigation capabilities in crowded or dynamic environments.

2.3 Sensors and Actuators

Smart robotic wheelchairs integrate various sensor technologies, including lidar, ultrasound, and infrared sensors, to perceive the environment and aid in navigation. In another study [30] utilized a fusion of lidar and vision-based sensors to develop a comprehensive perception system. This sensor combination enabled the wheelchair to accurately detect and recognize objects, facilitating safe maneuvering in dynamic environments [31].

Adaptive navigation techniques adjust the wheelchair's navigation behavior in real-time based on sensor feedback and user preferences. In [32], devised a sensor-based adaptive navigation system employing machine learning algorithms to model user preferences and adapt navigation parameters accordingly. This system provided personalized and context-aware navigation for wheelchair users.

Lidar (Light Detection and Ranging) sensors have gained prominence in robotics for their capability to offer precise 3D environmental mapping and object detection. In reference [33] discussed lidar sensor applications in mobile robots, encompassing robotic mapping, localization, and obstacle avoidance. The study underscored the robustness and reliability of lidar sensors in perception tasks.

Camera and vision sensors are extensively employed in robotics for visual perception, object recognition, and navigation. In study [34] provided an overview of camera-based perception systems in robotics, encompassing monocular and stereo vision, object detection, and scene understanding. The study emphasized the pivotal role of vision sensors in enabling robots to interpret and interact with the visual environment.

Inertial Measurement Units (IMUs) comprise accelerometers, gyroscopes, and magnetometers, furnishing data about the robot's orientation, acceleration, and angular velocity. In another method [35] discussed the utilization of IMUs in robot localization and motion tracking, highlighting their suitability for applications lacking external references. The study accentuated the integration of IMUs with other sensors for robust and accurate motion estimation.

Force/torque sensors empower robots to perceive and measure external forces and torques encountered during interactions with the environment. In this research [36] reviewed the applications of force/torque sensors in robotic tasks such as grasping, manipulation, and human-robot interaction, emphasizing their significance for safe and precise robotic interactions.

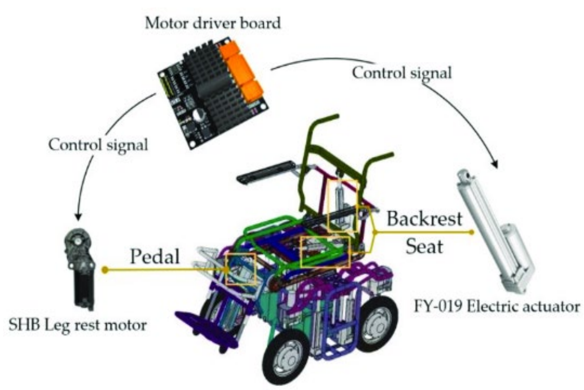

Fig 2. Various Sensors and Actuators are working together

Range sensors, including ultrasonic sensors and Time-of-Flight (ToF) cameras, offer distance measurements and obstacle detection capabilities. In this article [37] discussed the utilization of range sensors for localization, mapping, and obstacle avoidance in robotics, highlighting their complementarily with other sensor modalities for comprehensive perception.

Tactile and pressure sensors enable robots to sense and interpret physical contact with objects and the environment. In another research article [38] reviewed advancements in tactile and pressure sensors for robotic applications, encompassing object recognition, grasping, and haptic feedback. The study underscored the importance of tactile sensing in enabling safe and effective robot interaction and manipulation.

2.4 Human-Machine Interfaces

Efficient human-machine interaction is crucial for smart robotic wheelchairs to effectively meet users' needs and preferences. An intelligent interface for wheelchair control was developed using electromyography (EMG) signals, allowing users to control the wheelchair's movement by voluntarily activating specific muscles [39]. This approach provided a more intuitive and personalized control interface.

Gesture-based interaction enables users to communicate with machines through natural body movements. In reference [40] discussed the applications of gesture recognition in Human-Machine Interaction (HMI), highlighting its significance in robotics and virtual reality. The study underscored the importance of accurate and robust gesture recognition algorithms for seamless and intuitive human-machine communication.

Speech and voice interaction offer a natural and efficient mode of communication between humans and machines. In reference [41] reviewed advancements in automatic speech recognition and voice control technologies for HMI, emphasizing the importance of robust speech processing algorithms and adaptive models for accurate and context-aware voice interaction.

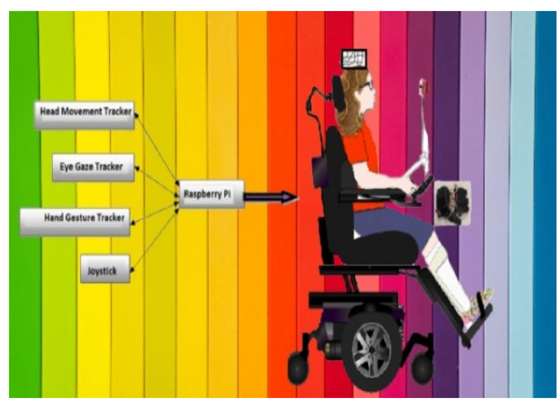

Fig 3. Human-Machine Interface for a Wheelchair

Touch-based interfaces, such as touch screens and touch pads, enable direct manipulation and tactile feedback in HMI. In a research article [42] discussed design principles and user experience considerations for touch-based interfaces, highlighting the importance of intuitive gestures, responsiveness, and haptic feedback for enhancing user interaction and satisfaction.

Brain-Computer Interfaces (BCIs) facilitate direct communication between the human brain and machines, allowing control and interaction without physical input.

A scientist reviewed recent advancements in BCIs for HMI, focusing on non-invasive techniques like electroencephalography (EEG) [43]. The study highlighted the potential of BCIs in enabling communication for individuals with severe physical disabilities.

Multimodal interfaces integrate multiple interaction modalities, such as voice, gestures, and touch, to enrich HMI. In article [44] reviewed advancements in multimodal interfaces, including fusion techniques and interaction design principles, emphasizing their benefits in enhancing communication efficiency and accommodating user preferences.

2.5 Safety considerations

As smart robotic wheelchairs evolve to be more sophisticated and autonomous, ethical and safety considerations must be carefully addressed. In research [45] underscored the importance of developing robust safety mechanisms to prevent accidents and ensure user well-being. The study emphasized the necessity for reliable fault detection, emergency stop systems, and compliance with safety standards in the design and implementation of smart robotic wheelchairs.

Robot ethics encompasses the examination of moral and ethical implications associated with the design, deployment, and use of robots. In research [46] discussed ethical considerations in robot design, programming, and behavior, highlighting the importance of incorporating ethical principles to ensure robots act in a socially responsible and acceptable manner.

Safety remains a paramount concern in robotics, especially in collaborative and physical human-robot interaction scenarios. In [47] reviewed safety measures and risk assessment methods for human-robot collaboration, stressing the significance of risk analysis, adherence to safety standards, and implementation of protective measures to prevent accidents and ensure safe operation.

Ethical guidelines and standards provide frameworks for the responsible and ethical development and utilization of robotics systems. In research [48] discussed ethical and legal challenges in robotics and proposed a code of ethics for robots, emphasizing the importance of transparent and accountable robot behavior, respect for human values, and adherence to legal and ethical norms.

Transparency and explain ability are essential for fostering trust and understanding in robotic systems. In [49] discussed the importance of transparency and explainability in AI and robotics and proposed an explainability framework for intelligent systems. The research emphasized the necessity for interpretable and understandable robot behaviors to enable users to trust and collaborate with robots effectively.

2.6 Technology and Research Gap

Smart robotic wheelchairs represent cutting-edge mobility solutions, integrating advanced technologies to enhance the independence and mobility of individuals with disabilities. Despite significant progress in this field, several research gaps and areas for further exploration remain. This review aims to pinpoint these gaps and identify novel aspects contributing to the advancement of mobility and independence for individuals with disabilities [50].

Research Gap:

• User-Centered Design: A notable research gap is the insufficient emphasis on user-centered design in the development of smart robotic wheelchairs. While technical advancements have been made, involving end-users, including individuals with disabilities and healthcare professionals, in the design process is crucial.

• Long-Term User Adaptation: Another gap lies in understanding long-term user adaptation to smart robotic wheelchairs. While initial studies have focused on short-term evaluations, there's a need to delve into how individuals with disabilities adapt to these wheelchairs over extended periods.

Novelty:

• Intelligent Navigation and Obstacle Avoidance: Smart robotic wheelchairs stand out for their integration of intelligent navigation and obstacle avoidance systems. These systems leverage advanced algorithms and sensors to autonomously navigate complex environments, detect obstacles, and plan efficient routes.

• Personalized Assistive Features: Another innovative aspect is the incorporation of personalized assistive features tailored to individual user needs. These include customizable seating positions, adjustable control interfaces, and adaptive functionalities based on user preferences, ensuring tailored support and comfort.

• Enhanced User Interfaces: Smart robotic wheelchairs boast enhanced user interfaces, employing intuitive control mechanisms like voice commands, gesture recognition, or brain-computer interfaces. These interfaces improve user experience, reduce cognitive load, and facilitate seamless interaction.

Despite progress, addressing research gaps such as user-centered design and long-term adaptation is essential. The novelty lies in intelligent navigation, personalized features, and enhanced interfaces. By bridging these gaps and integrating novel features, smart robotic wheelchairs can further advance mobility and independence for individuals with disabilities, empowering them to lead more fulfilling lives.

3 Peripherals of smart wheelchair

A smart wheelchair is a technologically advanced mobility device that integrates various components to enhance its functionality, autonomy, and user experience. The peripherals to design a smart wheelchair are discussed below:

3.1 System Drive

The drive system governs the mobility and manoeuvrability of the wheelchair, encompassing motors, wheels, and a control mechanism. Smart robotic wheelchairs commonly integrate sophisticated motor systems, like electric or brushless DC motors, ensuring seamless and effective propulsion. The control mechanism may involve traditional interfaces such as joystick control or touchpad interfaces, or it may incorporate cutting-edge methods like voice commands or brain-computer interfaces.

3.2 Sensors

Sensors play a vital role in smart robotic wheelchairs by providing essential input for perceiving the environment and enabling autonomous functions [51]. Some commonly utilized sensors include:

• Lidar (Light Detection and Ranging): Lidar sensors utilize laser beams to gauge distances and generate detailed 3D maps of the surroundings. They aid in navigation, obstacle detection, and localization.

• Camera and Vision Sensors: Cameras capture visual data, enabling the wheelchair to identify objects, detect obstacles, and interpret visual cues. Sophisticated vision algorithms enable functionalities such as object recognition and tracking.

• Ultrasonic Sensors: Ultrasonic sensors emit high-frequency sound waves and measure their reflections to identify nearby objects and obstacles. They are frequently employed for proximity sensing and collision avoidance.

• Inertial Measurement Units (IMUs): IMUs incorporate accelerometers, gyroscopes, and magnetometers to gauge acceleration, angular velocity, and orientation. IMUs are utilized for motion tracking, balance control, and maintaining stability.

3.3 Control technology

The control system acts as the central intelligence of the smart robotic wheelchair, tasked with processing sensor data, executing control algorithms, and orchestrating the wheelchair's movements [52]. It comprises microcontrollers or microprocessors that receive input from sensors, interpret the data, and generate commands for the drive system. Sophisticated control algorithms, such as path planning, obstacle avoidance, and navigation algorithms, are implemented to facilitate autonomous or semi-autonomous wheelchair operation.

3.4 User-interfaces

The user interface serves as the conduit for communication between the user and the wheelchair [53]. It enables users to interact with the wheelchair, input commands, and receive responses. Typical elements of the user interface include:

• Control Interfaces: These interfaces can vary from conventional joystick controllers to touch screens, touch pads, or alternative methods like voice recognition or gesture control. The interface should be intuitive and adaptable to accommodate the user's capabilities and preferences.

• Displays: Displays offer visual feedback to the user, presenting information such as speed, battery level, navigation instructions, or safety alerts. They can be integrated into the wheelchair's control interface or exist as separate screens.

• Auditory Feedback: Auditory cues, such as beeps or voice prompts, offer vital feedback to users, particularly those with visual impairments. They can signal obstacle proximity, changes in direction, or system status.

3.5 Interfacing technologies

Smart robotic wheelchairs frequently integrate connectivity features and interface with other devices and systems [54]. These features encompass:

• Wireless Connectivity: Smart wheelchairs often possess Bluetooth or Wi-Fi functionalities, facilitating connections with smart phones, tablets, or smart home devices. This enables users to remotely control the wheelchair or access additional features and functionalities.

• Integration with Assistive Technologies: Incorporating assistive technologies such as environmental control systems, speech synthesizers, or communication aids enhances the wheelchair's usability and broadens its capabilities.

• Data Logging and Analytics: Certain smart robotic wheelchairs have the ability to log sensor data, usage patterns, and performance metrics. Analysing this data allows for optimization of the wheelchair's performance, identification of user preferences, and insights for research and enhancement purposes.

3.6 Complementary factors

The power system of a smart robotic wheelchair encompasses batteries, charging systems, and power management. Sophisticated wheelchairs may employ lithium-ion or comparable high-capacity batteries to ensure ample power for prolonged usage. Effective power management systems are utilized to optimize battery utilization and offer details on battery status, remaining charge, and estimated range.

3.7 Mapping and Localization

Mapping and localization components are integral to enabling the wheelchair to comprehend its position and navigate through its surroundings. This often entails employing simultaneous localization and mapping (SLAM) algorithms, which amalgamate sensor data to generate a map of the environment and ascertain the wheelchair's position within that map [55]. Localization algorithms leverage this map to sustain precise positioning information as the wheelchair traverses its environment.

3.8 Safety factors

Safety constitutes a pivotal aspect of smart robotic wheelchairs, with safety features encompassing:

• Collision Detection and Avoidance: Employing sensors and algorithms to discern obstacles, whether static or dynamic, and enact appropriate measures to circumvent collisions. This can entail modifying the wheelchair's trajectory, decelerating, or halting as required.

• Stability and Balance Control: Implementing advanced control systems to uphold stability and balance, particularly in demanding terrains or during manoeuvres. This may entail adaptive control algorithms that fine-tune the wheelchair's stability parameters based on sensor feedback.

• Emergency Stop and Fall Detection: Equipping smart robotic wheelchairs with emergency stop buttons or automated fall detection systems to ensure user safety in critical scenarios.

4 Smart wheelchair design strategy

User-Centered Design (UCD) constitutes an approach to design that prioritizes comprehending the needs, preferences, and constraints of end-users throughout the design process [56]. When applied to the development of smart robotic wheelchairs, UCD guarantees that the design and functionality of the wheelchair are customized to the precise requirements of individuals with disabilities. Here's an extensive elucidation of UCD within the context of smart robotic wheelchairs:

• User Research: The UCD process initiates with exhaustive user research to garner a profound understanding of the target user group. This involves conducting interviews, surveys, and observations to pinpoint user needs, preferences, and challenges concerning mobility and independence. User research also delves into individual disparities, considering factors like physical abilities, cognitive capacities, and sensory impairments.

• User Personas and Scenarios: Informed by the user research, designers formulate user personas and scenarios to embody various user profiles and their specific objectives, capabilities, and usage contexts. User personas aid in empathizing with end-users and accommodating their diverse requirements and preferences throughout the design process. Scenarios furnish a narrative depicting how the smart robotic wheelchair would be utilized in distinct real-life scenarios, assisting in devising features and functionality that resonate with user needs.

• Participatory Design: UCD advocates for the active engagement of end-users in the design process. Participatory design methodologies, such as co-creation workshops and focus groups, enlist users in brainstorming, idea generation, and concept assessment. Through their involvement, users contribute to design decisions, ensuring that their viewpoints, aspirations, and pragmatic considerations are duly considered.

• Iterative Prototyping and Evaluation: UCD advocates for an iterative design methodology comprising multiple rounds of prototyping and evaluation. Designer's craft low-fidelity and High-fidelity prototypes of the smart robotic wheelchair allow users to interact with and provide feedback on various design iterations. This iterative approach empowers designers to refine the design based on user input, address usability issues, enhance features, and ensure the wheelchair meets user expectations.

• Accessibility and Inclusivity: A fundamental tenet of UCD entails prioritizing accessibility and inclusivity in the design of smart robotic wheelchairs. Designers embrace universal design principles to ensure that the wheelchair accommodates users with diverse abilities and constraints. This encompasses features such as adjustable seating positions, adaptable control interfaces, and customization options tailored to individual needs. By addressing accessibility and inclusivity, UCD endeavors to fashion a wheelchair that caters to a broad spectrum of individuals with disabilities.

• Usability Testing: Usability testing forms an integral facet of UCD to assess the efficacy and efficiency of the smart robotic wheelchair's design. Usability tests entail observing users as they execute tasks utilizing the wheelchair and collating feedback on their experience. This aids in pinpointing usability issues, areas for enhancement, and validation of design choices. Usability testing ensures that the wheelchair is intuitive, user-friendly, and aligned with users' functional requisites.

• Continuous User Feedback: UCD champions continuous user feedback even posts the initial design and development stages. Mechanisms for user feedback, such as user surveys or feedback channels, enable users to furnish ongoing input and recommendations for further refinements. This feedback loop aids in addressing emergent needs, fine-tuning features, and ensuring that the smart robotic wheelchair evolves in resonance with user requirements and evolving contexts.

By adhering to a user-centred design ethos, smart robotic wheelchairs can be tailored to cater to the specific needs and preferences of individuals with disabilities. UCD ensures that the wheelchair's design, features, and functionality resonate with user expectations, fostering augmented mobility, independence, and user contentment.

Long-term user adaptation refers to the gradual process through which individuals with disabilities acclimate to and integrate smart robotic wheelchairs into their daily routines over an extended duration [57]. It entails comprehending how users adjust to the wheelchair's features, functionalities, and overall user experience over time. Here's an exhaustive elucidation of long-term user adaptation within the context of smart robotic wheelchairs:

• Learning and Familiarization: During the initial phases of utilizing a smart robotic wheelchair, users undergo a learning curve to grasp its controls, functionalities, and capabilities. This entails acquainting oneself with the diverse control interfaces, navigation modes, and assistive features. Over time, users refine their proficiency and bolster confidence in operating the wheelchair, leading to more proficient and effective usage.

• Personalized Configuration: With prolonged usage, users often discern their preferences and tailor the settings to customize their experience. This might encompass adjusting the control interface sensitivity, seat positioning, or fine-tuning navigation parameters. Personalization empowers users to optimize their comfort, efficiency, and overall satisfaction with the wheelchair.

• Task Adaptation: Long-term user adaptation also encompasses the ability to adapt to varied tasks and environments using the smart robotic wheelchair. Users devise strategies and methodologies for navigating diverse terrains, circumventing obstacles, and executing daily activities. Through experience, they acquire the knack of leveraging the wheelchair's capabilities to surmount challenges and execute tasks with heightened ease and efficiency.

• Independence and Autonomy: A pivotal facet of long-term user adaptation entails cultivating heightened independence and autonomy. As users acquaint themselves with the smart robotic wheelchair's capabilities, they garner confidence in utilizing it to traverse their surroundings and undertake activities independently. This newfound independence amplifies their mobility and enriches their overall quality of life.

• Emotional Adaptation: Long-term user adaptation also encompasses emotional adjustments pertaining to the utilization of a smart robotic wheelchair. Initially, users may undergo a gamut of emotions such as excitement, frustration, or apprehension. However, over time, as users acclimate to the wheelchair, they may cultivate a sense of empowerment, liberation, and heightened confidence in their abilities. Emotional adaptation constitutes a pivotal facet of the long-term user experience with smart robotic wheelchairs.

• Continuous Learning and Skill Development: Long-term adaptation entails perpetual learning and skill enhancement. Users may explore novel functionalities, experiment with diverse operation modes, or pursue avenues to augment their proficiencies and knowledge pertaining to the smart robotic wheelchair. This ongoing learning process empowers users to optimize their utilization, unearth novel features, and adapt to technological advancements or evolving personal requisites.

• Feedback and Support: To facilitate long-term user adaptation, continual feedback and support mechanisms are imperative. Users should be afforded avenues to provide feedback, report issues, and solicit assistance as necessary. Feedback loops aid manufacturers and designers in identifying areas for enhancement, rectifying usability glitches, and refining the features and functionalities of the smart robotic wheelchair based on user experiences and evolving requisites.

Comprehending the long-term user adaptation process is pivotal for perpetually enhancing and refining smart robotic wheelchairs. By heeding user feedback, tailoring features to individual needs, and fostering user autonomy, smart robotic wheelchairs can progressively integrate into users' lives, bolstering their mobility, independence, and overall well-being over the long haul.

5 Navigation and obstacle avoidance strategy

Intelligent navigation and obstacle avoidance are critical functionalities in smart robotic wheelchairs, empowering individuals with disabilities to navigate safely and efficiently. Here's an in-depth exploration of these features:

5.1 Sensor technologies

Intelligent navigation relies on a suite of sensor technologies to perceive the wheelchair's surroundings comprehensively. Lidar sensors utilize laser beams to create detailed 3D maps, facilitating precise obstacle detection, localization, and environmental mapping. Cameras capture visual data, enabling object recognition, obstacle detection, and interpretation of visual cues through advanced vision algorithms. Ultrasonic sensors emit high-frequency sound waves to gauge distances and identify nearby objects, supporting proximity sensing and collision avoidance. IMUs, comprising accelerometers, gyroscopes, and magnetometers, offer crucial data on acceleration, angular velocity, and orientation, pivotal for accurate navigation and obstacle avoidance.

5.2 Mapping and trajectory generation

Mapping and localization techniques are integral to intelligent navigation, facilitating the wheelchair's understanding of its position within the environment. Simultaneous Localization and Mapping (SLAM) algorithms amalgamate sensor data, like lidar or camera inputs, to generate a map of the surroundings while simultaneously estimating the wheelchair's position within this map. This information enables optimal path planning and effective obstacle avoidance.

5.3 Path planning and trajectory generation

Path planning algorithms chart the optimal route for the wheelchair, accounting for factors like obstacle proximity, wheelchair dimensions, and user preferences. Trajectory generation algorithms subsequently translate the planned path into a smooth and feasible motion trajectory, considering the wheelchair's kinematics, dynamic constraints, and safety protocols.

5.4 Obstacle detection and avoidance

Real-time obstacle detection and avoidance are integral components of intelligent navigation. Leveraging sensor inputs, the wheelchair identifies obstacles and categorizes them based on their attributes. Advanced algorithms analyze this data to execute appropriate actions, such as adjusting trajectory, decelerating, or halting to avert collisions. Reactive strategies are deployed for immediate obstacle avoidance, while proactive approaches anticipate and circumvent potential hindrances.

5.5 Adaptive control

Intelligent navigation systems may feature adaptive control algorithms to dynamically adjust the wheelchair's behaviour in response to environmental changes and user preferences. Continuously monitoring sensor inputs, these algorithms optimize control parameters in real-time, ensuring stability, adaptability to diverse terrains, and responsiveness to evolving circumstances.

5.6 User interaction override

To maintain user control and foster a collaborative experience, intelligent navigation systems facilitate user interaction and override capabilities. Users can intervene and provide input to override autonomous navigation functions as needed, employing control interfaces like joysticks or voice commands to steer the wheelchair or modify its behavior.

5.7 Safety considerations

Safety is paramount in intelligent navigation and obstacle avoidance systems, with features including collision detection, emergency stop mechanisms, and fall detection systems. These safeguards mitigate risks, prevent accidents, and safeguard user well-being during wheelchair operation.

Intelligent navigation and obstacle avoidance in smart robotic wheelchairs bolster user safety, foster independent mobility, and alleviate cognitive and physical burdens associated with navigating complex environments. By integrating advanced sensors, mapping algorithms, trajectory planning, and adaptive control, these systems empower individuals with disabilities to traverse their surroundings confidently and efficiently.

6 Assistive features

Personalized assistive features in smart robotic wheelchairs are tailored to meet the unique needs and preferences of individuals with disabilities, enhancing comfort, control, and overall user experience [58]. Here are several examples of these personalized features:

Adjustable Seating Positions: Smart robotic wheelchairs offer customizable seating positions, including adjustable seat height, backrest angle, and leg rest positions. This customization promotes comfort, proper posture, and reduces the risk of pressure sores by allowing users to find ergonomic positions that suit their individual needs.

Flexible Control Interfaces: Users can select from various control mechanisms such as traditional joysticks, touchscreens, sip-and-puff systems, or head arrays. Additionally, users can adjust sensitivity, speed, and other control parameters to suit their abilities and preferences, enhancing control and usability.

Adaptive Driving Modes: Wheelchairs may offer adaptive driving modes that adjust responsiveness, speed, and maneuverability based on user capabilities. For instance, users with limited upper body strength may benefit from increased power assistance, while those with more control may prefer higher maneuverability.

Pressure Relief and Redistribution: To prevent pressure sores during prolonged use, smart robotic wheelchairs feature pressure-relieving features like pressure-sensitive seating surfaces or air cushions. Some models offer automatic pressure relief or shifting functions to alleviate pressure points periodically.

User Profiles: Wheelchairs can store user profiles containing customized settings for seating positions, control interface preferences, and driving modes. By recalling these profiles, the wheelchair adapts quickly to individual user requirements, facilitating convenience and usability for multiple users or those with changing needs.

Environmental Adaptation: Smart robotic wheelchairs integrate with smart home devices or IoT systems to adapt to the user's environment. This includes functions like automated door opening, environmental controls, or voice-activated assistants, enhancing user independence and control over their surroundings.

User Feedback Mechanisms: Incorporating user feedback mechanisms enables users to provide input on comfort levels, control preferences, and overall performance. This feedback informs the adaptation and refinement of personalized features, ensuring an optimal user experience tailored to individual needs.

By incorporating personalized assistive features, smart robotic wheelchairs empower users with greater control, comfort, and adaptability, promoting independence and optimizing user experience for individuals with disabilities.

7 Human-Machine interfaces

Enhanced user interfaces within smart robotic wheelchairs are dedicated to enhancing interaction and communication between the user and the wheelchair [59]. These interfaces strive to render wheelchair control and operation more intuitive, effective, and user-friendly. Here's a comprehensive explanation of enhanced user interfaces within smart robotic wheelchairs:

Intuitive Control Mechanisms: Advanced user interfaces provide intuitive control mechanisms that are straightforward to comprehend and operate. These mechanisms may include traditional joystick controls with ergonomic designs, touch screens featuring visual icons and intuitive gestures, or alternative control methods like voice commands, head arrays, or sip-and-puff systems. The aim is to offer users control options aligned with their abilities and preferences, facilitating seamless and effortless wheelchair control.

Gesture Recognition: Gesture recognition represents a sophisticated feature of user interfaces enabling users to control the wheelchair through hand or body gestures. Utilizing sensors, cameras, or depth-sensing technologies, the wheelchair identifies and interprets specific gestures to execute actions such as stopping, turning, or adjusting speed. Gesture recognition interfaces enhance user experience by providing a more natural and intuitive control method.

Voice Control and Natural Language Processing: Voice control interfaces empower users to interact with the smart robotic wheelchair using natural language commands. Integrated with speech recognition algorithms and natural language processing techniques, the wheelchair comprehends and interprets spoken instructions. Users can execute actions such as navigation, speed adjustment, or mode selection simply by speaking commands, enhancing accessibility and enabling hands-free interaction.

Visual Feedback Displays: Enhanced user interfaces integrate visual feedback displays to furnish users with critical information regarding the wheelchair's status, settings, and surroundings. These displays may feature high-resolution screens presenting real-time data such as speed, battery level, navigation instructions, obstacle alerts, or system diagnostics. Clear and informative visual feedback aids users in making informed decisions and heightens their situational awareness.

Auditory Feedback and Alerts: Auditory feedback and alerts constitute crucial components of enhanced user interfaces. The wheelchair delivers auditory cues like beeps, tones, or voice prompts to signify specific events or conditions. Auditory feedback conveys information about obstacle proximity, battery warnings, system status, or navigation instructions, assisting users, particularly those with visual impairments, in comprehending and responding to important wheelchair feedback [60].

Haptic Feedback: Haptic feedback employs touch-based interfaces to impart tactile sensations and feedback to users. Enhanced user interfaces may incorporate haptic feedback through vibration or tactile actuators integrated into the control interface. This feedback can confirm successful actions, indicate mode changes, or provide alerts, enriching the user's sense of control and engagement with the wheelchair.

Customization and Personalization: Enhanced user interfaces facilitate customization and personalization according to user preferences and requirements. Users can adjust settings such as control sensitivity, display layout, colour schemes, or font sizes to optimize the interface for their individual comfort and usability. Customization options ensure that the user interface accommodates varying abilities, preferences, and visual or cognitive impairments.

Multimodal Interaction: Multimodal interaction amalgamates multiple input and output modalities to craft a rich and flexible user interface. Smart robotic wheelchairs may support a blend of touch-based input, voice commands, gestures, and haptic feedback. Multimodal interfaces offer users the flexibility to select the most suitable interaction mode or a combination of modes based on their abilities and preferences, fostering a more inclusive and adaptable user experience.

Enhanced user interfaces within smart robotic wheelchairs elevate usability, accessibility, and the overall user experience. By integrating intuitive controls, gesture recognition, voice commands, visual and auditory feedback, haptic feedback, customization options, and multimodal interaction, these interfaces empower users to interact with the wheelchair more naturally, efficiently, and comfortably.

8 Conclusion

The research paper on smart robotic wheelchairs and their impact on advancing mobility and independence for individuals with disabilities present several promising avenues for future research and development. These opportunities aim to further enhance the functionality, usability, and accessibility of smart robotic wheelchairs. Here are some future scopes derived from the review:

Longitudinal Studies: Future research should prioritize conducting longitudinal studies to assess the long-term impact and effectiveness of smart robotic wheelchairs. These studies would track users' experiences, adaptations, and outcomes over an extended period, providing insights into durability, user satisfaction, and changes in mobility and independence over time.

User-Centered Design: Expanding on the user-centered design approach, future research can explore innovative methods to involve individuals with disabilities in the design process. This includes incorporating participatory design techniques, co-creation workshops, or virtual reality simulations to gather user feedback, preferences, and insights. The aim is to ensure that the design of smart robotic wheelchairs aligns with the specific needs, preferences, and limitations of the end-users.

Enhanced Sensor Technologies: Continued advancements in sensor technologies, such as lidar, vision sensors, and IMUs, hold promise for improving the perception and navigation capabilities of smart robotic wheelchairs. Future research can focus on developing more compact, accurate, and cost-effective sensor systems that can enhance obstacle detection, mapping, localization, and environmental perception.

Artificial Intelligence and Machine Learning: Integration of artificial intelligence (AI) and machine learning techniques can further enhance the autonomy and adaptability of smart robotic wheelchairs. Future research can explore the use of AI algorithms for real-time decision-making, personalized assistance, and learning from user interactions. Machine learning can be leveraged to analyze data collected from users, enabling the wheelchair to adapt and improve its performance based on individual preferences and needs.

Enhanced User Interfaces: Future research can explore novel user interface designs and interaction modalities to improve the usability and accessibility of smart robotic wheelchairs. This includes advancements in gesture recognition, natural language processing, haptic feedback, and multimodal interfaces. User-centric research should be conducted to assess the effectiveness and acceptance of these enhanced user interfaces among individuals with disabilities.

Integration with Assistive Technologies: Smart robotic wheelchairs can be further integrated with other assistive technologies to expand their functionalities and enhance user capabilities. Future research can explore seamless integration with communication aids, environmental control systems, robotic arms, or smart home devices. This integration would enable individuals with disabilities to perform a wider range of activities and improve their overall independence.

Ethical Considerations and Policy Development: As smart robotic wheelchairs become more prevalent, future research should address ethical considerations and guide policy development. This includes ensuring user privacy and data security, addressing ethical challenges related to decision-making and consent, and developing guidelines for responsible development and use of these technologies. Research in this area will help shape ethical frameworks, standards, and regulations for the responsible deployment of smart robotic wheelchairs.

By focusing on these future scopes, researchers can contribute to the ongoing development and advancement of smart robotic wheelchairs. These opportunities aim to improve user experiences, address limitations, and push the boundaries of mobility and independence for individuals with disabilities. Collaborative efforts among researchers, engineers, healthcare professionals, and end-users are vital for realizing the full potential of smart robotic wheelchairs in transforming the lives of individuals with disabilities.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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