

## PAPER

# Analysis of Autonomous Wheelchair Navigation Technologies in the Past Five Years: A Systematic Review

Mohsen Bakouri()  
Abdullah Alqarni, Sultan  
Alanazi, Ahmad Alassaf,  
Ibrahim AlMohimeed,  
Tareq Alqahtani

Department of Medical  
Equipment Technology,  
College of Applied Medical  
Science, Majmaah University,  
Majmaah, Saudi Arabia

[m.bakouri@mu.edu.sa](mailto:m.bakouri@mu.edu.sa)

## ABSTRACT

This study aims to analyze the latest developments in wheelchair navigation assistance systems. This analysis is obtained by conducting a systematic review of the significance of technologies for performance metrics and control strategies used. The autonomous category, input methods, tools used, technology used, test type, and accuracy were selected as reference metrics that set the comparison criteria, highlight innovative approaches, and discuss the development field of wheelchairs. In this work, to conduct the systematic review, four databases were identified. These include Science Direct, Taylor and Francis Online, Springer Journals, and IEEE Xplore. The pool of keywords set was selected to identify research articles published in the past five years. Inclusion and exclusion criteria were set to select the relevant studies that were consistent with the objectives of this study. Based on these criteria, 46 research papers were selected that met the inclusion requirements. The review study showed that wheelchair technology models such as autonomous control, 3D localization, and brain-computer interfaces (BCIs) were more precise in navigation and increased user independence. This systematic planning will help researchers, engineers, and practitioners make more realistic decisions to fill the gaps in available navigation aids and propose new and improved solutions for innovative assistant applications to ensure safety and accurate navigation. This study has many implications, especially the impact of reducing deaths and serious injuries among people with disabilities who use advanced technology wheelchairs.

## KEYWORDS

autonomous wheelchairs, wheelchair navigation, sensor technologies, control systems, smart technology integration

## 1 INTRODUCTION

Disability is a complex and diverse aspect of human existence, affecting individuals in various ways. One significant aspect of disability relates to mobility limitations, particularly for those who cannot move and rely on wheelchairs for their

Bakouri, M., Alqarni, A., Alanazi, S., Alassaf, A., AlMohimeed, I., Alqahtani, T. (2025). Analysis of Autonomous Wheelchair Navigation Technologies in the Past Five Years: A Systematic Review. *International Journal of Online and Biomedical Engineering (iJOE)*, 21(3), pp. 56–83. <https://doi.org/10.3991/ijoe.v21i03.52269>

Article submitted 2024-09-17. Revision uploaded 2024-12-07. Final acceptance 2024-12-07.

© 2025 by the authors of this article. Published under CC-BY.

daily mobility needs [1], [2]. These individuals often face a multitude of challenges that extend beyond the physical domain and into societal and technological dimensions. The challenges faced by people with disabilities who rely on wheelchairs are numerous. Physical barriers, such as inaccessible buildings and infrastructure, hinder their freedom of movement and participation in various activities [3]–[5]. The World Health Organization estimates that the total number of people with disabilities worldwide is about one billion people. Among them, between 110 and 190 million people use wheelchairs. Developing countries have the highest rates of wheelchair use due to limited access to treatments such as rehabilitation. Therefore, experts expect the global wheelchair market to reach \$16.8 billion by 2026 [6].

Meanwhile, integrating advanced sensor technologies, control methods, and machine learning algorithms into wheelchair navigation systems provides a unique opportunity to significantly improve the lives of wheelchair users. This technology can help users navigate difficult terrain and avoid obstacles easily and comfortably [7]. Furthermore, the growing prospects for smart technology and user-centered design highlight the need for continued research and development. For instance, Bakouri et al. [5] designed and implemented a neural method to drive and navigate a smart wheelchair. In this method, the authors used voice recognition integrated with a convolutional neural network (CNN) structure to develop the navigation of wheelchairs. The results demonstrated that the accuracy is about 87.2% for the method. In a different study, Abdulghani et al. [6] designed and implemented an adaptive neuro-fuzzy control technique to guide a wheelchair. In this technique, a sensor and voice recognition were used for obstacle avoidance based on real data. The results show that this method is more reliable and sophisticated to help disabled people.

Recently, many research issues have been addressed by developing human-machine interfaces and using different user inputs, such as speech, hand and head gestures, eye gaze, and body movements. The recognition technology based on eye movement to control wheelchairs was also developed [8]. In a new study, Luo et al. [9] designed an eye-tracking approach to determine the direction and wheelchair movement. The method utilized CNN feature extraction and classification to localize the proposed trajectory. The approach was practically tested and validated using a human-computer interaction system, and the results demonstrated that this method has high accuracy with 99%. Similarly, Liu et al. [10] proposed a novel strategy to detect the targets using the brain-controlled technique. In this method, computer vision and augmented reality were combined and integrated with a translucent head-mounted display to automatically detect environments. The method was experimentally tested, and the results show that the method has an accuracy of 83.6% in a fully automatic approach and 84.1% in a semi-automatic approach.

Although there are many studies and research concerned with helping the elderly and disabled, the motivation behind this study stems from the need to meet the growing demand for advanced mobility options for individuals with disabilities [11], [12]. Traditional manual wheelchairs and power wheelchairs, while useful, often fail to provide users with the independence and safety they need. Navigation assistive systems can potentially transform the disability seating market by providing them with greater mobility, safety, and independence. This review aims to analyze the latest developments in wheelchair navigation assistance systems, key technologies, methodologies, performance measures, control strategies, instrumentations and provide recommendations for future developments. We analyze the integration of sensor technologies, and control strategies and algorithms and relate these findings to key trends in the wheelchair market [13]–[15]. This study offers a thorough summary of

previous research in this field and highlights the most noteworthy advancements. This includes:

- Categorizing tasks as fully autonomous, semi-autonomous, or manual with assistive technology.
- Determining the various parameters that were considered throughout the development of wheelchair navigation systems. These factors encompass the methods of input, the tools and technologies employed, as well as the use of self-testing and real-time testing to ensure applicability.
- Demonstrating the types of tests conducted, their accuracy, and their extent of achievement.

## 2 MATERIALS AND METHODS

To determine the current status of research efforts in the field of autonomous wheelchair navigation, this study analyzes the published works within the past five years. We conducted a comprehensive systematic review of the current state of research, focusing on the most effective technologies to enhance the accuracy and reliability of autonomous wheelchair navigation systems. There are six primary procedures to execute this review, as illustrated in Figure 1. The stages involved in this process include researching the technique and objectives, selecting research questions, choosing relevant studies, collecting relevant papers from online repositories, assessing their quality, and extracting and synthesizing the data.

### 2.1 Selecting research questions

Given the importance of investigating technological advancements for self-navigating wheelchairs, a search approach that facilitates the effective retrieval of information from each study is required for a thorough examination. Table 1 presents the study questions and their respective motives, indicating the importance of the research questions.

**Table 1.** Study research questions

Research Question	Motivation
What are the different proposed autonomous classes developed for wheelchair navigation?	The classification of studies as fully autonomous, semi-autonomous, or manual with assistive features (limited autonomy) is crucial.
What kinds of tools and technologies go into developing wheelchair navigation?	The goal is to identify the input methods, instruments, and technology utilized in the development of wheelchair navigation.
What types of tests were applied, and what accuracy was achieved on wheelchairs?	The purpose is to outline the types of tests carried out and the accuracy attained by specific studies.

### 2.2 Keywords identification

We conducted a thorough keyword search in this work, applying a specific filter to narrow down the results based on the study's specific objectives. We identify

the keywords to extract the most relevant primary articles from the selected online digital libraries. We assigned the appropriate keywords to this query, as shown in Table 2.

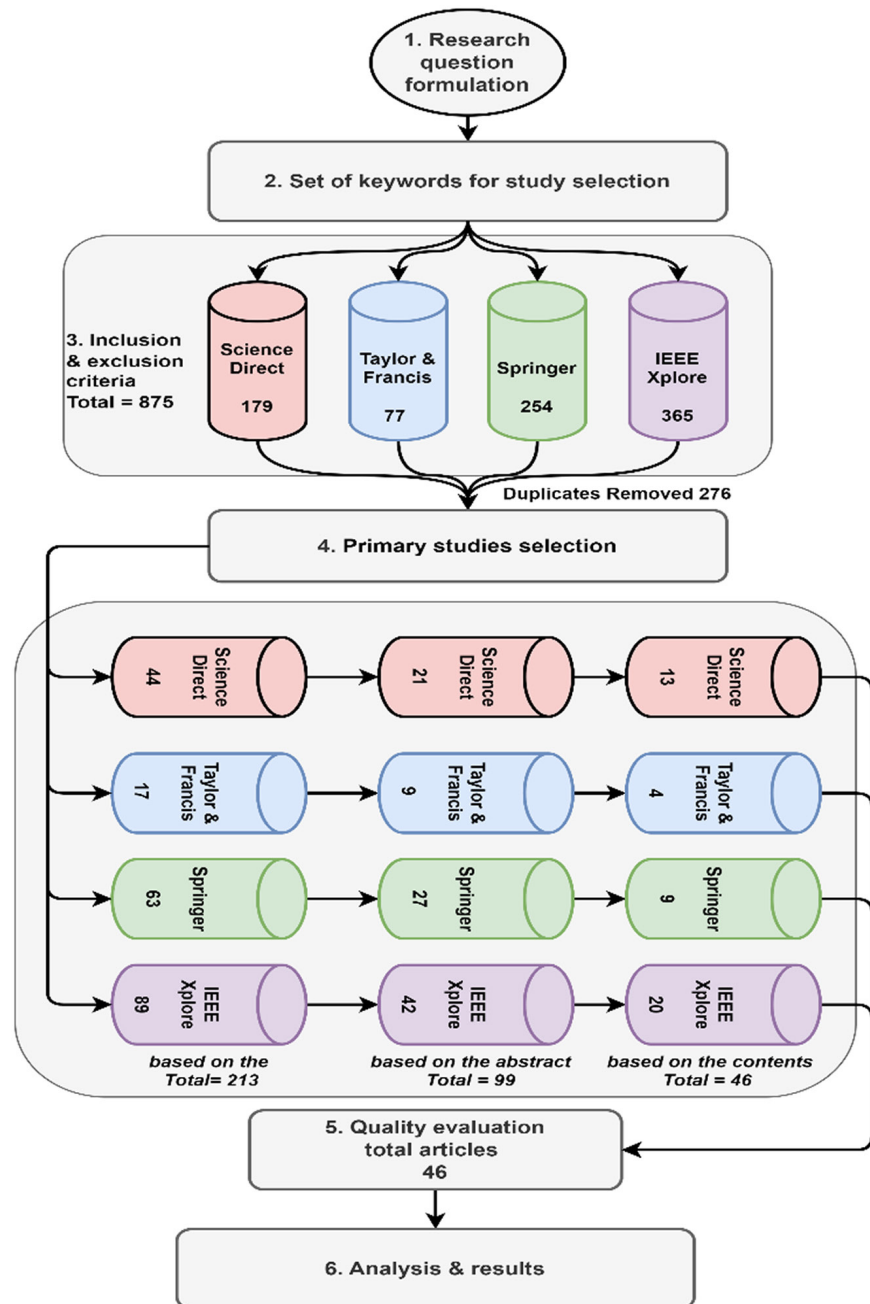


Fig. 1. The PRISMA flow diagram

Table 2. Search keywords

(“Autonomous wheelchair” OR “Advanced wheelchair control” OR “Smart wheelchair controlled” OR “Autonomous mobility aid” OR “Control systems for autonomous wheelchairs” OR “Wheelchair navigation”) AND (“Autonomous navigation” OR “Autonomous obstacle avoidance” OR “Path planning” OR “Route planning” OR “Route guidance” OR “Autonomous decision-making”) AND (“Artificial intelligence” OR “Machine learning” OR “Computer vision for autonomous wheelchairs” OR “Sensor technologies” OR “Communication technologies”)

### 2.3 Digital information sources

We suggest using four online digital libraries (refer to Table 3) to gather relevant and interesting research articles for the reader. In addition to being the most popular peer-reviewed digital libraries, they are also the sites of the majority of scholars who have published their most recent research work. We obtain documents from these digital libraries by preparing keywords and queries for each search in the library. Following the research procedure, we download the documents and subject them to additional analysis for re-evaluation. We remove any duplicate or irrelevant records. This method eliminates the possibility of conducting non-wheelchair-related research.

**Table 3.** List of the libraries selected for search process

No.	Digital Library	Link
1	ScienceDirect	<a href="https://www.sciencedirect.com">https://www.sciencedirect.com</a>
2	Taylor and Francis Online	<a href="https://www.tandfonline.com">https://www.tandfonline.com</a>
3	Springer Journals	<a href="https://link.springer.com">https://link.springer.com</a>
4	IEEE Xplore	<a href="https://ieeexplore.ieee.org/Xplore/home.jsp">https://ieeexplore.ieee.org/Xplore/home.jsp</a>

### 2.4 Determining inclusion and exclusion criteria

To ensure accuracy and consistency, we formulated the inclusion and exclusion criteria for this review based on the guidelines of the Preferred Reporting Items for Systematic Review and Meta-Analysis-Protocols (PRISMA-P) [16]. Determining the inclusion and exclusion of articles is the most challenging task in the review research process. This fundamental step of the review ensures the selection of the most important primary articles for the final pool of papers used in the quality evaluation procedure. Table 4 presents the inclusion and exclusion criteria for the primary studies relevant to the domain under consideration.

**Table 4.** The inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
<ul style="list-style-type: none"> <li>Peer-reviewed publications: To ensure the reliability and validity of the information, we only include peer-reviewed journal articles, conference papers, book chapters, and review/survey articles.</li> <li>Language: Only English studies have been published.</li> <li>Up-to-date research: conducted over the past five years to ensure information is current and relevant to today's technological developments and market trends.</li> <li>Studies examining self-supported wheelchair management systems.</li> <li>Studies are currently investigating the impact of self-reliant wheelchair control structures on a person's enjoyment and accessibility.</li> <li>There are studies discussing the difficulties and barriers that autonomous wheelchair manipulation structures must overcome.</li> <li>The studies suggest guidelines for future research on self-reliance in wheelchair use.</li> </ul>	<ul style="list-style-type: none"> <li>Non-Peer-Reviewed Sources: To maintain the evaluation's clinical rigor, exclude non-peer-reviewed articles, white papers, and reviews to maintain the clinical rigor of the evaluation.</li> <li>Language: Only non-English studies have been published.</li> <li>Outdated Research: Research carried out greater than ten years in the past, unless it is foundational and substantially contributes to understanding modern-day technology.</li> <li>There are studies that solely focus on designing or enhancing autonomous wheelchairs, without assessing their control systems.</li> </ul>

### 2.5 Primary studies selection

We set and used four primary filters, including query criteria, titles, abstracts, and article contents, to select all related papers (journal articles, conference proceedings,

book chapters, and review articles) from the final pool. Based on these filters, Table 5 illustrates the selected papers from the digital library. The final pool selected a total of forty-six papers for the proposed review.

**Table 5.** Selected papers from the digital library

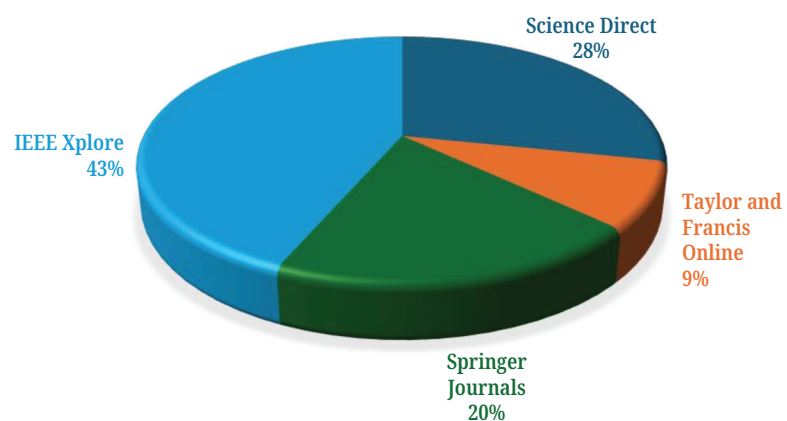
No.	Digital Library	Primary Studies Selection				
		Based on Query	Duplicates Removed	Based on Title	Based on Abstract	Based on the Contents
1	ScienceDirect	179	50	44	21	13
2	Taylor and Francis Online	77	19	17	9	4
3	Springer Journals	254	95	63	27	9
4	IEEE Xplore	365	112	89	42	20
Total		875	276	213	99	46

Table 6 shows the classification of the selected papers into journal articles, conference proceedings, book chapters, reviews, and survey articles. Among the 46 papers, there were 24 journal articles, 21 conference papers, and one review article.

**Table 6.** The classification of selected papers from the digital library

Digital Library	Journal Article	Conference Proceedings	Book Chapter	Review or Survey Article	Total
ScienceDirect	12	1	0	0	13
Taylor and Francis Online	3	0	0	1	4
Springer Journals	5	4	0	0	9
IEEE Xplore	4	16	0	0	20
Total	24	21	0	1	46

Figure 2 shows the percentage contribution from digital libraries to the final collection. It is clear that IEEE Explorer is an attractive platform for wheelchair applications and research work. Table 7 presents a list of selected papers categorized by year and frequency. The data reveals that 2023 saw the publication of over 28% of the selected papers.



**Fig. 2.** The percentage contribution of digital libraries

**Table 7.** List of selected papers based on year with frequencies

No.	References	Year	Frequency
1	[25], [30], [31], [33], [38], [40], [45], [54], [62]	2019	9
2	[24], [32], [35], [52]	2020	4
3	[19], [29], [34], [36], [37], [39], [43], [44], [48], [60]	2021	10
4	[18], [20], [23], [46], [49], [50], [55], [56], [61]	2022	8
5	[17], [21], [22], [26], [27], [28], [41], [42], [47], [51], [53], [57], [58], [59]	2023	13

## 2.6 Quality evaluation

We evaluate the quality of the final research set, which is most relevant to the required review, by sorting the papers based on the contribution percentage for each digital library. Table 8 demonstrates that we utilized a total of four quality criteria, comprising questions and responses, to analyze the selected articles. During the final stage of selection and filtering, quality assessment generates the formal list of articles. This is done to ensure that the research described in the papers is accurate and easy to understand.

**Table 8.** The quality criteria

Quality Criteria	Description
Qc 1	Is the research objective clearly stated and how does it relate to autonomous wheelchairs?
Qc 2	Is the research related to the development of autonomous wheelchair technology?
Qc 3	Does the research describe development methods in terms of input methods, tools, and techniques used?
Qc 4	Did the research address the types of tests used, their accuracy, and the extent of their success?

To determine the level of quality, the authors of this study go through the process of manually reviewing and analyzing each paper included in the final set. We assign weighting parameters to each discovered research question in a research paper to estimate this evaluation, as shown in Table 9.

**Table 9.** The weighting parameters

Criteria	Weight
If the publication does not include any helpful information	1 – low
If the document’s content is incomplete but otherwise satisfactory	2 – medium
If the publication provides a comprehensive explanation of the research issues	3 – high

After subjecting all relevant papers to a quality evaluation procedure, we use the following equation to determine the total score (TS) for each paper:

$$TS = \sum_{k=1}^4 Qc_k \tag{1}$$

where,  $k$  represents the sum of the five quality criteria that were specified. Upon analyzing forty-six publications, we found that every single primary study met all the quality criteria listed in Table 10, which displays the total score.

**Table 10.** The total score

Total Score	Reference No.
12	[17], [18], [20], [21], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [36], [37], [39], [40], [41], [42], [43], [46], [51], [54], [57], [60], [61]
11	[22], [35], [38], [44], [45], [47], [49], [50], [55], [56], [58], [59], [62]
10	[19], [48], [52], [53]

### 3 RESULTS

This section presents the most critical technologies required for wheelchair navigation. When integrated effectively, these technologies significantly improve the accuracy and reliability of autonomous mobility, resulting in safer and more dependable mobility solutions for users. In this context, Appendix in Table 1. A displays the individual analysis of selected papers for the most significant parameters.

Table 11 displays the autonomous category, which indicates the level of independence that characterizes wheelchairs. The review shows that 28 studies are characterized by complete independence, which represents 61% of the selected studies, while 14 studies are characterized by a semi-autonomous system, representing 30% of the selected studies. The table also shows that four studies are not specific and can rely on essential autonomous features to help users with specific tasks, but they do not operate autonomously for navigation.

**Table 11.** The autonomous category

Autonomous Category	Description	Reference No.
Full autonomous	In full autonomous mode, the wheelchair operates independently from any user input or control. The wheelchair navigates, avoids obstacles, and follows a predetermined path using its sensors, algorithms, and pre-programmed instructions, ensuring safety and efficiency in reaching the predetermined location.	[17], [18], [20], [21], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [34], [36], [37], [39], [40], [41], [42], [43], [46], [51], [54], [57], [60], [61]
Semi-autonomous	In semi-autonomous mode, the wheelchair operates based on some user input or control. The user retains control over certain aspects, such as choosing the direction, while the wheelchair assists with tasks like obstacle avoidance and path optimization.	[22], [33], [35], [38], [44], [45], [47], [49], [50], [55], [56], [58], [59], [62]
Not specified	The mode of operation of the wheelchair for the study has not been specified.	[19], [48], [52], [53]

Table 12 shows the controllers' input methods in the reviewed articles. This table effectively summarizes the control methods employed in the reviewed articles and offers a clear insight into the diverse approaches used in control systems for various applications. These methods, each with unique references, represent a broad spectrum of innovative technologies and techniques. The prioritization of autonomous control as the initial category underscores the inclination towards creating systems that necessitate no user intervention, depending instead on sophisticated algorithms and sensing technologies. Brain control, on the other hand, reflects the exciting advances in terotechnology and its applications in controlling devices through brain signals, with several references demonstrating the growing interest in this area.

**Table 12.** The input methods

Input Methods	Description	Reference No.
BCI/BMI	Both brain-computer interface (BCI) and brain-machine interface (BMI) involve translating neural signals into inputs for controlling the wheelchair.	[38], [45], [55], [56]
Eye Movement/Tracking	Eye movement and tracking involve translating eye movements into inputs for controlling the wheelchair.	[29], [30], [33]
Hand/Head motion	Hand and head motion involve translating head or hand motion into inputs for controlling the wheelchair.	[17], [19], [58]
Sensor	Different types of sensors are used to detect the path and translate the analyzed data into inputs for controlling the wheelchair.	[23], [25], [34], [37], [49], [51], [57], [60], [61]
Remote technology	Remote technology involves translating data received remotely into inputs to control the wheelchair.	[27]
Dynamic data	Dynamic data involves translating risk density function or Look Ahead Distance (LAD) function into inputs to control the wheelchair.	[18], [40]
Not specified	The paper hasn't explicitly specified the input.	Other references

Wheelchair manufacturers and operators utilize a wide variety of equipment and tools to ensure precise sensing, processing, and control during the manufacturing and operation process. These devices are necessary to allow the wheelchair to interact with its surroundings, navigate, and react to inputs from the user, as shown in Table 13. During the review, we discovered that 50% of the articles utilized sensors such as brain-computer interface/brain-machine interface (BCI/BMI) sensors, eye tracking sensors, LiDAR sensors, and cameras, while the remaining articles utilized other types of sensors.

**Table 13.** The instruments used

Instruments	Description	Reference No.
BCI/BMI sensor	Both brain-computer interfaces (BCIs) and brain-machine interfaces (BMIs) utilize signals such as EEG, head motion, or hand motion to generate basic movement commands like turning left, turning right, moving forward, and moving backward.	[45], [55], [58], [59]
Eye Tracking sensor	Eye-tracking sensors detect and monitor eye movements to determine where a user is looking, enabling control of a wheelchair through gaze motion. They use infrared light and cameras to track reflections from the eyes, allowing users to navigate and issue commands without any physical input.	[29], [33]
LiDAR sensor	Light Detection and Ranging (LiDAR) sensors use laser beams to measure distances to the surroundings, providing spatial awareness for secure wheelchair navigation by detecting obstacles and identifying alternative paths.	[23], [24], [25], [31], [34], [39], [52], [57]
Cameras	Cameras provide detailed depth perception and obstacle detection, enhancing navigation safety. They create a 3D map of the environment, allowing the wheelchair to avoid obstacles and find safe paths.	[21], [23], [24], [25], [30], [31], [46]
Other Sensor	The other half of the articles each used a unique type of sensor.	Other references

Table 14 shows the techniques used in the different studies, such as camera technologies, 3D sensors, Arduino modules, and navigation sensors, which are in increasingly important demand in the range of wheelchair applications. In this field, using "EEG headsets" suggests the control mechanism involves a BCI. In the fields of neuroscience and human interaction, EEG headgear plays a crucial role in evaluating and operating robotic arms and other equipment. Together, neuroscience and advanced technology provide a practical way to regain control. Many documents use the phrase "advanced control," emphasizing the accuracy and effectiveness

of humanizing control techniques. This may require using complex algorithms, machine learning, and feedback. Using a “mathematical controller” highlights mathematical models and calculations in control systems, emphasizing the importance of precise calculation and analysis to achieve the desired results.

**Table 14.** The technology used

Technology Used	Description	Reference No.
BCI, BMI, EEG	Brain-Computer Interfaces (BCIs) and Brain-Machine Interfaces (BMIs) allow users to control wheelchairs directly through brain signals, enabling hands-free navigation. These systems often use Electroencephalography (EEG) to capture electrical activity from the brain, which is then translated into commands for steering or moving the wheelchair.	[38], [45], [55], [58], [59]
ROS, SLAM, AMCL	The Robot Operating System (ROS) offers an adaptable structure for developing software to control wheelchairs, offering tools and libraries for navigation and sensor integration. Simultaneous Localization and Mapping (SLAM) and Adaptive Monte Carlo Localization (AMCL) are commonly used in ROS to help wheelchairs autonomously map their environment, localize themselves, and plan safe paths for navigation.	[17], [21], [23], [24], [25], [26], [27], [31], [39], [41], [46], [51], [57]
CNN	Convolutional Neural Networks (CNNs), as a type of deep learning model, are utilized in wheelchairs to process data from sensors, such as cameras, for obstacle avoidance and path and landmark recognition. By analyzing sensor data, CNNs support decision-making for autonomous navigation, ensuring safe and efficient movement of the wheelchair.	[30], [37], [54]
LiDAR	Light Detection and Ranging (LiDAR) sensors use laser beams to measure distances and create detailed 3D maps of the environment. In wheelchairs, LiDAR facilitates obstacle detection and navigation by providing real-time spatial awareness, ensuring safe and precise movement through complex or cluttered spaces.	[23], [34], [39], [52], [57]
Cloud	Cloud technology supports autonomous wheelchairs by integrating advanced artificial intelligence and speech recognition services into a cloud-based platform. This integration allows for enhanced functionality, including personalized recommendations, predictive analytics, and voice-controlled management of the wheelchair’s mobility and user location.	[27], [62]
Other Technology	The rest of the articles each used a unique type of technology.	Other references

We use various test types in the development and evaluation of autonomous wheelchairs to ensure the systems operate safely and reliably in real-world scenarios. These tests evaluate the wheelchair’s overall performance as well as its navigation, obstacle avoidance, and user interface capabilities. Table 15 illustrates the test types used for the reviewed papers. The table shows that 39% of the articles tested their methods through simulations, while 33% tested their methods experimentally.

**Table 15.** The test type

Test Type	Description	Reference No.
Experimental	Tests conducted in a controlled environment where variables are manipulated to observe their effects and validate hypotheses.	[32], [35], [51], [18], [59], [58], [42], [57], [54], [48], [25], [56], [62], [60], [26]
Simulation	Tests conducted in virtual environments to mimic real-world scenarios and predict outcomes without physical experimentation.	[32], [30], [24], [51], [18], [40], [33], [20], [57], [36], [27], [34], [25], [23], [41], [26], [35], [39]
Not specified	The paper hasn’t explicitly specified the test type.	Other references

In the context of autonomous wheelchairs, the term “accuracy” refers to the wheelchair’s precision in carrying out a variety of tasks. These duties include navigating through environments, responding to orders from the user, avoiding obstacles, and arriving at predetermined locations. This very important feature determines the wheelchair’s effectiveness, safety, and dependability of the wheelchair are all dependent on this very important feature. The analysis of autonomous wheelchairs’

accuracy is summarized in Table 16. The review demonstrated that 72% of reviewed articles have high accuracy.

**Table 16.** The accuracy

Accuracy	Description	Reference No.
High	Measurements are precise and consistent, with minimal error or deviation from the true value.	[17], [20], [21], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [49], [50], [51], [52], [55], [57], [58], [59]
Low	Measurements exhibit significant error or inconsistency, with a greater deviation from the true value.	[48]
Not specified	Accuracy of measurements hasn't been explicitly mentioned.	[19], [22], [23], [53], [54], [56], [60], [61], [62]

## 4 DISCUSSION

In the current review, we found 28 studies with a fully autonomous navigation approach and 14 studies with a semi-autonomous approach using all available techniques. The review also revealed that 15 studies were tested experimentally, while 18 others were tested through simulation. Notably, the high accuracy obtained by the selected studies was noteworthy, as the results showed that 35 studies had high accuracy, which constitutes 76% of the total selected studies. In this review, our results indicated differences in performance across multiple experiments, which showed each model had unique strengths and limitations. However, in reviews of wheelchair control techniques, various studies have made general recommendations, with limited reference to the risk of bias in selecting papers [63]–[66]. For instance, Cuervo et al. [67] conducted a comprehensive review of developments in automatic wheelchairs, focusing on devices and control systems to address mobility issues for individuals with physical disabilities. This study searched for articles published between 2012 and 2019 in specialized databases, selecting 97 relevant documents based on specific criteria. Deng et al. [68] addressed balancing control authority in shared control systems, particularly brain-computer interface (BCI)-based systems. They introduced a Brain State Evaluation Network (BSE-NET) using quantized attention-gated kernel reinforcement learning to assess subjects' brain control abilities in real time. They developed a shared controller to dynamically adjust the balance between robot autonomy and human operator input, based on the confidence score from the BSE-NET. Moreover, Ortiz et al. [69] also researched and developed control algorithms for robotic assistance and rehabilitation tasks for individuals with motor disabilities. The study addressed the practical challenge of implementing these algorithms by creating a framework for interactive virtual reality.

We align our review with the observations of Ikeda et al. [60], who developed an automatic control system for an assistive robot that assists in pushing a wheelchair while climbing steps. The system equipped the assistive robot with a wheeled mechanism and dual manipulators and enhanced a commercially available wheelchair model with sensors, circuits, and batteries. The system allowed the robot and the wheelchair to work in tandem when navigating steps. Hossain et al. [70] addressed the pressing mobility issue for disabled individuals. In their study, they designed and implemented an autonomous wheelchair that eliminates the need for a constant human attendant. Their autonomous wheelchair is equipped with four distinct control systems, providing users with flexibility based on their specific disabilities.

In general, there is an alignment in cross-research on instrumentation and control methods for automatic wheelchairs, as demonstrated by comparing our

findings [1], [7]. Through this alignment, we can build essential criteria for evaluating control methods based on examining them against the outputs of our study models. The difference might be more pronounced if our study evaluated the effectiveness of different control approaches, strategies, and tools. Based on this consensus, this study recommends developing policies to provide grants and incentives to wheelchair manufacturers and encouraging them to incorporate innovative control mechanisms into their models. Access to wheelchair adoption can be increased by encouraging funding initiatives focusing on mobility assistance's application and efficiency. Healthcare industry collaboration also ensures that advanced technology meets user requirements and clinical standards by collaborating with manufacturers and healthcare experts to provide real-world testing and feedback. Therefore, we emphasize that research-based innovation in collaboration with manufacturers, researchers, and healthcare professionals in research initiatives generates innovations that are technically sound, clinically feasible, and meet the different requirements of wheelchair users.

While this study provides valuable insights into improving wheelchair control, it is necessary to acknowledge and evaluate various limitations that can affect the interpretation of results. For example, limiting the selection to English-language articles published between 2019 and 2023 could lead to publication bias. Research suggests we have excluded languages or periods beyond this time frame. The study was also limited to selecting autonomous wheelchair research, so the review included significant research on wheelchair autonomy. However, bias may exist due to the complexity and novelty of these systems. Subsequent research endeavors must consider the evolving terrain of self-driving wheelchair operation and continually scrutinize biases related to technology development. In conclusion, while this study provides valuable insights, the above limitations underscore opportunities for improvement and refinement in future research efforts. Recognizing and overcoming these limitations would improve the validity and application of research findings to developing wheelchair control systems.

## 5 CONCLUSION

Recently, advanced wheelchair control systems have gained widespread use to improve efficiency and accuracy. This study conducted a systematic review evaluation of autonomous wheelchair control systems. We have studied and evaluated numerous research papers to improve the functionality and safety of wheelchair control system strategies, thereby enhancing the user's mobility and independence. We also investigated the effectiveness of these strategies and their potential impact on wheelchair users' quality of life. To achieve this goal, we collected data from four databases between 2019 and 2023, primarily applying inclusion criteria to articles related to wheelchair control systems. We collected 46 research papers and compared new insights with practical applications. The study demonstrated significant advances in wheelchair technology, including autonomous control, 3D localization, and BCIs, which facilitate precise mobility and enhance user independence. To summarize, each control method used in wheelchair technology offers specific benefits and faces individual obstacles. To address these difficulties effectively, it is necessary to prioritize research, development, and user training. Effective collaboration between wheelchair manufacturers, technology developers, and healthcare practitioners is essential to ensuring that users are able to obtain and derive benefits from the most appropriate control system tailored to their needs and skills. The ultimate goal is to develop mobility solutions that are user-centered, cutting-edge, and flexible, with a primary focus on safety, reliability, and cost-effectiveness.

## 6 ACKNOWLEDGEMENT

The authors extend their appreciation to the King Salman center For Disability Research for funding this work through Research Group no KSRG-2023-166.

## 7 REFERENCES

- [1] J. Leaman and H. M. La, "A comprehensive review of smart wheelchairs: Past, present, and future," *IEEE Trans. Hum. Mach. Syst.*, vol. 47, no. 4, pp. 486–489, 2017. <https://doi.org/10.1109/THMS.2017.2706727>
- [2] A. Saibene, T. Saichoo, P. Boonbrahm, and Y. Punsawad, "Investigating user proficiency of motor imagery for EEG-based BCI system to control simulated wheelchair," *Sensors*, vol. 22, no. 24, p. 9788, 2022. <https://doi.org/10.3390/s22249788>
- [3] X. Chen *et al.*, "Clinical validation of BCI-controlled wheelchairs in subjects with severe spinal cord injury," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 30, pp. 579–589, 2022. <https://doi.org/10.1109/TNSRE.2022.3156661>
- [4] E. Yulianto, T. B. Indrato, B. T. Mega Nugraha, and S. Suharyati, "Wheelchair for quadriplegic patient with electromyography signal control wireless," *Int. J. Onl. Eng.*, vol. 16, no. 12, pp. 94–115, 2020. <https://doi.org/10.3991/ijoe.v16i12.15721>
- [5] M. Bakouri *et al.*, "Steering a robotic wheelchair based on voice recognition system using convolutional neural networks," *Electronics*, vol. 11, no. 1, p. 168, 2022. <https://doi.org/10.3390/electronics11010168>
- [6] M. M. Abdulghani, K. M. Al-Aubidy, M. M. Ali, and Q. J. Hamarsheh, "Wheelchair neuro fuzzy control and tracking system based on voice recognition," *Sensors*, vol. 20, no. 10, p. 2872, 2020. <https://doi.org/10.3390/s20102872>
- [7] S. H. Bengtson, T. Bak, L. N. S. Andreasen Struijk, and T. B. Moeslund, "A review of computer vision for semi-autonomous control of assistive robotic manipulators (ARMS)," *Disabil. Rehabil. Assist. Technol.*, vol. 15, no. 7, pp. 731–745, 2020. <https://doi.org/10.1080/17483107.2019.1615998>
- [8] A. Sharmila, "Hybrid control approaches for hands-free high level human-computer interface-a review," *J. Med. Eng. Technol.*, vol. 45, no. 1, pp. 6–13, 2021. <https://doi.org/10.1080/03091902.2020.1838642>
- [9] W. Luo, J. Cao, K. Ishikawa, and D. Ju, "A human-computer control system based on intelligent recognition of eye movements and its application in wheelchair driving," *Multimodal. Technol. Interact.*, vol. 5, no. 9, p. 50, 2021. <https://doi.org/10.3390/mti5090050>
- [10] K. Liu *et al.*, "A novel brain-controlled wheelchair combined with computer vision and augmented reality," *Biomedical Engineering Online*, vol. 21, no. 1, p. 50, 2022. <https://doi.org/10.1186/s12938-022-01020-8>
- [11] H.-T. Bui, L.-V. Nguyen, A.-N. Tran Ho, Q.-B. Tao, and T.-N. Ngo, "Identifying factors that influence pressure ulcers by numerical simulation and experimentation methods," *Int. J. Onl. Eng.*, vol. 16, no. 11, pp. 104–119, 2020. <https://doi.org/10.3991/ijoe.v16i11.13817>
- [12] M. Piyaneeranart and M. Ketcham, "Automatically moving robot intended for the elderly with voice control," *Int. J. Onl. Eng.*, vol. 17, no. 6, pp. 19–48, 2021. <https://doi.org/10.3991/ijoe.v17i06.22299>
- [13] H. R. T. Bandara, K. S. Priyanayana, A. B. P. Jayasekara, D. P. Chandima, and R. A. R. C. Gopura, "An intelligent gesture classification model for domestic wheelchair navigation with gesture variance compensation," *Applied bionics and biomechanics*, vol. 20, no. 1, 2021. <https://doi.org/10.1155/2020/9160528>

- [14] C. Favey, R. Farcy, J. Donnez, J. Villanueva, and A. Zogaghi, "Development of a new negative obstacle sensor for augmented electric wheelchair," *Sensors*, vol. 21, no. 19, p. 6341, 2021. <https://doi.org/10.3390/s21196341>
- [15] R. Arnay, J. Hernandez-Aceituno, J. Toledo, and L. Acosta, "Laser and optical flow fusion for a non-intrusive obstacle detection system on an intelligent wheelchair," *IEEE Sens J*, vol. 18, no. 9, pp. 3799–3805, 2018. <https://doi.org/10.1109/JSEN.2018.2815566>
- [16] D. Moher *et al.*, "Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement," *Systematic Reviews*, vol. 4, no. 1, 2015. <https://doi.org/10.1186/2046-4053-4-1>
- [17] M. Kutbi *et al.*, "Egocentric computer vision for hands-free robotic wheelchair navigation," *Journal of Intelligent & Robotic Systems*, vol. 107, no. 10, 2023. <https://doi.org/10.1007/s10846-023-01807-4>
- [18] V. Sezer, "An optimized path tracking approach considering obstacle avoidance and comfort," *Journal of Intelligent & Robotic Systems*, vol. 105, no. 1, 2022. <https://doi.org/10.1007/s10846-022-01636-x>
- [19] A. Miharia, B. Prabadevi, S. Rajagopal, and B. Alhadidi, "Internet of Things based gesture controlled wheel chair for physically disabled," in *Learning and Analytics in Intelligent Systems*, 2021, pp. 99–107. [https://doi.org/10.1007/978-3-030-65407-8\\_9](https://doi.org/10.1007/978-3-030-65407-8_9)
- [20] N. Rodrigues, A. Sousa, L. P. Reis, and A. Coelho, "Intelligent wheelchairs rolling in pairs using reinforcement learning," in *Proceedings in ROBOT2022: Fifth Iberian Robotics Conference*, 2022, pp. 274–285. [https://doi.org/10.1007/978-3-031-21062-4\\_23](https://doi.org/10.1007/978-3-031-21062-4_23)
- [21] H. Bozorgi and T. D. Ngo, "Beyond shared autonomy: Joint perception and action for human-in-the-loop mobile robot navigation systems," *Journal of Intelligent & Robotic Systems*, vol. 109, no. 1, 2023. <https://doi.org/10.1007/s10846-023-01942-y>
- [22] S. Ahmed, Md. K. Alam, M. R. A. Dipu, S. Debnath, S. Haque, and T. Akhter, "A cost-effective unmanned ground vehicle (UGV) using swarm robotics technology for surveillance and future combat," in *Proceedings of the Fourth International Conference on Trends in Computational and Cognitive Engineering, Lecture notes in Networks and Systems*, 2023, pp. 159–171. [https://doi.org/10.1007/978-981-19-9483-8\\_14](https://doi.org/10.1007/978-981-19-9483-8_14)
- [23] N. Bharathiraman, A. Kaundanya, J. Singhal, Y. Wadalkar, and K. Talele, "An empirical approach for tuning an autonomous mobile robot in Gazebo," in *Advances in Intelligent Systems and Computing*, 2022, pp. 289–299. [https://doi.org/10.1007/978-981-16-9573-5\\_22](https://doi.org/10.1007/978-981-16-9573-5_22)
- [24] S. Liu, S. Yao, G. Zhu, X. Zhang, and R. Yang, "Operation status of teleoperator based shared control telerobotic system," *Journal of Intelligent & Robotic Systems*, vol. 101, no. 1, 2020. <https://doi.org/10.1007/s10846-020-01289-8>
- [25] M. Kamezaki, A. Kobayashi, Y. Yokoyama, H. Yanagawa, M. Shrestha, and S. Sugano, "A preliminary study of interactive navigation framework with situation-adaptive multimodal inducement: Pass-By scenario," *International Journal of Social Robotics*, vol. 12, no. 2, pp. 567–588, 2019. <https://doi.org/10.1007/s12369-019-00574-3>
- [26] B. Ganesamoorthy, S. Suryakumar, B. Vijay, and S. Sudhakar, "Autonomous wheelchair navigation using monocular slam and rapidly-exploring random trees," *International Conference on System, Computation, Automation and Networking (ICSCAN), PUDUCHERRY, India*, 2023, pp. 1–5. <https://doi.org/10.1109/ICSCAN58655.2023.10395685>
- [27] M. T. Islam, I. R. Hameem, S. Saha, M. J. R. Chowdhury, and M. E. Deowan, "A simulation of a robot operating system based autonomous wheelchair with web based HMI using Rosbridge," in *2023 3rd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST)*, Dhaka, Bangladesh, 2023, pp. 175–180. <https://doi.org/10.1109/ICREST57604.2023.10070046>
- [28] B. M. Luke, A. Tripathi, and S. A. Sampson, "Autonomous wheelchair robot for enhanced airport accessibility," in *2023 International Conference on Next Generation Electronics (NEleX)*, Vellore, India, 2023, pp. 1–6. <https://doi.org/10.1109/NEleX59773.2023.10420850>

- [29] M. Subramanian, S. Park, P. Orlov, A. Shafti, and A. A. Faisal, "Gaze-contingent decoding of human navigation intention on an autonomous wheelchair platform," in *2021 10th International IEEE/EMBS Conference on Neural Engineering (NER)*, Italy, 2021, pp. 335–338. <https://doi.org/10.1109/NER49283.2021.9441218>
- [30] M. Craciunescu, D. Baicu, M. Cîrciumaru, S. Mocanu, and R. Dobrescu, "Towards the development of autonomous wheelchair," in *2019 22nd International Conference on Control Systems and Computer Science (CSCS)*, Bucharest, Romania, 2019, pp. 552–557. <https://doi.org/10.1109/CSCS.2019.00101>
- [31] A. Juneja, L. Bhandari, H. Mohammadbagherpoor, A. Singh, and E. Grant, "A comparative study of SLAM algorithms for indoor navigation of autonomous wheelchairs," in *2019 IEEE International Conference on Cyborg and Bionic Systems (CBS)*, Munich, Germany, 2019, pp. 261–266. <https://doi.org/10.1109/CBS46900.2019.9114512>
- [32] C. Wang, M. Xia, and M. Q. H. Meng, "Stable autonomous robotic wheelchair navigation in the environment with slope way," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 10, pp. 10759–10771, 2020. <https://doi.org/10.1109/TVT.2020.3009979>
- [33] M. Subramanian, N. Songur, D. Adjei, P. Orlov, and A. A. Faisal, "A. Eye Drive: Gaze-based semi-autonomous wheelchair interface," in *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Berlin, Germany, 2019, pp. 5967–5970. <https://doi.org/10.1109/EMBC.2019.8856608>
- [34] L. F. Manta, C. F. Pană, D. Cojocaru, I. C. Vladu, D. M. Pătrașcu-Pană, and A. Dragomir, "APF-based control for obstacle avoidance in smart electric wheelchair navigation," in *2021 22nd International Carpathian Control Conference (ICCC)*, Velké Karlovice, Czech Republic, 2021, pp. 1–6. <https://doi.org/10.1109/ICCC51557.2021.9454660>
- [35] B. Zhang, C. Holloway, and T. Carlson, "A hierarchical design for shared-control wheelchair navigation in dynamic environments," in *2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Toronto, ON, Canada, 2020, pp. 4439–4446. <https://doi.org/10.1109/SMC42975.2020.9282838>
- [36] G. Vailland, V. Gouranton, and M. Babel, "Cubic Bézier local path planner for non-holonomic feasible and comfortable path generation," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, Xi'an, China, 2021, pp. 7894–7900. <https://doi.org/10.1109/ICRA48506.2021.9560854>
- [37] L. Qin, Z. Huang, C. Zhang, H. Guo, M. Ang, and D. Rus, "Deep imitation learning for autonomous navigation in dynamic pedestrian environments," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, Xi'an, China, 2021, pp. 4108–4115. <https://doi.org/10.1109/ICRA48506.2021.9561220>
- [38] L. Ciabattini, F. Ferracuti, A. Freddi, S. Iarlori, S. Longhi, and A. Monteriù, "ErrP signals detection for safe navigation of a smart wheelchair," in *2019 IEEE 23rd International Symposium on Consumer Technologies (ISCT)*, Ancona, Italy, 2019, pp. 269–272. <https://doi.org/10.1109/ISCT.2019.8900993>
- [39] D. Ranaweera, C. Athalage, M. S. Virajamana, C. Kaveesha, D. De Silva, and H. De Silva, "Assisting wheelchair: Assist W," in *2021 IEEE Region 10 Conference (TENCON)*, Auckland, New Zealand, 2021, pp. 128–133. <https://doi.org/10.1109/TENCON54134.2021.9707221>
- [40] A. Pierson, C.-I. Vasile, A. Gandhi, W. Schwarting, S. Karaman, and D. Rus, "Dynamic risk density for autonomous navigation in cluttered environments without object detection," in *2019 International Conference on Robotics and Automation (ICRA)*, Montreal, QC, Canada, 2019, pp. 5807–5814. <https://doi.org/10.1109/ICRA.2019.8793813>
- [41] D. Wang, W. Cao, B. Zhang, and M. Mukai, "Motion planning for a robotic wheelchair with SLERP MPC local planner," in *2023 62nd Annual Conference of the Society of Instrument and Control Engineers (SICE)*, Tsu, Japan, 2023, pp. 925–930. <https://doi.org/10.23919/SICE59929.2023.10354119>

- [42] M. S. SureshKumar *et al.*, “Design and development of indoor mobile robot for disabled people,” in *2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)*, Coimbatore, India, 2023, pp. 1–6. <https://doi.org/10.1109/ICAECA56562.2023.10199906>
- [43] J. Zhi, L.-F. Yu, and J.-M. Lien, “Designing human-robot coexistence space,” *IEEE Robotics and Automation Letters*, vol. 6, no. 4, pp. 7161–7168, 2021. <https://doi.org/10.1109/LRA.2021.3097061>
- [44] M. Cubuktepe, N. Jansen, M. Alshiekh, and U. Topcu, “Synthesis of provably correct autonomy protocols for shared control,” *IEEE Transactions on Automatic Control*, vol. 66, no. 7, pp. 3251–3258, 2021. <https://doi.org/10.1109/TAC.2020.3018029>
- [45] X. Deng, Z. L. Yu, C. Lin, Z. Gu, and Y. Li, “A bayesian shared control approach for wheelchair robot With brain machine interface,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 28, no. 1, pp. 328–338, 2020. <https://doi.org/10.1109/TNSRE.2019.2958076>
- [46] G. A. G. Ricardez *et al.*, “Autonomous service robot for human-aware restock, straightening and disposal tasks in retail automation,” *Advanced Robotics*, vol. 36, nos. 17–18, pp. 936–950, 2022. <https://doi.org/10.1080/01691864.2022.2109429>
- [47] L. K. Kenyon, J. Farris, L. Veety, and D. K. Zondervan, “The IndieTrainer system: A clinical trial protocol exploring use of a powered wheelchair training intervention for children with cerebral palsy,” *Disability and Rehabilitation Assistive Technology*, vol. 19, no. 4, pp. 1579–1589, 2023. <https://doi.org/10.1080/17483107.2023.2218436>
- [48] D. Nardi *et al.*, “Navigating without vision: spontaneous use of terrain slant in outdoor place learning,” *Spatial Cognition and Computation*, vol. 21, no. 3, pp. 235–255, 2021. <https://doi.org/10.1080/13875868.2021.1916504>
- [49] Y. Lyu and A. Forsyth, “Technological devices to help older people beyond the home: An inventory and assessment focusing on the neighborhood and city scales,” *Cities & Health*, vol. 8, no. 1, pp. 91–106, 2022. <https://doi.org/10.1080/23748834.2022.2094884>
- [50] P. Mishra and S. Shrivastava, “IoT based automated wheel chair for physically challenged,” *Materials Today Proceedings*, vol. 56, pp. 533–541, 2022. <https://doi.org/10.1016/j.matpr.2022.02.183>
- [51] O. V. Altunpinar and V. Sezer, “A novel indoor localization algorithm based on a modified EKF using virtual dynamic point landmarks for 2D grid maps,” *Robotics and Autonomous Systems*, vol. 170, p. 104546, 2023. <https://doi.org/10.1016/j.robot.2023.104546>
- [52] Q. Hou and C. Ai, “A network-level sidewalk inventory method using mobile LiDAR and deep learning,” *Transportation Research Part C Emerging Technologies*, vol. 119, p. 102772, 2020. <https://doi.org/10.1016/j.trc.2020.102772>
- [53] V. Tatano and R. Revellini, “An alternative system to improve accessibility for wheelchair users: The stepped ramp,” *Applied Ergonomics*, vol. 108, p. 103938, 2023. <https://doi.org/10.1016/j.apergo.2022.103938>
- [54] Y. Sakai, H. Lu, J.-K. Tan, and H. Kim, “Recognition of surrounding environment from electric wheelchair videos based on modified YOLOv2,” *Future Generation Computer Systems*, vol. 92, pp. 157–161, 2019. <https://doi.org/10.1016/j.future.2018.09.068>
- [55] L. Tonin *et al.*, “Learning to control a BMI-driven wheelchair for people with severe tetraplegia,” *iScience*, vol. 25, no. 12, p. 105418, 2022. <https://doi.org/10.1016/j.isci.2022.105418>
- [56] D. A. Oladele, E. D. Markus, and A. M. Abu-Mahfouz, “Towards an adaptable framework for mobility assistive technologies,” *Procedia Computer Science*, vol. 198, pp. 301–306, 2022. <https://doi.org/10.1016/j.procs.2021.12.244>
- [57] E. Kawaguchi, K. Sekiguchi, and K. Nonaka, “Self-driving electric wheelchair in crowded environments using a fuzzy potential model predictive control,” *IFAC-PapersOnLine*, vol. 56, no. 2, pp. 11827–11833, 2023. <https://doi.org/10.1016/j.ifacol.2023.10.582>

- [58] L. Jiang *et al.*, “SmartRolling: A human–machine interface for wheelchair control using EEG and smart sensing techniques,” *Information Processing & Management*, vol. 60, no. 3, p. 103262, 2023. <https://doi.org/10.1016/j.ipm.2022.103262>
- [59] J. C. Badajena, S. Sethi, and R. K. Sahoo, “Data-driven approach to designing a BCI-integrated smart wheelchair through cost–benefit analysis,” *High-Confidence Computing*, vol. 3, no. 2, p. 100118, 2023. <https://doi.org/10.1016/j.hcc.2023.100118>
- [60] H. Ikeda, T. Toyama, D. Maki, K. Sato, and E. Nakano, “Cooperative step-climbing strategy using an autonomous wheelchair and a robot,” *Robotics and Autonomous Systems*, vol. 135, p. 103670, 2021. <https://doi.org/10.1016/j.robot.2020.103670>
- [61] A. Botta, R. Bellincioni, and G. Quaglia, “Autonomous detection and ascent of a step for an electric wheelchair,” *Mechatronics*, vol. 86, p. 102838, 2022. <https://doi.org/10.1016/j.mechatronics.2022.102838>
- [62] A. Koložvari *et al.*, “Speech-recognition cloud harvesting for improving the navigation of cyber-physical wheelchairs for disabled persons,” *Microprocessors and Microsystems*, vol. 69, pp. 179–187, 2019. <https://doi.org/10.1016/j.micpro.2019.06.006>
- [63] R. M. Van der Slikke, P. Sindall, V. L. Goosey-Tolfrey, and B. S. Mason, “Load and performance monitoring in wheelchair court sports: A narrative review of the use of technology and practical recommendations,” *European Journal of Sport Science*, vol. 23, no. 2, pp. 189–200, 2023. <https://doi.org/10.1080/17461391.2021.2025267>
- [64] A. Gallagher, G. Cleary, A. Clifford, J. McKee, K. O’Farrell, and R. J. Gowran, “Unknown world of wheelchairs” A mixed methods study exploring experiences of wheelchair and seating assistive technology provision for people with spinal cord injury in an Irish context,” *Disability and Rehabilitation*, vol. 44, no. 10, pp. 1946–1958, 2022. <https://doi.org/10.1080/09638288.2020.1814879>
- [65] A. Verma, S. Shrivastava, and J. Ramkumar, “Mapping wheelchair functions and their associated functional elements for stair climbing accessibility: A systematic review,” *Disability and Rehabilitation: Assistive Technology*, vol. 19, no. 1, pp. 200–221, 2024. <https://doi.org/10.1080/17483107.2022.2075476>
- [66] R. J. Gowran, A. Clifford, A. Gallagher, J. McKee, B. O’Regan, and E. A. McKay, “Wheelchair and seating assistive technology provision: A gateway to freedom,” *Disability and Rehabilitation*, vol. 44, no. 3, pp. 370–381, 2022. <https://doi.org/10.1080/09638288.2020.1768303>
- [67] M. Callejas-Cuervo, A. X. González-Cely, and T. Bastos-Filho, “Control systems and electronic instrumentation applied to autonomy in wheelchair mobility: The state of the art,” *Sensors*, vol. 20, no. 21, p. 6326, 2020. <https://doi.org/10.3390/s20216326>
- [68] X. Deng, Z. L. Yu, C. Lin, Z. Gu, and Y. Li, “Self-adaptive shared control with brain state evaluation network for human-wheelchair cooperation,” *Journal of Neural Engineering*, vol. 17, no. 4, p. 045005, 2020. <https://doi.org/10.1088/1741-2552/ab937e>
- [69] J. S. Ortiz, G. Palacios-Navarro, V. H. Andaluz, and B. S. Guevara, “Virtual reality-based framework to simulate control algorithms for robotic assistance and rehabilitation tasks through a standing wheelchair,” *Sensors*, vol. 21, no. 15, p. 5083, 2021. <https://doi.org/10.3390/s21155083>
- [70] Md. A. Hossain, Md. F. K. Khondakar, Md. H. Sarowar, and Md. J. U. Qureshi, “Design and implementation of an autonomous wheelchair,” in *2019 4th International Conference on Electrical Information and Communication Technology (EICT)*, 2019, pp. 1–5. <https://doi.org/10.1109/EICT48899.2019.9068851>

Table A1. A displays the individual analysis of selected papers

Ref	Summary	Input Method	System	Control Strategy	Instrumentation	Navigation Type	Technology Used	Autonomous Type	Test Type	Findings	Accuracy	Limitations
[17]	Hands-free robotic wheelchair navigation using egocentric computer vision for users with limited upper-limb mobility.	Head movements tracked by a wearable camera to control a virtual joystick on a screen.	Modified commercial wheelchair with Arduino micro-controller, Kinect v2 sensor, tablet display, and wearable webcams.	Head motion tracking with a visual marker to control cursor on a display; includes automatic braking for safety.	Kinect v2 sensor, Logitech webcams, tablet display, QR visual marker, Arduino Mega 2560.	Manual (head movements), Autonomous (map-based, attention-driven, person-guided, people-following).	Egocentric computer vision, RGB-D sensors for SLAM, visual markers, head-mounted cameras, machine learning for user preferences.	Varying levels from manual to fully autonomous based on user input and environment.	User studies with healthy subjects for usability, autonomous navigation, and preference learning.	Effective, robust control with high user preference; minimal effort required; performs well in static and dynamic environments.	85-90% accuracy in autonomous mode; higher with user involvement in decision-making.	Tested with healthy subjects, need clinical trials; requires custom wheelchair modification; further validation needed for user preference model.
[18]	Follow the Gap Method (FGM) for dynamic waypoint tracking using Look Ahead Distance (LAD) optimized for tracking, avoidance, and comfort.	Dynamic Look Ahead Distance (LAD) adapted from geometric path tracking methods.	Autonomous robot system integrating FGM with a global planner and optimizing LAD based on various metrics.	Dynamic and optimized LAD function that adjusts based on robot velocity to improve tracking, avoidance, and comfort.	Not specified	Dynamic tracking of a global plan of consecutive waypoints using FGM with optimized LAD.	Follow the Gap Method (FGM), Look Ahead Distance (LAD), optimization techniques, and various weight coefficients for cost function.	Full autonomy with real-time adjustments based on tracking error, distance to obstacles, and comfort metrics.	Simulations and real-world experiments.	Optimization of LAD improves tracking, obstacle avoidance, and comfort. Real-world experiments validate simulation results.	Improved tracking distance to path metric from 0.424m to 1.23m when tracking coefficient is doubled.	Not explicitly mentioned, but the need for further validation in diverse real-world scenarios can be inferred.
[19]	Gesture-controlled wheelchair designed for physically disabled users, allowing operation via hand signals and wireless control using ZigBee.	Hand movements interpreted as control signals for the wheelchair.	Gesture-controlled wheelchair with a focus on effortless hand signal operation and wireless communication.	Interpreting hand gestures to calculate and direct the wheelchair's motion.	ZigBee for creating a personal area network and transferring data wirelessly.	User-controlled navigation through hand signals.	Gesture recognition technology and ZigBee wireless communication.	Not applicable; the system relies on user input for navigation.	Not specified	Aim is to provide easy and effortless control for physically disabled users using hand signals and wireless technology.	Not specified	Not specified
[20]	Enhancing autonomy in intelligent wheelchair navigation using reinforcement learning algorithms, with a focus on both individual and pair navigation to promote social activities.	Not explicitly specified but controlled through reinforcement learning algorithms.	Intelligent wheelchairs using reinforcement learning for autonomous navigation in a simulated environment.	Reinforcement learning algorithms for navigating to desired locations individually or in pairs.	Simulated environment using Gazebo and ROS for testing and development.	Autonomous navigation, both individual and pair-based, promoting social activities.	Reinforcement learning algorithms (DQN and Q-Learning).	Fully autonomous navigation using reinforcement learning.	Simulated environment tests with metrics collected on task completion time and trajectories.	Deep Q-Network (DQN) performed better than Q-Learning, achieving successful pair navigation behavior between two chairs.	DQN demonstrated better performance metrics than Q-Learning, particularly in pair navigation scenarios.	The study is based on a simulated environment; real-world validation is needed.
[21]	Incorporating human-robot joint perception and action with autonomous safety and learning from demonstration.	Human-teleoperated control with autonomous safety and user-customizable arbitration function.	Shared autonomy framework integrating human skills and social preferences with robotic sensing and action.	Shared autonomy with online user-customizable arbitration, learning from demonstration for autonomous behaviors.	Two mobile robot platforms for implementation and validation.	Human-in-the-loop and fully autonomous navigation, adjustable based on user preferences and specific applications.	Robotic sensing, learning from demonstration, neural networks, user-customizable arbitration function.	Shared to full autonomy, managed by users based on application needs.	Reproducibility, practicality, and feasibility are assessed by implementation on two mobile robot platforms.	The framework effectively incorporates personal skills and guiding the development of deployable systems.	Validated through experimental results showing successful application of shared autonomy framework.	Not explicitly mentioned, but real-world deployment and application are implied challenges.
[22]	Swarm robotics technology is used to develop an affordable, remotely driven, multidirectional Unmanned Ground Vehicle (UGV).	Android-based application (Blynk) for controlling speed and direction.	Swarm robotics UGV with components like NodeMCU, DC motor, L298N Servo motor, ESP32 cam, and mechanical wheels.	Remote control via smartphone using the Blynk application to navigate the UGV.	Node MCU, DC motor controller, Servo motor, ESP32 cam, mechanical communication module.	Remote-operated navigation through smartphone application.	Swarm robotics, Wi-Fi MCU, ESP32 cam, Android-based Blynk application.	Semi-autonomous with remote control capabilities.	Performance optimizations tested through hardware and software improvements.	UGVs can be effectively used in contemporary warfare for various objectives, including as a robotic army and surveillance device.	Not explicitly specified, but improvements noted through hardware and software optimizations.	Not explicitly mentioned, but real-world deployment and application in warfare scenarios imply challenges.

(Continued)

**Table A1.** A displays the individual analysis of selected papers (Continued)

Ref	Summary	Input Method	System	Control Strategy	Instrumentation	Navigation Type	Technology Used	Autonomous Type	Test Type	Findings	Accuracy	Limitations
[23]	Simulation of an autonomous mobile robot (AMR) using ROS in Gazebo to find the shortest path and traverse coordinate-based checkpoints quickly.	Sensors for input, including LIDAR, depth camera, IMU, and encoders.	Autonomous mobile robot simulated in Gazebo, using ROS for software development.	Uses global and local planners for path determination and collision avoidance.	Sensors used include LIDAR, depth camera, IMU, and encoders.	Autonomous navigation with coordinate-based checkpoint traversal.	ROS, SLAM, AMCL, global and local planners, LIDAR, depth camera, IMU, encoders.	Fully autonomous navigation.	Simulated environment in Gazebo.	The robot can effectively travel from point to point in the quickest time possible without crashes, applicable to real-life scenarios like autonomous cleaners and delivery robots.	Not explicitly mentioned, but the focus is on achieving quick and collision-free navigation.	The study is based on a simulated environment; real-world validation is needed to confirm effectiveness.
[24]	The paper focuses on the simulation of an autonomous mobile robot (AMR) using the robot operating system (ROS) in Gazebo.	Coordinate-based checkpoints.	Robot Operating System (ROS).	Global planner and local planner.	Sensors like LIDAR, depth camera, IMU, and encoders.	Autonomous navigation.	ROS, Gazebo, SLAM, AMCL.	Fully autonomous.	Simulation.	The robot can travel from point to point in the quickest time possible without crashes.	High accuracy in navigation and collision avoidance.	Only simulation, real-world applicability not tested.
[25]	The study presents an interactive navigation framework for autonomous mobile robots with situation-adaptive multimodal induction to enhance safety and efficiency in human-coexisting environments.	Sensors (LIDAR, depth camera, IMU, encoders) and human-environment information (space attributes, human positions, postures, and velocities).	Autonomous mobile robot with an interactive navigation framework incorporating human-aware navigation and induction methods.	Uses a situation-adaptive induction selector to dynamically choose the most appropriate induction method (visual, auditory, or haptic) based on real-time human-robot proximity and environment data.	LIDAR, depth camera, IMU, encoders, speakers for auditory induction, robot arm for haptic interaction.	Human-aware navigation with interactive and adaptive multimodal induction methods.	ROS, SLAM, AMCL, machine learning for dynamic adaptation, sensors for human detection and environment mapping.	Fully autonomous with interactive and adaptive capabilities based on human and environmental context.	Simulated and real-world experiments in a corridor scenario with human participants to evaluate the effectiveness and psychological impact of the navigation framework.	The proposed system effectively solves the freezing problem, provides safe and efficient trajectories, and improves human psychological responses to robot navigation.	High accuracy in selecting suitable induction methods based on the situation, leading to efficient navigation and positive human-robot interaction outcomes.	The study is limited to specific scenarios and hardware configurations; further validation in diverse real-world environments and with different robot designs is needed.
[26]	The paper proposes an advanced autonomous wheelchair model to assist physically challenged individuals and the elderly.	User input for marking locations on a virtual map.	Autonomous wheelchair model incorporating trajectory modeling as a virtual map for navigation.	Uses SLAM for localization and mapping, RRT for path planning, and Differential Drive algorithms for movement control.	Sensors and hardware required for SLAM, RRT, and Differential Drive algorithms.	Autonomous navigation towards specified destinations with the ability to remember and revisit locations.	Rapidly Exploring Random Trees (RRT), Differential Drive algorithms, Simultaneous Localization and Mapping (SLAM).	Fully autonomous with minimal user input required.	Not explicitly mentioned but implied to be simulations and/or real-world experiments to validate navigation capabilities.	The proposed model reduces the need for user control and enables easy navigation to previously visit locations, particularly aiding those with limited mobility.	Not explicitly mentioned, but the use of advanced algorithms like SLAM and RRT suggests high accuracy in navigation and localization.	Not explicitly mentioned, but potential limitations could include the need for robust sensors and real-world testing to ensure reliability in various environments.
[27]	The paper presents a simulation of a ROS-based autonomous wheelchair and a cloud-based platform for remote control and tracking of the wheelchair's mobility and the patient's location.	Remote control from any Internet-enabled device using a cloud-based platform.	ROS-based autonomous wheelchair integrated with a cloud-based online platform for control and tracking.	Autonomous navigation with remote control capabilities via the cloud-based platform.	Sensors and hardware compatible with ROS for autonomous navigation, and internet connectivity for cloud-based control.	Autonomous navigation with remote control functionality.	Robot Operating System (ROS), cloud computing for remote control and tracking, internet connectivity.	Fully autonomous with optional remote control.	Simulations demonstrating the practicability and performance of the designed system.	The designed system is practical and performs well in simulations, offering mobility support to disabled and elderly individuals.	High accuracy in navigation and remote control as demonstrated in simulation results.	The study is based on simulations; real-world validation is needed to confirm effectiveness and reliability.

[28]	The paper presents a theoretical feasibility study of an autonomous wheelchair robot (AWR) designed to assist the elderly and people with limited mobility in navigating complex and crowded airport terminals.	Destination information obtained from a bar code on the ticket or direct input.	Autonomous wheelchair robot (AWR) using the grapping module for generating detailed airport maps and determining efficient routes.	Automatic navigation through check points with motion detection for obstacle avoidance and speed/heating adjustments by passengers.	Bar code scanner or direct input device for obtaining destination information, sensors for motion detection and obstacle avoidance.	Autonomous navigation through airport check points including check-in counters, security checks, and boarding gates.	Grapping module for map generation, motion detection module for obstacle avoidance, and various sensors for navigation and control.	Fully autonomous navigation with obstacle avoidance capabilities.	Comprehensive performance evaluation assessing navigation accuracy and efficiency.	The AWR system enhances airport transportation accessibility, safety, and convenience for travelers with limited mobility. Potential applications extend to other public spaces like shopping centers, hospitals, and museums.	High navigation accuracy and efficiency demonstrated in the performance evaluation.	The study is theoretical, real-world validation is needed to confirm effectiveness and reliability in diverse public spaces.
[29]	The paper presents the "Where-You-Go" approach for controlling mobility platforms by decoding user eye movements to determine navigation intentions.	Eye movements and visual attention decoded using deep computer vision and machine learning classifiers.	AEye-Drive autonomous wheelchair platform that navigates based on decoded visual attention and navigation intentions.	Decodes user intentions to navigate to objects based on eye movements and visual attention, using deep computer vision and machine learning classifiers.	Eye-tracking sensors, deep computer vision algorithms, and machine learning classifiers for decoding navigation intentions.	Autonomous navigation to desired objects based on cognitive-level human interaction, without continuous user steering.	Deep computer vision, object bounding box analysis, machine learning classifiers, eye-tracking sensors.	Fully autonomous navigation based on decoded user intentions from eye movements.	Theoretical feasibility and practical implementation in the AEye-Drive platform.	The system effectively decodes navigation intentions from eye movements, allowing cognitive-level interaction for navigation and successfully navigating to desired objects while avoiding obstacles.	High accuracy in decoding user intentions and navigating to desired objects, demonstrated through practical implementation.	The potential for the Midas Touch Problem, where not all eye movements are relevant for navigation intentions; requires further validation in diverse real-world scenarios.
[30]	The paper aimed at developing an autonomous electric wheelchair.	Computer vision for detecting floors and doors using images of corridor environments.	Autonomous electric wheelchair with a system architecture dedicated to precise indoor navigation using image segmentation.	Uses fully convolutional neural networks (FCN) for image segmentation to identify floor areas and compute safe paths for navigation.	Cameras for capturing corridor images and processing hardware for running FCN-based image segmentation algorithms.	Precise indoor navigation in unknown environments, specifically within corridors.	Fully convolutional neural networks (FCN), computer vision for image segmentation, path planning algorithms.	Fully autonomous navigation.	Not explicitly mentioned, but likely includes simulations and real-world tests to validate the navigation system.	The proposed system achieves high accuracy and speed in detecting floors and doors, enabling safe path computation for indoor navigation.	High accuracy in image segmentation and path planning, ensuring precise navigation.	Not explicitly mentioned, but potential limitations could include the need for extensive testing in diverse indoor environments to ensure robustness and reliability.
[31]	The paper focuses on developing an autonomous wheelchair system for patients with rare diseases like Motor Neuron Disease (MND) and Amyotrophic Lateral Sclerosis (ALS).	LiDAR, Kinect camera, IMU and wheel encoders for perception and localization.	Modified electric powered wheelchair with integrated sensors for autonomous navigation.	Uses SLAM algorithms to build maps and localize the wheelchair in real-time, with dynamically generated navigation rules through machine learning or deep learning.	LiDAR, Kinect camera, IMU, wheel encoders.	Autonomous indoor navigation with real-time map building and localization.	SLAM algorithms (Gmapping, Hector, RTAB-Map, VINS-Mono, RGB-D-SLAM), machine learning, deep learning.	Fully autonomous.	Functional testing of the wheelchair with comparisons of SLAM algorithms based on defined metrics for localization and mapping accuracy.	RTAB-Map was found to be the most scalable and accurate algorithm, producing reliable maps and consistent localization across different sensor combinations and speeds.	High accuracy with RTAB-Map in both map building and localization.	Not explicitly mentioned, but real-world application and usability for patients with varying medical conditions imply further validation needed.
[32]	The article presents a path planning approach for stable robotic wheelchair navigation in environments with slopes.	Adaptive weighting Gaussian Mixture Model (GMM) for sampling.	Robotic wheelchair navigation system using a lightweight navigation map and a sampling-based path planning scheme.	Path planning using a modified extension function, path optimization with a utility function, and adaptive weighting in GMM during the planning process.	Sensors and hardware necessary for mapping and path planning in environments with slopes (specific instruments not detailed).	Autonomous navigation in environments with slopes.	Lightweight navigation map, sampling-based path planning scheme, modified extension function, adaptive weighting GMM, utility function for optimization.	Fully autonomous.	Simulation and real-world experiments to verify effectiveness and efficiency.	The proposed path planning method effectively generates feasible and safe trajectories for robotic wheelchair navigation in sloped environments, ensuring human comfort and path cost efficiency.	High accuracy in generating feasible paths and indicating unsafe regions in the navigation map.	Nor explicitly mentioned, but further validation in diverse environments with various slope conditions might be necessary.

(Continued)

**Table A1.** A displays the individual analysis of selected papers (Continued)

Ref	Summary	Input Method	System	Control Strategy	Instrumentation	Navigation Type	Technology Used	Autonomous Type	Test Type	Findings	Accuracy	Limitations
[33]	The paper introduces AEye Drive, a "Zero UI" driving platform combining eye-tracking/gaze-contingent intention decoding with computer vision context awareness, and continuously updates path planning for obstacle avoidance.	Eye-tracking/gaze-contingent intention decoding.	AEye Drive platform integrating eye-tracking with computer vision and autonomous navigation technology.	Decodes user gaze to determine navigation intentions, uses computer vision for context awareness, and continuously updates path planning for obstacle avoidance.	Eye-tracking sensors, computer vision algorithms, autonomous navigation systems.	Autonomous navigation based on decoded gaze intentions.	Autonomous navigation from self-driving vehicles, eye-tracking, gaze-contingent intention decoding, computer vision context-aware algorithms	Fully autonomous with continuous path updates for obstacle avoidance.	Not explicitly mentioned but implied to include simulations and/or real-world testing for validation.	The AEye Drive platform reduces cognitive load on users, enabling more independent and safer navigation by allowing users to drive by looking at their intended destination.	High accuracy in decoding gaze intentions and navigating to the intended destination, continuously updating paths for static and dynamic obstacles.	Not explicitly mentioned, but further validation in real-world scenarios and with diverse user needs may be necessary.
[34]	The paper proposes an autonomous and real-time navigation module for a smart electric wheelchair (SEW), using Lidar for obstacle avoidance and an artificial potential field (APF) method for trajectory planning.	Remote sensing technology (Lidar) for real-time mapping and obstacle detection.	Smart electric wheelchair (SEW) with autonomous navigation capabilities.	Uses the artificial potential field (APF) method to generate desired trajectories, balancing attraction to the target and repulsion from obstacles.	Lidar for real-time environmental mapping and obstacle detection.	Autonomous navigation in dynamic 3D environments.	Lidar for sensing, artificial potential field (APF) method for trajectory planning, virtual obstacle avoidance control algorithm.	Fully autonomous navigation with real-time obstacle avoidance.	Simulation results in a corridor with obstacles to validate the algorithm's effectiveness.	The proposed APF algorithm effectively plans trajectories and avoids obstacles, ensuring efficient and continuous navigation of intelligent wheelchairs.	High accuracy in obstacle detection and trajectory planning, as confirmed by simulation results.	The study is based on simulations; real-world validation is needed to confirm effectiveness in diverse scenarios.
[35]	The paper presents a hierarchical shared-controlled wheelchair using a velocity-based approach and probabilistic shared control (PSC), compared to other methods.	Velocity-based input approach.	Hierarchical shared-controlled wheelchair system integrating velocity-based control and probabilistic shared control (PSC).	Combines velocity-based control with probabilistic shared control (PSC) for dynamic environments, focusing on collision avoidance and robot-pedestrian interaction.	Not explicitly mentioned, but likely includes sensors for collision avoidance and interaction modeling.	Shared-controlled navigation in dynamic environments.	Velocity-based control, probabilistic shared control (PSC), Unity3D simulation for testing.	Semi-autonomous with shared control.	Unity3D-based simulator with human participants for validation.	The proposed approach resulted in the least number of collisions, low computational cost, and high user agreement when compared with other state-of-the-art methods.	High accuracy in collision avoidance and user agreement in dynamic environments.	The study is based on simulations; real-world validation is needed to confirm effectiveness in practical applications.
[36]	The paper proposes a local path planner for non-holonomic robot navigation, specifically designed for power wheelchair navigation.	Path planning using Cubic Bézier curves and the CBB-RRT* algorithm.	Power wheelchair navigation system with a local path planner for non-holonomic robots.	Uses a local path planner with bounded curvature and continuous Cubic Bézier piecewise curves, implemented through the CBB-RRT* algorithm.	Not explicitly mentioned, but likely includes sensors for real-time path planning and navigation.	Local path planning for non-holonomic robot navigation.	Cubic Bézier curves, CBB-RRT* (cubic Bézier-based Rapidly exploring Random Tree) algorithm.	Fully autonomous path planning and navigation.	Simulations to test the local path planner and the CBB-RRT* algorithm.	The proposed local path planner generates feasible and smooth paths with bounded curvature, enhancing passenger comfort in power wheelchair navigation.	High accuracy in generating smooth and feasible paths suitable for non-holonomic constraints.	The study is based on simulations; real-world validation is needed to confirm effectiveness in practical applications.

[37]	The research introduces a path planning system that enables autonomous navigation in dynamic pedestrian environments by utilizing imitation learning.	Raw sensory data processed through a fully convolutional neural network.	Autonomous wheelchair equipped with an end-to-end path planning system based on imitation learning.	Uses a fully convolutional neural network for mapping sensory data to confidence maps and a classification network for reducing unnecessary re-planning.	Sensors for collecting raw data and processing hardware for running the neural network algorithms.	Autonomous navigation in dynamic pedestrian environments.	Fully convolutional neural network, imitation learning, classification network for path planning.	Fully autonomous with human-like trajectory generation.	Real-world testing in dynamic pedestrian environments.	The system generates paths for various driving tasks, following and obstacle avoidance, outperforming state-of-the-art methods in generating human-like trajectories.	High accuracy in generating human-like trajectories and reducing unnecessary re-planning.	Not explicitly mentioned, but further validation in diverse environments might be necessary.
[38]	The paper presents a smart wheelchair equipped with semi-autonomous navigation capabilities and a Brain-Computer Interface (BCI) to enhance user safety.	Brain-Computer Interface (BCI) capturing error-related potentials (ErrPs) from the user.	Smart wheelchair with semi-autonomous navigation and BCI for user feedback.	Semi-autonomous navigation with real-time user feedback via BCI to correct navigation errors and ensure safety.	Electric powered wheelchair, BCI for detecting ErrPs, sensors for navigation and obstacle detection.	Semi-autonomous navigation with human supervision via BCI.	Brain-Computer Interface (BCI), error-related potentials (ErrPs), electric powered wheelchair, navigation sensors.	Semi-autonomous with user feedback.	Not explicitly mentioned, but likely includes real-world testing with the BCI feedback mechanism.	The system effectively uses BCI feedback to enhance navigation safety, allowing users to correct the trajectory when issues are detected.	High accuracy in detecting ErrPs and correcting navigation issues in real-time.	Not explicitly mentioned, but further validation in diverse environments and with different users may be necessary.
[39]	The paper introduces Assist W an autonomous assisting wheelchair designed to help disabled people perform daily activities independently and safely.	Voice and touch commands.	Assist W autonomous assisting wheelchair with SLAM and LIDAR for mapping and navigation, AR chatbot, fall detection system, and automatic lifting system.	Autonomous navigation based on user commands (voice and touch) and map data.	LIDAR sensor, AR chatbot, fall detection system, automatic lifting system.	Autonomous navigation within the mapped environment.	SLAM algorithm, LIDAR sensor, AR chatbot, voice and touch command interface, fall detection system, automatic lifting system.	Fully autonomous with user input for commands.	Simulation testing.	Assist W facilitates independent and safe daily activities for disabled individuals, supports mental health with an AR chatbot, and ensures physical safety with fall detection and lifting systems.	High accuracy in mapping and navigation, as well as effective detection and response to falls and other emergencies.	Tested only in simulation; real-world validation is needed to confirm effectiveness and reliability.
[40]	The paper presents a navigation approach for autonomous wheelchairs in cluttered environments without explicit object detection and tracking.	Dynamic risk density computed from occupancy density and velocity fields.	Autonomous wheelchair using dynamic risk density for navigation in cluttered environments.	The agent navigates based on a cost function derived from dynamic risk density, mapping congestion and spatial flow to determine risk levels.	Sensors to measure occupancy density and velocity fields (specific sensors not detailed).	Autonomous navigation in unstructured, crowded, and cluttered environments.	Dynamic risk density, occupancy density, velocity fields, cost function for risk determination.	Fully autonomous.	Simulations and implementation on an autonomous wheelchair.	The dynamic risk density approach effectively encodes information for the ego agent and models congestion cost without explicit object detection, enabling efficient navigation in cluttered environments.	High accuracy in encoding movement information and modeling congestion by simulations.	Further real-world validation may be needed to confirm effectiveness in diverse and dynamic environments.
[41]	The research introduces a motion planning method for a four-wheeled robotic wheelchair.	SLAM for environment mapping and localization.	Four-wheeled robotic wheelchair described using the unicycle model.	Dual quaternion-based SLERP model predictive control (MPC) for local path planning combined with A* algorithm for global path planning.	Sensors for SLAM, robotic wheelchair hardware compatible with ROS.	Autonomous navigation in unknown environments with a focus on safety and comfort.	Dual quaternion-based SLERP model predictive control (MPC), SLAM A* algorithm, Robot Operating System (ROS).	Fully autonomous.	Simulations within the Robot Operating System (ROS).	The proposed strategy allows the robotic wheelchair to move safely and smoothly from its initial position to a target location, demonstrating effectiveness in simulations.	High accuracy in path planning and navigation as demonstrated by simulation results.	The study is based on simulations; real-world validation is needed to confirm effectiveness in practical scenarios.

(Continued)

**Table A1.** A displays the individual analysis of selected papers (Continued)

Ref	Summary	Input Method	System	Control Strategy	Instrumentation	Navigation Type	Technology Used	Autonomous Type	Test Type	Findings	Accuracy	Limitations
[42]	The paper presents the development of a wheelchair assistant robot designed to autonomously assist wheelchair-bound individuals.	User requests made through a webpage.	Wheelchair assistant robot that docks with and navigates wheelchairs autonomously.	Autonomous navigation and docking/undocking procedures based on user requests and predefined destinations.	Sensors and docking mechanisms to enable autonomous navigation and wheelchair handling.	Autonomous navigation to specified destinations with docking and undocking capabilities.	Autonomous docking algorithms, docking mechanisms, requests for user navigation, charging station for idle periods	Fully autonomous.	Real-time testing with and without a payload to evaluate performance and feasibility	The system successfully enhances mobility and independence for wheelchair users, reduces the need for constant supervision, and demonstrates potential for cost reduction in healthcare settings.	High accuracy in navigation and docking/undocking operations, as demonstrated by real-time tests.	Further research and testing are needed to understand and address limitations in various real-world scenarios and environments.
[43]	The letter investigates computational design in human-robot coexistence spaces, using autonomous wheelchairs as an example, constraints.	Room size and objects (O) in the room.	Computational design framework for optimizing human-robot coexistence spaces.	Uses a motion planner to evaluate navigation constraints and human preferences to compute optimal layouts.	Computational tools for design and evaluation of room layouts.	Autonomous navigation within optimized room layouts.	Motion planner, computational design framework.	Fully autonomous navigation within designed environments.	Implementation and comparison of design times and effectiveness in various room layouts.	The proposed framework significantly reduces design time from 10–20 minutes to 3–5 minutes and produces reasonable designs even for tight spaces and different user preferences.	High accuracy in producing effective and human-preferred room layouts that facilitate autonomous wheelchair navigation.	Further validation in diverse real-world environments and with a broader range of user preferences may be needed.
[44]	The paper presents a framework for synthesizing shared control protocols for robots, specifically focusing on probabilistic temporal logic specifications.	Human commands and autonomy protocol blended through a shared control interface.	Shared control system modeled as a Markov decision process (MDP) with probabilistic temporal logic specifications.	Blending human commands with autonomy protocol commands using a blending function and quasiconvex programming to ensure safety and performance.	Sensors and input interfaces to capture human commands, computational tools for MDP modeling and optimization.	Semi-autonomous navigation in shared control settings.	Markov decision processes (MDP), inverse reinforcement learning, quasiconvex programming, probabilistic temporal logic specifications.	Semi-autonomous with shared control between human and autonomy protocol.	Case studies involving autonomous wheelchair navigation and UAV mission planning, with data collection from human participants.	The synthesized shared control protocols ensure safety and performance while closely matching human behavior, demonstrated through case studies.	High accuracy in meeting safety specifications, with minimal deviation from human strategy as shown in simulations and case studies.	Assumes consistent human commands throughout execution; further research needed to handle non-consistent commands and explore transfer learning for generalization to other domains.
[45]	The paper proposes a Bayesian shared control approach for wheelchair robots with a brain-machine interface (BMI) to enhance performance by combining robot automatic control and brain-actuated control.	Brain-machine interface (BMI) using steady-state visual evoked potential (SSVEP) signals.	Bayesian shared control system (BSC-BM) for continuous wheelchair navigation.	Combines brain-actuated control and robot automatic control using a Bayesian approach based on maximum a posteriori probability (MAP).	EEG signals acquired by a 32-channel Quik cap and 40-channel amplifier NuAmps device, Kinect sensor for visual feedback, LEDs for stimuli, and a PC for data processing.	Continuous autonomous navigation with shared control between human and robot.	Bayesian approach, SSVEP-based BMI, maximum a posteriori probability (MAP), hierarchical brain control mechanism.	Semi-autonomous with shared control.	Experimental validation with eleven subjects in different navigation scenarios.	The system effectively integrates human and robot control, reducing user mental burden and improving navigation performance. Subjects showed a high success rate and reduced task completion time with the BSC-BMI system.	High accuracy in decoding EEG signals and generating appropriate control commands, as indicated by successful navigation tasks and user feedback.	The system's performance depends on the accuracy of the EEG signal decoding and the probabilistic models. Further research is needed to adjust model parameters dynamically and explore advanced EEG decoding methods.

[46]	The paper presents an autonomous service robot designed for human-aware restock, straightening, and disposal tasks in retail automation.	User commands through a webpage to pick up and transport items.	Autonomous service robot with a mobile manipulator and custom-made automated shelf.	The robot uses a combination of SLAM (Simultaneous Localization and Mapping) for navigation, a hierarchical task strategy, and a straightening algorithm for item arrangement.	Extendable and compliant end effector, RealSense D415 camera, Hokuyo laser range finders, AR markers, Dynamixel motors, OpenCR controller.	Autonomous navigation in a retail environment, capable of traversing narrow spaces.	SLAM, motion planning algorithms (* for global planning, SLERP-MPC for local planning), computer vision for object detection and pose estimation, suction-based end effector.	Fully autonomous with human-awareness and interaction capabilities.	Tested in the Future Convenience Store Challenge (FCS) 2020 and in a laboratory, setting designed to mimic a convenience store scenario.	The robot successfully completed restock, straightening, and disposal tasks, obtaining first place in FCS 2020. The system achieved high scores in both the competition and laboratory tests, demonstrating effective manipulation, navigation, and human interaction.	High accuracy in item manipulation and placement, achieving up to 95% in laboratory experiments and 88% in the FCS 2020 competition.	The system relies on fiducial markers for pose estimation, which may not be practical in all real-world scenarios. The current system needs to be adapted to operate without markers and to handle a wider variety of items and environmental conditions.
[47]	The IndieTrainer system, consisting of a mobility device and gamified training modules, was developed to help children with cerebral palsy (CP) acquire powered wheelchair (PWC) skills.	User commands through a webpage to request assistance.	IndieTrainer system comprising a mobility device and gamified training modules designed for PWC skills acquisition.	The system combines autonomous navigation with user commands to facilitate training and mobility.	PWC equipped with the IndieTrainer system, sensors for tracking movements, and a webpage interface for user commands.	Semi-autonomous navigation with user input and gamified training modules.	IndieTrainer system, gamified training modules, webpage interface for user commands.	Semi-autonomous with user guidance.	Open-label, single-arm clinical trial with 25 child-parent/caregiver dyads, involving a three-week intervention and a retention trial four weeks post-intervention.	The system successfully aids children in improving their PWC skills and provides a positive experience for both children and their caregivers. Parents/caregivers reported high satisfaction with the system.	High accuracy in facilitating skill acquisition and positive user experience as indicated by the outcome measures and qualitative feedback.	The study is small-scale and further research is needed to validate the findings in larger and more diverse populations.
[48]	The study examines terrain slant as a nonvisual cue for navigation in outdoor environments.	Proprioceptive/kinesthetic and vestibular cues from terrain slant.	Human navigation system utilizing terrain slant as a nonvisual cue.	Utilizing proprioceptive/kinesthetic and vestibular cues for navigation without explicit visual information.	None specified; relies on natural human sensory systems.	Nonvisual navigation based on environmental cues.	None specified; study focuses on natural human sensory processing.	Not applicable; study involves human participants.	Place-learning task in outdoor field experiment with blindfolded, sighted participants.	Participants made fewer errors in the slanted site, indicating effective use of proprioceptive/kinesthetic and vestibular cues for navigation.	Lower accuracy compared to visual cues, but still significantly better than guessing.	The study involved blindfolded, sighted participants; results may differ for individuals who are blind or have different sensory processing abilities.
[49]	The study investigates technological devices available to support older people in their neighborhood and city environments.	Various technological devices (e.g. sensors, robots, activity monitors) operated by the users or automatically.	A combination of different technological devices designed for mobility, safety, health monitoring, and social connectedness in urban environments.	Automated and semi-automated control mechanisms embedded in devices like smart streetlights, robots, and activity monitors to assist older individuals.	Sensors, robots, smart streetlights, smart bus stops, pedestrian crossing devices, in-vehicle sensors, activity monitors, and other assistive technologies.	Mobility assistance for pedestrians and vehicles, including navigation aids for visually impaired individuals.	Smart technologies, robotics, activity monitoring systems, smart infrastructure (e.g. smart streetlights), and assistive devices for mobility and health monitoring.	Combination of autonomous and semi-autonomous devices.	Various studies and implementations in urban environments including real-world trials and laboratory settings.	Many technological devices effectively improve mobility and safety for older adults.	Varies by device; generally high accuracy in mobility and safety-related applications, but further evaluation needed for social and health-related devices.	Many devices rely on existing infrastructure, which may not be evenly distributed. There is also a lack of evaluation for some emerging technologies, and more research is needed to address diverse needs.

(Continued)

**Table A1.** A displays the individual analysis of selected papers (Continued)

Ref	Summary	Input Method	System	Control Strategy	Instrumentation	Navigation Type	Technology Used	Autonomous Type	Test Type	Findings	Accuracy	Limitations
[50]	The proposed automatic wheelchair (AWC) assists and supports paraplegics, particularly quadriplegics, by enabling control through head movements.	Patient's head movements monitored by an accelerometer.	Microcontroller-based wheelchair controlled by head movements.	Uses accelerometer data to control wheelchair movements (LEFT, RIGHT, FORWARD, BACKWARD) through a microcontroller.	Accelerometer for head motion recognition, Bluetooth for communication, ultrasonic sensors for obstacle detection, pulse rate, and blood oxygen level sensors for health monitoring.	Indoor navigation based on head movement commands.	Internet of Things (IoT) for health monitoring, viber motors for movement, and microcontroller for processing commands.	Semi-autonomous; relies on user input for movement commands.	Practical implementation and testing within a household environment.	The system effectively aids quadriplegics in controlling the wheelchair using head movements, enhances patient safety, and monitors health parameters.	High accuracy in detecting head movements and controlling the wheelchair, with reliable health monitoring.	Limited to indoor environments; further research needed for outdoor applications and to enhance system robustness.
[51]	The study presents novel solutions to two significant challenges in localization for autonomous mobile robots: the lack of distinct features within the environment and the imperfectness of the map, platform.	Data from sensors and environmental features, processed through a modified EKF algorithm.	Autonomous localization system for mobile robots using VDP, approach and modified EKF algorithm.	Extended Kalman Filter (EKF) with modifications to account for map errors and use of VDP for position tracking.	Sensors to detect environmental features, SLAM-generated maps, and an autonomous wheelchair platform for real-world testing.	Autonomous navigation in environments with few distinct features.	Extended Kalman Filter (EKF), virtual dynamic point landmark (VDP), SLAM (Simultaneous Localization and Mapping).	Fully autonomous localization and navigation.	Multiple simulations in randomly generated maps and real-world tests using an autonomous wheelchair platform.	The proposed VDP approach significantly improves localization performance in environments with few distinct features. The modified EKF algorithm effectively reduces position errors due to map inaccuracies.	High accuracy in localization and position tracking as shown by simulation and real-world test results.	Further research needed to generalize the approach to various environments and improve robustness under different conditions.
[52]	The study proposes a network-level sidewalk inventory method using mobile LIDAR data and a customized deep neural network (PointNet++) for efficient segmentation.	Mobile LIDAR data segmented using PointNet++.	Network-level sidewalk inventory system using mobile LIDAR and a deep neural network for data segmentation and analysis.	Automated extraction and analysis of sidewalk features for ADA compliance and condition assessment.	Mobile LIDAR, PointNet++ deep neural network, stripe-based sidewalk extraction algorithm.	Data collection and analysis for pedestrian and wheelchair navigation.	Mobile LIDAR, PointNet++ deep neural network, automated extraction algorithms.	Fully automated extraction and analysis process.	Experimental test conducted on State Route 9, Massachusetts, and a case study in Columbus District, Boston, Massachusetts.	The method achieved high accuracy (IoU value of 0.946) and efficiency (approximately 6.5 min/mile) in extracting sidewalk features.	High accuracy in sidewalk extraction with an IoU value of 0.946.	Further research needed to validate the method in different environments and enhance the robustness of the system.
[53]	The study evaluates the effectiveness of "stepped ramps" designed for historic cities like Venice, where space constraints often make it impossible to conform to standard ramp slopes.	Observational analysis of wheelchair users navigating ramps.	Stepped ramps designed with a steeper slope than standard regulations allow, specifically for historic cities.	Assessment of user comfort and safety through observational studies and friction coefficient analysis.	Wheelchairs, ramps with varying slopes and surfaces, and measurement tools for friction coefficients.	Wheelchair navigation on ramps with varying slopes and surface materials.	None specified; focus on physical ramp design and analysis.	Not applicable; study involves human participants using wheelchairs.	Empirical study involving the analysis of ten different ramps in real-world conditions.	Steeper ramps, while not adhering to standard regulations, can improve accessibility in constrained environments.	The study provides detailed measurements of friction coefficients and user comfort levels, indicating reliable data for specific scenarios.	The steeper ramps may not be suitable for all users or environments, and further research is needed to generalize findings to different settings and populations.

[54]	This study develops a system for detecting sidewalk, crosswalks, and traffic lights to enhance the safety and convenience of electric wheelchair users.	Object recognition using a modified YOLOv2 algorithm.	An autonomous electric wheelchair equipped with environmental recognition capabilities for detecting sidewalk, crosswalks, and traffic lights.	Uses convolutional neural networks (CNNs) for object detection and processing steps like unnecessary bounding box deletion and interpolation.	Modified YOLOv2 algorithm, sensors for detecting sidewalk, crosswalks, and traffic lights.	Autonomous navigation based on detected environmental features.	Convolutional neural networks (CNNs), YOLOv2 algorithm, object detection technology.	Fully autonomous detection and navigation system.	Experimental results demonstrating the detection rate with an average AUC of 0.587.	The system showed promising results in detecting sidewalk, crosswalks, and traffic lights, improving the safety and convenience of electric wheelchair users. The average AUC of the detection rate was 0.587.	Average AUC of the detection rate is 0.587.	The system's accuracy and robustness improved for real-world applications.
[55]	The study investigates the use of brain-machine interface (BMI) technology to control mind-controlled wheelchairs for individuals with complete paralysis.	Brain-machine interface (BMI) using motor imagery.	Non-invasive, self-paced thought-controlled intelligent wheelchair.	Shared-control methodology blending human and artificial intelligence, focusing on motor imagery BMI.	EEG-based BMI for decoding brain signals, intelligent wheelchair with autonomous navigation capabilities.	Autonomous navigation with human-in-the-loop control via BMI.	Brain-machine interface (BMI), motor imagery decoding algorithms.	Semi-autonomous with shared control between user and artificial intelligence.	Training and testing with three tetraplegic spinal-cord injury users performing complex navigation tasks.	Two out of three users achieved high navigation performance, showing significant improvements in decoding performance, feature discriminancy, neuroplasticity, and BMI command latency.	High accuracy in navigation performance for users with improved BMI decoding and control command latency.	Only two users achieved high navigation performance, indicating variability in user training and adaptation to BMI.
[56]	The study proposes an adaptable framework for mobility assistive technologies inspired by ACT-R and the desiderata for developing cognitive architectures.	Signals from visual, auditory, tactile, and brain-computer interfaces (BCI), along with nonverbal cues like heart rate variability (HRV) and signals from peer devices.	An intelligent wheelchair system incorporating the proposed adaptive framework for shared control and autonomous mobility.	The framework utilizes a combination of symbolic and connectionist representations to achieve shared control and autonomous navigation, with learning mechanisms and reward systems for adaptation.	Sensors for capturing visual, auditory, tactile, and BCI signals, as well as HRV and other nonverbal cues.	Autonomous navigation and shared control in dynamic environments.	Cognitive architectures (ACT-R), symbolic and connectionist representations, learning mechanisms, reward systems, and observation/inference systems.	Semi-autonomous with shared control between user and system.	The framework is proposed for implementation on an intelligent wheelchair, with plans for future experimental validation.	The proposed framework aims to balance user input with automated control, ensuring seamless collaboration, personalized user profiling, and enhanced safety.	Not explicitly stated; accuracy will be evaluated in future experimental validation of the framework.	The study identifies the need to resolve details of the adaptation/learning process and the most suitable connectionist and symbolic processes for the hybrid framework.
[57]	This study proposes a method combining fuzzy potential methods with model predictive control (MPC) for self-driving electric wheelchairs to navigate in crowded environments.	Not explicitly stated; inferred to be automated based on the wheelchair's sensors and predictive algorithms.	Self-driving electric wheelchair system integrating fuzzy potential methods and MPC for dynamic obstacle avoidance.	Combination of fuzzy potential method and model predictive control (MPC) with Monte Carlo optimization for evaluating and selecting optimal paths.	LIDAR sensor for obstacle detection, rotary encoders for wheel rotation measurement, Raspberry Pi for communication, PC for control input calculations.	Autonomous navigation in dynamic and crowded environments using real-time data from sensors.	Fuzzy potential method, model predictive control (MPC), Monte Carlo optimization, LIDAR, Raspberry Pi, MATLAB, Autoware, ROS.	Fully autonomous with real-time obstacle avoidance and path optimization.	Simulations and real-time experiments to verify the effectiveness of the proposed method.	The proposed method demonstrated flexible obstacle avoidance and effective path planning in both simulations and real-time experiments, confirming its potential for crowded environments.	High accuracy in obstacle detection and avoidance, with effective real-time path planning and decision-making.	Further research needed to improve robustness and performance in more complex real-world scenarios.

(Continued)

**Table A1.** A displays the individual analysis of selected papers (Continued)

Ref	Summary	Input Method	System	Control Strategy	Instrumentation	Navigation Type	Technology Used	Autonomous Type	Test Type	Findings	Accuracy	Limitations
[58]	This paper presents "SmartRolling," an intuitive human-machine interaction approach for directly controlling a robotic wheelchair by leveraging EEG signals and motion sensing techniques.	EEG signals, head motion, hand motion, inertial measurements, computer vision techniques.	SmartRolling system for robotic wheelchair control.	Recognition of EEG patterns from motor execution tasks (e.g. eye blink, jaw clench, fist open/close) and estimation of steering intentions using inertial measurements and computer vision.	EEG device, motion sensors, inertial measurement units (IMUs), computer vision systems.	Autonomous navigation based on EEG signal processing and motion sensing.	Brain-computer interface (BCI), EEG signal processing, inertial measurements, computer vision techniques.	Semi-autonomous with shared control between user and the system.	Experimental tests with users to evaluate system robustness and effectiveness.	The system is robust and effective in meeting individual user needs, demonstrating potential for promoting better health and independence for disabled individuals.	The system accurately recognizes and processes EEG patterns and user intentions, facilitating reliable control of the wheelchair.	Further research is needed to validate the system in diverse real-world environments and improve robustness and adaptability.
[59]	This study presents a data-driven approach to designing a BC-integrated smart wheelchair using cost-benefit analysis.	EEG signals captured using a NeuroMax32 device.	Smart wheelchair integrated with brain-computer interface (BCI) for mobility assistance.	Machine learning-based knowledge and cost-benefit analysis to enhance decision-making and control efficiency.	NeuroMax32 EEG device, sensors for capturing brain signals, PC for data processing.	Autonomous navigation based on EEG signal processing and user intention.	Brain-computer interface (BCI), EEG signal processing, machine learning algorithms (SVM, Naive Bayes, decision tree).	Semi-autonomous with shared control between user and artificial intelligence.	Experiments with 100 human subjects, evaluating the performance using various classifiers (SVM, Naive Bayes, decision tree).	The proposed model showed improved accuracy and usability of the smart wheelchair by using a cost-benefit analysis method, achieving high accuracy in classification and control.	The system demonstrated high accuracy in classification, with the decision tree (48) achieving the best performance.	Further research is needed to validate the system in diverse real-world environments and improve robustness.
[60]	The study describes an automatic control system enabling an assistive robot to push a wheelchair up steps.	The system uses sensors to detect the environment and control the step-climbing process.	The system consists of a wheelchair and a robot connected to perform step-climbing cooperatively.	The control strategy involves the use of velocity differences between the wheelchair and the robot, along with a theoretical analysis to determine the most suitable distance for lifting the front wheels.	The system includes sensors, circuits, batteries, an accelerometer system, and ultrasonic sensors for both the wheelchair and the robot.	Autonomous step-climbing navigation.	Sensors: accelerometer system, ultrasonic sensors, and motion controllers.	Fully autonomous for the step-climbing process.	Experimental tests were conducted on a 120 mm step height with a friction coefficient of 0.72.	The system successfully performed the step-climbing process, demonstrating improved convenience and reliability compared to previous methods.	The system effectively prevented collisions between the wheelchair's front wheels and the step, ensuring safe and reliable step-climbing.	The step-climbing operation remains complicated, and further improvements are needed to enhance robustness and applicability in diverse real-world environments.
[61]	The study proposes a method for detecting and classifying steps, enabling an electric wheelchair to autonomously climb stairs and steps.	Detection and classification of steps and obstacles using sensors.	Electric stair-climbing wheelchair equipped with sensors for detecting and classifying steps.	Autonomous control system based on the detection and classification of steps, allowing the wheelchair to climb or descend stairs safely.	Sensors for detecting steps and obstacles, control algorithms for autonomous navigation.	Autonomous navigation for climbing and descending stairs and steps.	Step detection and classification, autonomous control algorithms.	Fully autonomous for stair climbing and descending.	Experimental tests on a stair-climbing wheelchair prototype in various conditions.	The method proved to be reliable for detecting and classifying steps, enabling the wheelchair to autonomously climb stairs.	Reliable detection and classification of steps for safe stair climbing and descending.	Further research is needed to improve the system's robustness and applicability in diverse real-world environments.
[62]	This study proposes a cyber-physical system for a speech-controlled wheelchair based on cloud-harvesting principles, which significantly improves the command error rate (CER).	Speech commands using predefined basic set of commands (e.g. go, stop, left, right, back).	Cyber-physical wheelchair control system with cloud-based speech recognition.	Parallel inclusion of two cloud speech APIs (Google Cloud Speech API and IBM Watson Speech API) to improve speech recognition accuracy.	Mobile part (wheelchair) with user and cloud part for remote usage, control, and programming.	Speech-controlled navigation.	Cloud-harvesting IBM Watson Speech API, Google Cloud Speech API.	Semi-autonomous with speech input for navigation commands.	Experiments with two groups: 16 students and 4 patients in a clinical environment.	The combination of IBM Watson and Google Cloud Speech APIs significantly improved speech recognition accuracy, demonstrating the potential and usability of speech-controlled wheelchairs.	The experiments showed that the proposed approach had a significantly better command error rate (CER) than solitary speech recognition APIs.	The study was limited to a small number of participants, and further research is needed to validate the system in diverse real-world environments.

## 9 AUTHORS

**Mohsen Bakouri** is currently a Professor in the Department of Biomedical Equipment Technology at Majmaah University, Saudi Arabia. His research interests include bio-signal processing, modeling, Cardiovascular system control, and other mathematical modeling techniques. This research has been multidisciplinary, involving techniques ranging from the design of sophisticated control applications in biomedical engineering to computational modeling and systems identification and bio-signal processing. He has authored or coauthored different papers and abstracts in international journals and conferences (E-mail: [m.bakouri@mu.edu.sa](mailto:m.bakouri@mu.edu.sa)).

**Abdullah Alqarni** has graduated from Master of sciences in Biomedical Engineering, Majmaah University, Saudi Arabia. He is a professional with extensive experience in biomedical engineering, operations management, contracts, and cost management. He currently serves as the General Director of the General Department for Medical Equipment Maintenance at the Ministry of Health since March 2024, also served as the Assistant General Manager for Technical Affairs at the Ministry of Health since February 2023, and the Director of Contract and Cost Management since July 2022 (E-mail: [431104654@s.mu.edu.sa](mailto:431104654@s.mu.edu.sa)).

**Sultan Alanazi** graduated from Master of sciences in Biomedical Engineering, Majmaah University, Saudi Arabia. He is a seasoned biomedical engineer, has been managing biomedical engineering operations within the Northern Border Health Cluster, Saudi Arabia, since 2008 (E-mail: [431104619@s.mu.edu.sa](mailto:431104619@s.mu.edu.sa)).

**Ahmad Alassaf** is currently an Associate Professor in the Department of Biomedical Equipment Technology, Majmaah University, Saudi Arabia. His Research interests include Biomedical Engineering and its application. Physiological signal processing, and tissue Engineering including Organs on Chip technology. He has authored or coauthored different papers and abstracts in international journals and conferences. He works with multidisciplinary research groups from different areas such as physicians, neuroscientists, pathologist, and Engineers (E-mail: [am.alassaf@mu.edu.sa](mailto:am.alassaf@mu.edu.sa)).

**Ibrahim Almohimeed** is an Assistant Professor in the Department of Biomedical Equipment Technology at Majmaah University, Saudi Arabia. His research interests include bio-signal processing, Bioinstrumentation, biosensors, and medical imaging. He has authored or co-authored several multidisciplinary papers and abstracts in international journals and conferences (E-mail: [i.almohimeed@mu.edu.sa](mailto:i.almohimeed@mu.edu.sa)).

**Tareq Alqahtani** is an Associate Professor with the Department of Biomedical Equipment Technology, Majmaah University, Saudi Arabia. His research interests include medical technology management, such as medical equipment replacement and medical device risk management (E-mail: [talqahtani@mu.edu.sa](mailto:talqahtani@mu.edu.sa)).