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Review article

Systematic review of mobile robots applications in smart cities with future directions

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ABSTRACT

Smart cities can create a connected and efficient urban environment by integrating advanced technologies with mobile robots. Mobile robots play a significant role in various smart city applications, ranging from transportation and logistics to surveillance and maintenance tasks, and have the potential to revolutionize the way people live and work in smart cities. Ensuring the efficient, greener and safe operation of these robots is crucial for the success and sustainability of smart city operations. However, several challenges must be addressed, such as safe autonomous navigation, motion control and security. This systematic literature review explores the current state of knowledge and emerging trends in autonomous motion control of personal and assistive mobile robots from 2015 to 2023, as well as the challenges and opportunities for possible application in smart city environments. In particular, it investigates the navigational approaches for future application of mobile robotic systems in the essential smart city components of personal transportation, assistive technologies and road and highway robots. Additionally, it contributes to the ongoing research about integrating mobile robotics into smart city applications and highlights future research directions. Researchers can incorporate insights from this review into their development plans for industrial integration by designing infrastructure that accommodates and leverages mobile robots for numerous smart city operations, including transportation, waste management and surveillance.

1. Introduction

The smart city concept is a framework that *inter alia* integrates information and communication technology (ICT) and various mechanical systems connected to the Internet of Things (IoT) network to optimize the efficiency, autonomy, and connectedness of city operations and services. As a result, smart cities are responsive, intelligent, connected and sustainable and are invariably designed for human support, care and comfort. Advanced technology and data analytics are utilized in a smart city to improve the quality of life, enhance sustainability and streamline urban and industrial services [1–3]. Integrating Artificial Intelligence (AI) into data analytics enables more sophisticated analysis, automation, and the extraction of meaningful patterns and predictions from large datasets, where diagnostic insights inform predictive models and prescriptive recommendations guide future actions. The concept of smart cities has been evolving for decades, but its roots can be traced back to the early 1970s when the city of Los Angeles in the US implemented the first major urban data project: "A Cluster Analysis of Los Angeles" [4]. This project came from the Community Analysis Bureau, which used computer databases to gather and process data about the city's infrastructure and services and provide city officials with real-time monitoring and management capabilities [5].

In the 1990s, the concept of smart cities emerged, focusing on using digital technologies to improve city service delivery and enhance residents' standard of living [6]. Many cities worldwide began experimenting with smart city attributes such as intelligent transportation, energy management for industrial integration and smart grids during this time [7,8]. However, it was not until the early 2000s that the term "smart city" came into everyday use [9]. The concept gained momentum as more and more cities began to adopt smart technologies and integrate them into their urban nd industrial infrastructure [6,10]. To assist cities in using technology to improve their sustainability, efficiency and living standards, the International Business Machines Corporation introduced its Smarter Cities project in 2008 [1,6]. Today, the smart city movement continues to grow, with cities worldwide investing in various technologies, renewable energy systems and industrial integration to create more sustainable, connected and greener urban environments.

The importance of smart cities is driven by the need to address the challenges faced by urban areas and city dwellers alike [1]. With

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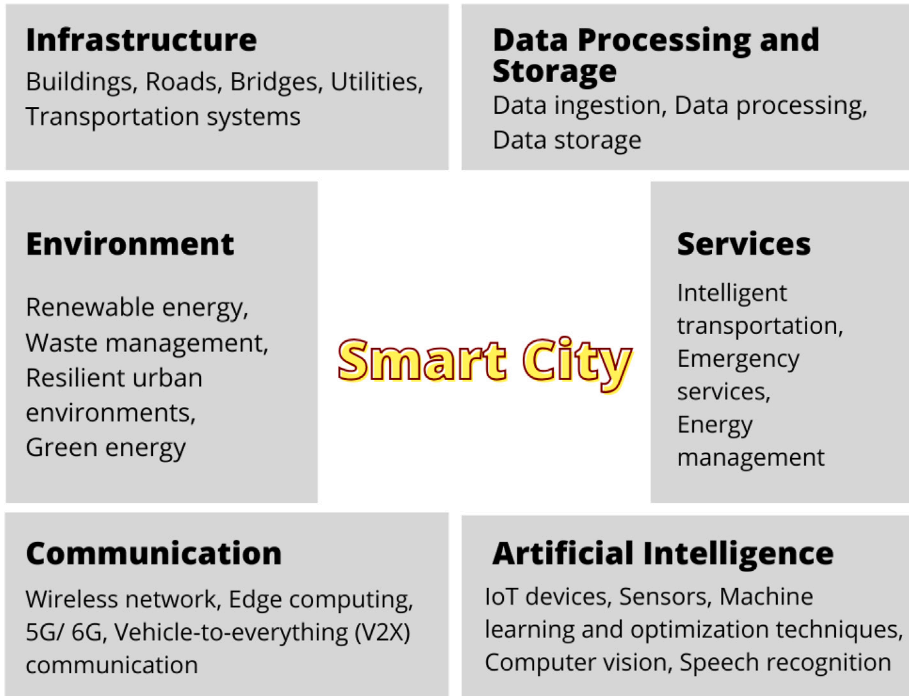


Fig. 1. An overview of the essential components and attributes of a smart city. This review focuses on the domain of autonomous transportation systems.

the rapid growth of cities and industrialization, innovative solutions are needed to address problems such as traffic congestion, performance management, greener environment, pollution, industrial informatization, and intelligent resource planning. According to Law and Lynch [2], smart city technology offers solutions to these issues by providing data-driven insights that enable city planners to make more informed decisions. Fig. 1 illustrates that attributes such as interconnected infrastructure, advanced data processing, storage systems and management, a sustainable and greener environment with optimized services driven by technology and active citizen engagement form the fundamental elements of a smart city.

As per the objective of this systematic review, we switch focus to transportation in smart cities. Integrating advanced technology into smart city transportation enables the deployment of connected and autonomous vehicles, facilitating safer and better adaptive traffic environments. For instance, machine learning techniques can analyse vast amounts of data, such as traffic patterns, weather conditions and historical travel times, to generate optimized vehicle routes. Additionally, implementing smart infrastructure, such as sensor networks and vehicle-to-infrastructure (V2I) communication, improves the coordination and efficiency of autonomous transportation systems in smart cities. The modern design and development of autonomous vehicles also involve incorporating environmentally sustainable practices through greener technology, performance management and an increased emphasis on energy efficiency. For example, intelligent transportation systems can help ease traffic congestion and optimize traffic flow, while innovative energy management and the use of eco-friendly transportation options such as electric vehicles can promote renewable energy sources and reduce greenhouse gas emissions in industrial processes [2]. Current research trends on smart cities indicate an interdisciplinary direction with different perspectives, whereby essential components such as mechanical, electrical, modelling, industrial information integration and social science are combined to provide a fuller solution, giving scope to many researchers collaborating in different programs [9]. The rise of greener technologies, such as electric vehicles, further contributes to sustainable urban transportation, aligning with smart city initiatives by promoting energy efficiency while enhancing overall mobility solutions. Robotics technology has been increasingly used to improve transportation and industrial services in smart city initiatives.

Mobile robots can navigate complex urban roads and environments, collecting data and performing tasks that would otherwise be difficult, dangerous or impossible for humans to achieve [11]. Equipped with perception devices such as cameras and Light Detection and Ranging (LiDAR) sensors, mobile robots can be used for industrial information integration and data collection on environmental features such as traffic congestion, air quality, weather monitoring and noise pollution [12]. Robots operating within the context of IoT with communication modules such as Wi-Fi, 4G and 5G can transmit data to external servers or cloud platforms for analysis [13]. This valuable information can then be used by relevant authorities and policymakers to take appropriate action to provide better services.

As mobile robots become more advanced and affordable, their use in smart cities and industries will expand. For example, autonomous robots can deliver goods and groceries throughout the city, reducing labour costs while providing faster and fault-proof service [14]. Mobile robots can also be used for personal transportation, tour guides, surveillance, security, patrolling public spaces and for detecting potential threats [15,16]. Thus, integrating mobile robots into smart city infrastructure can lead to efficient and sustainable cities. However, using mobile robots in smart cities presents several challenges that need to be addressed, including navigation, traffic control and human safety.

By reviewing the literature of the past decade, this study provides an in-depth survey on the progress of robotic systems, the potential applications of mobile robots, and related technologies in the context of autonomous industrial and smart city operations. This review paper provides an overview of the navigation techniques and real-world cases associated with autonomous motion control systems in smart cities while exploring the applications, challenges and future directions. Additionally, it emphasizes the importance of perception, planning and control algorithms and analyses the benefits of integrating mobile robots to create more efficient and connected smart cities. The findings from this review paper will offer valuable insights for policymakers, urban planners and researchers in shaping future smart cities by guiding sustainable development initiatives and fostering innovation in industrial infrastructure and technology deployment.

The remainder of the paper is organized as follows. The research questions and methodology are provided in Sections 2 and 3, respectively. Section 4 briefly overviews why cities worldwide are adopting mobile robots. Section 5 reviews the current applications of autonomous personal transporters and assistive technologies, while Section 6 reviews the existing applications of roads and highway robots. A discussion and analysis are provided in Section 7, and the significant challenges faced by the applicability of mobile robots in smart cities are outlined in Section 8. The future research directions stemming from this review are presented in Section 9. Then, Section 10 compares this systematic review with other similar work while some limitations of this study are highlighted in Section 10. Finally, conclusive remarks are provided in Section 11.

2. Research questions

A smart city harnesses the power of ICT to create a connected and sustainable environment, where insights from fields such as data science, industrial information integration, environmental science, cybersecurity, robotics and automation synergize to create innovative solutions. In transportation, robotics contributes by enabling the development of autonomous vehicles and intelligent traffic management systems, revolutionizing mobility with efficient and sustainable modes of transportation. The study's primary objective is to analyse and evaluate significant papers in the autonomous mobile robotics domain of applications on personal transporters, assistive technologies, and roads and highway robots in the smart city context. Therefore, this article aims to address the following research questions:

1. What are the current applications of mobile robots in the transportation sector on roads and highways and as autonomous personal transporters and assistive technologies in smart cities?
2. What are the advantages and specific challenges associated with implementing and deploying mobile robots as transporters and assistive technologies in smart cities?
3. What are the future directions and emerging trends in using autonomous mobile robots in smart cities?

3. Methodology

3.1. Research strategy

This study was conducted by implementing a systematic review of related literature from 2015 to 2023 on mobile robot applications to answer the research questions developed in Section 2. The literature was compiled using three online databases: IEEE Xplore, Elsevier and Robotica, the most extensive robotics research database. The keywords used to search for the articles were "smart city framework", "mobile robots", "smart city robots", "robotics in urban environments", "collaborative robotics", "robotic transportation in cities", and "service robots in smart cities". Appropriate sources of work were researched while assessing the quality of selected studies per the inclusion and exclusion criteria. The data acquired from the studies were summarized and interpreted in this research.

3.2. Inclusion and exclusion criteria of the articles

The following inclusion/exclusion criteria were used for selecting the articles in this study:

1. Studies conducted on the applications of mobile robots in a smart city concept, whereby the research focuses on the motion planning and control of the autonomous system, the control method utilized and the application of the robotic system to appropriate smart city operations.
2. The article is in an English journal and a conference paper.
3. The publication period is between 2015 to 2023.
4. The research excluded articles on mobile robot navigation that did not consider challenges and applications within the smart city context.

3.3. Sample selection

The authors systematically searched to compile the scientific records related to the research objectives. The abstract and title were screened before the full text of this set of articles was assessed by selecting literature. The papers that passed the title and abstract screening were then subjected to a full-text review. The papers were evaluated at this stage based on their contribution to the field and relevance to our survey's objectives. After ruling out literature as per the exclusion criteria and research questions, 57 publications were selected from the final stage of the literature search, of which 43 were from IEEE Xplore, 6 were from Elsevier, and 8 were from Robotica. IEEE Xplore was more freely available than other subscription-based databases. This accessibility likely contributed to the higher number of selected papers from IEEE Xplore in our final set for our survey.

3.4. Comparison with systematic review of related literature on mobile robots and smart cities

Rubio et al. [17] in 2019 conducted a study of several mobile robots and discussed their locomotion, perception, cognition and navigation in environments such as air, underwater and land. New trends in mobile robotics concerning artificial intelligence, autonomous driving, network communication, cooperative work, nanorobotics, friendly human–robot interfaces, safe human–robot interaction, emotion expression and perception are discussed. The future applications of these news trends to different fields such as medicine, health care, sports, ergonomics, industry, distribution of goods and service robotics are also discussed. Compared to [17], this article reviews articles on personal transporters, assistive technologies, roads and highway robots and outlines their potential applicability to perform tasks in specifically smart city environments.

Rivera et al. [11] in 2020 followed a qualitative analysis to evaluate the literature involving the interaction between robotics and service delivery in smart cities. They presented an exploratory literature review on agriculture, air and land traffic monitoring, cleaning services, education, healthcare, surveillance, emergencies, tourism and environment, as well as information regarding usability, management and storage of data related to the use of robotic systems in service management in smart cities. While the work done in [11] focussed on service delivery applications only, this article goes beyond and focuses on diverse applications of mobile robots in the context of smart cities.

In 2021, Sun et al. [18] reviewed the mobile robot motion planning methods based on Deep Reinforcement Learning (DRL) in unstructured environments. By categorizing the conventional techniques of DRL into value-based, policy-based and actor–critic-based algorithms, the authors surveyed the corresponding theories and applications of several types of mobile robots. Thus, only motion planning methods based on DRL involving imitation learning, meta-learning and multi-robot systems were surveyed in [18]. In comparison, this article discusses the motion planning and control techniques of several mobile robots in general, focussing on their applications in personal transportation, roads, and highway robots in smart city environments.

Moreover, with AI being one of the most advanced technologies of modern times, systematic review articles such as [19,20] focussed on how AI can contribute to the development of smarter cities. In summary, researchers have conducted literature reviews on the capabilities of smart city mobile robots in different environments, the services they provide and the utilization of AI in various applications. When comparing this survey to other systematic reviews on mobile robots and smart cities, it becomes evident that each has a unique focus, with

Table 1
Some mobile robots used in different smart cities around the world.

City	Degree of automation	Sector	Application	Source
Car-like robots				
Amsterdam	Semi	Municipal service	Collecting waste from streets and public spaces	[22]
Austin	Fully	Hospitality, Food	Delivery of goods and groceries	[23]
Guangzhou	Semi	Tourism	Providing assistance to tourists	[24]
Helsinki	Fully	Municipal service	Electric sweeper - street and public space cleaning	[25]
Las Vegas	Fully	Retail	Delivery of groceries	[26]
Seoul	Semi	Healthcare	Assisting with medical care	[27]
Singapore	Semi	Food service, Healthcare	Delivery of goods, food and medical supplies	[28]
Humanoid robots				
Dubai	Fully	Public security	Police patrolling and surveillance in public areas	[29]
Guangzhou	Semi	Public service	Providing assistance to shoppers	[24]
Las Vegas	Fully	Public service	Street and public space cleaning	[26]
Seoul	Semi	Healthcare	Assisting with rehabilitation	[27]
Tokyo	Fully	Education, Entertainment	Tour guide in public spaces, airports and museums	[30]
Robot Dog				
San Francisco	Fully	Public security	Security and surveillance in public areas	[31]

varying degrees of alignment to the research questions posed in this survey. Rubio et al. [17] explored mobile robots' locomotion, perception, cognition and navigation across different environments, emphasizing new trends like AI and autonomous driving, but did not specifically address smart city transportation applications. Rivera et al. [11] focused on the interaction between robotics and service delivery in smart cities, covering a wide range of applications but mainly in the context of service management, leaving out a detailed exploration of mobile robots as personal transporters or road and highway robots. Sun et al. [18] reviewed motion planning methods for mobile robots, especially in unstructured environments. Still, their study was limited to motion planning techniques rather than a comprehensive analysis of robots' roles in smart cities. Additionally, Yigitcanlar et al. [19] and Lauri et al. [20] focused on AI's contribution to smart cities without delving into the specific applications of mobile robots in transportation. In contrast, this study fills a gap by systematically reviewing the literature on motion planning and control techniques of diverse mobile robots, emphasizing smart city transportation services. To the authors' knowledge, no scholarly work provides a systematic review of the applicability of different mobile robots as personal transporters, assistive technologies, and road and highway robots in smart cities.

4. Cities adopting mobile robots

As technology evolves, the field of robotics keeps growing, creating new opportunities for improving different aspects of human life and industry. Hui et al. [21] stated that more innovative applications of mobile robots are expected in cities worldwide, with some of the major cities across the world, particularly in Asia and the United States, already adopting mobile robots to overcome the challenges of performing specific operations, mainly due to their high precision and efficiency capability, leading to increased productivity and faster task completion [12]. Table 1 shows selected examples of cities implementing mobile robots in their smart city initiatives. These advanced autonomous machines in cities enhance urban life and operations by providing diverse benefits and applications, including improved efficiency, safety and convenience.

From performing risky tasks like monitoring security threats or patrolling dangerous places to collecting waste or, delivering goods or cleaning and maintaining constrained environments, robots can perform repetitive tasks more efficiently and consistently than humans. Moreover, the extensive use of mobile robots integrated with intelligent tools such as AI in modern-day cities indicates that they have the potential to enhance urban living standards and convenience. Over the past decade, researchers have also proposed various robotic systems with different motion planning and control approaches to ensure safe and reliable navigational solutions, which is at the heart of all algorithms and methods. Among these autonomous mobile systems, robots for personal transportation, assistive technology, and road and highway services play a significant role in delivering efficient transportation solutions that benefit city service providers and dwellers. Table 2 provides a taxonomy that guides understanding the various types of mobile robots discussed in the following sections, outlining their specific applications and contributions to smart city environments.

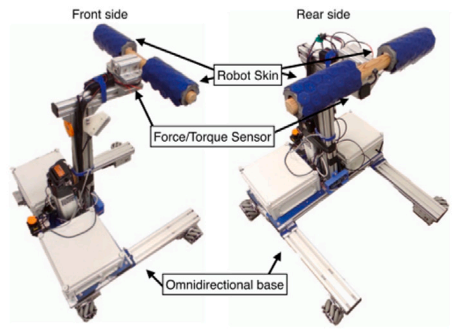
5. Autonomous personal transporters and assistive technologies

Personal transportation robots, or personal transporters, have revolutionized how people commute and navigate their surroundings. With its compact size, this innovative mobility system offers a convenient, eco-friendly solution for short and long-distance travel. Mainly used for short-distance journeys, personal transporter robots prioritize user comfort by balancing compactness for manoeuvrability in confined spaces and agility required for travelling routes that are impossible with traditional transporters. Whether navigating through obstacle-ridden workspaces, hovering along sidewalks, or manoeuvring through large facilities and crowded spaces, these intelligent robots are becoming increasingly popular. In this era of rapid industrialization and the quest for sustainable transportation, autonomous personal transporters have emerged as an efficient means of moving from one destination to another, making commuting practical and exciting. Numerous personal transporter robots, each with a unique design and functionality, are available today. They are used to assist individuals in their daily lives, seeking improved mobility assistance in health care, delivery and services, security and entertainment sectors of a smart city. Each application will now be considered in detail.

Table 2
Taxonomy of different types of robots and their applications.

Category	Description	Applications
Assistive and Personal transporter robots	Compact and agile robots to enhance mobility for the elderly and disabled and provide utility services.	Healthcare, personal mobility, service and utility.
Delivery robots	Autonomous mobile platforms for transporting goods.	Package delivery, food delivery and healthcare.
Service robots	Robots designed to assist with specific tasks in homes, healthcare facilities and public spaces.	Healthcare, cleaning and customer service.
Facility navigation robots	Specialized robots for assisting with navigation in large and complex buildings.	Guidance, emergency evacuation and maintenance.
Tour guide robots	Interactive robots designed to provide guided tours and educational information.	Educational institutions, museums and exhibitions.
Roads and Highway robots	Autonomous vehicles and robots for transportation, delivery and maintenance.	Transportation, delivery, surveillance and security.

(a) The OmniBed [32]



(b) The robotic assistive walker [33]

Fig. 2. Personal transporter robots for mobility assistance.

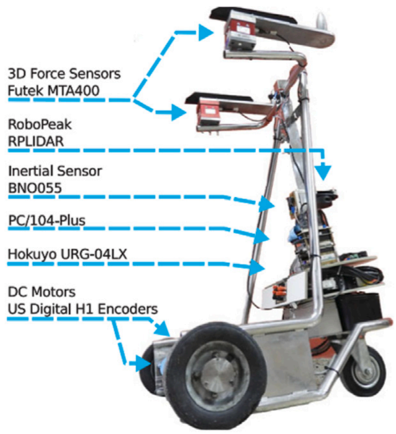
5.1. Mobility assistance in health care

In the health sector, personal transporters offer mobility assistance, allowing users to autonomously navigate their surroundings safely with minimal control from the users. To prevent work-related injuries, reduce human resources and improve working efficiency, Guo et al. [32] in 2018 presented a motorized robotic bed mover called OmniBed (Fig. 2(a)) with omnidirectional mobility. This patient transportation system was based on two sets of active split offset castors, a force/torque sensor-based human–machine interface with an admittance controller, and systematic control hardware. The omnidirectional wheels of the OmniBed enabled it to do one-step "parallel parking", which is essential for bed-to-bed patient transfer as transfer trolleys must be parked beside ward beds in situations where patients cannot walk. Despite taking longer to complete tight turns and having more collisions due to the longer wheel-to-wheel length, the OmniBed performed relatively well in crowded wards and tight spaces.

In 2019, De Mello et al. [33] presented a cloud-enabled human-in-the-loop cyber–physical system (CPS) for mobility assistance using three different control functionalities, namely an odometry algorithm, a path-following controller, and an admittance-based controller. By implementing a pilot experiment through CloudWalker using the UFES Smart Walker shown in Fig. 3(a), the authors investigated the performance of the cloud-enabled device in assisting users' navigation throughout a nursing home environment. Although the CPS system proved resilient to unfavourable quality of service, the slow data transfer across the network resulted in lower quality of experience while extra instructions also needed to be given to the participants due to potential safety concerns. To help patients with mobility disorders, Itadera et al. [34] presented the in-Hand Admittance Controller (i-HAC) to steer a robotic assistive walker (Fig. 2(b)) in a forward motion with one hand and in a rotation motion with both hands. The walker robot consisted of a velocity-controlled omnidirectional mobile base with four mecanum wheels and a sensory system including a force/torque sensor and robot skin patches wrapped around the left and right handlebars. The proposed concept could effectively operate the walker robot as the i-HAC generated desired dynamic behaviour, thus making it helpful for people with reduced mobility and caregivers to steer the walker with low physical effort.

Also in 2019, Ophaswongse et al. [35] designed and evaluated the functions of a Wheelchair Robot for Active Postural Support (WRAPS) as a therapeutic robotic tool, as shown in Fig. 3(b), for people with severe trunk control deficits and spinal cord injury. With kinematic chains comprising universal, revolute, prismatic and spherical joints, the device allowed users to sit upright and actively lean forward to reach for objects. By calculating the desired joint positions using inverse kinematics and feeding them to a closed-loop proportional–integral–derivative (PID) controller, the authors showed that WRAPS could accommodate trunk trajectories that were close to the physiological trunk range of motion in a sitting position along the sagittal and frontal planes, considering the hardware limitations. However, system stability, robustness, velocity, and acceleration profiles of mobile devices with trunk movements were vital aspects that the authors failed to investigate in their study. To ensure independent movement for individuals with physical handicaps, assistive technology researchers and engineers constantly seek to address disability and mobility issues. One such innovation was the tongue drive system presented in 2021 by Chand et al. [36], whereby a tongue-monitoring wireless technology allowed disabled individuals to direct their intents into commands that a small permanent magnet on a wheelchair could sense. Artificial neural networks were used for accurate translation of the tongue gestures.

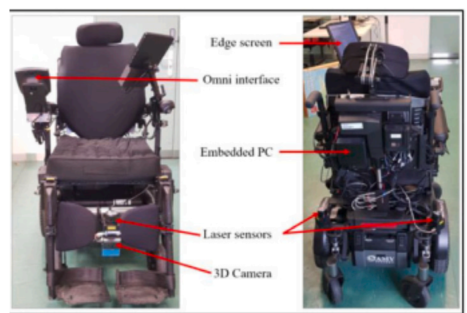
For patients seeking short-distance travel, the Segway robot is an excellent alternative to a bicycle or motorcycle, as it is light and portable. However, the uneven force acting on the tyre and the instantaneously large impact force usually affect the Segway's motion, giving rise to the instability of its body and subsequently increasing the risk of rollover. To address this, Yun et al. [37] in 2021 used a series elastic actuator (SEA) to construct an active suspension system and proposed



(a) The UFES Smart Walker [34]

(b) The WRAPS wheelchair [35]

(c) Segway equipped with SEA [36]



(d) The AMY wheelchair [37]

Fig. 3. Personal transporter robots for mobility assistance.

the SEA controllers to improve the stability of the Segway's linear and curved driving (Fig. 3(c)). The SEA controllers were successfully used to compensate for the force of impact on the tyres resulting from uneven road surfaces or uneven forces on both tyres and the possibility of a rollover. Experimental verifications via road tests proved that the Segways with the proposed active suspension system and SEA devices installed were more stable than those without. Unfortunately, the SEA system failed to reduce vibrations, particularly on uneven and bumpy roads, which could have been achieved by optimizing the mechanical impedance of the SEA.

Later, in 2022, Ech-Choudany et al. [38] presented a human–machine cooperative system for controlling a smart mobility-aided wheelchair for people with motor disabilities using active and passive feedback controllers. A collaborative approach by focusing on the interaction between the pilot and the robot was established via combined feedback control, where the navigation control changed from manual control of the wheelchair to automatic during the navigation task to correct an erroneous trajectory or provide strategic information for obstacle avoidance. The experimental platform was based on a mid-wheel powered wheelchair, AMY (Fig. 3(d)), equipped with an onboard processor and three laser range sensors. The system's functionality was successfully tested in different situations to achieve the desired reliability and security so that people with minimal cognitive, sensory and physical abilities could efficiently operate the proposed transporter.

Findings and analysis — Mobility assistance robots

Mobile robots such as the OmniBed and robotic assistive walker enhance mobility assistance in healthcare, highlighting their utility in crowded or confined spaces. The findings from [33,35] further demonstrate the integration of advanced control mechanisms to improve the user experience and safety, focusing on specific challenges in implementing these technologies, including issues related to system stability and data transfer delays. These studies stress the need for robust and responsive mobile robots capable of operating reliably under varied conditions. Moreover, the work by Yun et al. [37], and Ech-Choudany et al. [38] emphasizes the emerging trends such as the development of SEA controllers for stability improvement and human–machine cooperative systems for enhanced user interaction. These innovations suggest a need for further research in designing more adaptive intelligent systems that can adapt to changing user needs and environmental conditions.

5.2. Delivery

Personal transporters in the form of delivery robots can make deliveries by carrying items and packages from one location to another. These help reduce the need for human involvement in delivering items, especially within a local area. The ability of personal transporters to navigate safely in confined and crowded spaces ensures efficient route planning and flexible delivery schedules with reduced operational costs. In 2021, Lee et al. [39] introduced an assistive delivery robot for assisting postal workers by carrying heavy boxes in a complex urban environment such as an apartment complex. Using a 3-D point cloud map-based matching localization with position estimation and a perception-based visual servoing algorithm, the car-like robot (Fig.

4(a)) could search for a collision-free drivable region while communicating with its control centre. Data obtained from experimental results revealed that the proposed map-matching algorithm performed well in environments where the robot could navigate with reliable position accuracy and obstacle avoidance capability. In addition, Lee et al. [40] in 2022 proposed a practical navigation strategy for an outdoor delivery service robot called Husky (Fig. 4(b)) while addressing challenges such as robust localization, reliable detection of traversable regions and efficient path planning that utilizes accumulated environmental information. A localization method comprising a Global Navigation Satellite System, map matching and LiDAR-inertial odometry was used to achieve the four-wheeled campus delivery robot's safe, reliable and collision-free navigation in a dynamic university campus environment.

A viable option suitable for certain types of delivery tasks is Segways. Depending on the specific requirements and conditions, Segways as personal transporters offer agility and the ability to navigate through tight spaces, making them suitable for smart city environments with narrow sidewalks and crowded areas. Autonomous segways can be more cost-effective than unmanned ground vehicles (UGV), as recently demonstrated in [37,41], where an autonomous Segway robot was used for personal mobility and transportation and tasks such as delivery of packages in urban areas and healthcare facilities.

Integrating aerial robots into delivery services offers enhanced flexibility, reachability and navigational capabilities to remote delivery locations. This was demonstrated by Gao et al. [14] in 2020 while attempting to improve the effectiveness of emergency resource delivery during major public health emergencies. The authors synergized the widely used UGVs and unmanned aerial vehicles (UAV) as a UGV-UAV cooperative system as shown in Fig. 4(c), where the UAV took a package from the UGV and delivered it to a customer and later returned to the UGV at a different location to serve another customer. In the first stage, the Lin–Kernighan Heuristic algorithm was used to generate the travelling salesman problem solution for the UGV, while the Clarke and Wright saving heuristic algorithm was used in the second stage to create the baseline solution for the UGV-UAV assistive technology system. Similar decentralized delivery task planning for cooperative UGV-UAV robotic systems was also successfully presented by Qin et al. [42], and Krizmancic et al. [43] to autonomously deliver items in complex environments.

Moreover, specific tasks, such as delivering heavy objects, can be easily performed by multiple robots rather than a single one. In 2021, Li et al. [44] showed that a team of micro aerial vehicles (MAV) could cooperatively transport objects to overcome the physical limitations of a single vehicle while concurrently increasing the system's resilience to vehicles' failures. By implementing the Visual Inertial Odometry algorithm to address issues such as state estimation, control and trajectory tracking, the MAVs shown in Fig. 4(d) could successfully perform cooperative transportation of cable-suspended rigid body payloads using monocular vision and inertial sensing. A heterogeneous robotic system can execute autonomous delivery tasks with higher efficiency, combining the different capabilities of mobile robots for optimum results [23, 42]. A similar decentralized task planning and coordination framework for multi-agent systems was demonstrated by Arbanas et al. [45], using two Pioneer P3DX car-like robots and a quadrotor equipped with a dual-arm manipulator, and Camisa et al. [46] utilizing a team of TurtleBot3 ground robots and Crazyflie2 aerial robots to perform pickup and delivery requests. Such a multi-agent approach has great potential to be deployed in commercial or healthcare services such as e-commerce package delivery, transportation of medicines, food delivery and other time-sensitive transportation tasks. These complex tasks that require diverse and simultaneous operations can be easily accomplished with efficient coordination within a multi-robotic approach.

Findings and analysis — Delivery robots

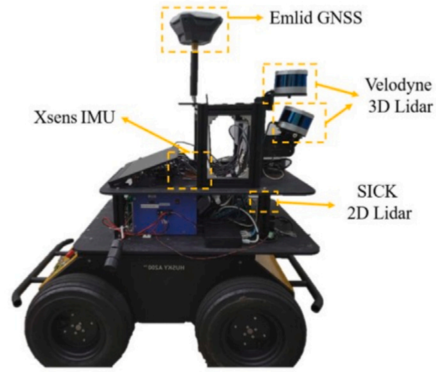
The deployment of an assistive delivery robot for postal workers in [39] and autonomous Segways in [37,41] illustrate how mobile robots can reduce human labour in delivery tasks, especially in crowded and confined spaces, which is essential for agile transportation solutions in smart cities. Additionally, the integration of aerial robots into delivery services, as explored by [14,42–44] demonstrates the enhanced flexibility and reachability provided by UAVs in remote or hard-to-access areas. This approach is essential for smart cities where delivery tasks may involve diverse and challenging scenarios. On the other hand, the outdoor delivery service robot utilized in [40] and the multi-agent systems presented in [45,46] further emphasize the challenges and solutions related to robust task planning and coordination frameworks for executing complex delivery tasks, indicating a growing need for adaptable navigation strategies applicable to dynamic industrial and smart city environments. Collectively, these studies provide a comprehensive understanding of the applications and challenges of mobile robots as personal transporters and delivery systems, emphasizing the need for continued innovation in navigation, coordination and multi-robot systems to meet the evolving demands of smart cities.

5.3. Cleaning and public service

By providing improved mobility and independent navigation in indoor and outdoor situations, personal transporter robots serve as assistive technologies, providing improved accessibility in confined areas. These robots help enhance people's quality of life by offering indoor support services such as cleaning and companion robots. Additionally, personal transporters can help clean outdoor utilities such as tunnels and public spaces. During the COVID-19 pandemic, an increase in the demand for service robot technologies was observed, particularly as cleaning robots in healthcare [47,48]. In 2020, Ramalingam et al. [49] used deep-learning-based detection and classification algorithms based on convolutional neural networks for door-handle cleaning automation using the Toyota Human Support Robot (HSR) shown in Fig. 5(b). The deep learning methodology generated a set of coordinates surrounding the door handles. These coordinates were employed to create the operational space of the robot using the data from 2D LiDAR and Inertial Measurement Unit sensors from the robot and to develop the robot's motion planning. Moreover, an adaptive Monte Carlo Localization (AMCL) algorithm was utilized to avoid collision and localize the robot at every step in the environment. To address outdoor autonomous cleaning, Kouzehgar et al. [50] presented a vertical climbing robot equipped with a locomotive wheel mechanism for facade cleaning with a flexible high friction rubber and an on-board camera for monitoring purposes. A Convolutional Neural Network (CNN) was trained with a sufficient data set, including photos taken from video snapshots for crack detection and avoidance, with experimental results indicating a 90% accuracy in task accomplishment. However, for such practical applications, factors such as obstacle avoidance, acceptable degree of human interaction and safe navigation need to be investigated in parallel.

Monitoring safe social distancing in crowded public places was necessary but challenging, especially during the COVID-19 pandemic. To address this issue, Le et al. [51] in 2021 presented a 3D human space-based surveillance system that enabled a selective cleaning framework. The authors proposed a vision-based AI perception algorithm for the HSR equipped with autonomous navigation, Lidar, and vision sensors to closely generate a heat map based on the 3D human interaction model. The HSR (Fig. 5(d)) developed a human density map as a grid-based heatmap to perform safe human distance monitoring tasks while navigating autonomously inside the pre-built map before cleaning selected areas. The experiment was successfully tested with standard performance metrics in public places, including food courts and wet markets.

(a) The assistive delivery robot [39]



(b) The campus delivery robot, Husky [40]

(c) The UGV-UAV delivery system [14]

(d) Multiple quadrotors as MAVs [44]

Fig. 4. Personal transporters as assistive delivery robots.

Service robots can significantly assist in accomplishing tasks for the benefit of medical staff and patients. For instance, car-like robots shown in Fig. 5(a) were used to transport material and supplies to the Zealand University Hospital in Denmark [52]. The mobile robots were also used for telepresence, enabling doctors and nurses to visit patients remotely. At the same time, a Combinatorial Search Method, which consisted of searching for all the possible path combinations and selecting the least complex combination with the shortest distance, was utilized for the motion planning of those car-like robots.

Dadi et al. [53] in 2021 used a tracked mobile robot car (Fig. 5(c)) to automate mundane tasks with the help of a service robot while reducing physical contact and the workload on healthcare workers. The robot was equipped with Raspberry Pi sensors to provide care, service and other necessities to patients with infectious diseases during the COVID-19 pandemic. The service robot performed tasks requested by the patients through a functional cellphone application, and a Python microservice used the A* algorithm for path planning by finding the shortest path to the destination while avoiding obstacles. The constant communication between the robot and the server allowed for successful tracking the robot's movement.

Findings and analysis — Cleaning and public service robots

The work of [49,51] on using HSR with deep learning and AI techniques reflect the increasing demand for intelligent service robots in enhancing sanitation and safety, particularly during public health crises like the COVID-19 pandemic. Similarly, Kouzehgar et al.'s vertical climbing robot for outdoor cleaning using AI techniques showcases the role of personal transporter robots in maintaining outdoor utilities in constrained environments. Additionally, the deployment of car-like robots in [52] and the tracked car robot used in [53] highlight that these mobile robots not only assist in routine tasks like material handling but also ensure efficient patient care in the health sector. These studies reveal that while personal transporter robots offer significant benefits in enhancing essential public services, challenges such as safe navigation, effective human–robot interaction, and obstacle avoidance remain critical in robotics research.

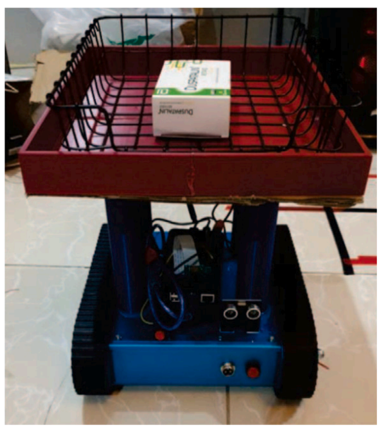
5.4. Facility navigation

In large facilities such as airports, universities, hotels or corporate offices, personal transporter robots can assist in navigating the premises in several situations, including emergencies. Facility navigation robots can help travellers, visitors, and employees go to different buildings, offices, or specific locations, providing valuable customer services and convenient personal assistance and transportation. These areas are now targeted for deploying more miniature mobile robots such as personal transporters. Because of the deployment of such cost-effective robots, these robots are now found in other connected areas of the smart city to improve the service. The concept of a smart city revolves around the interconnected nature of its facilities and services. In 2016, Kim et al. [15] designed a two-wheel balancing vehicle robot, TransBOT (Fig. 6(a)), that could carry people or objects. Using monitor and gain scheduling control methods based on linear controllers for different drivers for personal transportation, desired balancing angles were specified for the different sizes of drivers to have a stable balancing control performance. The feasibility of TransBOT as a vehicle was verified using experimental tests and proved effective for driving and facility navigation in indoor and outdoor environments.

Mobile robots must encounter uneven surfaces, such as different floor levels and stairs, for navigation inside facilities. Ikeda et al. [54]

(a) A car-like assistive robot [51]

(b) The door-handle cleaning robot [49]



(c) The tracked mobile robot car [52]

(d) The Human Support Robot (HSR) [53]

Fig. 5. Assistive technologies as cleaning and service robots.

in 2021 used an ultrasonic sensor system and Faulhaber motion controllers on an autonomous wheelchair and a teleoperated assistive robot shown in Fig. 6(b) for navigation in buildings comprising stairs. The cooperative step-climbing system was effective in eliminating the complicated operations that were required by previous methods used in similar work [54] and could also prevent collisions between the wheelchair's front wheels and the step. Considering the safety of such systems while navigating through the stairs, researchers need to study the mobility of such systems at different speeds while carrying out complicated navigation. Integrating highly accurate external sensor systems could further enhance the mobility assistive system's safety and suitability for practical use.

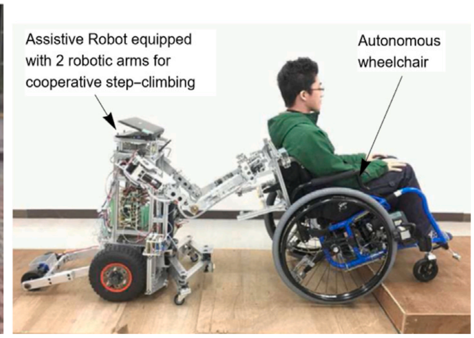
In 2021, Sangeetha et al. [55] designed the IoT-based intelligent sensing and alarm system with autonomous guiding robots for efficient fire emergency evacuation system to provide immediate monitoring and alerts, allowing for efficient emergency evacuation with robotic assistance using a robot guide and a robot transporter. The NodeMCU-controlled Vex Navigating Robot directed people to the closest and most appropriate safety exits, while the Arduino-based robot transporter shuttled restrained or older people. The system employed an IoT-based microcontroller to read and process data from sensors that detected temperature, humidity and the number of people in each room. In this system, the robot system played an essential role in evacuation, avoiding delays and saving lives. A similar mechanical system for emergencies was presented by Schneider and Wildermuth in 2017 [56] who used a tracked firefighting car-like robot as shown in Fig. 6(c) that could navigate in indoor and outdoor environments. Due to its caterpillar drive, the robot had high off-road capabilities ideal for evacuation, rescue, and independent material transport.

Robots must manoeuvre structures such as walls and corridors while navigating inside large buildings. In the case that a person's visibility is lost for prolonged periods, especially when the robot is circumventing a corner or making a sharp turn, Malviya et al. [57] in 2023 proposed an algorithm that could track people for prolonged times while navigating a facility in indoor scenarios such as museums and shopping centres. The experimental results from an Amigobot differential wheel drive robot (Fig. 6(d)) using a web camera sensor and a Particle Filter algorithm showcased that the approach was better than the tracking in the image and projecting in 3D, and tracking using a Kalman Filter and using Long Short Term Memory Network (LSTM) for trajectory prediction [57]. However, the use of tracker uncertainty as an input in the robot's planning algorithm must be explored to enhance the robot's effectiveness for practical applications.

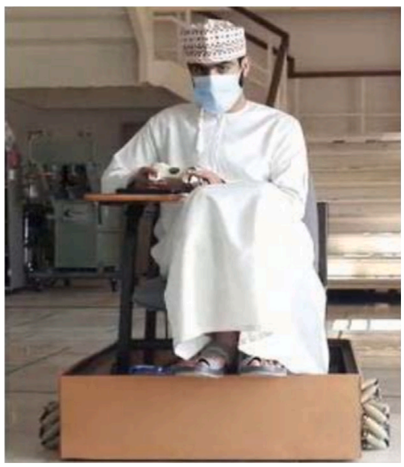
Findings and analysis — Facility navigation robots

The evolution of mobility assistive technologies in [15,54] for indoor and outdoor environments suggest a path forward for enhancing safety and reliability in challenging scenarios, which is crucial for industrial and smart city applications. Such systems, along with emergency response and facility navigation robotic systems presented in [55–57], highlight the critical roles of mobile robots in saving lives during emergencies. Such studies further emphasize the ongoing challenges, such as optimizing sensor integration and improving

(a) The TransBOT [15]



(b) Wheelchair and assistive robot [54]



(c) Transporter robot for emergency [55]

(d) The Amigobot robot [56]

Fig. 6. Personal transporter robots suitable for facility navigation in complex environments including step-climbing and rapid emergency response.

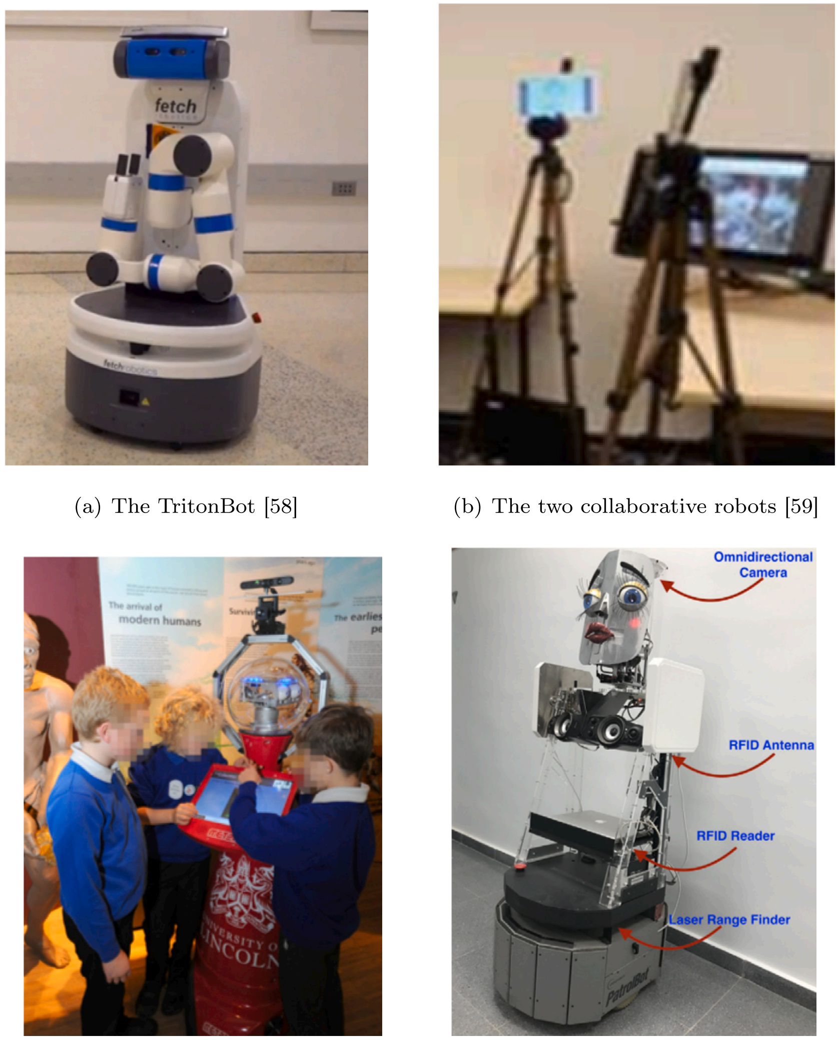
tracking accuracy in developing robust mechanical systems for real-time monitoring and decision-making during rescue operations in large, crowded spaces.

5.5. Tour guides plus

Personal transporters are also a safe and interactive solution for tour organizations. Tour guide robots feature advanced communication systems to enhance the visitor experience and provide personal assistance by navigating the user to a destination. Their precision, lack of distraction and adherence to programmed routines make them ideal for tasks that require repetitive and reliable execution compared to humans. Designed to replace human tour guides, some personal transporter robots offer guided tours in public places such as museums, large universities or historical sites. Apart from their primary role as a guide, these autonomous systems can also serve educational purposes, as they can offer audio or visual information, guide visitors through exhibits or exciting locations, and offer commentary or additional details. In 2018, Wang et al. [58] presented an autonomous robot called TritonBot (Fig. 7(a)), deployed as a tour guide in an unsupervised open environment. TritonBot's motion was controlled by a topological map and Robotic Operating System (ROS) navigation method, and they worked as a receptionist and a tour guide at a university office building. TritonBot could recognize people's faces, talk to people and show them labs and facilities in the building. Besides serving and assisting visitors, TritonBot was also used as an experimental toolbox to discover the short-term and long-term interaction patterns between the robot and humans since the robot receptionist engaged in many interactions daily.

Tour guide robots must possess an appropriate level of cheerfulness to create a positive and enjoyable user experience. To make the robotic tour guide experience more enjoyable and exciting, Velentza et al. [59] in 2019 proposed a pair of collaborative robots as museum guides with "cheerful personalities" that could also enhance kids' learning and entertainment by making interaction with robots more pleasant. Based on their idea that people tend to have more effective interactions with robots that have human characteristics, the authors used two P3 DX robots (Fig. 7(b)), operated by the Reallusion Crazy Talk 8 program, with each one interconnected to a PC Tablet running Android that acted as their faces. Their experimental results showed that cheerful collaborative robots were more suitable for entertainment, while a serious single robot provided a better educational experience for museum visitors.

In 2019, Duchetto et al. [60] presented a tour guide robot system called Lindsey, a Scitos G5 robot (Fig. 7(c)) manufactured by MetraLabs GmbH, which used the ROS framework for topological navigation, people tracking, task scheduling and data collection. Lindsey operated autonomously, navigating around the museum and engaging with the public, and was deployed at a museum displaying local archaeology, where it provided guided tours and information to visitors. The data collected from experiments designed to study long-term deployment indicated that beyond short-term engagement, further attention needed to be paid to increasing the social interactivity of the robot. Furthermore, Vasquez et al. [16] in 2020 used the Branch and Bound algorithm and the A$*$ algorithm to develop Doris, an interactive robot (Fig. 7(d)) for guided tours around museums and laboratories. The authors developed an emotion system and a new programming language to achieve a more realistic human–robot interaction by integrating robot components such as sensors, facial expressions and voice interaction, emotional responses, navigation, and a mix of three common programming languages — C, Pascal and JavaScript. The experiments revealed



(a) The TritonBot [58]

(b) The two collaborative robots [59]

(c) Students with Lindsey [60]

(d) Doris [16]

Fig. 7. Personal transporter robots as tour guides.

that Doris was well accepted by the visitors, considering the speed with which she moved from one point to another and her robotic appearance.

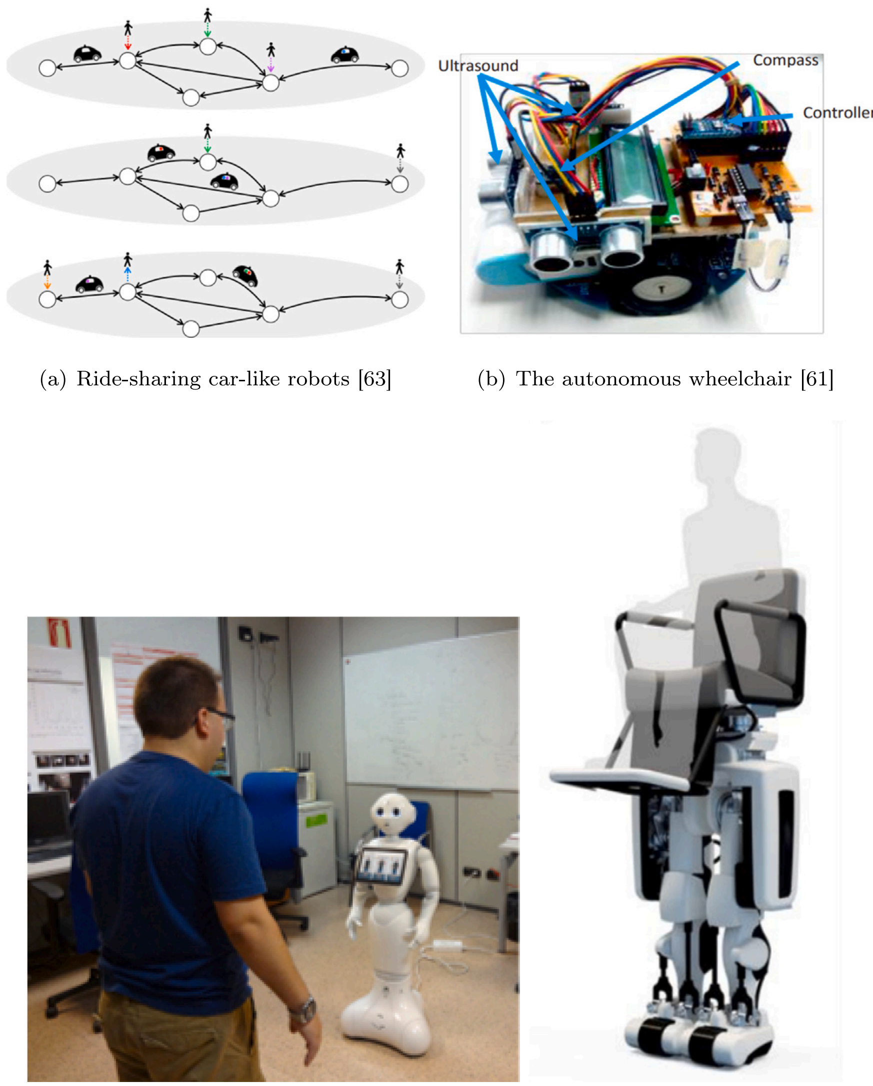
Findings and analysis — Tour guides robots

As demonstrated in [58,59], the increasing demand for tour guide robots in public spaces implies that the emotional and social aspects of human–robot interaction are vital to their successful deployment in public spaces so that they become more relatable and effective as guides. Additionally, the research work of [16,60] using their interactive robots suggests that future tour guide robots will need to integrate advanced programming and sensor integration with sophisticated interaction features to meet the evolving expectations of users in smart cities. These studies collectively reveal that while tour guide robots significantly enhance visitor experiences in smart city environments, ongoing research is needed to address social interactivity and emotional engagement challenges.

5.6. Entertainment and social interaction

Personal transporter robots could serve as a form of entertainment while also providing personal assistance for individuals. Entertainment and social interaction robotic systems are designed to provide entertainment value and facilitate social interactions to engage users in fun activities such as games and amusement. For the entertainment of older people, Wu et al. [61] in 2016 utilized an Arduino microcontroller to operate a steady-state visual evoked potential-based brain–computer interface (SSVEP based BCI) application on a wheelchair robot (Fig. 8(b)). The SSVEP-based BCI system processed the brain signals generated by the user to control the navigation of the autonomous wheelchair, making it suitable for the entertainment of the elderly and physically disabled. Later, in 2019, Martinez-Martin et al. [62] presented a socially assistive entertainment robot (Fig. 8(c)) with social and therapeutic capabilities for entertainment and to engage older people in daily physical exercise. Deep learning techniques such as CNN, Recurrent Neural Networks (RNN) and LSTM were combined as CNN-RNN and CNN-LSTM and analysed, showing that the best architecture for exercise recognition was the combination of CNN-LSTM layers. Along with entertainment, such autonomous systems offer health benefits to older people through physical activities.

In 2019, Tsao et al. [63] presented a model predictive control algorithm to coordinate a fleet of self-driving car-like vehicles for servicing travel requests in a ride-sharing setting as shown in Fig. 8(a). After deriving an integer network flow model representing the transportation network, the authors designed a Ride-sharing Autonomous Mobility on-demand algorithm based on receding horizon network flow



(a) Ride-sharing car-like robots [63] (b) The autonomous wheelchair [61]

(c) The socially assistive robot with a user [62] (d) The wheel–leg mobility [64]

Fig. 8. Personal transporter robots for entertainment and social interaction.

optimization. The proposed approach was successfully presented in a real-world case study for the city of San Francisco, CA, by using the microscopic traffic simulator MATSim, and the simulation results showed that an autonomous ride-sharing system could significantly improve social welfare and on-demand mobility for entertainment purposes for older adults and kids alike. The autonomous ride-sharing approach and the unified algorithms used in this study would be of great practical interest, whereby new models could be developed using deep learning techniques.

A robot that can switch between different modes of mobility, such as wheel, walk or step, offers significant advantages in terms of adaptability, efficiency and versatility, making it a valuable tool for a wide range of applications. In 2021, Imaoka et al. [64] proposed a compact boarding-type personal transporter robot in the form of a transformable leg–wheel mobile robot as shown in Fig. 8(d) with a high payload that could smoothly switch between the wheel, walk or step ascent modes of travel. Experimental verifications with an actual robot confirmed that the expected operation was feasible and safe for boarding purposes. While the system's wheel mode was used to aid mobility, a walking mode was utilized for entertainment, particularly for people with mobility issues.

Findings and analysis — Entertainment and social interaction robots

The personal transporter robots in [61,62] were designed using deep learning techniques to engage users in daily activities that promote physical and mental well-being, making them valuable assets in the care of elderly and physically disabled residents in smart cities. Moreover, the autonomous ride-sharing system and the transformable leg–wheel mobile robot, presented in [63,64], respectively, illustrate the potential of autonomous mobility systems to improve social welfare while offering accessible transportation for both practical and recreational applications in smart cities.

Remark on the applicability of autonomous personal transporters and assistive technologies to smart city framework

Autonomous personal transporters and assistive technologies have significant potential for smart city operations, and their applicability can positively impact and improve the living standards of city dwellers. As technology advances, their range of uses in diverse applications will expand further, providing residents with innovative solutions to their destinations and everyday tasks. In the framework of smart city transportation, personal transporter robots can help automate processes such as loading/ offloading items, reduce traffic congestion and the demand for parking spaces, complement existing public transportation systems, provide mobility assistance to the physically disabled in navigating the city, and enhance healthcare, security and maintenance services. The potential future use of these assistive technologies in smart cities and industries will expand as advancements in artificial intelligence, sensor technology and robotics progress. Equipped with sensors and communication technologies, these robots gather real-time information on traffic patterns, environmental conditions, industrial processes and infrastructure status, providing a dynamic and up-to-date data stream contributing to the city's intelligent infrastructure and decision-making processes. As these personal transporter robots become more advanced, their integration into industries and smart city operations will expand, leading to a more efficient, sustainable and user-friendly urban environment.

6. Roads and highway robots

Roads and highway robots are versatile mobile machines with numerous applications. Since these mobile robots have to operate in different road and highway environments and roadside public facilities, researchers have to be cautious with their approach, motion planning and control algorithms to ensure safe and reliable navigation while avoiding obstacles, pedestrians and other vehicles, thereby reducing the risk of accidents and collisions. The autonomous systems are deployed on roads and highways to perform transportation, delivery, surveillance, cleaning and maintenance tasks. Each of these will now be considered in detail.

6.1. Transportation

Autonomous vehicles offer an alternative to traditional human-driven cars, especially in areas with high demand for mobility. Autonomous taxis can offer cost-effective and flexible public transportation solutions in urban and suburban areas, providing better mobility options for older people and people with disabilities. Pandey et al. [65] in 2015 modified a standard daily-use bicycle to move autonomously while maintaining its manual drive to benefit road users who are visually impaired or have mobility issues in crowded cities. Capable of traversing through narrow and congested lanes, the autonomous bicycle shown in Fig. 9(a) offered flexible transportation solutions and could be used either manually or autonomously as per the rider's needs. The motion control with obstacle avoidance capability was achieved using a PID controller algorithm implemented on an electronic chip. While the authors successfully demonstrated obstacle avoidance at slower speeds, research on the mechanical system is needed to avoid obstacles and collisions at higher speeds.

A couple of years later, Pandey et al. [66] used PID controllers and implemented them with discrete-time controller hardware for velocity control and autonomous trajectory control of an autonomous three-wheeled mobile robot (Fig. 9(b)). The mobile robot offered promising solutions as self-driving autonomous vehicles for use on streets as public transport. Despite the challenging task of attaining control and stability of three-wheeled vehicles, the authors achieved the desired trajectory control using the proposed controllers. However, the robot must be controlled with more advanced techniques, such as adaptive and fuzzy PID control designs, to perform under challenging roads and highway environment conditions.

To enhance the mobility options for city residents, Zheng and Mueller [67] in 2021 proposed a thermal control design for a rider-focused autonomous electric robotaxi called Zoox (Fig. 9(c)). Since the Zoox robotaxi was an autonomous, as well as an electric vehicle, the authors overcame the control design challenges by utilizing heating, ventilation, air conditioning (HVAC) control as thermal control, and a complicated multi-input-multi-output system comprising about one hundred sensors such as temperature sensors, solar radiation sensors, valve position sensors, flowrate sensors, and air quality sensors in the HVAC system to ensure a safe and comfortable experience to its riders. By further applying AI and an adaptive scheme, Zoox can potentially make the system smarter in serving riders.

Travelling off-road could be a more feasible approach for navigation in less accessible areas. In 2023, Lee et al. [68] proposed a multi-degrees-of-freedom two-wheeled inverted pendulum robot (mD-TWIPR) for off-road transportation to navigate through challenging tracks and road sidewalks. The system, as shown in Fig. 9(d), had high mobility due to its simple structure without steering or suspension and its car-like frame with a low and elongated body, providing advantages for transporting long objects such as pipes or transferring patients on off-road terrain. A model-based controller was designed for mD-TWIPR and consisted of two PID controllers controlling the wheels and a sliding mechanism for slope traversal and step-climbing capabilities along street sidewalks. The experimental results substantiated that the mD-TWIPR with a sliding mechanism could be successfully used for transporting patients in off-road terrain with several slopes and steps and for going to work, sightseeing tours, or outdoor activities.

Findings and analysis — Transportation robots

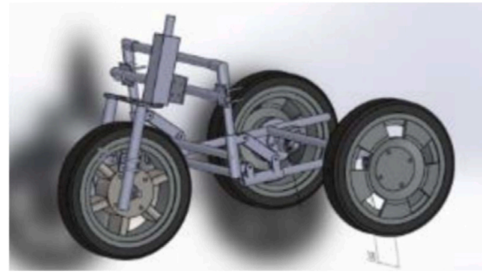
Studies on two-wheeled [65,68] and three-wheeled mobile robots [66] demonstrate their potential in navigating constrained industrial environments. However, these studies also highlight the need for further research on more advanced control techniques for enhancing obstacle avoidance capabilities at higher speeds, reflecting the challenges of deploying such transportation robots in complex real-world environments. On the other hand, the autonomous electric vehicle utilized in [67] emphasized the importance of AI and adaptive motion control schemes in improving the comfort and safety of passengers that could revolutionize public transportation by offering smart, rider-focused solutions.

6.2. Delivery and logistics

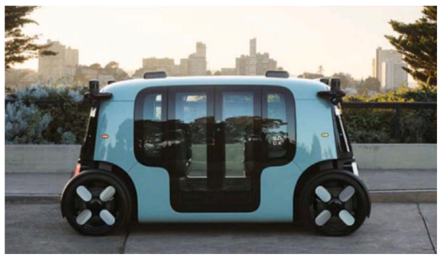
Road and highway robots can also deliver packages and goods in urban areas, as they can navigate sidewalks and roads to deliver items efficiently and cost-effectively. Since roads and streets connect different city centres and public facilities, road robots can autonomously transport items to one or more locations, optimizing inventory management and reducing the need for manual labour. Buchegger et al. [69] in 2018 presented an autonomous car-like electric vehicle (Fig. 10(a)) that could safely navigate in large-scale urban environments such as a university campus or a city centre and deliver parcels to customers efficiently. To generate the topological path, the authors applied the AMCL and A$*$ search algorithm on the road map for safe navigation in urban areas while supporting long routes and respecting the vehicle's unique kinematics. While on the road, the robot encountered issues such as obstacle recognition and avoidance and negotiating crossings and narrow streets, which could have been overcome by including connected and smart technology to obtain environmental information.

To deliver essential packages on flooded roads, Mostafa et al. [70] in 2019 proposed a product delivery car-like robot shown in Fig. 10(b) that could move on land and at a certain water level to automate the delivery process. For autonomous navigation, the authors embedded Arduino Pro mini microcontroller, water sensors, and IR sensors in the mechanical system to ensure timely product delivery. To diversify delivery services, Zhu et al. [71] in 2020 proposed a multifunctional car-like robotic system (Fig. 10(c)) with multiple sensor modules that could provide delivery service content information and collect customer service demand information. The A$*$ algorithm, computer vision and face recognition techniques were employed to enhance the self-decision-making of the delivery robot. With the ability to navigate roads with adverse conditions effectively, the smart car system could significantly improve customers' delivery experience.

(a) Autonomous bicycle [65]



(b) The three-wheeled mobile robot [66]

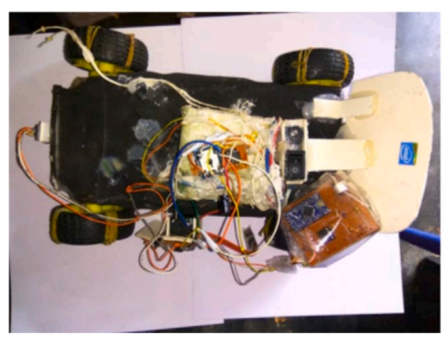


(c) The autonomous robotaxi, Zoox [67]

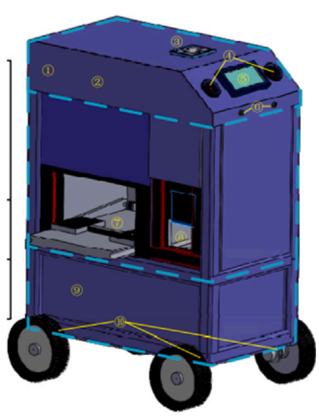
(d) The car-like mD-TWIPR [68]

Fig. 9. Public transportation road and highway robots.

(a) The car-like electric robot [69]



(b) The product delivery car-like robot [70]



(c) The smart car system [71]

(d) The delivery robot, ZebraT [72]

Fig. 10. Delivery and logistics road robots.

With regards to creating a more efficient, safe and customer-oriented delivery system, collaboration between car-like robots could enhance safety and information sharing in accomplishing assigned tasks. Such a collaborative system was investigated in 2022 when Tian and Shi [72] proposed four-wheeled car-like robots called ZebraT (Fig. 10(d)) that could perform autonomous delivery in urban environments using a Reinforcement Learning algorithm. ZebraT could perform autonomous navigation on urban roads while avoiding static and dynamic obstacles while performing designated delivery tasks. Experiments conducted on ZebraT reveal that the system could cooperate with other autonomous mobile robots to deliver goods to customers.

Findings and analysis — Delivery and logistics robots

While the research on car-like delivery robots used in [69,70] demonstrated their potential for parcel delivering goods in dynamic industrial settings, the studies also highlighted challenges such as obstacle recognition, avoidance, and navigation through narrow streets, which could be mitigated by integrating connected and smart technologies for better environmental awareness. The work of Zhu et al. [71] also revealed future research directions involving advanced sensor modules, computer vision and face recognition techniques for car-like robotic systems to ensure improved and reliable delivery services in challenging road conditions. Furthermore, Tian and Shi's [72] focus on cooperation between autonomous robots highlights future trends in developing more sophisticated, interconnected delivery systems that can work together to address the unique demands of delivery systems in complex industrial and smart city environments.

6.3. Law enforcement, surveillance and security

According to Gong et al. [73], policing road traffic is listed among the most dangerous tasks since many traffic police personnel are injured in accidents at intersections. Thus, to improve the efficiency of traffic guidance and surveillance, in 2017, the authors of [73] presented a humanoid robot, InMoov (Fig. 11(a)), for mobile surveillance with Raspberry Pi camera-based eyes and omnidirectional Mecanum wheels. InMoov's motion was controlled by the Android App, which enabled the authors to watch the live video stream of the robot, make it execute specific traffic commands and get the location of InMoov's exact point through network communication.

For both pedestrian robots and autonomous vehicles, street intersections threaten them and surrounding traffic if mismanaged. Robots need to cross the road to perform surveillance and monitoring operations effectively. For unsignalized crossing situations, the problem is even more challenging. In 2017, Radwan et al. [74] employed a wheeled pedestrian robot, as shown in Fig. 11(b), that used multiple sensor modalities and electronically scanning radars to address the problem of autonomous road crossing. Taking into account the dynamics of the environment, such as the width of the street, road curvature, lighting and weather conditions, the robot used laser and radar data and a classifier based on the Random Forests approach to predict when it was safe to cross the road, yielding a safe and accurate street-crossing behaviour.

Autonomous vehicles can perform traffic-specific tasks to accomplish specific objectives, such as exploring unknown or unmapped road sections and searching for road accidents. In 2019, Magsinoy et al. [75] presented a cooperative search algorithm based on behavioural rules to direct five mobile robots, called PBOT (Fig. 11(c)), to cooperatively search for road accidents in the city. The PBOTs followed a hierarchical set of behavioural rules to achieve a cooperative search. They used the cellular network for communication and data exchange among PBOTs, where the transmissions took place via a cellular network. For navigation, the PBOTs were programmed to follow random and deterministic paths in sensing the city grid map by following the Uniform Distribution Movement or Manhattan Mobility Model approaches. With advanced sensor systems, these robots could detect obstacles, pedestrians and other vehicles to prevent collisions and ensure safer roadways.

Moreover, Liu et al. [76] in 2019 presented an autonomous navigation system for a wheeled mobile robot shown in Fig. 11(d), with 16-line LiDAR installed on top and a low-precision GPS which could be used for surveillance in unstructured and dynamic environments. The proposed system consisted of a LiDAR-based mapping and relocalization module, a traversable path and obstacle detection module, and a path planning and trajectory tracking module. Motion control of the car-like mobile robot was achieved by integrating RRT∗ and RRT-connect algorithms. The system was applied to roads in campus environments with many pedestrians and vehicles, and it accurately completed navigation tasks such as patrol and ground search.

Findings and analysis — Law enforcement, surveillance and security robots

The potential of humanoid robots in reducing human risk by performing traffic commands was demonstrated in [73], and the importance of robust sensor integration for environmental awareness of a wheeled pedestrian robot operating in dynamic traffic conditions was highlighted in [74]. Additionally, the research work in [75,76] emphasizes the importance of advanced navigation systems in enhancing the operational capabilities of mobile robots in complex, real-world industrial environments, paving the way for their broader adoption in smart cities. These insights point to future directions in developing more intelligent, adaptable and collaborative autonomous systems that can significantly enhance mobility and road safety in smart cities.

6.4. Street cleaning

Road robots can be equipped with cleaning tools to sweep and clear debris from streets, sidewalks and roadside drains, improving urban cleanliness and beauty. Recent studies show the applicability of mobile robotic systems to tackle operational challenges, mainly accelerating clean city initiatives such as autonomous garbage detection and collection [77]. In 2019, Ahsan et al. [78] proposed a drain cleaner robotic vehicle system shown in Fig. 12(a) that would remove waste materials, such as leaves, bottles, and polyethylene, that usually disrupt the water flow in roadside drains. Developed for solving the drain clogging problem along city streets, a four-wheeled robot was attached with a wiper motor for moving on the drains and a chain-sprocket-based grabber fitted with a fixed number of claws to pick up the waste material. The system's motion was controlled through a Bluetooth app that communicated through a microcontroller and provided an effective autonomous solution for city dwellers to keep their roadside drains clean. With the rise of smart cities, there is an evergrowing need to develop an autonomous garbage-collecting robot that accurately monitors, identifies and collects garbage from the environment. Chang et al. [79] in 2020 presented an intelligent mobile garbage collection robot (Fig. 12(b)) based on visual recognition technology that could carry out path planning, traverse the given area, scan and identify and pick up recyclable roadside garbage. The adaptive Monte Carlo positioning algorithm controlled the four-wheel system's motion, including target identification and sorting control units. The target recognition unit consisted of a MobileNetv3-SSD deep learning algorithm to perform target detection and target classification on the images obtained by the camera, get the coordinates of the target and its angle information as the input information, and hence control the sorting control unit to execute garbage grabbing task. Another garbage-collecting robot was presented by Assis et al. [77] in 2021, comprising a four-wheel drive on a flat chassis and ultrasonic sensor (Fig. 12(c)) for object detection, garbage identification and garbage collection. The garbage detection was done using the You Only Look Once (YOLO v3) algorithm and CNN. After a comparative analysis, the authors noted that YOLOv3 had better detection than CNN. The accuracy and efficiency of the mobile robot in collecting roadside garbage can be

(a) Traffic police on duty [73]

(b) Autonomous street crossing [74]

(c) The PBOT [75]

(d) The LiDAR-based Mobile Robot [76]

Fig. 11. Law Enforcement, surveillance and security road robots.

improved by utilizing advanced image detection algorithms such as AI techniques.

In 2021, Chen et al. [80] proposed an unmanned street cleaning system platform solution called Robo-Sweeper (Fig. 12(d)) that used embedded artificial intelligence to enhance the capabilities of traditional cleaning equipment. To control Robo-Sweeper's autonomous navigation, a set of driving algorithm frameworks was developed: mapping, positioning, path planning, and sweeping operations according to the cleaning requirements. The results of road sweeping experiments demonstrated the practical applicability of the unmanned sweeper in complex city environments.

Findings and analysis — Street cleaning robots

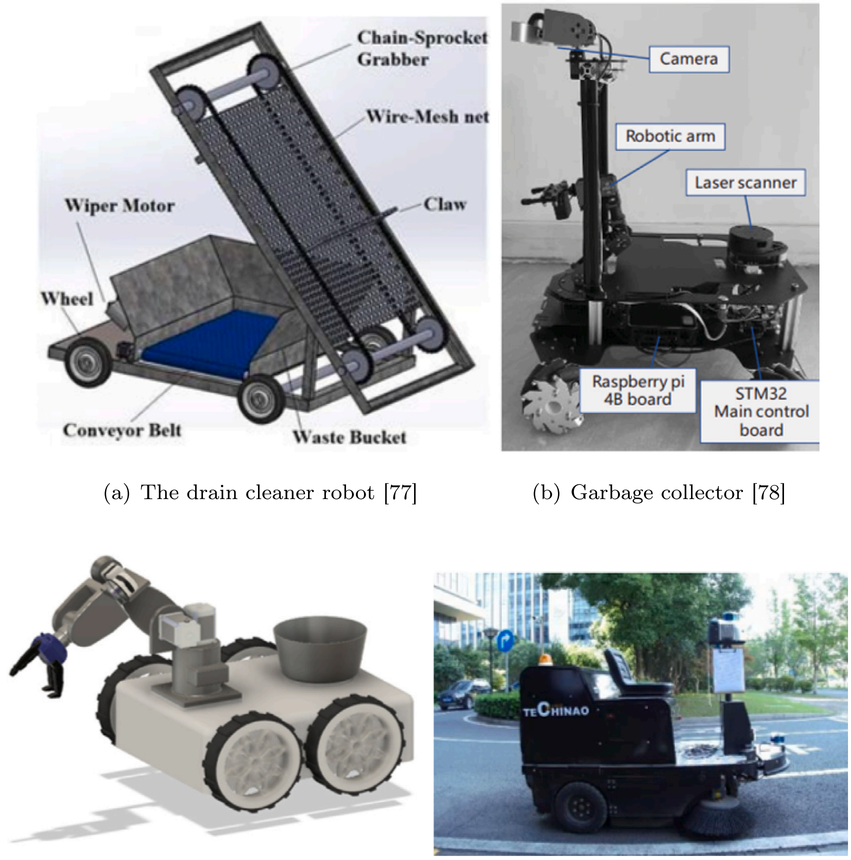
The drain-cleaning robotic and garbage-collecting robots utilized in [77–79], respectively, demonstrate the potential of integrating AI with robotics to enhance the efficiency and effectiveness of industrial cleaning operations. The use of deep learning for target detection and classification represents a significant advancement in autonomous waste management, particularly in tasks requiring precise identification and collection of waste materials. Furthermore, the unmanned street cleaning robot developed by Chen et al. [80] highlights the future direction of street maintenance, where autonomous systems are increasingly utilized to maintain city cleanliness with minimal human intervention.

6.5. Maintenance of public service facilities

Road robots can be deployed to maintain public spaces such as bridges, tunnels and sidewalks. Such road infrastructure condition assessment is vital to maintaining the quality of highway roads for public transportation. In 2017, Le et al. [81] used a skid-steering four-wheel-drive robot model (Fig. 13(a)) that could move along a narrow bridge deck for autonomous bridge deck inspection. The mobile robot's localization and navigation were based on extended Kalman filter-based sensor fusion from GPS, inertial measurement unit and wheel odometry data. An automated rebar detection method proposed in the study allowed the robot to process the ground penetrating radar data in real time and accurately generate the bridge deck condition map. The proposed approach could be widely applied to reduce bridge maintenance costs and could be easily adapted for other complex applications such as tunnel and waterpipe inspection by equipping it with non-destructive evaluation sensors.

An environmentally friendly approach to urban landscape management was presented by Adeodu et al. [82] in 2018 using solar energy as a renewable energy source to develop a solar-powered grass cutter (Fig. 13(b)) to maintain the green spaces autonomously. Equipped with IR sensors to detect obstacles in its path, the four-wheeled vision-based grass cutter robot achieved path planning and obstacle avoidance aided by an Arduino microcontroller. With the ability to navigate in narrow spaces, features of this robotic system could be enhanced with the inclusion of computer vision for obstacle avoidance in unknown environments.

Using cleaning robots in public transport ensures a higher level of hygiene and sanitation and enhances road transport users' overall cleanliness and safety. In 2021, Western et al. [83] proposed a four-wheeled car-like robot (Fig. 13(c)) to collect and dispose of public transport waste. Using model-based control, the authors implemented the robotic cleaning system to benefit public transport providers and users. Despite the benefits, the autonomous cleaning system could be further improved by introducing a flexible navigation scheme for detecting waste and guiding the robot [84]. A similar solution was found by Hurtado et al. in 2022 [85] but using a sensor-based disinfection robot for public transportation. The robot, as shown in Fig. 13(d), had four UV-C lamps for destroying bacteria and viruses on surfaces and



(a) The drain cleaner robot [77] (b) Garbage collector [78]

(c) The garbage collecting robot [79] (d) Robo-Sweeper, the street sweeper [80]

Fig. 12. Street cleaning road robots.

could perform disinfection operations in places that were difficult to access. Its onmiwheels and mecanum wheels provided manoeuvrability in climbing small stairs found inside some models of public service vehicles such as transport buses. Equipped with IR sensors for detecting obstacles and thermal sensors for detecting people in the work area, a Raspberry Pi controller controlled the robot's motion.

Findings and analysis — Maintenance robots

The bridge inspection [81] and grass cutter [82] robots highlight the potential of mobile robots to reduce maintenance costs and improve the efficiency of industrial infrastructure inspections. Both studies reveal future research directions by integrating computer vision for improved obstacle avoidance and information integration in unknown environments. Moreover, the waste collection [83] and disinfection [85] robots used sensors for obstacle detection. However, the studies highlighted the need for advanced navigation and detection capabilities in complex industrial environments. These studies also suggest promising future research directions, particularly the integration of AI and renewable energy sources, which could further advance the effectiveness of mobile robotic systems in performing diverse maintenance tasks.

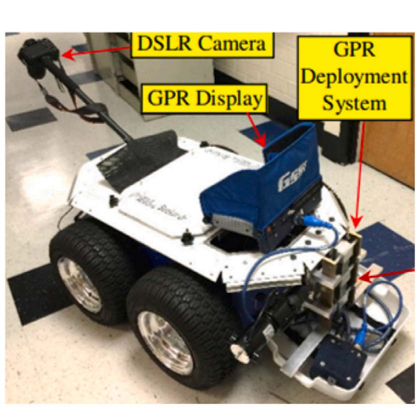
Remark on the applicability of roads and highway robots to smart city framework

Road robots' capabilities will likely expand as technology advances, leading to numerous innovative and practical use cases. The applications discussed in this section demonstrate the potential benefits of autonomous energy-efficient vehicles to smart cities' road and highway transportation services. By contributing to improved traffic management, road safety, effective public transport, and efficient road maintenance, roads and highway robots play a vital role in making industrial and smart city operations more efficient and sustainable. Autonomous electric vehicles can be integrated into smart city transportation systems, reducing dependence on traditional fuel sources and promoting energy-efficient travel. Despite these benefits, incorporating road and highway robots into a smart city framework also comes with challenges, including concerns about information security and the need for significant investment in industrial infrastructure and technology. Data privacy and cybersecurity concerns underline the importance of strict regulations to safeguard technology. Addressing these challenges is vital to successfully implementing road and highway robots in smart cities.

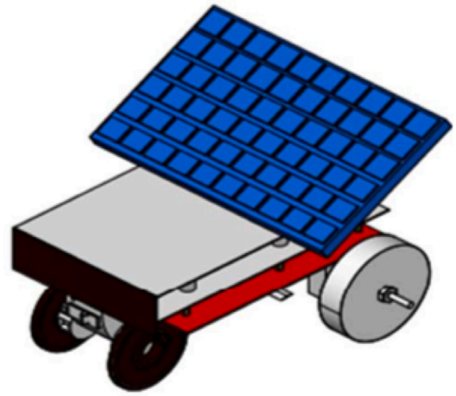
7. Discussion and analysis

The surveys, reviews and research on mobility technologies indicate that robots can play a critical role in smart cities. The mobile robots used as personal transporters in indoor environments can also navigate outdoors on roads and highways to give users a broader spectrum of usage. This versatility is further improved by integrating cutting-edge smart technologies, enabling mobile robots to navigate with enhanced autonomy, adaptability and connectivity, thus contributing to a seamless and intelligent urban and industrial mobility experience. Table 3 analyses the different types of personal transporters (PT) and roads and highway (RH) robots used in the reviewed literature and the potential areas of applicability in smart city environments.

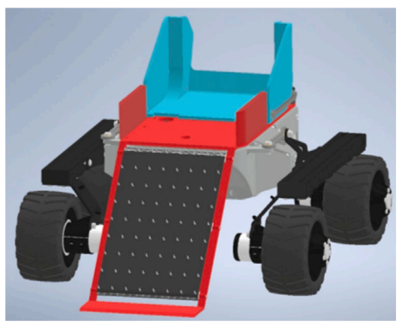
The analysis from Table 3 indicates that a car-like robot is currently the most popular type of mobile robot used for personal transportation, assistive technologies and road and highway robots, and has excellent potential to be integrated into industrial and smart city applications.



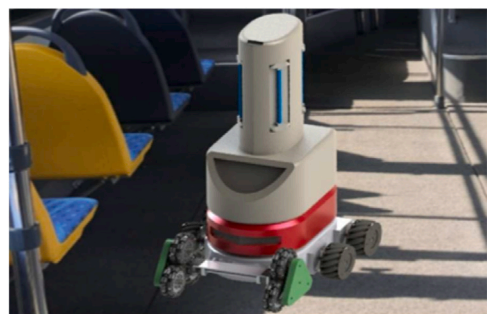
(a) The bridge deck inspection robot [81]



(b) Solar-powered grass cutter robot [82]



(c) Public vehicle cleaning robot [83]



(d) The sensor-based disinfection robot [84]

Fig. 13. Public service road robots.

Table 3
Type of robots and algorithms used, and potential smart city application.

Robot	Paper	AI/ IoT	PT	RH	Potential application
Humanoid	[73]	✓	×	✓	Personal assistance
UAV	[42–44]	×	✓	×	Delivery, surveillance
Bicycle	[65]	×	✓	✓	Transportation
Segway	[15,37,41]	×	✓	✓	Health, transportation
3-wheeled	[33,66]	×	✓	✓	Health
Wheelchair	[35,36,38,54,61]	×	✓	✓	Health, transportation, entertainment
Car-like	[39,40,63,67,68,76]	×	✓	✓	Health, transportation, security
Car-like	[14,52]	✓	✓	✓	Health, transportation
Car-like	[57,69,71,72,75,77–80]	✓	×	✓	Delivery, surveillance, cleaning
Car-like	[70,81–83]	×	×	✓	Delivery, maintenance
Tracked	[53,56]	✓	✓	✓	Health, transportation

Amongst the main reasons researchers prefer car-like robots could be factors such as stability, cost-effectiveness and ease of design that could play a significant role in transport, logistics and distribution. While car-like robots may be the current choice, they may only be efficient for some purposes, and there is potential to bring in different robots for specific tasks. Robotic systems that are efficient and fit for purpose are designed to meet their intended functions with precision and the ability to integrate with advanced technologies, making them valuable assets for industrial integration in smart city applications. Researchers have already studied autonomous systems such as humanoids, tracked robots, wheelchairs, bicycles and segways, but other mechanical systems need to be included for specific smart city operations such as reliable human–robot interaction and safe autonomous navigation through crowded streets, markets and public spaces [2,6,11]. Furthermore, most of the retrieved articles generally utilized AI and IoT technologies to enhance the navigational capabilities of robotic systems, particularly for use in transportation and public service.

The result from the literature reviewed in this paper highlights that mobile robots are increasingly being integrated into the transportation sector on roads and highways, serving as autonomous personal transporters and assistive technologies in smart cities. Current applications highlight the use of mobile robots on roads and highways for tasks such as delivery, healthcare assistance, navigating complex environments, enhancing mobility for people with disabilities, improving public transportation efficiency and contributing to urban cleanliness through autonomous cleaning and maintenance. However, challenges related to cybersecurity, data privacy, industrial information integration and the need for advanced motion planning and control algorithms to ensure safe navigation in dynamic environments persist. Emerging trends suggest a growing focus on integrating advanced sensors, AI and collaborative multi-robot systems that can perform complex tasks like traffic policing, emergency response and infrastructure maintenance in smart city contexts. Moreover, integrating heterogeneous robotic systems that work together will likely lead to more sustainable and efficient smart city operations as technology evolves.

8. Challenges on application of mobile robots in smart cities

The use of mobile robots in smart cities poses several challenges, the main ones of which are discussed below.

8.1. Navigation in complex environments

Navigating roads, highways, pedestrian pathways and parks while maintaining robustness and stability could be difficult for mobile robots. The dynamic nature of industrial and smart city settings, such as complex architecture, narrow alleys, pathways, and crowded urban environments with pedestrians, vehicles, and unexpected obstacles, remains challenging in autonomous navigation. Smart city and industrial environments can experience rapid landscape changes such as infrastructure development, construction of tall buildings, narrow alleyways, multi-level bridges and underground passages, causing inaccurate localization and signal interference. For instance, narrow alleyways often lead to GPS signal loss, requiring mobile robots to switch to alternative localization methods, such as visual odometry or LiDAR-based SLAM, which can introduce errors in dynamic environments. Moreover, dynamic or changing terrains and landscapes, such as ongoing industrial projects, further complicate navigation by creating unpredictable obstacles and causing frequent updates to digital maps. Current technologies, such as sensor fusion combining LiDAR, radar and visual odometry, offer some solutions but remain susceptible to adverse weather conditions. Therefore, innovative research is necessary for a scrutinized integration of appropriate smart sensors, wireless communication and advanced mapping techniques so that robots can maintain their accurate position awareness and update their navigation plans accordingly while performing assigned tasks.

According to Radwan et al. [74], mobile robots should be robust systems to operate reliably in weather conditions like rain, snow and fog. Thus, the demand for new robotic systems implies that due to evolving communication networks, greener technologies and technological advancements, the search for advanced algorithms in perception, planning, control, machine learning, greener communication and human–robot interaction strategies will be an ongoing and long-term research. Emerging areas such as quantum communication networks and deep learning-based predictive models hold promise for advancing the capabilities of mobile robots.

8.2. Human interaction and safety

Robot–human interaction and safety in smart city environments present unique challenges due to urban settings' complex and dynamic nature. Ensuring that robots understand human behaviour and respond appropriately in specific or sudden situations, such as avoiding collision, is essential for successfully integrating into these environments. The unpredictable and diverse behaviours humans exhibit as pedestrians could require robots to be highly adaptable. This adaptability involves learning from past interactions and predicting future behaviours. For example, robots need to understand the behaviour patterns of pedestrians based on age, intent, or even cultural norms, which can significantly impact the nature of interactions. Language barriers, cultural differences, physical disabilities, and the need for intuitive communication can further challenge the establishment of effective human–robot interaction. Moreover, these factors necessitate the development of advanced communication systems, allowing for adequate interpretation of non-verbal cues such as gestures or facial expressions, which is crucial for equitable interaction involving people with different physical abilities.

Navigating crowded areas requires robots to accomplish challenging tasks such as following social norms, respecting personal space and obeying the traffic and driving rules on street sidewalks and crossings [74,76]. Robots would require advanced perception and prediction capabilities to differentiate between pedestrians waiting to cross the road and those merely standing on the sidewalk. In different sets of weather conditions of smart cities, robots should be able to react appropriately, optimize their functionality and make informed navigation and interaction decisions by accurately detecting humans, obstacles, vehicles and road infrastructure [75]. Combining robust sensor fusion techniques requires incorporating data from multiple sensors, such as LIDAR, cameras and weather sensors, to provide a comprehensive understanding of changing weather patterns.

8.3. Data privacy and security

Mobile robots interact using vehicle-to-vehicle (V2V), V2I and vehicle-to-everything (V2X) communication systems. These communication systems facilitate information exchange crucial for autonomous operations, making them vulnerable to cyber-attacks. A bulk of data is passed around in real life through IoT. If, for instance, a device fails to retrieve sensitive data, it may make wrong decisions; thus, further research is essential to bring completeness to such truncated or incomplete data. There is a need for secure communication systems so that sensitive/non-sensitive data may be sorted out and made available for appropriate use. Implementing data encryption techniques helps distinguish and protect sensitive information from non-sensitive data [86]. Protecting sensitive information, face recognition for optimal data, crowdsourcing identities, use of computer vision, preventing unauthorized access and ensuring responsible deployment of robotics technology are some critical challenges associated with data privacy and security for mobile robots in smart city settings. Moreover, robots' wireless communication channels to network and transmit data can be vulnerable to interception or interference [9]. Regular security updates are vital to address emerging threats in wireless communication channels. Ensuring the privacy and security of the data and safeguarding the robots from hacking or malicious use are critical [11,55,87]. Continuous research into industrial information integration and adaptive cybersecurity solutions is essential to stay ahead of evolving attack vectors and tactics.

The data acquired by robots must be encrypted during transmission and stored securely to prevent unauthorized access and misuse [12]. End-to-end encryption ensures that data remains protected throughout its lifecycle, from acquisition and transmission to storage and retrieval. Addressing these challenges requires a comprehensive approach that involves developing safe and secure communication channels to ensure safe and secured robotic assignments using encryption and secure communication protocols while adhering to privacy regulations. Protecting against data breaches, unauthorized control, and malicious attacks requires robust cybersecurity measures. Effective collaboration with cybersecurity experts and adherence to international security standards can enhance resilience against potential threats. As IoT-based systems evolve, AI increasingly enters the security sector to safeguard citizens and data protection; hence, it is also gaining higher interest from researchers [19,88]. AI-driven security solutions can provide advanced threat detection against cyber attacks, enhancing security measures in smart city infrastructures.

9. Future directions for using mobile robots in smart city operations

While mobile robots have contributed significantly to industrial and smart city applications, numerous ongoing challenges that require further research and development still need to be addressed. The growing demand for mobile robotic systems to accomplish many new and future tasks implies that research is necessary to address the challenges and possibilities that mobile robots offer in transportation, healthcare, logistics and other smart city sectors. As robotic technologies evolve, solutions to these challenges will be critical in enabling safer, greener and more efficient mobile robot deployment in complex smart city environments. The social science aspects of robotics research must be considered to enhance human–robot interaction, accessibility, and inclusivity to ensure mobile robots' seamless integration into smart cities. Some future directions for research and development in this area are discussed below.

9.1. Transition towards wireless communication

Urban connectivity and infrastructure are evolving significantly as smart cities move toward wireless communication. The development of new wireless technologies and their integration with already-existing wire-based systems have allowed wireless communication to expand quickly. As such, mobile robots must be able to communicate with other devices and infrastructures in smart cities to perform complex tasks. Cities may improve the reliability of networks during emergencies, respond to changing connectivity demands, and enable real-time data collecting for informed decision-making by deploying mobile robots equipped with advanced communication technologies and information-sharing capabilities [20]. While collaborative efforts among stakeholders are crucial to addressing the challenges and regulatory considerations associated with this innovative approach, the versatile robots can also potentially improve public services, environmental monitoring and industrial infrastructure maintenance. Just as hand-held mobile phones worldwide are connected by wireless communications today, mobile robots in various sectors can communicate with one another and their respective service providers through wireless connectivity mechanisms and network architecture as discussed in studies such as [73,75]. In modern wireless networks like 5G, where high data rates and efficient management of data transmission are crucial [13], network architecture using backhaul (transports data between the mobile robots and core network) and fronthaul (connects the mobile robots to the central processing unit) will ensure efficient and high-performance wireless communication systems amongst different smart city sectors. By focusing on these areas, researchers can contribute to developing new robotic systems that harness the full potential of 5G and anticipated 6G technologies to enhance further the efficiency, capabilities and applications of mobile robots. The integration of edge computing with 5G and 6G networks could be explored as they can improve the processing capabilities of robots without relying solely on onboard computing power. Additionally, the high bandwidth capabilities of such networks could enable faster transmission of large amounts of sensor data, thereby accommodating an increasing number of connected robots in smart city environments.

In the future, personal transporters will rely on wireless communication for navigation and tracking capabilities via smartphones and other technologies. With 5G on the roll and 6G being the next generation of wireless technology with even faster speeds and more advanced capabilities, frequent software updates and data sharing will be more accessible for performance and personal transporter experience [89,90]. Advanced communication protocols that enable seamless integration of 6G technology in robots must be developed, allowing efficient and secure communication while operating in a smart city environment. Moreover, road and highway robots may benefit from wireless connectivity by providing real-time industrial infrastructure monitoring and maintenance. These robots may get information on traffic conditions, road closures, and industrial maintenance requirements through wireless connectivity, resulting in more efficient traffic flow and reduced congestion through practical research efforts in this area. Furthermore, wireless connectivity will improve coordination among robotic units, allowing for collaborative efforts in delivery, security and surveillance applications. Collaborative interdisciplinary research involving robotics and telecommunications experts can explore innovative ways to leverage 6G technology for enhanced sensor fusion, enabling robots with improved navigational and decision-making capabilities. Transportation robots must use wireless communication to operate, interact and contribute to modern transportation networks. As a result, further research is essential for developing wireless communication-enabled robots in the form of 5G-enabled or 6G-enabled robot swarms that use high-speed communication to collaboratively perform tasks like environmental monitoring, disaster response, or maintenance of roads and highways in smart cities.

9.2. Integration with IoT and AI

Intelligent digital tools like AI, Blockchain, Virtual reality/Augmented reality and IoT can facilitate optimized robot navigation for smart cities. Mobile robots equipped with advanced AI algorithms can become a vital component of the IoT ecosystem in smart cities, collaborating with other devices and systems to optimize resource utilization and performance of smart city operations. Research-driven innovations such as reinforcement learning and swarm intelligence algorithms [91–93] can lead to AI-enabled mobile robots that can handle increased computational demands in smart cities. With the integration of IoT and AI, personal transporters and road and highway robots can use AI-driven advanced navigation algorithms incorporated with sensor data to adapt to new situations and challenges autonomously and evolve into intelligent and advanced technologies as demonstrated in [51,80]. Advanced AI algorithms can be implemented to improve robotic manipulation skills while utilizing real-time data from interconnected IoT devices to optimize tasks like waste management, traffic control and public security [16]. Research based on incorporating IoT technologies such as sensors and edge computing with robotics will equip these robots to adapt to dynamic scenarios as intelligent robotic systems, improving the overall efficiency and cohesiveness of smart city industrial operations. In addition, IoT-enabled communication will allow personal transporters and road robots to exchange information, facilitating cooperative actions for smoother traffic management and accident prevention. Thus, future research in this area should focus on secure V2X communication protocols, industrial integration of edge computing in IoT-enabled transportation systems and examination of the scalability challenges of IoT networks in transportation. Soori et al. [94] demonstrated the future applicability of AI in advanced transportation systems whereby smart cameras and smart traffic lights controlled by AI could be used to manage traffic by optimizing traffic flow and reducing congestion. This implies that by adopting smart technologies, AI-powered traffic management strategies could be implemented to improve the overall efficiency of the transportation network. Researchers can extend the work of Soori et al. by exploring how AI in transportation can integrate with other smart city infrastructure elements such as parking systems and smart grids [7].

Future research could focus on designing advanced predictive algorithms by utilizing data acquired from IoT sources to manage smart city transportation systems. The potential of AI-driven autonomous vehicles to optimize transportation services must be investigated as it represents a promising avenue for innovation. In addition to transportation, data analytics, encryption, and forecasting, AI is utilized in various other areas of smart cities, including industrial infrastructure maintenance, healthcare services, energy and waste management. Finally, exploring the ethical and societal implications of AI deployment, including privacy and algorithmic bias issues, will ensure the inclusive development of smart city transportation systems.

9.3. Public awareness and acceptance

Despite playing a significant role in vital sectors such as health care [32–35,37,38], delivery [14,39,44] and entertainment [61,62,64], mobile robots are yet to be widely accepted by the general public. As city robots become more common, educating the public about their benefits, functions and safety precautions will be critical to gaining complete acceptance and trust. Public attitudes toward using robots can be complex and vary widely depending on culture, technological familiarity and personal preferences. Some people may oppose robots sharing space with humans, but others may be more accepting [2]. Hence, research should focus on developing communication platforms such as interfaces, chatbots, and communication apps that prioritize human-centric interactions in smart cities. People may be concerned that the widespread use of robotic systems would result in job losses in industries that rely on human labour [4]. In-depth studies on public attitudes and perceptions toward robots on specific roles and responsibilities whereby factors influencing the public's mindset must be investigated. Research can also focus on including further functionality by designing mobile robots with user-friendly interfaces and effective communication strategies. The service providers see robots as a means of improving transportation efficiency, reducing traffic congestion and providing a higher level of convenience [12]. Some may be concerned about the perceived lack of safety and accidents involving robots, how robots interact with pedestrians, bicycles and traditional cars, or the uncertainties involved in their accuracy and myth of eventually controlling humans [19]. Thus, there is a need for cross-disciplinary research that considers various dimensions such as privacy, inclusivity and adaptability to design user-friendly robotic systems. Comprehensive risk assessments should be conducted through research to identify potential hazards associated with human–robot collaboration and explore ways to ensure compliance with safety standards.

Furthermore, the incorporation of transportation robots might cause privacy and surveillance concerns. People may need clarification about the data the robots collect and how these will be used to track individuals' movements and behaviours [2]. Therefore, research must be conducted to explore the effectiveness of public education and awareness campaigns on the capabilities and benefits of transportation robots. The perceived mindset needs to be changed, emphasizing the potential for robots to complement human tasks rather than replace them [4]. Research should address job displacement and worker rights concerns, ensuring a balance between technological advancement and human well-being and satisfaction.

10. Limitations of this study

This systematic review provides valuable insights into research conducted on personal transporters, assistive technologies, roads, and highway robots, laying the foundation for research directions in the future of mobile robot applications in smart city operations. It contributes to the academic literature by providing an overview of the past ten years of knowledge in this field, serving as a valuable resource for researchers and scholars. Despite these benefits, it is worth noting that this research has some limitations:

1. By searching three, although large, databases, the entire field of mobile robots in the context of smart cities is not covered.
2. By restricting the study to the past ten years, significant studies on mobile robots that could have potential applications in smart city operations are not included.
3. This research might not provide a comprehensive perspective on the general changes and developments of mobile robots; however, it captures the transportation aspect of mobile robotics research within the past ten years.

Therefore, more research must be conducted to develop relevant mobile robotic systems that enable smart cities to serve their citizens better. As technologies are being developed and new fields of study are being influenced by robotics, the challenge for researchers is to try to understand what new opportunities and applications these technologies bring to smart cities and which technologies will be most beneficial to meet the requirements of the dynamic environment. In addition, further research should explore public attitudes and perceptions towards advanced technology in smart cities and can inform strategies to enhance public awareness and acceptance.

11. Conclusion

Integrating mobile robots into a smart city framework creates a sustainable urban landscape with inclusive and improved living and working standards. The multifunctional roles that mobile robots play across diverse applications, such as transportation, surveillance, logistics and maintenance, highlight their potential to revolutionize urban living and working conditions. Effective integration of mobile robots into industrial and smart city environments relies on addressing critical challenges such as modelling complex smart city environments, efficient human–robot interaction and data security. Furthermore, integrating advanced navigation techniques with AI, computer vision, and communication technologies opens pathways to creating mega-hybrid robotic systems for various smart city operations. As highlighted in this systematic literature review, the domain of safe, smart city autonomous navigation of mobile robotic systems is a critical component that must be continually addressed.

Over the past decade, researchers have substantially contributed to developing and refining perception, planning, and control algorithms for mobile robots operating within smart city contexts. These advances are particularly evident in personal transportation, assistive technologies and road infrastructure management. From traffic management and enhancing public safety to aiding individuals with mobility challenges, there is high potential for the applicability of mobile robots in smart city operations.

Autonomous mobile robots are critical to a dynamic smart city future. As the field continues to evolve, an interdisciplinary collaborative effort to address existing challenges and capitalize on emerging opportunities will propel smart cities toward a new era of efficiency, sustainability and improved quality of life for all. Future research should focus on integrating robots with more advanced smart city technologies, developing more intelligent motion control techniques and autonomous robots for deployment in complex environments, and evaluating the social and ethical implications of robots in smart cities. Additionally, there is an imperative need to explore advanced adaptive algorithms for multi-robot collaboration, optimize sensor integration, and enhance emotional engagement, as these factors are essential for achieving scalability and social acceptance for industrial integration of mobile robots in diverse smart city applications.

CRediT authorship contribution statement

Ravinesh Chand: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Bibhya Sharma:** Validation, Supervision, Project administration, Conceptualization. **Sandeep Ameet Kumar:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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