Proceedings Paper:

Karakaya, Rabia, Camara, Fanta and Perinpanayagam, Suresh (2025) Human Interactions with Autonomous Mobile Robots in Public Spaces:A Survey. In: 2025 IEEE International Conference on Robot and Human Interactive Communication (RO-MAN). 2025 IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 25-29 Aug 2025 IEEE , NLD (In Press)

Human Interactions with Autonomous Mobile Robots in Public Spaces: A Survey

Rabia Karakaya[1] Fanta Camara[1] Suresh Perinpanayagam[2]

***Abstract*— As autonomous mobile robots (AMRs) are increasingly deployed in public spaces, understanding how they are designed to interact with humans is crucial. This paper reviews existing research on AMRs in real-world environments, analysing their development and deployment from a human-robot interaction (HRI) perspective. Through in-depth analysis of 46 selected studies from the Scopus and Web of Science databases, this study examines the interaction strategies employed in AMRs, the key design requirements, and the challenges they face in human environments. The findings highlight a growing emphasis on delivery, assistance, and guide robots, with interaction methods primarily relying on visual or explicit cues. This study also identifies challenges related to public perception, safety, and usability, emphasising the need for improved design strategies to enhance the effectiveness of HRI and ensure the seamless integration of AMRs into everyday environments.**

I. Introduction

Robots are becoming common in daily life, from small home cleaning robots to delivery robots in cities. Their growing presence requires making them safe and user-friendly. As autonomous mobile robots (AMRs) advance and enter urban areas, research now focuses not only on technology but also on human interaction to ensure safe, efficient, and socially acceptable integration [1], [2].

Robots have long been used in production lines, where users are typically experts such as engineers [3]. Although human-robot interaction (HRI) was less critical in these settings, advances in collaborative robots have increased its importance [4]. In contrast, AMRs in public spaces interact with diverse people, including those without robotics knowledge, such as children, the elderly, and individuals with special needs. Recent research [5] shows that HRI involves not only individual users but also how robots integrate socially, affecting public perception and acceptance.

The term ‘autonomous mobile robot’ (AMR) can encompass a broad range of robotic systems. For this review, we define an AMR as a relatively small robot that operates autonomously, without requiring direct human control, in indoor or outdoor environments at lower speeds. It typically shares its environment with humans and serves, assists, or performs tasks on behalf of humans. The present work aims to provide guidance on the design and deployment of AMRs in the real world, and facilitate their interactions with people in public spaces. This work contributes with the following:

- a bibliometric analysis and an in-depth review of the existing deployment of AMRs in public spaces;
- a taxonomy of AMRs, social cues and key HRI aspects considered in their deployment;
- requirements and challenges related to HRI aspects for AMRs in public spaces.

[1] Institute for Safe Autonomy, University of York, UK
[2] School of Physics, Engineering and Technology, University of York

II. Related Work

Advances in HRI have enabled users to interact with various devices and systems more naturally and efficiently. Beyond technical specifications such as price, reliability, and lifecycle, the success of a technological product is also heavily influenced by its usability and ease of use [6]. Several review papers have explored the role of HRI in robots, highlighting its importance in real-world deployments. Previous studies have examined different aspects of HRI, including usability challenges, safety considerations, and user acceptance [7], [8].

Regarding AMRs in public spaces, existing reviews have mainly focused on their regulatory and security aspects. For example, Thomasen [9] reviewed the regulatory aspects of the deployment of robots in public spaces in the North American context and argued that the laws that regulate these robots may affect the public nature of these spaces. Similarly, Woo et al. [10] argued that states and the federal government should work with cities and provide them with more autonomy in regulating the design and deployment of robots in their public spaces. Mintrom et al. [11] reviewed the public policy approaches used in the deployment of robots in public spaces and developed a policy design checklist to help regulate seven key issues ranging from safety, privacy, and ethics to productivity, aesthetics, co-creation, equitable access, and system innovation. Oruma et al. [12], [13] reviewed the security aspects of social robots in public spaces, considering cybersecurity, data privacy, physical and legal/ethical factors.

Despite these contributions, existing review papers often lack a comprehensive analysis of the real-world challenges AMRs face in public spaces, particularly regarding the safety and social acceptance of people. This review aims to fill these gaps by synthesising findings from recent studies and providing a broader perspective on the deployment of AMRs, with a focus on human interactions.

III. Methodology

In this study, a review has been conducted on AMRs operating in public spaces. The literature review was carried out using the Scopus and Web of Science databases with the following keywords: ”mobile robot” OR ”autonomous vehicle” AND ”public spaces”. As of December 2024, this

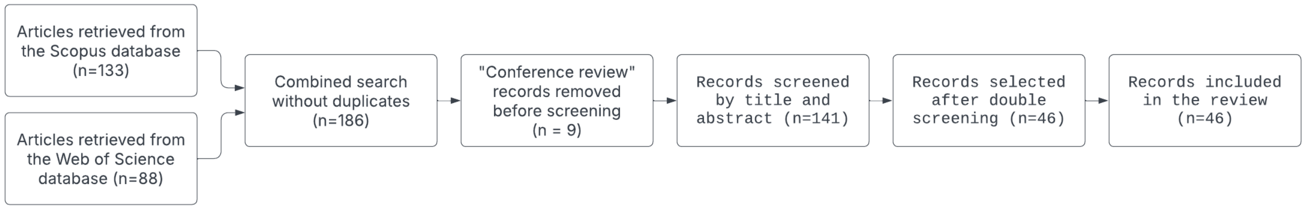

Fig. 1: Flowchart showing the screening process

search returned 133 results for Scopus and 88 from Web of Science. To ensure access to high-quality, peer-reviewed, and thematically relevant studies while maintaining a manageable scope, Scopus and Web of Science were selected as the primary databases for this literature review. These platforms offer robust filtering and indexing systems, making them well-suited for identifying reliable publications within the field. Duplicate records appearing in both databases were identified and removed before the screening process to avoid redundancy. The selection process began by excluding conference reviews in order to focus on full research articles that provide more comprehensive and rigorously peer-reviewed findings, ensuring higher quality and reliability of the included studies. Then, a double-screening process was conducted by two reviewers in two stages: first, by reviewing titles, followed by abstracts. Any discrepancies in the selections were resolved through discussion until consensus was reached. Studies were included if they met both of the following criteria: (1) involved the development of an AMR; (2) included testing in a public space. After independently screening the records, both reviewers compared their selections. Only studies that they mutually agreed upon were included in the final review, resulting in 46 papers. The flowchart in Fig. 1 illustrates this screening process. The in-depth review was then guided by three key questions:

- What are the current HRI approaches used in AMRs?
- How do humans perceive AMRs, and how can their design enhance both safety perception and social acceptance?
- Which HRI areas require further research on AMRs?

Data were analysed using a systematic approach. Specifically, this study seeks to understand the purposes for which various robots are deployed, how they interact with humans, and the solutions provided for these interactions. In conducting a review of the literature, various data from the articles were considered, including the types of real-life experimental tests conducted in the studies and the environments in which these experiments took place. Attention was also paid to the demographics of the participants, HRI methods employed, and whether any interfaces were used for HRI. Additionally, this review explores public perception of these robots and considers strategies for improving people's attitudes toward them.

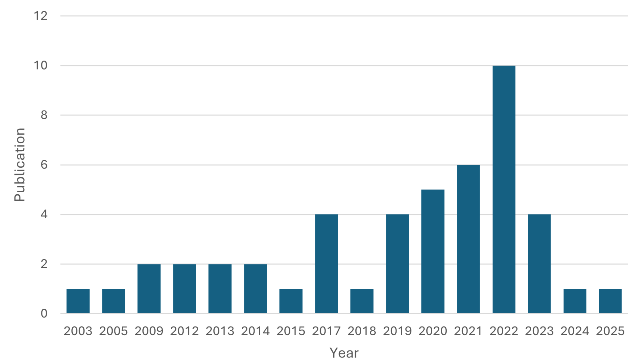

Fig. 2: Trend chart of article publication

IV. Bibliometric Analysis

Bibliometric analysis is performed to uncover emerging trends in the literature.

A. Growth and Countries of AMRs' Deployment

As shown in Fig. 2, the number of AMRs' deployments in public spaces has increased over the years. Early research (2003–2015) remained limited, with research interest growing after 2015, where big advancements in deep learning approaches improved performance in many robotics areas such as robot perception. The highest number of publications occurred in 2022. The increase in publications during this period may be linked to the COVID-19 pandemic, as six of the reviewed articles dated 2021 and 2022 and focused on pandemic-related applications [14], [15], [16]. In general, this graph suggests a continuous increase in studies conducted in public spaces. It is important to note that most studies were conducted in Japan (13 out of 46), followed by the USA and Germany (6 each). China and Canada contributed 3 studies each, while the remaining papers mainly originate from various European countries. This reflects Japan's strong focus on deploying AMRs in public spaces.

B. Keyword co-occurrences

Fig. 3 presents the keyword co-occurrence analysis, revealing four research clusters. The red cluster covers behavioural research and social robotics, focusing on human perception and interaction. The blue cluster highlights robot programming, motion planning, and human-aware navigation. The green cluster centers on service robots in environments like

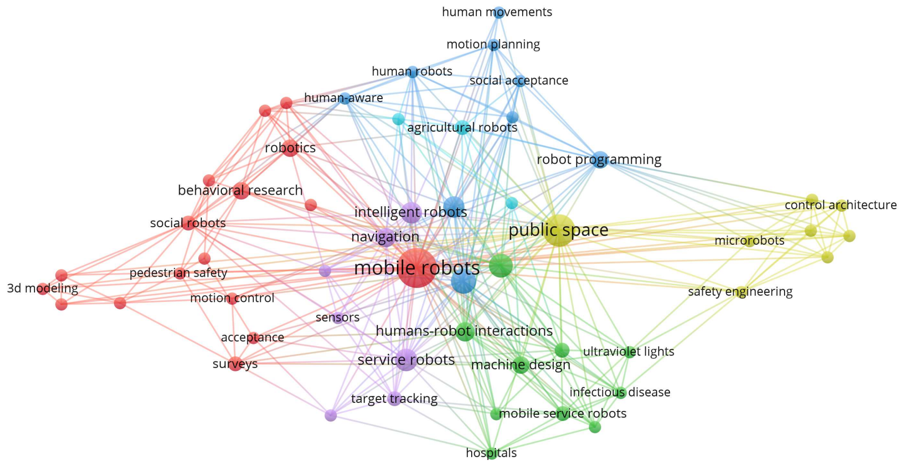

Fig. 3: Keyword co-occurrences map

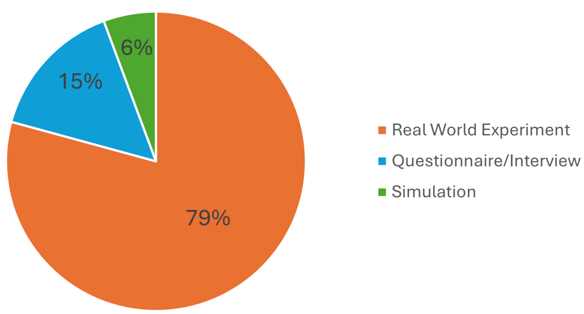

Fig. 4: Experiment types

hospitals, emphasising healthcare and assistive robotics. The yellow cluster addresses safety engineering and control architecture, focusing on robust system development. This analysis highlights the interdisciplinary nature of AMR research in public spaces, balancing human-centred and technical considerations.

V. Findings

This section presents an in-depth analysis of the reviewed literature, examining how AMRs are tested and deployed in public environments. It first explores the different experiment types used in studies, distinguishing between observational studies and real-world deployments. Next, it introduces a taxonomy that categorises AMRs based on their types and the environments in which they operate. Finally, the section delves into key HRI aspects in AMRs, including safety, trust & acceptance, communication, and human assistance, highlighting their significance in ensuring effective and seamless integration into public spaces.

A. *Experiment Types*

A few observational studies (15%) involved AMRs in public spaces, as shown in Fig. 4. These studies that include interviews or questionnaires with people are particularly useful for understanding the requirements of human-robot interaction [17]. They provide insights into what makes people feel safer around robots, what encourages them to use these robots, and how external human-robot interfaces (eHMI) can enhance interaction. Observational studies combined with user feedback suggest that robots operating in public spaces generally coexist well with people, as most individuals feel safe in their presence. Trust and acceptance tend to increase when a robot's behaviour appears predictable [18]. At this point, studies that gather user feedback on HRI methods play a crucial role [19]. Such research enhances our understanding of human perceptions of existing HRI solutions and provides valuable insights for future developments [20]. Fig. 4 shows that the reviewed literature mostly includes real-world experiments with a physical robot (79%). Among these, approximately 80% involved interactions with real, uninstructed participants in authentic public environments, rather than controlled laboratory settings or trials conducted with experts or individuals familiar with the system. These studies offer more ecologically valid insights into how humans perceive and respond to AMRs in everyday contexts. Therefore, the rest of the analysis focuses primarily on these studies.

B. *Taxonomy of AMRs in Public Spaces*

Fig. 5 illustrates the types of robots examined in the reviewed studies, along with their respective testing environments. Delivery robots account for the highest proportion (52%) of deployments in public spaces. In large indoor environments such as museums, shopping malls, and hospitals, assistance robots are more commonly deployed [21], [22], [23], [24]. Additionally, some robots have been tested in multiple environments to ensure a more comprehensive evaluation. For instance, a robot may first be tested in a controlled indoor setting, such as a building, before being deployed in a larger public space like a shopping mall [21]. A taxonomy of AMRs is proposed in Fig. 6 where mobile robots in public spaces are classified based on their environment of operation and function. This taxonomy helps

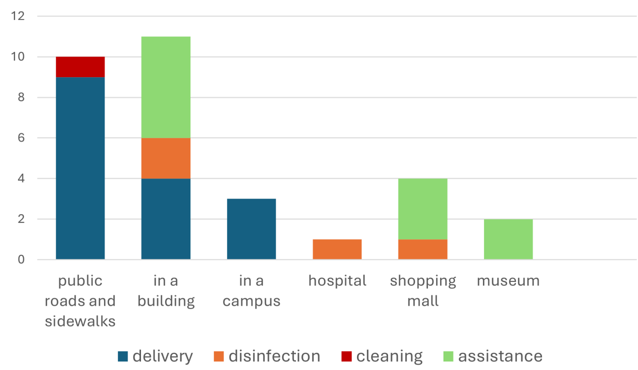

Fig. 5: Robot types and testing environments

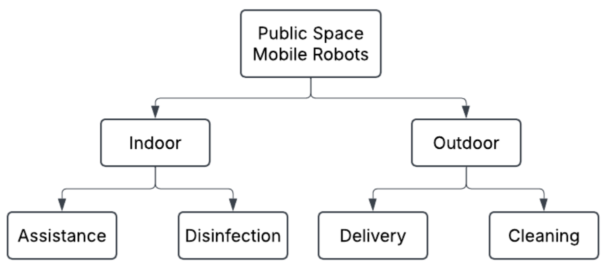

Fig. 6: Taxonomy of AMRs in public spaces based on environment types and functions

to understand the scope of AMRs in public spaces. Indoor robots are most likely to communicate with humans on a one-to-one basis [23], [14], [25]. Whereas outdoor robots focus on completing their tasks while ensuring human safety and comfort [26], [27]. The broad categorisation in this taxonomy is primarily due to the limited number of studies available for each subcategory. Since only 46 papers were included in the review, creating more granular categories would result in subgroups with very few examples, limiting meaningful analysis and generalizability. Therefore, more nuanced differences are not addressed in this taxonomy.

C. Key HRI Aspects in AMRs

Safety: Ensuring safety is a fundamental aspect of human interaction with AMRs, which benefits both the general public and the robots themselves [22]. A key challenge in terms of safety is the robot's ability to avoid collisions, particularly through accurate human detection [22], [28]. Reliable human detection is crucial not only for safety but also for providing assistance and delivering effective services [29], [30]. To address this issue, various studies have explored the use of LiDAR and camera-based systems to detect human presence [27], [31], [32], [33], [34]. A study on guide robots highlighted the importance of maintaining an appropriate public distance from humans to ensure both safety and acceptance [35]. Robots should not only perceive humans as obstacles to avoid; rather, they should maintain a slightly greater distance than they would from an inanimate object in their path [36], [37]. Avoiding collisions with humans is essential, but it is equally important to prevent causing discomfort or fear [38]. Similarly, socially-aware navigation models help robots move in a way that considers both the environment and human behaviour, improving their acceptance in shared spaces [39]. Ensuring human safety goes beyond collision avoidance; it requires a two-way communication between humans and robots. Studies have shown that robots can employ anthropomorphic cues to improve human safety [40], [38]. By signalling their intended movements, robots can explicitly guide humans to navigate shared environments safely. In addition to perception-based safety measures, system design also plays a critical role in ensuring safe robot operation. A study [41] introduces a new robot control design splits robot functions into smaller, independent parts, making the system more flexible and safe. This allows the robot to respond quickly to issues and recover from errors in real-world settings. Moreover, the ability for the user to manually control the robot in emergency or necessary situations is also important [42], [41]. For example, a study on the German legal framework stated that fully autonomous driving was not permitted in public spaces at the time, requiring a human operator to supervise and intervene if necessary [43].

Trust and Acceptance: Once robots successfully detect humans, the next challenge is building trust to encourage interaction, acceptance, and even seamless coexistence in public spaces. People often experience a sense of curiosity and fascination toward robots, particularly in environments like museums and malls, where they are engaged with their surroundings [44], [45]. A five-year study involving three different museum tour guide robots revealed that when people are intrigued by robots and willing to communicate, they actively seek ways to interact within the limits of the robot's available methods [22]. Notably, when a robot initiates interaction by simply approaching a person and saying "Hello", people are more likely to engage with it. To enhance both perceived safety and willingness to interact with robots, several strategies can be employed. One approach is designing robots with a friendly and non-threatening appearance, achieved through modifications to their external design [46]. Another effective method involves incorporating anthropomorphic features to make robots more approachable. Various studies have explored this concept, from using expressive eyes to convey emotions [47] to implementing head movements that enhance engagement and relatability [48], [38]. One study involving a hand disinfection robot, designed to encourage usage, continuously faced the user, even if it did not perfectly reach its intended position, and it showed that maintaining eye contact significantly improves HRI [14]. A study involved an autonomous robot dressed up as Santa Claus during Christmas who played Jingle Bells through a loudspeaker upon detecting a person and displayed emotions via 126 red diodes on its head in a shopping mall. It randomly selected individuals to follow at a distance and attempted interaction. Post-interaction interviews revealed that 92% of participants responded positively when first approached, and 67% remained comfortable when followed, though some found it unsettling. The study suggests that robots with friendly appearances are generally well-received. Future research could focus on detecting human interest based on movement patterns before initiating interaction [49]. Sometimes, humans may also feel discomfort around robots and harm them. In a study with an indoor cleaning robot, it was observed that AMRs in public spaces are sometimes subjected to obstruction, bullying, and even vandalism [18]. Humans may block a robot's path, touch, or hit it for various reasons, e.g., fear, frustration, misunderstanding, or curiosity, especially among children. Robots need strategies to protect both themselves and humans from such behaviours. Public feedback suggests that robots should proactively warn people against harmful interactions, e.g., touching or blocking them. In another study with a delivery robot in an outdoor setting, no instances of bullying behaviour or attempts to sabotage the robot's performance were reported [26].

Communication: AMRs in public spaces must communicate effectively with diverse groups, including the elderly, children, and people with disabilities. Multimodal HRI systems that combine touchscreens, speech recognition, and visual cues help robots receive commands and respond appropriately [21]. For example, a five-month deployment of a museum tour guide robot showed advantages of using both perceptive modalities—speech recognition, physical buttons, face tracking—and expressive ones; a mechanical face and LED matrix displaying icons and animations [44]. Experimental results and user surveys revealed that people of all ages found robots with multiple communication methods more engaging and easier to interact with.

Human Assistance: In real-world environments, AMRs face challenges such as unpredictable changes, narrow pathways, and diverse human behaviours [1]. Sometimes, they require human assistance. A study on Starship delivery robots found most people perceive them as harmless and are willing to help by clearing obstacles, pushing stuck robots, or pressing traffic lights, although it is unclear if pressing buttons was to assist the robot or for personal convenience [26]. Similarly, an indoor service robot that requested help with tasks like pressing elevator buttons saw about 20% of participants respond quickly [50]. These results suggest a generally positive attitude toward aiding robots but also raise ethical concerns regarding dependence on human intervention [26].

D. Social Cues and HRI Aspects

A summary of the relevant literature on HRI methods used in the reviewed papers is presented in Table I as a guide for researchers. This overview provides a foundation for understanding the key aspects of HRI explored in this study. Table I classifies relevant studies based on social cues and key HRI aspects: Safety, Trust & Acceptance, and Communication. It highlights how different social cues, such as gazing eyes, head movement, robot approaching behaviour, motion legibility contribute to these aspects. Motion legibility refers to how easily humans can understand and predict a robot's movements, making interactions more intuitive. Online user studies using videos of motion legibility cues indicate that these cues enhance the social acceptability of robots, positively influencing public acceptance and contributing to the successful deployment of robots in shared spaces [51]. Some cells in Table I are empty, reflecting the fact that certain social cues are more relevant to some specific aspects of interaction. For example, the robot's approaching behaviour plays a significant role in fostering trust and encouraging user engagement, making it more relevant to the Trust & Acceptance aspect [14]. In contrast, detecting human presence has the highest number of cited papers because, for AMRs, human and obstacle detection is a fundamental safety requirement. While some studies focus on developing robust detection systems primarily for navigation, they inherently contribute to HRI by ensuring safe interactions, even if HRI is not their primary focus [52]. The communication aspect has fewer studies for certain cues, indicating potential gaps for future research. Overall, Table I provides insights into current research trends and areas that need further exploration for the safe deployment AMRs in human public spaces. Fig. 7 presents a frequency-based summary of the reviewed studies, visualising how often each social cue appears across the three key HRI aspects and complementing the classification in Table I by offering a more immediate view of research emphasis and gaps across social cues. Notably, detecting human presence is the most frequently studied cue, primarily in relation to safety. Conversely, cues like motion legibility and a safe-looking robot appear less frequently, especially under the communication category, indicating areas for future exploration.

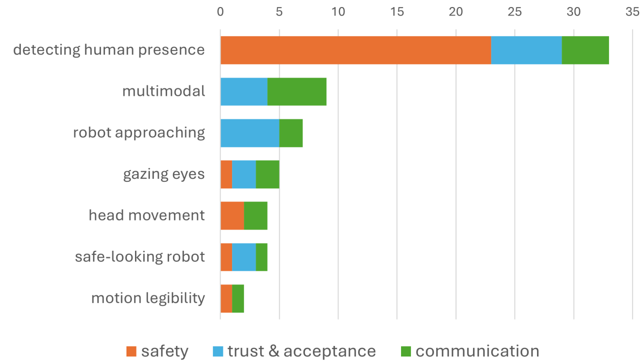

Fig. 7: Distribution of studies by social cues and HRI aspects

E. Requirements

Developing AMRs for public spaces requires careful consideration of various environmental and social factors. Pelikan et al. [62] identified four key characteristics that influence and are influenced by robot design: (1) localism, (2) environment, (3) activities, and (4) sociability. Localism refers to designing AMRs for close human interaction, such as friendly, approachable delivery robots [46] or multimodal guide robots for diverse audiences [22]. Environmental design focuses on enabling robots to navigate effectively, with some systems avoiding contact unless approached [44]

TABLE I: Classification of relevant studies based on social cues and HRI aspects

Social Cues	**Aspects of HRI**		
	Safety	**Trust & Acceptance**	**Communication**
Gazing Eyes	Mikawa [40]	Mikawa [40], Wang [47]	Wang [47], Palinko [14]
Head Movement	Mikawa [48], Lyu [38]		Mikawa [48], Lyu [38]
Robot Approaching Behavior		Palinko [14], Schomakers [17], Svenstrup [49], Hetherington [20], Yamamoto [25]	Uotani [53], Yamamoto [25]
Multimodal (Voice, Screen, Buttons, etc.)		Jeanpierre [21], Nourbakhsh [22], Jensen [44], Rea [19]	Jeanpierre [21], Nourbakhsh [22], Jensen [44], Kashif [50], Seok Ahn [23]
Detecting Human Presence	Schrick [43], Gade [32], Shoji [31], Umetani [54], Hara [27], Babel [18], Blunder [55], Marquez Gamez [52], Hiroi [35], Yang [15], Mohammadi [16], Gil [56], Karahan [24], Blunder [55], Pennisia [57], Yan [34]. Cheng [28], Hu [58], Tomizawa [42], Gunji [59], Muramatsu [60], Ventura [33], Schrick[41]	Babel [18], Hiroi [35], Gil [56], Muramatsu [60], Shahrezaie [39], Ventura [33]	Glas [45], Marquez Gamez [52], Tanaka [61], Shahrezaie [39]
Safe-Looking Robot	Kakigi [46]	Kakigi [46], Palinko [14]	Dobrosovestnova [26]
Motion Legibility (Flashing Lights & Arrows)	Hetherington [51]		Hetherington [51]

and others tailored for outdoor use [27]. Activities reflect how AMRs must adapt to dynamic and unpredictable surroundings—for instance, robots that adjust to real-time environmental changes [31]. Sociability, one of the most emphasised requirements, involves designing robots that are safe, respectful, and engaging. Examples include disinfection robots that implement safety measures [16], robots that recognise and respect personal space [35], those using music to attract attention [49], and anthropomorphic robots that clearly communicate movement intentions [14], [47].

Additional considerations include emergency preparedness, legal and ethical compliance [43], and inclusive design for accessibility, especially for users with special needs [42]. Schomakers et al. [17] proposed a two-step empirical approach to identifying key deployment requirements for semi-automated urban delivery robots. Their findings, incorporating views from bystanders and customers, highlight seven core categories, including technical specifications, safe integration into traffic, autonomous behaviour, and broader ethical and societal expectations.

VI. Discussion

From the analysis, it is evident that safety is the most crucial factor in the deployment of AMRs in public spaces. A robot should not only be safe but also appear and feel safe to users. Multimodal communication can enhance the ability of robots to interact effectively with a diverse range of people, making them more approachable and intuitive. Additionally, a deeper understanding of human psychology and behaviour is essential for designing AMRs that align with human expectations and social norms.

While this review provides a foundation for exploring these issues, the limited number of included studies highlights the need for a broader and more comprehensive review. Future research should expand on these findings by incorporating a wider range of studies and perspectives to gain deeper insights into improving HRI in AMRs. Another key limitation of the reviewed works is about testing environments. Some reviewed studies conducted experiments in controlled settings, such as laboratories or small buildings with limited human presence [40], [31]. However, since these robots are primarily designed for public spaces with higher human density, such settings may not fully capture real-world interactions. This highlights the need for better experimental environments to generate more relevant data and improve HRI functions for AMRs in public spaces. Another important limitation is that many papers do not provide specific details regarding the number of participants or their demographics, as well as the robot design specifications (e.g. size, shape or speed). The lack of such information makes it difficult to analyse HRI across different age groups, nationalities, and other demographic factors. A more comprehensive understanding of these variations would require future studies to include and report detailed participant data and robot specifications. Therefore, developing a standard for reporting HRI studies would help the community.

This review does not cover the role of robotics companies currently developing AMRs for public spaces. Investigating how these companies address HRI challenges and the specific issues they encounter could provide valuable insights for both researchers and industry professionals. Future work could explore the strategies these companies employ and the difficulties they face in deploying AMRs in real-world environments. The reviewed papers revealed that the use of sound in HRI is relatively rare. When implemented, it is typically used for multimodal responses triggered by user requests, where the system provides either written or spoken feedback [21], [23]. However, sound has not been widely utilised for navigation purposes or as yielding cues. Existing research indicates that incorporating sound in HRI can positively impact safety and perception. Sounds influence how robots are perceived, helping to communicate intent and support the localisation of mobile robots [63]. Given these findings, further research could investigate how interaction-focused sound design can facilitate more intuitive and effective communication between robots and people in shared spaces.

VII. Conclusions

The present review provides insights into the current landscape of AMR deployment, offering a taxonomy of their use in public settings and outlining key HRI requirements. Through an in-depth analysis of existing research, we identified critical aspects of HRI, including safety, trust, and communication, and examined how different interaction strategies contribute to these factors. As AMRs continue to be deployed in public spaces, ensuring effective HRI is vital for their safe and seamless integration.

Our findings highlight that safety remains the most critical element in HRI. Robots must not only operate safely but also be perceived as safe and trustworthy by the public. Additionally, multimodal communication can enhance interactions by making AMRs more approachable and intuitive. However, many challenges persist, including gaps in public perception, usability, and the limited use of sound as an interaction modality. Despite the contributions of this study, some limitations remain. The reviewed literature often lacks detailed demographic data and robot design information, making it difficult to analyse HRI across diverse studies and user groups. Moreover, this study does not examine the role of robotics companies in addressing HRI challenges, an area that deserves further investigation.

Future research should focus on expanding the scope of HRI studies to include a wider range of participants and real-world contexts. Additionally, exploring how sound-based interaction can enhance communication and navigation in AMRs may provide valuable insights. By addressing these challenges, researchers and developers can design AMRs that are not only functionally efficient but also socially acceptable, fostering greater trust and adoption in public environments.

Acknowledgements

This work was partially funded by the Turkish Ministry of National Education.

References

[1] H. R. Pelikan, S. Reeves, and M. N. Cantarutti, "Encountering autonomous robots on public streets," in *In Proc. of ACM/IEEE HRI*, pp. 561–571, 2024.

[2] S. Brill, W. Payre, A. Debnath, B. Horan, and S. Birrell, "External human–machine interfaces for automated vehicles in shared spaces: A review of the human–computer interaction literature," *Sensors*, vol. 23, no. 9, p. 4454, 2023.

[3] I. Nielsen, Q.-V. Dang, G. Bocewicz, and Z. Banaszak, "A methodology for implementation of mobile robot in adaptive manufacturing environments," *Journal of intelligent manufacturing*, vol. 28, pp. 1171–1188, 2017.

[4] A. Cherubini, R. Passama, A. Crosnier, A. Lasnier, and P. Fraisse, "Collaborative manufacturing with physical human–robot interaction," *Robotics and Computer-Integrated Manufacturing*, vol. 40, pp. 1–13, 2016.

[5] A. Dobrosovestnova, F. Babel, and H. Pelikan, "Beyond the user: Mapping subject positions for robots in public spaces," in *Proceedings of the 2025 ACM/IEEE International Conference on Human-Robot Interaction*, pp. 163–173, 2025.

[6] J. Carmona, C. Guindel, F. Garcia, and A. De La Escalera, "ehmi: Review and guidelines for deployment on autonomous vehicles," *Sensors*, vol. 21, no. 9, p. 2912, 2021.

[7] A. Boch and B. R. Thomas, "Human-robot dynamics: a psychological insight into the ethics of social robotics," *International Journal of Ethics and Systems*, vol. 41, no. 1, pp. 101–141, 2025.

[8] A. Apraiz, G. Lasa, and M. Mazmela, "Evaluation of user experience in human–robot interaction: a systematic literature review," *International Journal of Social Robotics*, vol. 15, no. 2, 2023.

[9] K. Thomasen, "Robots, regulation, and the changing nature of public space," *Ottawa Law Review*, vol. 51, no. 2, 2020.

[10] J. Woo, J. Whittington, and R. Arkin, "Urban robotics: Achieving autonomy in design and regulation of robots and cities," *Conn. L. Rev.*, vol. 52, p. 319, 2020.

[11] M. Mintrom, S. Sumartojo, D. Kulić, L. Tian, P. Carreno-Medrano, and A. Allen, "Robots in public spaces: implications for policy design," *Policy design and practice*, vol. 5, no. 2, pp. 123–139, 2022.

[12] S. O. Oruma, M. Sánchez-Gordón, R. Colomo-Palacios, V. Gkioulos, and J. K. Hansen, "A systematic review on social robots in public spaces: Threat landscape and attack surface," *Computers*, vol. 11, no. 12, p. 181, 2022.

[13] S. O. Oruma, Y. Z. Ayele, F. Sechi, and H. Rødsethol, "Security aspects of social robots in public spaces: a systematic mapping study," *Sensors*, vol. 23, no. 19, p. 8056, 2023.

[14] O. Palinko, R. P. Junge, D. G. Holm, and L. Bodenhagen, "A mobile social hand disinfection robot for use in hospitals," in *International Conference on Social Robotics*, pp. 348–358, Springer, 2022.

[15] H. Yang, M. V. Balakuntala, A. E. Moser, J. J. Quiñones, A. Doosttalab, A. Esquivel-Puentes, T. Purwar, L. Castillo, N. Mahmoudian, and R. M. Voyles, "Enhancing safety of students with mobile air filtration during school reopening from covid-19," in *IEEE ICRA*, pp. 10757–10763, 2021.

[16] A. Mohammadi, A. Kucharski, and N. Rawashdeh, "Uvc and far-uvc light disinfection ground robot design for sterilizing the coronavirus on vertical surfaces," in *Autonomous Systems: Sensors, Processing and Security for Ground, Air, Sea and Space Vehicles and Infrastructure 2022*, vol. 12115, pp. 57–63, SPIE, 2022.

[17] E.-M. Schomakers, V. Lotz, and M. Ziefle, "Requirements for automated micro-vehicles from the german public: a survey study," *European Transport Research Review*, vol. 16, no. 1, pp. 1–13, 2024.

[18] F. Babel, J. Kraus, and M. Baumann, "Findings from a qualitative field study with an autonomous robot in public: exploration of user reactions and conflicts," *International Journal of Social Robotics*, vol. 14, no. 7, pp. 1625–1655, 2022.

[19] D. J. Rea, J. E. Young, and P. Irani, "The roomba mood ring: an ambient-display robot," in *Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction*, pp. 217–218, 2012.

[20] N. J. Hetherington, R. Lee, M. Haase, E. A. Croft, and H. M. Van der Loos, "Mobile robot yielding cues for human-robot spatial interaction," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 3028–3033, 2021.

[21] L. Jeanpierre, A.-I. Mouaddib, L. Locchi, M. T. Lazaro, A. Pennisi, H. Sahli, E. Erdem, E. Demirel, and V. Patoglu, "Coaches: An assistance multi-robot system in public areas," in *2017 European Conference on Mobile Robots (ECMR)*, pp. 1–6, IEEE, 2017.

[22] I. R. Nourbakhsh, C. Kunz, and T. Willeke, "The mobot museum robot installations: A five year experiment," in *Proceedings 2003 ieee/rsj international conference on intelligent robots and systems (iros 2003)(cat. no. 03ch37453)*, vol. 4, pp. 3636–3641, IEEE, 2003.

[23] H. S. Ahn, I.-H. Kuo, C. Datta, R. Stafford, N. Kerse, K. Peri, E. Broadbent, and B. A. MacDonald, "Design of a kiosk type healthcare robot system for older people in private and public places," in *Simulation, Modeling, and Programming for Autonomous Robots: 4th International Conference, SIMPAR 2014, Bergamo, Italy, October 20-23, 2014. Proceedings 4*, pp. 578–589, Springer, 2014.

[24] S. Karahan, E. Lopez, B. Montoya, J. Shepard, H. Wu, and S. Anderson, "Real-time autonomous miniature car perception and control for package delivery," International Foundation for Telemetering, 2022.

[25] T. Yamamoto, K. Terada, A. Ochiai, F. Saito, Y. Asahara, and K. Murase, "Development of human support robot as the research platform of a domestic mobile manipulator," *ROBOMECH journal*, vol. 6, no. 1, pp. 1–15, 2019.

[26] A. Dobrosovestnova, I. Schwaninger, and A. Weiss, "With a little help of humans. an exploratory study of delivery robots stuck in snow," in *2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, pp. 1023–1029, IEEE, 2022.

[27] S. Hara, T. Shimizu, M. Konishi, R. Yamamura, and S. Ikemoto, "Autonomous mobile robot for outdoor slope using 2d lidar with uniaxial gimbal mechanism," *Journal of robotics and mechatronics*, vol. 32, no. 6, pp. 1173–1182, 2020.

[28] J. Cheng, Y. Sun, and M. Q.-H. Meng, "Robust semantic mapping in challenging environments," *Robotica*, vol. 38, no. 2, pp. 256–270, 2020.

[29] F. Camara, N. Bellotto, S. Cosar, D. Nathanael, M. Althoff, J. Wu, J. Ruenz, A. Dietrich, and C. W. Fox, "Pedestrian models for autonomous driving part i: low-level models, from sensing to tracking," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 10, pp. 6131–6151, 2020.

[30] F. Camara, N. Bellotto, S. Cosar, F. Weber, D. Nathanael, M. Althoff, J. Wu, J. Ruenz, A. Dietrich, G. Markkula, *et al.*, "Pedestrian models for autonomous driving part ii: high-level models of human behavior," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 9, pp. 5453–5472, 2020.

[31] M. Shoji, K. Oshio, and N. Kubota, "A spatial attention-based behavior coordination and scaling rule of action outputs of mobile robot in dynamic environment," in *2023 IEEE/SICE International Symposium on System Integration (SII)*, pp. 1–6, IEEE, 2023.

[32] V. Reddy Gade, D. Seth, M. K. Agrawal, and B. Tamma, "Development of autonomous uvc disinfectant robot," in *International Conference on Human-Computer Interaction*, pp. 135–151, Springer, 2021.

[33] R. Ventura and A. Ahmad, "Towards optimal robot navigation in domestic spaces," in *Robot Soccer World Cup*, pp. 318–331, Springer, 2014.

[34] Z. Yan, T. Duckett, and N. Bellotto, "Online learning for 3d lidar-based human detection: experimental analysis of point cloud clustering and classification methods," *Autonomous Robots*, vol. 44, no. 2, pp. 147–164, 2020.

[35] Y. Hiroi and A. Ito, "A pedestrian avoidance method considering personal space for a guide robot," *Robotics*, vol. 8, no. 4, p. 97, 2019.

[36] F. Camara and C. Fox, "Space invaders: Pedestrian proxemic utility functions and trust zones for autonomous vehicle interactions," *International Journal of Social Robotics*, vol. 13, no. 8, pp. 1929–1949, 2021.

[37] F. Camara and C. Fox, "Extending quantitative proxemics and trust to hri," in *31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, pp. 421–427, IEEE, 2022.

[38] J. Lyu, M. Mikawa, M. Fujisawa, and W. Hiiragi, "Mobile robot with previous announcement of upcoming operation using face interface," in *2019 IEEE/SICE International Symposium on System Integration (SII)*, pp. 782–787, IEEE, 2019.

[39] R. S. Shahrezaie, B. N. Manalo, A. G. Brantley, C. R. Lynch, and D. Feil-Seifer, "Advancing socially-aware navigation for public spaces," in *31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, pp. 1015–1022, IEEE, 2022.

[40] M. Mikawa, J. Lyu, M. Fujisawa, W. Hiiragi, and T. Ishibashi, "Previous announcement method using 3d cg face interface for mobile robot," *Journal of Robotics and Mechatronics*, vol. 32, no. 1, pp. 97–112, 2020.

[41] M. Schrick, J. Hinckeldeyn, M. Thiel, and J. Kreutzfeldt, "A microservice based control architecture for mobile robots in safety-critical applications," *Robotics and Autonomous Systems*, vol. 183, p. 104795, 2025.

[42] T. Tomizawa, S. Muramatsu, M. Sato, M. Hirai, S. Kudoh, and T. Suehiro, "Development of an intelligent senior-car in a pedestrian walkway," *Advanced robotics*, vol. 26, no. 14, pp. 1577–1602, 2012.

[43] M. Schrick, J. Hinckeldeyn, and M. Thiel, "A novel control architecture for mobile robots in safety-critical applications," in *2022 27th International Conference on Automation and Computing (ICAC)*, pp. 1–6, IEEE, 2022.

[44] B. Jensen, N. Tomatis, L. Mayor, A. Drygajlo, and R. Siegwart, "Robots meet humans-interaction in public spaces," *IEEE Transactions on Industrial Electronics*, vol. 52, no. 6, pp. 1530–1546, 2005.

[45] D. F. Glas, T. Kanda, H. Ishiguro, and N. Hagita, "Simultaneous people tracking and localization for social robots using external laser range finders," in *IEEE/RSJ IROS*, pp. 846–853, IEEE, 2009.

[46] Y. Kakigi, K. Inoue, M. Hijikata, and K. Ozaki, "Development of flexible cowl covered mobile robot in consideration with safety and design property," *Journal of Robotics and Mechatronics*, vol. 29, no. 4, pp. 630–638, 2017.

[47] Y. Wang, S. Wijenayake, M. Hoggenmüller, L. Hespanhol, S. Worrall, and M. Tomitsch, "My eyes speak: Improving perceived sociability of autonomous vehicles in shared spaces through emotional robotic eyes," *Proceedings of the ACM on Human-Computer Interaction*, vol. 7, no. MHCI, pp. 1–30, 2023.

[48] M. Mikawa, Y. Yoshikawa, and M. Fujisawa, "Expression of intention by rotational head movements for teleoperated mobile robot," in *2018 IEEE 15th international workshop on advanced motion control (AMC)*, pp. 249–254, IEEE, 2018.

[49] M. Svenstrup, T. Bak, O. Maler, H. J. Andersen, and O. B. Jensen, "Pilot study of person robot interaction in a public transit space," in *Research and Education in Robotics—EUROBOT 2008: International Conference, Heidelberg, Germany, May 22-24, 2008. Revised Selected Papers*, pp. 96–106, Springer, 2009.

[50] O. Kashif, J. Lim, E. Liu, B. MacDonald, and H. S. Ahn, "Interactive indoor logistics robot design by interacting with human," in *20th IEEE UR*, pp. 526–531, IEEE, 2023.

[51] N. J. Hetherington, E. A. Croft, and H. M. Van der Loos, "Hey robot, which way are you going? nonverbal motion legibility cues for human-robot spatial interaction," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 5010–5015, 2021.

[52] D. A. Márquez-Gámez and M. Devy, "Active vision-based moving objects detection from a motion grid," in *European Conference on Mobile Robots*, pp. 373–378, IEEE, 2013.

[53] K. Uotani, M. Kanbara, S. Nishimura, T. Kanbara, S. Satake, and N. Hagita, "Social common sense modeling of a spread-out queue in public space for a service robot," in *Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, pp. 311–312, 2017.

[54] T. Umetani, S. Ujiro, H. Matsumoto, and G. Mochizuki, "Rapid development of mobile service robot in public space for robotics challenge experiments," in *2024 8th International Artificial Intelligence and Data Processing Symposium (IDAP)*, pp. 1–4, IEEE, 2024.

[55] N. Blunder, M. Thiel, M. Schrick, J. Hinckeldeyn, and J. Kreutzfeldt, "Integration and evaluation of a close proximity obstacle detection for mobile robots in public space," *Logistics Journal: Proceedings*, vol. 2022, no. 18, 2022.

[56] O. Gil, A. Garrell, and A. Sanfeliu, "Social robot navigation tasks: Combining machine learning techniques and social force model," *Sensors*, vol. 21, no. 21, p. 7087, 2021.

[57] A. Pennisi, F. Previtali, F. Ficarola, D. D. Bloisi, L. Iocchi, and A. Vitaletti, "Distributed sensor network for multi-robot surveillance," *Procedia Computer Science*, vol. 32, pp. 1095–1100, 2014.

[58] K. Hu, C. Gu, and J. Chen, "Ltrack: A lora-based indoor tracking system for mobile robots," *IEEE Transactions on Vehicular Technology*, vol. 71, no. 4, pp. 4264–4276, 2022.

[59] K. Gunji, K. Ohno, S. Kojima, R. Bezerra, Y. Okada, M. Konyo, and S. Tadokoro, "Layoutslam: Object layout based simultaneous localization and mapping for reducing object map distortion," in *IEEE/RSJ IROS*, pp. 2825–2832, IEEE, 2022.

[60] S. Muramatsu, H. Matsuda, S. Nakamoto, D. Chugo, T. Suehiro, and H. Hashimoto, "Consideration of human movement prediction for human friendly mobile robot's path planning," in *IEEE 4th International Conference on Cognitive Infocommunications (CogInfoCom)*, pp. 235–240, 2013.

[61] H. Tanaka, "Ultra-high-accuracy visual marker for indoor precise positioning," in *IEEE International Conference on Robotics and Automation (ICRA)*, pp. 2338–2343, IEEE, 2020.

[62] H. R. M. Pelikan, B. Mutlu, and S. Reeves, "Making sense of public space for robot design," in *Proceedings of the 2025 ACM/IEEE International Conference on Human-Robot Interaction*, HRI '25, p. 152–162, IEEE Press, 2025.

[63] H. R. Pelikan and M. F. Jung, "Designing robot sound-in-interaction: The case of autonomous public transport shuttle buses," in *Proc. of ACM/IEEE HRI*, pp. 172–182, 2023.