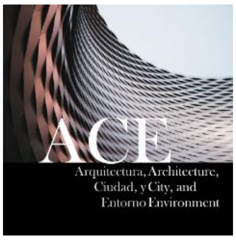

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Collaborative Transport Robots (CTRs) Applicable in the Proximal Urban Environment: A Review

Robots de transporte colaborativo (CTR) aplicables en el entorno urbano próximo: una revisión

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Abstract

Collaborative Transport Robots (CTRs) are not yet a frequent or well-known reality for many urban stakeholders, including city agents, transportation planners, policymakers, construction professionals, service providers, and other relevant participants in the urban mobility ecosystem. This lack of familiarity presents a significant barrier to the development and implementation of novel, adaptive, and creative urban mobility solutions. It also hinders the integration of CTRs into already-existing transport networks, systems, and physical infrastructure. CTRs represent a broad, versatile, and rapidly evolving category of robotic systems designed specifically for deployment in urban environments. These robots are typically equipped with an array of advanced sensors, artificial intelligence technologies, and connectivity features. These tools enable them to operate autonomously, navigate complex urban landscapes, and interact safely and efficiently with humans, vehicles, and other robotic systems in real time. Moreover, CTRs hold the potential to significantly increase the efficiency, sustainability, and safety of urban transit systems. They can help reduce congestion, streamline last-mile delivery, enhance pedestrian experiences, and offer novel mobility options for individuals who face transportation barriers, such as the elderly or those with disabilities. In addition, CTRs may contribute to reducing carbon emissions and improving air quality through the automation of low-emission mobility tasks. As the technology behind CTRs continues to develop, urban decision-makers and stakeholders must become more aware of and engaged with these innovations. A better understanding of CTR capabilities and applications will be essential for shaping future cities that are more accessible, resilient, and responsive to the needs of all residents.

Palabras clave:
Robots de Transporte Colaborativo (CTR), robots urbanos, interacción persona-robot

Resumen

Los Robots de Transporte Colaborativo (CTRs, por sus siglas en inglés) aún no son una realidad frecuente ni ampliamente conocida para muchos actores urbanos, incluidos agentes municipales, planificadores de transporte, responsables políticos, profesionales de la construcción, proveedores de servicios y otros participantes relevantes en el ecosistema de movilidad urbana. Esta falta de familiaridad representa una barrera significativa para el desarrollo e implementación de soluciones de movilidad urbana novedosas, adaptativas y creativas. También dificulta la integración de los CTRs en redes de transporte, sistemas e infraestructuras físicas ya existentes. Los CTRs representan una categoría amplia, versátil y en rápida evolución de sistemas robóticos diseñados específicamente para su implementación en entornos urbanos. Estos robots suelen estar equipados con una variedad de sensores avanzados, tecnologías de inteligencia artificial y funciones de conectividad. Estas herramientas les permiten operar de forma autónoma, navegar por paisajes urbanos complejos e interactuar de manera segura y eficiente con personas, vehículos y otros sistemas robóticos en tiempo real. Además, los CTRs tienen el potencial de aumentar significativamente la eficiencia, sostenibilidad y seguridad de los sistemas de transporte urbano. Pueden ayudar a reducir la congestión, optimizar la entrega de última milla, mejorar la experiencia peatonal y ofrecer nuevas opciones de movilidad para personas que enfrentan barreras de transporte, como los adultos mayores o personas con discapacidades. Asimismo, los CTRs pueden contribuir a la reducción de emisiones de carbono y a la mejora de la calidad del aire mediante la automatización de tareas de movilidad de bajas emisiones. A medida que la tecnología detrás de los CTRs sigue avanzando, los responsables de la toma de decisiones urbanas y otros actores deben familiarizarse más con estas innovaciones. Comprender mejor las capacidades y aplicaciones de los CTRs será esencial para dar forma a ciudades futuras más accesibles, resilientes y receptivas a las necesidades de todos los residentes.

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1. Introduction

Since the year 2000, Urban Robotics (UR) has grown rapidly due to active research in mechatronics, computer science, and mechanical engineering, but has had minimal influence on urban engineering and architecture (Tiddi et al., 2020). The urban public space -which is the context for Collaborative Transport Robots (CTRs) - is a complex environment both in terms of its activity and its structuring and at the same time, it is one that is always changing (Shaheen, 2016).

CTRs are one of the UR technologies which demonstrate the most potential. CTRs are autonomous robots that are intended to collaborate with humans to transport people and products throughout cities (Fig. 1). Unlike conventional forms of transportation like cars and buses, CTRs have a variety of benefits, such as, they are safer, more effective and more beneficial for the environment (Rezwana, 2023).

Figure 1. Delivery robots in urban areas

Source: Left: Nuro Robot (NURO, 2018); Center: Ona Robot (Puig-Pey, 2023); Right: FedEx (FedEx, n.d.).

Before CTRs may be widely used in urban settings, there are, nevertheless, a number of issues that must be resolved. The necessity to create secure and dependable navigation and planning algorithms is one of the main problems (Hataba, 2022). CTRs must be able to safely navigate through complex and dynamic urban areas without colliding with people or other vehicles (Campbell, 2010).

The requirement to create efficient coordination and communication protocols between CTRs and people is another challenge. CTRs must be able to express their goals to people and cooperate with their regulations and demands. Additionally, they must be able to communicate and cooperate with other CTRs and human transit modes. Despite these obstacles, there are numerous chances for CTRs to completely transform urban transit. CTRs can aid in reducing air pollution, noise pollution, and traffic congestion (Fagnant & Kockelman, 2015).

According to UR, cities are dynamic and complex systems that are continually changing. They are locations where interactions between people, buildings, and infrastructure occur. From the viewpoint of UR, the city's three dimensions are:

- The population of humans: People from different walks of life come together in the city to live, work, and have fun. The city is driven by its human population, which also provides the energy and vigor of the metropolis. The ability to recognize and comprehend human emotions, behaviors, and intentions is consequently a requirement for UR (Lehtovuori et al., 2015).
- Interactions between people: People engage in a range of interactions with other individuals in the city. They can either be face-to-face or digitally mediated, urban robots must, therefore, be able to navigate through groups of humans quickly and safely (Wirth, 1938).
- The physical infrastructure of the city: additionally has to be capable of preventing interference with human relationships. Buildings, streets, bridges, and other infrastructure constitute the city. The city's foundation and functional support are provided by this infrastructure. Urban robots need to be able to navigate across the city's roadways, walkways, and other infrastructure safely and effectively. They must also be capable of avoiding risks and barriers.

Urban robots are designed to work alongside humans to complete a wide range of activities, such as delivery, transportation, patrolling, and security. As described in (Munfort, 1937, p. 29) “the city, in its complete sense, then, is a geographic plexus, an economic organization, an institutional process, a theater of social action, and an aesthetic symbol of collective unity.” In order to be successful, urban robots must be able to interact with the city's three dimensions. They must first be able to navigate comfortably and securely, then they must be able to understand and recognize interpersonal relationships while maintaining pedestrians' personal space, and finally, they must be able to adapt their behaviour in response to the changing demands of the city.

As a result, UR is a rapidly growing field that has the potential to fundamentally alter how we live, work, and play in cities.

The robot's interactions with the social and physical spaces of the urban environment are called Robot City Interaction (RCI) and is influenced by a range of dimensions (Tiddi et al., 2020):

a) Robot characteristics: the specific nature of the robots that act in and with a city. This dimension considers the size, shape, speed, and capacities of the robot. The traits of the robot will influence how it interacts with the city, including how it moves through groups of people and avoids obstacles.

b) Urban characteristics: the specific urban nature of each city or neighborhood, as a set of connected infrastructures that provide services to citizens. This dimension includes elements like the design, facilities, and population density of the city.

c) Information characteristics: the specific nature of the information continuously exchanged between the robot and the city. This dimension comprises elements such as the nature and manner of information transferred between the robot and the city. The robot's ability to understand and react to its surroundings, such as how it recognises pedestrians or takes instructions from a traffic control system, will depend on the information characteristics.

d) Interaction characteristics: the nature of the interactions between robots and the city regulated by local regulations. This dimension covers elements like the laws and rules governing how robots and the city interact. The robot's ability to interact with the city, including how it may move through public areas and engage with people, will depend on its interaction features.

Urban environments and robot interactions are complex as well as varied. A strong basis for understanding these relationships is provided by the four dimensions mentioned above. We can develop robots that are safe, effective, and efficient in urban settings by better understanding these dimensions (Wu, 2020).

Table 1. Contexts and Dimensions for Collaborative Transport Robots (CTRs) in Urban Environments)

Agent Context						
Robot Type	Non-moving	Humanoid	Wheeled		Aerial	Marine
Robot Actions	Navigation	Perception	Management	Manipulation	Verb. Communication	Acquisition
Level Autonomy	Low		Medium		High	
Urban Context						
City actuators	Land		Citizens	Government	Technology	
City Domains	Living	Economy	Governance	Mobility	Environment	People
Information Context						
Data Volume	Megabytes		Gygabytes		Terabytes	Pentabytes
Data Velocity	Batch		Periodic		Near-time	Real-time
Data Variety	Unstructured			Semi-structured		Structured
Data Openness		Restricted			Open	
Information Context						
Robot-Citizens	Intimate		Personal	Social	Public	
Robot-Land	Exhibit		Passage	Special use	Secure	Backstage
Robot-Governm.		Yes			No	
Robot-Data	Acquisition		Processing		Dissemination	
Robot-Robot	Heterogenous team		Homogenous team		Single-robot team	

Source: Adapted from Tiddi et al. (2020).

2. Literature review

Urban robots, a branch of robotics science, have advanced significantly in recent years, providing ground-breaking answers to the particular problems presented by urban settings (Yigitcanlar, 2021). The development of autonomous ground robots for urban logistics and delivery is one important topic (Sonnberg, 2019). Wheeled robots that navigate sidewalks and streets to deliver products have been used for the first time by businesses. Starship Technologies, founded in 2014, launched their 40-pound delivery robot in March of 2016 in London and partnered with Domino's ((Starship, n.d.). Also, Amazon developed a fully electric delivery system called Amazon Scout. They designed it as Starship and described it as delivering packages safely to their customers. This design features an array of cameras, other technology to make the robot work autonomously (Girija, 2021). All these robots use cutting-edge cameras and sensors, including LiDAR, combined with complex algorithms to move around cities safely and efficiently, to engage with pedestrians, and to perform last-mile deliveries.

Furthermore, the use of autonomous street-cleaning robots in urban areas is growing (Kocsis, 2020; Kocsis2022). Such devices can autonomously wash streets, collect trash, and maintain cleanliness in public spaces. They decrease the environmental impact of traditional street cleaning methods while enhancing the general cleanliness of communities. Also, robots can be used in public safety and security (Räty, 2010). Autonomous security robots that are equipped with cameras and sensors patrol urban areas, providing law enforcement and security agencies with real-time surveillance and data collection. These robots can help in emergency response situations and improve their situational awareness (Burke et al., 2004; Erdelj et al., 2017).

As a nutshell, urban robots are an area of robotics that is fast developing and has a wide range of applications. They are in a prime position to be instrumental in solving logistical, sanitary, and security-related urban problems. The state-of-the-art in urban robots will probably see more innovation and adoption as urbanization increases and technology develops, eventually resulting in more effective, sustainable, and safe urban life.

More specifically, due to increasing demands for sustainable urban logistics solutions, the field of UR for last-mile delivery has seen notable improvements and innovation in recent years (Ranieri, 2018). These robots are made to handle the difficulties that come with the last stage of delivery in densely populated urban areas. They are essential in lowering prices, carbon emissions, and delivery times while boosting total productivity.

Autonomous ground robots are one of the most popular types of urban robots for last-mile delivery. These robots navigate city sidewalks and streets using advanced sensors and AI algorithms to deliver packages and other items to customers (Buchegger et al., 2018). Such ground robots have been used by firms like Starship Technologies (*Starship*, n.d.) and Kiwibot to demonstrate how they can safely interact with people and moving cars.

Drone delivery is another new technology in this field. Autonomous drones are being tested by businesses like Amazon Prime Air (Jung, 2017) and Wing for quick and distant deliveries (Benarbia, 2021). The widespread use of drones in urban settings continues to be severely restricted by regulatory issues and safety concerns.

Finally, improved path planning optimization, real-time decision-making, and enhanced obstacle avoidance are now possible in urban robot systems due to the combination of machine learning, AI, and new sophisticated sensors. These technologies are essential for ensuring that robots operate responsibly and efficiently in dense urban settings (Hoffmann, 2018). In conclusion, a variety of robotic solutions, each with specific advantages and disadvantages, constitute the state of the art in UR for last-mile delivery. These developments have the potential to transform urban logistics and have a significant impact on how last-mile delivery in cities will evolve in the future. Achieving the complete potential of urban robots for last-mile logistics will require ongoing research, regulatory cooperation, and public acceptance.

3. Robot characteristics

We might initially concentrate on three dimensions to describe the characteristics of an urban robot:

- Type of robot: This dimension describes the physical traits of a robot, such as its size, form, and abilities. This is crucial in determining the strengths and weaknesses of a robot. For instance, a large, stationary robot is best suited for tasks like manufacturing or research, whereas a small, mobile robot is well suited for tasks like transporting goods or offering aid in a hospital medical center.

- Robot actions: The tasks that a robot is capable of performing, such as delivering items, offering assistance, or gathering data, are referred to in this dimension. The robot's activities influence how the city might be affected. For instance, a robot that assists elderly people can help to enhance their quality of life, while a robot that distributes groceries can help to minimize road congestion and pollution.

- Level of autonomy and integration: This component relates to the robot's capacity to work autonomously as well as its capacity to communicate with other city facilities and systems. How the robot can interact with the city depends on its level of autonomy and integration. A highly autonomous robot can function without human supervision, whereas a highly integrated robot can communicate with other urban structures and infrastructure, such as traffic lights or intelligent buildings.

A framework for comprehending the nature of urban robots can be found in these three dimensions. Understanding these factors can help us create and use urban robots that are safe, effective, and efficient in urban settings. Furthermore, the three dimensions mentioned above do not need to be rigid. For instance, a robot that is intended to distribute goods might also be able to help people who are in need, or as another example, by incorporating new technologies, a robot's level of autonomy and integration could change over time.

3.1. Type of robot

Based on Scholtz (2003), the types of robots likely to be inserted in the Urban Robot City are classified into:

- Land-based robotic platforms: A sort of robot that is frequently employed in industrial settings with fixed bases and mobile parts, like arms. The fixed platform on which these robots are normally installed offers stability and support. The robot can move around and operate objects in its environment because of its mobile parts, such as its arms and grippers. These robots are frequently employed for tasks including product assembly, metal welding, and object painting. In warehouses and distribution centers, they can also be employed for activities like moving and handling things. For instance, Baxter platforms (Baxter platform, 2023), see Fig. 2 (a).

- Humanoid mobile robots: Robots that move around and have human-like features are known as mobile humanoid robots. They can move autonomously since they usually sit on a moving platform. Mobile humanoid robots can interact with their surroundings and perform a variety of tasks as they are equipped with a variety of sensors, actuators, and CPUs. Although they are still in the early stages of research, mobile humanoid robots have the power to completely alter how humans live and work. For example, IVO (Laplaza et al., 2022), see Fig. 2(b).

- Ground mobile robots: Usually equipped with wheels, robots that can move around on the ground. They are used for a variety of applications, including transportation, inspection and maintenance, agriculture, and military and security. In urban spaces can be found as delivery robots, like Starship, see Fig. 2(c).

Figure 2. Examples of Collaborative Transport Robot Platforms in Urban Applications

(a) (b) (c) (d)

Sources: (a) Baxter Platform (Baxter platform, 2023), (b) IVO robot (Laplaza, 2022), (c) Robot delivery starship (*Starship*, n.d.), and (d) an Autonomous Surface Robot (Storey et al. 2016).

- Marine robots and drones: The term "marine robots" refers to unmanned vehicles, both surface and underwater, commonly referred to as autonomous surface vehicles (ASVs) and autonomous underwater vehicles (AUVs). They frequently have thrusters or propellers, which enable them to move across the water, Searobotics (Autonomous surface, 2023), see Fig. 2 (d). Aerial robots (also known as drones) are unmanned aircraft systems (UAS) that can fly autonomously or be remotely controlled by a human operator. They are typically equipped with rotors, which allow them to take off and land vertically and hover in mid-air.

3.2. Robot actions

The actions that a urban robot mainly carry out in interactive scenarios include those described in Steinfeld (2006):

- Navigation: The ability of a robot to move from one point to another in a given environment. This requires the robot to be able to perceive its surroundings, plan a path, and execute that path.
- Perception: The capability of a robot to gather information about its surroundings. This information can be gathered through a variety of sensors, such as cameras, LiDAR, and radar.
- Management: The competence of a robot to coordinate its actions with those of other robots or humans. This is important for tasks that require collaboration, such as manufacturing or search and rescue.
- Manipulation: The skill of a robot to interact with objects in its environment. This can involve picking up objects, moving objects, or assembling objects.
- Verbal communication: Robot's ability to communicate with humans through speech. This can be used for tasks such as giving instructions or providing information.
- Acquisition: This is the ability of a robot to learn new skills or abilities. This can be done through experience or through training.

3.3. Levels of autonomy and integration

The definition of autonomy is already a complex problem in itself, and many taxonomies have been proposed in the literature (Goodrich & Schultz, 2007; Sheridan et al., 1978). We chose to adopt a simplified scale (from least to most) to describe the autonomy of Urban robots:

- Low autonomy: This level includes, for example, manual operations, teleoperation, and assisted teleoperation, in which aspects of a task to be performed (for example, detection, planning, execution) are performed totally or partially by a human tutor.
- Medium autonomy: This level includes the entire range of computer processing, decision support, and shared control (with or without robot initiative). In general, the robot performs its tasks autonomously, and the additional support from an external agent range from defining the task set, to determining the objectives, and monitoring the execution.
- High autonomy: This level includes the highest levels of autonomy of a robot, for example, executive control, supervisory control, and total autonomy, where detection, planning, and execution are performed by the robot under or without external control.

A multitude of problems including battery capacity, localization, decision-making, and recognition skills, restrict robot autonomy. Due to these constraints, robots find it challenging to navigate and operate in complex environments such as indoor buildings (Limosani et al., 2018).

The level of integration relates to robots' capacity to collaborate as a team with humans or other robots. This is critical for operations that necessitate the use of several robots, such as delivering products or performing services.

The introduction of Urban Micro-mobility Robots (UMRs) in the LAST MILE urban space is a promising new development in transportation technology. However, it is important to consider the demands that UMRs will place on the urban environment and on themselves.

One important requirement is the ability to operate in a network. UMRs may be able to collaborate to increase efficiency and safety. UMRs, for example, might coordinate their movements in order to avoid collisions and optimize their paths. They might also exchange information about traffic conditions and other possible difficulties.

Another important requirement is the capacity to comprehend the city as a transportation path. UMRs must be able to navigate in urban contexts safely and efficiently. This includes the ability to identify and avoid impediments like people, bicycles, and other cars. It additionally involves the ability to follow traffic rules and regulations.

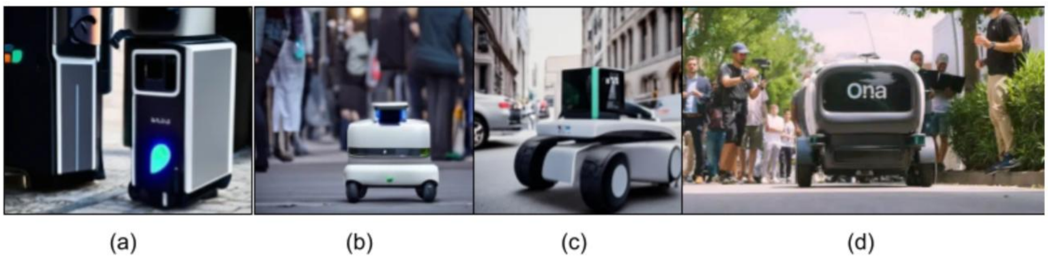
In urban contexts, UMRs must also be able to interact with humans and other robots. This includes being able to communicate with pedestrians, cyclists, and other vehicles in a safe and effective manner. It also entails being able to avoid collisions and, when required, yield to pedestrians and other cars. UMRs will need a variety of sensors, actuators, and communication devices to satisfy these requirements. They will also need advanced algorithms to enable them to travel securely and efficiently in urban situations.

The implementation of UMRs in the LAST MILE urban region is a difficult task. However, the potential advantages are substantial. UMRs might aid in the reduction of traffic congestion, the improvement of air quality, and the accessibility and affordability of transportation. We can secure the success of UMRs by carefully examining the demands they will impose on the urban environment and on themselves.

For that reason, a CTR has its own attributes:

- *Localization*: It must be able to localize itself within the urban environment, which is a very complex problem due to the limitations of GNSS systems in urban contexts caused by the multi-path and occlusions produced by the urban canyon effect in the propagation of GNSS signals (del Pino, 2020).
- *Autonomy*: it must be able to charge its batteries autonomously when it runs out of energy, see Fig. 3 (a).
- *Planning*: It must be capable of computing and following a safe path avoiding static and dynamic obstacles, see Fig. 3 (b).
- *Load, volume, and format*: The CTR must be able to transport a load with mechanical safety. The CTR must be able to transport a volume without impacting urban clearances, Fig. 3 (c).
- *Velocity*: The CTR must be able to adjust the speed of its trajectory to the conditions of each section and urban platform.
- *Stability while navigating*: The requirement is that the CTR must be able to maintain its stability while moving. This includes being able to avoid tipping over, colliding with other objects, or falling into potholes.
- *Predictability (anticipation capability):* The CTR must be able to anticipate (react) to unforeseen events that appear on the route.
- *Parking*: The CTR, during its inactivity (waiting, resting, charging) or by indication of the teleoperator, must be able to find suitable shelter for its repair, storage, or maintenance. In a scenario of urban congestion and energy saving, CTR must be parked in suitable places.
- *Communication (local and remote interaction):* The CTR must be able to communicate with the citizens it crosses and clearly express its intentions or requests, without generating reactions of adversity or distrust.

Figure 3. Scenarios of Autonomous Robot Functionality



Notes: (a) Robot charging its batteries autonomously, (b) robot navigating avoiding pedestrians in urban areas, (c) CTR transporting a load, and (d) ONA robot with decorous presence. Source: Own elaboration base on Puig-Pey et al. (2023).

- *Presence*: The CTR must be able to manifest a decorous presence (color, volume, noise), see Fig. 3 (d).
- *Remote assistance (teleoperator):* The CTR must receive remote assistance from a teleoperator (control center) in case of needing assistance (blocking, accident, doubt).

Although the previously mentioned challenges are not unsolvable, they will require a large amount of research and development. However, CTRs have many potential advantages. CTRs may contribute to reduced delays, better air quality, and more pleasant regions.

In conclusion, CTRs are a promising new technology with the potential to revolutionize urban transportation. However, several challenges need to be addressed before CTRs can be widely deployed. These challenges include ensuring that CTRs can safely navigate the urban environment, that they are accepted by the public and can communicate and express their intentions to pedestrians.

4. Urban Characteristics

From the point of view of UR, the city constitutes a complex system made up of various components that are not necessarily always included in its real implementation (Dameri, 2013). Below are the 4 main characteristics that determine urban space (i) land, or the region in which the projects are situated; (ii) technologies that are used to provide high-quality infrastructures, services, and governance procedures that benefit people; (iii) citizens, or those who should profit from the smart city, are the target audience for all smart initiatives; and (iv) the government, or the public authorities in charge of this region who are chosen by the people to make choices and decisions regarding the public space.

Concretely, urban robots can collaborate with a smart city. It is well known that a smart city is a place where traditional networks and services are made more efficient with the use of digital solutions for the benefit of its inhabitants and business (Nagenborg, 2020). Beyond employing digital technologies to better manage resources and reduce pollution, a smart city goes above and beyond. It entails improved water supply and waste disposal systems, better urban transportation networks, and more effective building lighting and heating systems. It also entails creating a city administration that is more responsive and engaging, making public areas safer, and addressing the requirements of an older population.

Urban robots are incorporated into the city as a key element of smart cities. They support a wide range of activities that are essential to the well-being of citizens and the sustainability of cities.

Specifically, urban robots can be used to improve economic competitiveness by promoting innovation, entrepreneurship, and economic growth; enhance social and human capital by promoting civic education, plurality, flexibility, creativity, cosmopolitanism, and participation in public life; improve governance by making government more transparent and participatory; make transportation more efficient and safe; protect the environment by reducing energy consumption and improving resource management; and, improve the quality of life of citizens by providing access to cultural facilities, health care, security, and affordable housing.

Therefore, urban robots have the potential to make cities more liveable, sustainable, and equitable. They are a powerful tool that can be used to address the challenges and opportunities facing cities in the 21st century.

Nevertheless, it is necessary to think about the ethical consequences of using urban robots in addition to the difficulties previously highlighted. For instance, it has to be considered who will be in charge of programming urban robots and how they will be held accountable for their activities. Furthermore, it has to be taken into account how the employment market will be affected by urban robots and how to make sure that everyone gains from their implementation, which will favor the human acceptance of these new technologies (Fig. 4). Urban robots have the potential to improve cities as places to live, regardless of the difficulties. Because they can create and use urban robots in an ethical, safe, dependable, and equitable manner.

5. Information characteristics

Urban robots must develop their assigned task in the city with agility and efficiency, so they will need to be equipped, on the one hand, with a large amount of information produced by its interior sensors, and on the other hand, with the information produced by external sensors that form part of the city's infrastructure. Typically, data is characterized by large volume (in bytes), variety (degree of structure), speed (generation, modification, processing and exchange) and access. Access to data is a crucial aspect to verify the veracity and reliability of data. In this dimension, we are interested in understanding the aspect of data sharing, that is, whether the connection is exploited privately or rather (in whole or in part) is shared. We analyse the Robot City Interaction (RCI) scenarios based on two possible values: (i) restricted if they only use private access data; and, (ii) open if they include some externally available information, such as open access data.

Figure 4. Urban robot in a last-mile delivery context

Source: Pui-Pey et al. (2023).

Urban robots are intended to handle small quantities of unstructured data (mainly sensory) in real time, mainly private or closed data. This constitutes a notable discrepancy regarding how information is managed in modern urban systems, thus, a high degree of organization is required to manage large amounts of heterogeneous information collected from different sources. In short, one of the main aspects of intelligent cities is the use of open data to promote the exchange of connections.

The opening of data has a significant impact on urban robots. Robots that have access to a broader range of information can make more informed decisions and perform tasks more efficiently and autonomously. For example, delivery robots can use real-time traffic data to avoid congested areas, cleaning robots can use camera data to identify areas that need cleaning, and security robots can use sensor data to detect potential threats.

Furthermore, robots are so far mainly used as mobile agents for data acquisition and processing thanks to advanced network technologies in cities, while less efforts are devoted to improving cooperative aspects, as demonstrated by the limited literature that it involves intimacy-personal robot-citizen interaction, multi-robot cooperation (both heterogeneous and homogeneous teams), robot-governance interaction, and data exchange/dissemination.

One important consideration in smart cities, where robots collaborate and interact with the environments, are the cooperative aspects of urban robots. Urban robots are increasingly being dedicated to perform tasks that require cooperation between multiple robots. For example, a team of robots could be used to construct a building or to provide security for a large event. Some aspects that should been mentioned are the following ones: (i) Intimacy-personal robot-citizen interaction, robots that interact with citizens need to be able to do so in a way that is respectful and sensitive to their privacy; (ii) multi-robot cooperation (both heterogeneous and homogeneous teams), robots must cooperate with each other, even if they are different types of robots with different capabilities; (iii) robot-governance interaction, robots need to interact with government agencies in order to obtain permits and permissions, and, (iv) data exchange/dissemination, robots should exchange data with each other and with other systems in the city.

In conclusion, as smart cities are rapidly evolving, the role of information and robots is becoming increasingly important. Robots that are prepared to handle the large volume, variety, and speed of smart city data will be well-positioned to play a significant role in the future of smart cities.

6. Main characteristics of robot-city interaction (RCI)

The study of interactions between robots and urban settings is known as "robot-city interaction" (RCI). Although it is a relatively new field, its significance is developing quickly as robots are more incorporated into our cities. RCI is an interdisciplinary field of study that combines cutting-edge methods and technologies from a wide range of areas, such as robotics, information and communication technologies, artificial intelligence, knowledge representation, ethics, security and privacy, to design and implement systems in which autonomous agents are integrated into complex urban environments.

An RCI system consists of various elements:

- Urban robots that act autonomously in urban contexts, both as data producers and data consumers of city knowledge;
- Smart infrastructures that centralize and digitize urban knowledge from a range of heterogeneous sources, for example, such as energy, water, transport and, ultimately, autonomous robots;
- Open interactions between robots and the environment that surrounds them, where proactivity in decision-making is necessary to face an unpredictable number of situations to be dealt with;
- Assistance services, that is, robots are deployed by and for the city to improve its own services and, consequently, the quality of life of its citizens.

RCI is a complicated and difficult field, but it has the ability to improve the quality of life in our cities. For instance, food, groceries or packages are being transported by delivery robots to people's residences and places of business; streets, parks, and other common areas are maintained by cleaning robots; to monitor neighbourhoods and prevent crime, security robots are utilized; or, people and goods are moved throughout cities by transportation robots.

Although RCI is still in its early stages, it has the potential to completely alter how people live in cities. We might expect an increase in the importance of robots in our urban life as they become more advanced and accessible.

An ideal RCI scenario would be one in which robots are already enabled with the main cognitive abilities, for example, they can fully observe (through sensors and feedback), reason (through integration, analysis and decision making) and act (through collaborative exchange of data); all actors in a city (territory, citizens, technologies and governance) are involved, that is, everyone should play an active and responsible role in the scenario and benefit from it.

There is a two-way interaction between the robot and the city ecosystem, in which robots contribute to the knowledge of the city as mobile data collectors (through data acquisition), but also benefit from the heterogeneous knowledge provided by the city (through dissemination and data exchange).

Accordingly, the primary current challenge for RCI is to comprehend how robots can interact with these extensive dynamic environments in a way that respects the following three constraints: include fully autonomous cognitive robots, involve all city agents, and establish bidirectional data communication.

6.1. RCI Challenges

In order to facilitate the design and implementation of systems in which robots and cities can better interact with each other, there exist three main challenges that will be described below: data infrastructure challenges, with the aim of improving the integration of robots into city ecosystems; challenges to improve robots reasoning; and ethical and policy challenges, with the objective of determining new rules and regulations that allow the real implementation of RCI scenarios.

- *Data infrastructure challenges*

One of the main issues that arise from the analyzed works is the difficulty of facing the high dynamism, heterogeneity and scale of modern cities (Abbas et al., 2018; Ahern, 2011; Tiddi et al., 2020). Factors such as hardware deterioration due to ambient conditions and continuous use, or the presence of citizens, whose actions are unpredictable, bring uncertainty and contradictions, difficult to handle even by the most advanced cognitive robots.

Planning in uncertain environments remains a challenge for robotics and, for this reason, few projects that are implemented on a large scale (e.g., cities, buildings, streets) have been reported (Ferguson et al., 2008; Madridano et al., 2021). One way forward is to look at it from the perspective of IoT (internet of things) and sensor networks, therefore, finding ways to ensure robust and maintainable infrastructures for reliable data collection, communication and sharing. Sensor technologies currently work in small-scale environments (smart offices, smart homes) but are often not scalable to cities, as evidenced by the little effort made to bring ambient intelligence solutions to RCI scenarios. On the other hand, it is evident that a great challenge lies in the difficulty of experimenting with an environment as large, diverse and physically distributed as a city. Issues such as deployment, testing, and simulation of RCI systems are critical to developing robust research contributions.

In addition, RCI requires efforts to rethink robots not as independent units, but as part of a larger, more complex infrastructure. This means not only improving the computational and connectivity capabilities of the platforms, but also designing and implementing methods and approaches for reliable data communication and processing, thus ensuring the seamless integration of robots with interconnected dynamic environments. While this would naturally empower robots with the ability to manage the large amounts of data they produce and that are provided by the city (the data quantity problem), an important aspect that needs to be better investigated is whether they can deal with the variety of information sources (the problem of data heterogeneity) (Lee et al., 2021).

This also opens up an interesting challenge from an ICT perspective, in terms of the capabilities offered by the data infrastructures provided by cities. Data infrastructures are a crucial element in modern cities, as they provide adequate support for the interaction of different city systems, including robots. Within smart city initiatives, core data management infrastructures have emerged as innovative solutions to build a common facility to efficiently manage, integrate and re-deliver heterogeneous data from the urban environment.

These “city data centers” (Bischof et al., 2014) are centralized nodes that control and monitor the heterogeneous information provided by different city systems (e.g. government services, transportation and traffic control, water, health, energy , waste), and whose objective is to reduce the development costs of applications that depend on said services, in addition to enabling intelligent data processing mechanisms (mining, analysis, aggregation, alignment, linking) at the scale of the entire city, in a common data infrastructure.

A robust infrastructure for data communication is the necessary condition for the interaction of robots with city environments, and would allow them to better model the environment and better plan the achievement of objectives. To do this, such infrastructures require new algorithms to process, compute, protect and privatize the flow of information from robots to the city, and new mechanisms that clearly lay out how to make sense of the available data. In other words, data science techniques that have so far been employed only in very restricted scenarios (Zweigle et al., 2009), need to be adapted to enable more flexible online data processing and sharing mechanisms. Using data with a high degree of organization, or delegating the computation to the main reasoning engine of the data hubs, are solutions that would alleviate the workload of robots, facilitating their management capabilities, their cooperation and their integration into the infrastructure. By empowering robots with the ability to extract and exploit knowledge from data centers, they could filter, prune, and constrain their reasoning, thereby improving performance in accomplishing their tasks. At the same time, robots must integrate the knowledge they continually collect into the city's data centers, so that consistent information about objects.

In summary, from the first research challenge we can identify the need to integrate robots into the infrastructures of smart cities, this more specifically requires: more robust sensors and network communications to guarantee reliable data exchange; increase the computing and connectivity capabilities of robots to address data volume issues; expand and improve the capabilities that city data infrastructures offer to robots; and, new data science solutions to extract and exploit city knowledge and address data heterogeneity.

- *Robot Capability Improvement Challenges*

The second direction to consider consists of improving the ability of robots to understand and reason with the available city data. As seen, the lack of structure in robots' knowledge representations makes data compilation and processing a time and energy-consuming task. From this point of view, semantic technologies (Berners-Lee et al., 2001) (successfully applied in scenarios that aggregate knowledge from heterogeneous sources) provide support for both the representation, integration and curation of data between sources, as well as the interaction between data and domain experts, towards what can be defined as multi-domain, navigable and accessible conceptual “knowledge city graphics.”

Semantic technologies have proven useful in robotics for high-level planning and understanding, and could be exploited as a layer for knowledge representation and sharing to facilitate the integration of mobile agents in cities (Tiddi et al., 2017). Therefore, these technologies could represent the key that allows robots to behave as drivers and contributors to a city's knowledge base, better understand the surrounding environment, reason about multiple heterogeneous knowledge sources, and improve their task performance.

Another opportunity developed by knowledge-based data management is the use of external knowledge to improve the performance of robotic tasks. In the last decade, a large amount of domain-specific knowledge has been openly published in the form of structured data, with the aim of encouraging information sharing, reuse and discovery. With this data avalanche phenomenon, building intelligent systems that are capable of exploring, integrating and exploiting large amounts of heterogeneous data collected from a variety of distributed sources has become a priority (d'Aquin et al., 2016). It has been observed that there is still a long way to go before autonomous agents take full advantage of the accessible, machine-readable knowledge available for reuse and redistribution. External knowledge could help robots improve their tasks: for example, more robust navigation could be performed by relying on open sources that represent the geometry of the environment; object search and recognition could be improved by integrating domain knowledge available in existing ontologies into robots' semantic maps; while a better understanding of the environment could be achieved by also relying on domain ontologies, rather than relying only on ad-hoc designed robot knowledge representations.

From an AI perspective, more effort should be put into representing knowledge that is relevant to robotics. There is an urgent need to design and develop symbolic representations to make robots more robust and reliable, and focused efforts on representing more common domain knowledge (as opposed to widely spread instance-based knowledge representations). Methods for evaluation and validation of robot knowledge bases are also required. From an institutional perspective, this also means expanding and encouraging open data initiatives, through the participation of citizens and data providers in the integration and acceptance of robots operating in smart city environments.

We can define the second research challenge for RCI as the need to empower robots with the ability to reason with knowledge of the city, addressing problems such as: to leverage semantic technologies to increase interoperability between robots and urban ecosystems; to exploit the large amounts of external (and open) knowledge accessible to the machine to improve the robot's tasks; to extend and refine domain knowledge representations that may be relevant to robots (and robotics in general); and, to promote and exploit open data initiatives.

- *Ethical and policy challenges*

The use of flying drones, which are primarily used in safe spaces, or driverless vehicles, which are only used as driving or pedestrian assistants, are two examples of how social and ethical barriers prevent robots from being widely used in cities. These issues must be taken into consideration when regulating a robot-city interaction. Researchers in fields like robot ethics, social sciences, data security, and privacy have the chance to look into how to make robots more morally, socially, and legally acceptable. It is important to research the best ways to create intimate and private relationships between robots and people. Trust difficulties must be resolved when it comes to social and public distance since robots in RCI must operate in settings with people who might not have given their consent to interact with them.

The social acceptance of robots by inexperienced users is a crucial issue, and ethical techniques are required to protect the safety of non-experts by promoting dynamic environments for robot operation, which will increase the interest of citizens to coexist with robotic platforms in metropolitan areas. To explain the reasoning behind robotic behaviour and decision-making, we also need resources to foster AI trust and transparency (Veruggio et al., 2016). So that robots respect laws and fundamental rights, it is necessary to have clear regulations and procedures establishing transparency of data exchange and communication. Public organizations and local authorities might better comprehend what robotic technologies can be provided in response to their urban demands by strengthening policy frameworks and focusing on people' needs, which would facilitate the interaction of robotic technologies with political and institutional components (Veruggio et al., 2020).

The final research challenge for the RCI is to establish more conscious social regulations for robots, that is:

- increasing social acceptability of robots;
- transparency tools that allow robots to explain their behavior;
- safety provisions for citizens when robots operate nearby; and,
- data protection policies when communicating and exchanging data.

Based on the above discussion, we can conclude that RCI must combine knowledge-based urban environments with modern data infrastructure technologies and robot-aware regulations.

Lastly, Roboethics also addresses the interaction between robots and humans, but rather focuses on the human ethical implications of robot designers, manufacturers, and users (Beerbaum et al., 2019). This area overlaps with RCI in that they both address social and ethical issues of the application of robots to our daily lives. However, roboethics focuses on more bioethical issues, while RCI addresses ethical implications from an urban policy perspective.

6.2. *Types of interactions in RCI*

The research field of Robot-City Interaction includes a multitude of interaction fields, the most important ones are detailed below.

- *Human Robot Interaction (HRI)*

In contrast to UR, HRI focuses primarily on human-robot interaction (and its ethical and psychological implications). Depending on elements like participant proximity or the type of robots involved, HRI examines different kinds of interactions. The main difference between RCI and HRI is that RCI studies how city services and the quality of life of citizens can be improved by deploying robots as part of an interconnected digital infrastructure.

Here, the goal is to describe how robots interact with citizens. To do this, it can use Hall's proxemic spaces tool (Hall, 1966), which additionally makes it possible to determine the interpersonal distance at which these interactions take place. Then, each space is combined with the operations that can be performed in that space, as proposed (Garrell et al., 2013; Hüttenrauch et al., 2006; Repiso et al., 2020):

  - Intimate space (0 to 0.45 m) the space closest to oneself. Allowed actions range from approaching to touching.
  - Personal space (0.45 to 1.2 m) usually reserved for interactions with friends and family. Allowed actions include following, approaching and touching.
  - Social space (1.2 to 3.7 m) for interactions between acquaintances. Allowed actions include passing, following, and approaching.
  - public space (from 3.7 m): for public speaking interactions. Allowed actions range from none (the robot and citizens do not interact at all), to avoid and follow.

Thus, researchers can develop robots and urban settings that encourage beneficial and useful human-robot interaction by studying how robots and humans behave in various settings.

- *Robot-Scenario Interaction*

The study of robot-scenario interaction focuses on how robots can interact with their surroundings to accomplish particular objectives. Robots are being used to create novel products and services in a number of contexts that can be divided into indoor and outdoor (Goffman, 2016).

Additionally, the development of robots that can learn as well as adapt to their environment is being encouraged by scientific issues in robot-scenario interaction. Creating robots that can cooperate with people and other robots is another difficult task. Then, by conceiving a future in which robots serve as our companions and helpers, robot-scenario interaction has the potential to revolutionize numerous aspects of everyday life.

- *Robot-Government Interaction*

This kind of interaction intends to assess the level of commitment of the municipal administration, for instance, whether robots are used to show effective municipal governance, or if they cooperate with municipal public services through data sharing/task assignment.

Robot-Data Interaction

This dimension's goal is to analyse how robots manage the city's data, what actions they can carry out, or how and whether they can manage the heterogeneity of data sets. Common themes about the activities that can be carried out with the data in an urban setting can be found cited in the literature (Daga et al., 2016; Sinaeepourfard et al., 2016):

  - Activities for data acquisition to gather, assess the quality, filter, and describe new data.
  - Activities involving the processing of data to handle, manipulate, and analyse the collected data in order to provide new information that supports certain data-related tasks.
  - Data dissemination activities intended to disseminate, provide, and share processed information with external systems and end users.

Thus, robots need to be able to effectively manage data to perform their tasks and improve the lives of citizens. Robots can acquire, process, and disseminate data in a variety of ways.

However, there are challenges such as heterogeneity of data sets and the need to ensure security and privacy.

- *Robot-Robot Interaction*

One exciting area of robotics research is the study of Robot-Robot Interaction. Researchers are not only testing the limits of technology but also fundamentally rethinking the potential of autonomous systems by examining and improving how robots cooperate, communicate, and coordinate with each other.

This complex field covers a broad range of applications, from teams of production robots interacting efficiently on factory floors to swarms of autonomous drones working together in search and rescue missions. Scientists and engineers are studying a number of topics, including multi-agent planning, machine learning, computer vision, and natural language processing, to fully realize the potential of Robot-Robot Interaction.

Furthermore, this research field explores the interactions between robots. Specifically, the goal is to examine whether and to what extent robot-city interactions involve robot teamwork. Yanco et al. (2004) categorized such cooperation into two types: (i) heterogeneous teams, composed of different robot types, and (ii) homogeneous teams, consisting of identical robots. While a single-robot team is also possible, it inherently involves no robot-robot interaction.

7. Autonomous Urban Transport

Autonomous Urban Transport (AUT) is a rapidly expanding area of research with the potential to revolutionize the way we move around cities. AUT refers to transportation systems that operate without human intervention. This includes self-driving cars, buses, trucks, and other vehicles.

AUT is aimed at the use of robotic agents to monitor, control, manage, etc. traffic and city mobility. Contributions in this area combine image processing, data collection, navigation and planning techniques, with the aim of improving the performance of intelligent vehicles that can navigate in dynamic and uncertain environments.

Due to accelerating technological improvements, evolving mobility paradigms, and rising environmental concerns, AUT has made significant advances in recent years. Here, we present the most recent developments in autonomous urban mobility along several key dimensions:

- Autonomous vehicle technology: Since first appearing as experimental prototypes, Autonomous Vehicles (AVs) have developed into dependable and capable ways of transportation. Modern AVs have powerful sensor systems including LiDAR, radar, cameras, and ultrasonic sensors that allow them to have an acute awareness of their surroundings. Autonomous vehicles can already make decisions in real time based on complex inputs due to machine learning techniques, especially Deep Learning. For instance, some works deal with vision and detecting issues, such as how to navigate through rain (Hashim et al., 2012; Lee et al., 2016; Schneemann et al., 2016).

- Connectivity: Communication between vehicles and other objects (V2X) is essential for autonomous urban transportation. As AVs become more linked, immediate data exchange with other vehicles, the road network, and centralized traffic control systems is made possible. The resulting connection improves adaptive cruise control, traffic flow optimisation, and vehicle safety (Lawitzky et al., 2013).

- Infrastructure Adaptation: In order to manage AVs, smart cities are investing in infrastructure enhancements. To develop environments that are AV-friendly, dedicated lanes, traffic signal synchronization, and vehicle-to-infrastructure (V2I) communication technologies are being introduced. These changes are made to improve traffic flow and reduce congestion (Ahmed et al., 2022).

- Public Transit Integration: Public transport systems include autonomous shuttles and buses. With this integration, first-mile/last-mile connection is improved, public transit is easier to reach, and the carbon impact of urban mobility is decreased (Shen et al., 2018).

- Regulatory Structure: In order to address the safe deployment of autonomous vehicles, governments are building regulatory frameworks. These frameworks address data privacy, liability, safety regulations, and vehicle testing. To manage this complex environment, cooperation between policymakers and industry collaborators is essential (Faisal et al., 2019).

- Customer approval: Consumer perceptions of autonomous city transport are changing. Safety, dependability, and cost-effectiveness are a few examples of the characteristics that affect public perception. In order to gain the public's reliability, producers of autonomous vehicles are investing more on testing and security measures (Beirão & Cabral, 2007).

The current level of autonomous urban transport represents an increasingly changing environment with huge potential for transforming urban mobility. Although technology continues to develop, it will be essential to overcome sociological, safety, and regulatory issues before autonomous vehicles are eventually to be extensively utilized in urban settings. Industry, academic, and governmental partnerships will continue to be essential in determining the direction of autonomous urban transportation.

8. Conclusions

The proper integration of robotic technologies into modern urban systems is a complex problem, as evidenced by the variety of research areas involved. However, the growing interest in research topics involving robots in cities requires an identification of the problems raised from a unified perspective.

Currently, cities are already integrating some robots with advanced perception and navigation capabilities, thanks to modern motion planning algorithms and detection technologies. The type of robots that are mostly used are terrestrial ones. This is mainly due to three reasons: firstly, robust and ready-to-use terrestrial robots are already common today, while high-performance non-terrestrial robots are still cost-prohibitive and are therefore only employed in very controlled scenarios; secondly, the known techniques for the mobility of terrestrial robots are much more advanced with respect to those of aerial and marine robots; and thirdly, current regulations significantly limit the deployment of aerial robots and, therefore, experimenting with them in specific environments remains problematic.

Interest in integrating robotic technologies in the urban environment is growing and this is demonstrated by the great involvement of urban actors in the study of city-robot interactions. Furthermore, advanced data processing and communication technologies, which are already largely involved in RCI scenarios, already enable the creation of more robust urban infrastructures, ensuring safe and efficient interactions between robots and cities.

Finally, public institutions and governments, at the same time, are promoting investments and initiatives in this area with the aim of improving their offer of services to citizens. The lack of balance in the way in which the various city agents participate in robot-city interactions, as well as the small number of experiences carried out that involve economic aspects and people's well-being, suggest that new research should be undertaken in the next future.

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10. Authorship

First author conceptualized and designed the research and authored the primary sections of the manuscript. Second and third author contributed to the completion of the paper by incorporating additional insights, and critically revising the manuscript for intellectual content, coherence, and clarity. Fourth author provided overall supervision, guided the research direction, and ensured the scientific rigor of the work. All authors reviewed and approved the final version of the manuscript.

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