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Review

From caged robots to high-fives in robotics: Exploring the paradigm shift from human–robot interaction to human–robot teaming in human–machine interfaces

Filippo Sanfilippo [a,b,*], Muhammad Hamza Zafar [a], Timothy Wiley [c], Fabio Zambetta [c]

[a] Department of Engineering Sciences, University of Agder, Grimstad, 4879, Norway
[b] Department of Software Engineering, Kaunas University of Technology, Kaunas, 51368, Lithuania
[c] School of Computing Technologies, Royal Melbourne Institute of Technology, Melbourne, AU-3000, Australia

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ABSTRACT

Multi-modal human–machine interfaces have recently undergone a remarkable transformation, progressing from simple human–robot interaction (HRI) to more advanced human–robot collaboration (HRC) and, ultimately, evolving into the concept of human–robot teaming (HRT). The aim of this work is to delineate a progressive path in this evolving transition. A structured, position-oriented review is proposed. Rather than aiming for an exhaustive survey, our objective is to propose a structured approach in a field that has seen diverse and sometimes divergent definitions of HRI/C/T in the literature. This conceptual review seeks to establish a unified and systematic framework for understanding these paradigms, offering clarity and coherence amidst their evolving complexities. We focus on integrating multiple sensory modalities — such as visual, aural, and tactile inputs — within human–machine interfaces. Central to our approach is a running use case of a warehouse workflow, which illustrates key aspects including modelling, control, communication, and technological integration. Additionally, we investigate recent advancements in machine learning and sensing technologies, emphasising robot perception, human intention recognition, and collaborative task engagement. Current challenges and future directions, including ethical considerations, user acceptance, and the need for explainable systems, are also addressed. By providing a structured pathway from HRI to HRT, this work aims to foster a deeper understanding and facilitate further advancements in human–machine interaction paradigms.

1. Introduction

Humans are inherently social beings who communicate through multi-modal means spanning audio, visual and physical forms. This social nature heavily impacts how people work together in a team of equals to collaborate on a shared goal, and the effectiveness of their combined efforts in reaching their goal. Robots that are designed to work collaboratively with humans are physical embodied systems that co-inhabit a space with their human partners. It is no surprise that the nature of how humans work collaboratively with other humans, has a heavy influence on how humans collaborate with embodied robots, using similar forms of multi-modal (audio, visual and physical) communication. Therefore, the design of multi-modal human–machine interfaces is critical to the successful design of a collaborative robot. The ultimate pursuit being a robot that is accepted by humans collaborators and an equal member of a mixed human/robot team, all of whom are striving towards a shared goal.

This position-oriented review outlines the state-of-the-art of the design of robot human–machine interfaces, and plots the remarkable paradigm shift transitioning from human–robot interaction (HRI), to human–robot collaboration (HRC), and the advent of human–robot teaming (HRT). The field of human–machine interfaces (and interaction) is vast, and can refer to widely different concepts. The starting point of human–machine interface design is HRI that delves into the study of the utilisation and interaction of humans and robots. While HRI considers the multi-modal means by which humans socialise and communicate, it has a limited focus on the exchange of commands between a human and a robot. This is typified in a "caged" robot following the directives of its human operator. HRI is thus insufficient for true team-based collaboration, much like how true human-to-human teamwork is not conducted between people in caged-off rooms. Physical interaction within a shared space is essential. Thus, the design of human–machine interfaces morphs into human–robot collaboration (HRC) paradigms that enable the exchange of forces between humans

* Corresponding author at: Department of Engineering Sciences, University of Agder, Grimstad, 4879, Norway.
E-mail address: filippo.sanfilippo@uia.no (F. Sanfilippo).

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and robots through physical contact. Of course, the safety of the human in this collaborative synergism is of prime importance. Although, "de-caged" HRC is yet insufficient as the robot is still typically viewed as a "tool" to be used by the human, rather than an equal teammate. In human teams, each individual has a role with independent thought and action, and can contribute as an equal member of the team. This is why a focus is now shifting towards the fledgling concept of human–robot teaming (HRT), where the robot is viewed as a true teammate. Yet, at the core of HRI, HCI, and HRT, is a focus on the human perspective of how humans and robots can coexist.

Regarding the possibility of coexistence between humans and robots, Isaac Asimov postulated his now-famous three "laws" of robotics that were hardwired in his fictional robots [1]:

- a robot may not injure a human being or, through inaction, allow a human being to come to harm;
- a robot must obey orders given it by human beings except where such orders would conflict with the First Law;
- a robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

These, importantly, prioritise human safety and well-being while interacting with robots. However, a real-world robot may not strictly encode these "laws" as part of its autonomous software. Instead, the focus of these "laws" on human safety has long served as a guiding principle for the ethical conduct of, and fostering trust in, the design of robot behaviours and interactions [2]. Minimal ISO safety standards for industrial robots date back to 1992 [3], with the current ISO 10218-1:2011 standard [4] noting that it can, and should, be used for non-industrial robot settings. Fundamentally, at all levels of autonomy, the top priority of interaction is that it must be safe to work with a robot. In HRI, human safety is assured by keeping the workspace of the robot separated from the human. In HRC, the complexity of autonomous software logic is gradually increased in parallel with the level of co-operative engagement, guaranteeing that robots work within predetermined limitations (such as a separation distance and limited velocity). In HRT, safety must govern the collaborative decision-making processes and undertaking of shared duties between humans and robots. Thus, at all levels, productive human–machine interfaces are predicated on safe and peaceful coexistence.

1.1. Background and significance of human–machine interfaces

To achieve any sort of cooperation, human–machine interfaces (HMIs) are essential. An HMI facilitates user-friendly interaction between humans and machines [5]. An HMI enables the exchange of information between humans and machines, making it easier for users to manage the operation of the system. Hence, its usability is the extent to which the system is effective, efficient, and satisfying for the user. Some common examples of HMIs include: Graphical User Interfaces (GUIs), commonly found in software applications, computers, smartphones, and other devices with visual elements following a WIMP (Windows, Icons, Menus, and Pointing) model [6]; Control Panels, adopted industrial settings, to provide operators with ways to control complex machinery; Voice Interfaces, allowing users to interact with machines "hands-free", i.e., only using voice commands and natural language [7]; Virtual Reality (VR), Augmented Reality (AR) or Mixed Reality (MR) Interfaces, providing immersive and interactive experiences e.g., in games, real-time simulations or training applications [8].

1.2. Relevance of multi-modal human–machine interfaces

With the increasing level of integration between humans and machines, multi-modal HMIs are becoming more and more relevant. A multi-modal HMI facilitates interaction between humans and machines through multiple modes of communication (usually referred to as input/output channels) to enhance user experience. Sensory modalities in a multi-modal HMI typically include: Vision, using graphical elements on a screen or head mounted displays (HMDs) [6]; Speech, using voice commands and receiving voice responses [7]; Gestures, using hand movements, body posture, or eye/head tracking [9]; Touch, using touch or haptic feedback [10].

The goal of a multi-modal HMI is to create a more immersive, natural and intuitive way for humans to interact with machines, mimicking how humans communicate with each other using a combination of visual, auditory, and tactile cues [11]. By leveraging multiple modalities, the interface can provide redundancy and robustness, allowing users to interact effectively in noisy and complex environments. This will be of particular importance in immersive MR applications, lending tangible and embodied form to digital data, services, and information. The variety of tasks that humans perform in real environments will only be possible to manage through the coordination of multi-modal communication channels.

1.3. Purpose and scope of the paper

The contribution of this study is to propose a novel framework for understanding and organising the evolving landscape of HRI, HRC, and HRT. Rather than providing an exhaustive survey, our aim is to offer a structured, position-oriented review that delineates the progression from simple HRI to more advanced HRC, culminating in the advent of HRT. This work examines the integration of sensory modalities, such as visual, auditory, and tactile inputs, in human–robot interfaces. A realistic running use case of a warehouse workflow is employed to illustrate key features such as modelling, control, communication, and technology throughout this evolutionary trajectory. The paradigm shift from HRI to HRT is investigated in light of current advances in machine learning (ML), sensing, actuation, robot perception, human intention detection, and participation in collaborative activities. Additionally, the study discusses current challenges and future research directions in the field of multi-modal human–machine interfaces. Key areas of focus include ethical considerations, user acceptability, and the explainability of robotic systems. By addressing these issues, we aim to contribute to a more coherent and unified understanding of HRI, HRC, and HRT, providing clarity and guidance for future research and development.

1.4. Overview of the paper organisation

This paper is organised as follows. Motivation, methodology, and comparison with existing works are delineate in Section 2. A running use case is outlined in Section 3. HRI is described in Section 4. The transition into HRC is explained in Section 5. The evolution into HRT is addressed in Section 6. The ethical and philosophical aspects of the HRI/HRC/HRT are elaborated in Section 7. Finally, conclusions and future work are outlined in Section 8.

2. Motivation, methodology, and comparison with existing works

2.1. Motivation

The objective of this work is to delineate the transition from simple HRI to more advanced HRC, and ultimately to the concept of human–robot teaming HRT. Unlike exhaustive surveys, our aim is to propose a novel framework for understanding and organising the evolving landscape of HRI/C/T. The terms HRI, HRC, and HRT are often used inconsistently across the literature, referring to disparate concepts and applications. This work strives to offer a unified, coherent, and systematic perspective on HRI/C/T, highlighting the integration of multi-modal sensory inputs and their implications for robot perception, human intention recognition, and joint task engagement. By providing a structured narrative based on a realistic running use case, we seek to clarify the distinctions and overlaps between these paradigms, and to establish a comprehensive understanding that can guide future research and applications in this field.

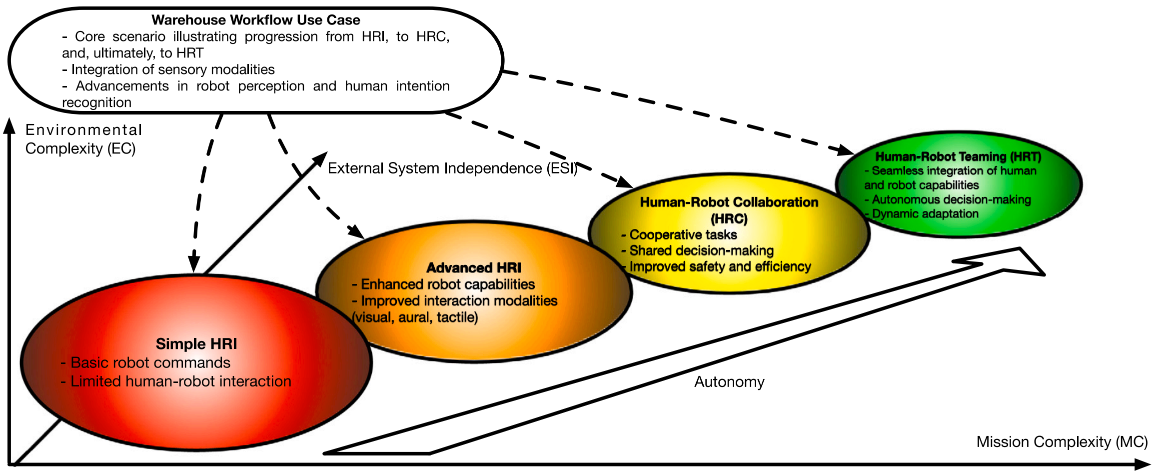

Fig. 1. The proposed review is synthesised into a narrative that follows the evolutionary path from HRI to HRT, using the warehouse workflow as a running use case.

2.2. Methodology

To ensure a systematic and replicable approach to our review, we followed a structured methodology for literature search and selection. The steps are outlined below.

The following Search Strategy was adopted:

- Databases Searched: several academic databases were utilised, including IEEE Xplore, ACM Digital Library, ScienceDirect, and Google Scholar.
- Keywords Used: a combination of keywords was used to capture the breadth of research in HMIs. These included "human–robot interaction", "human–robot collaboration", "human–robot teaming", "multi-modal interfaces", "robot perception", "human intention recognition", and "joint tasks".

The following Selection Criteria were used:

- Inclusion Criteria: We included peer-reviewed journal articles, conference papers, and review articles published in the last ten years that represent fundamental advances in the transition from HRI to HRC, and HRT. The selected papers had to explicitly address aspects of HRI, HRC, or HRT with a focus on sensory modalities, perception, and collaboration.
- Exclusion Criteria: Articles that did not provide empirical data or case studies, or those that were purely theoretical without practical implementation, were excluded.

The following Analysis and Synthesis approach was followed. As shown in Fig. 1, the analysis was synthesised into a narrative that follows the evolutionary path from HRI to HRT, using the warehouse workflow as a running use case to demonstrate practical implications. The selected papers are aggregated to each progressive step of the transition from HRI, to HRC, and, finally, HRT. This transformation can be analysed by considering different metrics. For instance, the environmental complexity (EC)—a measure of entropy and the intricacy of the environment as seen by the robot's sensors [12] may be used. Another useful metric is the mission complexity (MC), which is an estimation of the complicatedness of the environment as seen by the robot's perception system [13]. By additionally considering the external system independence (ESI) metric, which represents the independence of snake robots from other external systems or from human operators, the so-called ALFUS framework [13] can be adopted to provide a more in-depth overview of the consider transition. Progressing from HRI, to HRC, and, ultimately to HRT, the levels of EC, MC, and ESI increase.

In our work, we aim at using a more general inclusive perspective to the paradigms of HRI, HRC, and HRT. These paradigms can include robots with diverse morphologies and functionalities. The transition from HRI, to HRC, and ultimately to HRT involves not only robot arms but also mobile robots such as AGVs (Automated Guided Vehicles) and other forms of robotic systems. This evolution signifies a shift from homogeneous small groups of robots to more diverse and integrated robotic systems capable of collaborative interaction with humans.

2.3. Comparison with existing works

While existing reviews offer substantial contributions to the field, our work distinguishes itself by presenting a unified, coherent, and systematic perspective on HRI/C/T, addressing the inconsistencies in terminology and conceptual frameworks prevalent in the literature. Below, we outline how our review differs from notable existing works.

In [14], the authors revise a hierarchical framework for human–machine collaboration (HMC) that emphasises perception, decision-making, and execution within HMC. The review places particular focus on the layered and hierarchical interactions between various collaboration techniques and control methods. Our review, on the other hand, integrates several sensory modalities and emphasises practical implications through a consistent use case, aiming to present a broader, evolutionary perspective on HRI/C/T instead of restricting itself to hierarchical structures.

In [15], the authors focus on surveying HRC in industrial environments, giving particular attention to applications, safety, and intuitive interfaces. This review extensively covers physical and cognitive interaction challenges, and presents commercially available solutions and their industrial applications. While recognising the significance of these elements, our work extends beyond industrial settings to offer a more general framework applicable across various domains. Furthermore, our attention to multi-modal sensory integration and its role in changing HRI/C/T paradigms offers an additional level of study.

In [16], the authors provide an in-depth review of the literature regarding the development of industrial environments that facilitate HRC. Their work classifies guidelines and recommendations based on complexity levels of influencing factors in HRI contexts. Although this approach is thorough for industrial applications, our evaluation attempts to address the dynamic nature of these interactions, and the discrepancies in terminology and frameworks in order to unify and systematise the larger HRI/C/T domain. Our use of a running use case to illustrate practical implications also provides a unique perspective.

By positioning our review in this context, we aim to fill the gaps identified in existing literature and offer a comprehensive, evolutionary framework that can guide future research and practical applications. As summarised in Table 1, the proposed review highlights the distinct contributions and provides an evolutionary perspective on HRI/C/T that differentiates it from existing review papers.

Table 1
Highlights of Notable Existing Reviews Compared to the Proposed Evolutionary Perspective on HRI/C/T.

Aspect	[14]	[15]	[16]	Proposed review
Focus	Hierarchical HMC framework, perception, decision-making, execution	HRC in industrial settings, safety, intuitive interfaces, applications	Designing HRC workspaces, complexity levels of influencing factors	Evolutionary path of HRI/C/T, multi-modal sensory integration, unified framework
Domains Covered	General HMC	Industrial settings	Industrial settings	General across various domains with specific use case illustration
Key Themes	Hierarchical control, cooperation strategies	Safety, intuitive interfaces, industrial applications	Complexity levels, ergonomic and human-centred workspace design	Evolutionary perspective, sensory modalities, robot perception, human intention recognition
Methodology	Review of common methods in HMC framework	Extensive review of physical and cognitive interaction challenges	Systematic literature review, framework of complexity levels	Structured review with focus on fundamental advances in HRI/C/T, multi-modal integration
Use Case	None	None	None	Consistent warehouse workflow use case
Unique Contribution	Hierarchical and nested cooperation strategies	Safety and interface design in industrial HRC	Guidelines for designing safe, ergonomic, sustainable workspaces	Unified, systematic perspective on HRI/C/T, addressing terminological and conceptual inconsistencies

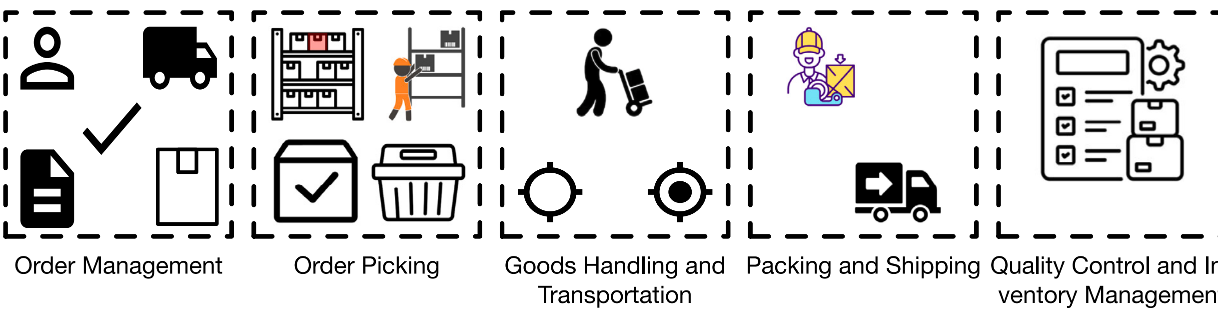

Fig. 2. Running use case: warehouse management system.

3. Running use case

A running use case is considered to demonstrated the transforming journey, transitioning from simple HRI to more enhanced HRC, consequently evolving into the concept of HRT. The running use case scenario involves a team of humans and robots working together in a warehouse, as shown in Fig. 2. The warehouse keeps various goods on shelves, and the purpose is to pick, pack, and ship the items on hand accurately and efficiently.

The following actors are considered:

- Humans: warehouse workers responsible for managing order information, picking goods, packing, and shipping;
- Robots: automated machines intended to assist with material handling, transportation, or other specific warehouse duties.

The primary objective of a warehouse is to efficiently utilise space, labour, and equipment while satisfying the expectations of customers. To achieve this, the following goals are considered:

- Efficient Order Fulfilment: the primary aim is to handle client orders properly, rapidly, and affordably;
- Optimised Warehouse Operations: the objective is to simplify warehouse procedures, reduce errors, and increase production by leveraging the combined strengths of humans and robots;
- Safe Work Environment: assuring worker safety and ergonomics by automating physically demanding or repetitive jobs.

The following general workflow is given, as shown in Fig. 2:

- Order Management:
  - orders are received;
  - orders are scheduled, resources are assigned, and picking procedures are set up.
- Order Picking:
  - the required goods are identified and collected from the shelves, verified in terms of accuracy and put into bins or containers.
- Goods Handling and Transportation:
  - bins or containers are transported from picking areas to packing stations.
- Packing and Shipping:
  - goods are retrieved from bins or containers and securely packaged for transportation;
  - shipments are labelled, prepared for delivery, and any relevant documentation is added.
- Quality Control and Inventory Management:
  - quality checks are performed to guarantee order accuracy, completeness, and compliance with standards;
  - inventory records are updated, stock levels are monitored, and shelves get refilled as needed.

Taking inspiration from [17], Fig. 3 presents a comprehensive depiction of the journey from HRI, through HRC, to the realisation of HRT. With reference to the selected running use case, this figure encapsu-

Paradigm	Caged robots	Human-Robot Interaction (HRI)	Human-Robot Collaboration (HRC)	Human-Robot Teaming (HRT)
Working steps	Sequential			Simultaneous
Working space	Separated working spaces		Shared collaboration space If synchronised: timely separated	
Working tasks	Tasks are not linked		Linked tasks	Shared tasks
Physical contact	Impossible		Possible, not necessary	Possible, often desired
Safety requirements (ISO 10218-1)	Automatic operation with safeguards	Safety-rated monitored stop	Speed and separation monitoring Power and force limiting Hand-guided control	
Robot speed	Maximum speed	Limited speed		
Interfaces	Pick-to-light systems, teach-pendant programming interfaces (smartPADs), control panels, screens or buttons		Virtual Reality (VR), Augmented Reality (AR), force feedback	

Fig. 3. Different HMIs and their characteristics.

Table 2
Human–Robot Interaction (HRI) components, separating sensors/actuators from interfaces specifically for interactions.

Sensors	Actuators	Human–Robot Interfaces
Camera	Gripper	Button Voice command Touch screen Physical switches

lates the core concepts and transitions that define the framework we propose. This figure will serve as a reference throughout this paper.

4. Human–robot interaction (HRI)

4.1. Definition and characteristics of HRI

Definition 1. Human–Robot Interaction (HRI) is a branch of research that focuses on the design and utilisation of robots, and how they interact with humans [18,19].

In this work, HRI is merely defined by the exchange of commands between a human and a robot. The workspace of the robot is separated from the human, which implies that the robot does not need to be intrinsically safe. During the early stages of HRI in industrial settings, robots were caged within protective barriers to avoid accidental collisions that may be harmful for human workers, for the robots, and for the surrounding environment. In this scenario, human personnel interacted with caged robots from outside the safety enclosures, typically for programming or supervision purposes, or with the robot powered off, for maintenance.

Referring to Fig. 3, the possibility of achieving full automation with industrial robots or HRI is considered. Working steps are sequential, working spaces are separated, working tasks are not linked, and physical contact is impossible. Safety requirements, according to the standard ISO 10218-1 [4], consider automated operations with safeguards and safety-rated monitored stops. Robot speed is either unlimited or restricted. The components of a robot that are required for implementing HRI are presented in Table 2. All components are involved in HRI. However, components that are specifically designed interfaces for interaction are listed separately.

4.2. Modelling

As shown in Fig. 4, the classic modelling of teleoperation follows the master–slave paradigm, where a human operator controls a remote system [20]. The system consists of a master device operated by the human and a slave device that replicates the operator's actions. The master device captures the operator's movements using input devices like joysticks or exoskeletons, translating them into control signals. These signals are then transmitted to the slave device, which mimics the movements of the master device, allowing the operator to control the remote system. The slave device may include sensors to provide feedback to the operator, enhancing their perception of the remote environment through haptic or visual cues. A reliable and low-latency communication link, either wired or wireless, is crucial for transmitting the control signals and sensory feedback.

In the classic master–slave teleoperation paradigm, the operator relies on the feedback from the slave device to make informed decisions and effectively control the remote system. The sensory feedback, such as haptic sensations or visual information, plays a significant role in enhancing the operator's situational awareness [21]. The teleoperation system aims to provide high precision and dexterity, enabling the operator to interact with the remote environment accurately. By combining the operator's control inputs and the sensory feedback from the slave device, teleoperation systems based on the classic paradigm facilitate various applications, including robotic surgery, hazardous environment operations, and remote exploration.

To develop a comprehensive understanding of teleoperation systems, it is essential to establish a mathematical model that describes the kinematics, dynamics, and delays involved. This mathematical modelling enables us to analyse and design control strategies for teleoperation, ensuring accurate replication of human operator inputs on the remote slave device. By formulating the equations that govern the relationship between the master and slave devices, we can investigate the impact of different factors and optimise the system's performance. This section presents the mathematical equations encompassing kinematics, dynamics, and delays, laying the groundwork for a deeper exploration of teleoperation control.

4.2.1. Kinematics equations

The kinematics equations [22] describe the relationship between the positions, velocities, and accelerations of the master and slave devices. Let q_m and q_s represent the joint positions of the master and slave devices, respectively. The corresponding velocities and accelerations are denoted by $\dot{q}_m$, $\dot{q}_s$, $\ddot{q}_m$, and $\ddot{q}_s$, respectively.

The kinematic relationship between the master and slave devices can be written as:

$$q_s = f(q_m) \tag{1}$$

where $f(\cdot)$ represents the mapping function.

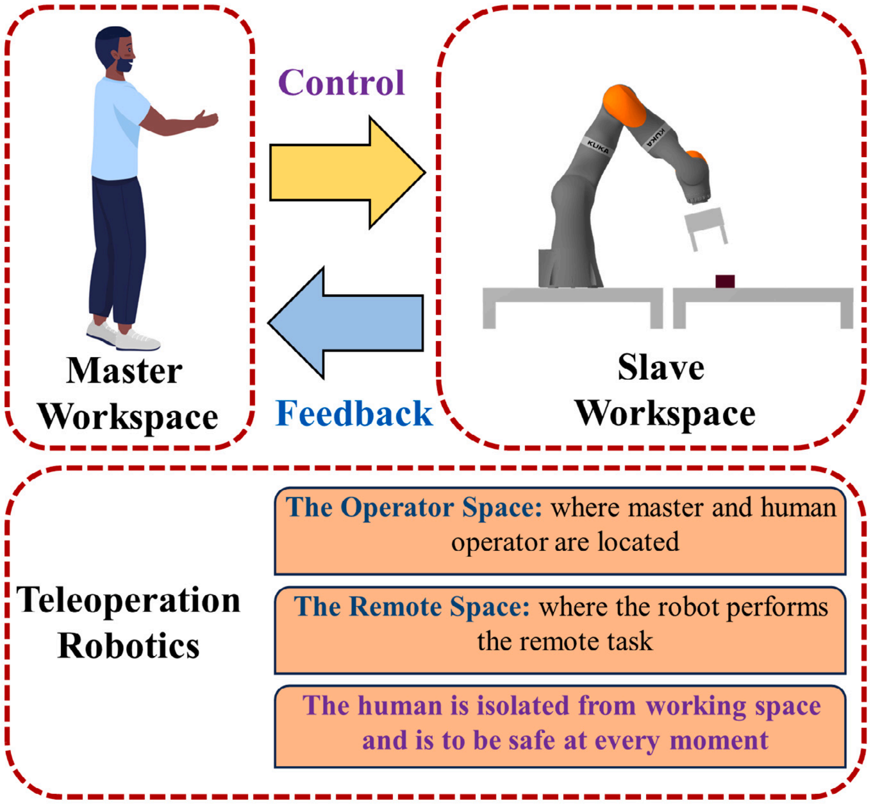

Fig. 4. Teleoperation working environment.

The velocities and accelerations of the slave device can be computed using the chain rule:

$$\dot{q}_s = J(q_m)\dot{q}_m \qquad \ddot{q}_s = J(q_m)\ddot{q}_m + \dot{J}(q_m)\dot{q}_m \tag{2}$$

where $J(\cdot)$ and $\dot{J}(\cdot)$ denote the Jacobian and its time derivative, respectively.

4.2.2. Dynamics equations

The dynamics equations describe the forces and torques acting on the master and slave devices. Let u_m and u_s denote the control inputs to the master and slave devices, respectively. The dynamics equations can be written as:

$$M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + G_m(q_m) = u_m \tag{3}$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + G_s(q_s) = u_s \tag{4}$$

where $M_m(\cdot)$, $C_m(\cdot)$, $G_m(\cdot)$, $M_s(\cdot)$, $C_s(\cdot)$, and $G_s(\cdot)$ represent the mass, Coriolis, gravity matrices for the master and slave devices, respectively.

4.2.3. Delay equations

The delay in the teleoperation system can be modelled using a discrete time-delay operator, denoted by e^{-sT_d}, where T_d represents the delay time. The delay equations can be written as:

$$q_s(t) = q_s(t - T_d) \qquad \dot{q}_s(t) = \frac{q_s(t) - q_s(t - T_d)}{T_d} \tag{5}$$

4.3. Control

Teleoperated robots can be controlled using various strategies, depending on the specific requirements of the task and the capabilities of the robot [23]. Some common control strategies for teleoperation robots are described below.

4.3.1. Direct control

Direct control is a teleoperation strategy in which the operator's input signals exhibit a one-to-one correspondence with the resulting actions of a remote robot. This control approach facilitates precise and immediate manipulation of the robot's movements, establishing a direct and responsive link between the operator and the remote environment [24]. The effectiveness of direct control relies on establishing an accurate mapping between the operator's input and the robot's output, ensuring that the intended commands are faithfully executed.

Direct control systems employ various input devices such as joysticks or control knobs, enabling the operator to exert control over the robot's motion [25]. The operator's manipulation of these input devices translates into corresponding movements of the remote robot, enabling real-time interaction. The immediate feedback loop inherent in direct control allows the operator to perceive and adjust the robot's actions based on the received feedback, fostering a sense of telepresence and enhancing situational awareness.

The advantages of direct control lie in its capacity to provide precise and responsive manipulation capabilities, enabling the operator to perform complex tasks in remote or hazardous environments. By having direct influence over the robot's actions, the operator can navigate through intricate environments, manipulate objects, and execute tasks requiring fine-grained control. However, challenges such as the operator's workload, dexterity limitations, and the need for accurate perception of the remote environment should be considered in the design and implementation of direct control systems to optimise their effectiveness and safety.

4.3.2. Gesture recognition

Gesture recognition-based control is a teleoperation strategy that enables operators to command robots using hand or body gestures [26]. This approach leverages advanced sensor technologies such as cameras or depth sensors to capture and interpret the operator's gestures, translating them into corresponding robot commands [27]. Gesture recognition-based control offers an intuitive and natural interface for teleoperation, as it allows operators to communicate their intentions through familiar physical gestures.

The process of gesture recognition involves capturing and analysing the operator's gestures in real-time. Computer vision techniques are commonly employed to extract relevant features from the captured images or depth maps, enabling the recognition and interpretation of different gestures [28]. Machine learning algorithms, such as convolutional neural networks or hidden Markov models, can be utilised to classify and map specific gestures to corresponding robot actions. By accurately recognising and mapping gestures to control commands, operators can effectively manipulate robots without the need for manual input devices or complex programming interfaces.

The advantages of gesture recognition-based control lie in its naturalness and ease of use. By leveraging familiar physical gestures, operators can intuitively convey their intentions and interact with the remote environment. This approach can be particularly beneficial in scenarios where manual dexterity is limited or where a hands-free control interface is desirable. Gesture recognition-based control finds applications in various domains, including human–robot interaction, VR/AR/MR, and rehabilitation robotics, offering a promising avenue for enhancing teleoperation experiences.

However, challenges exist in gesture recognition-based control, such as the need for robust and accurate gesture recognition algorithms, especially in complex and dynamic environments. Variations in lighting conditions, occlusions, and individual differences in gesture execution can affect the system's performance. Additionally, ensuring a diverse and comprehensive set of recognisable gestures that covers the required range of robot commands can be a non-trivial task. Nonetheless, ongoing advancements in sensor technologies and machine learning techniques continue to drive improvements in gesture recognition-based control systems, making them increasingly viable and effective for teleoperation applications.

4.3.3. Speech recognition

Speech recognition-based control is a teleoperation strategy that allows operators to command robots using spoken language [29]. By leveraging advancements in speech recognition technology, operators can communicate their instructions verbally, which are then transcribed and processed into actionable commands for the robot. This approach provides a natural and efficient means of controlling remote robots, eliminating the need for manual input devices and allowing operators to interact with the robot in a hands-free manner.

The process of speech recognition involves capturing the operator's spoken commands using microphones or other audio input devices. These audio signals are then processed using automatic speech recognition (ASR) algorithms that analyse the acoustic and linguistic features of the speech, transforming it into textual representations [30]. The recognised text is further interpreted and mapped to specific robot actions or tasks, enabling the robot to execute the desired commands. Speech recognition-based control systems can employ various ASR techniques, including traditional statistical models or more advanced deep learning-based approaches, to enhance the accuracy and robustness of the recognition process.

Speech recognition-based control offers several advantages, including ease of use and increased operator flexibility. Operators can interact with the robot using natural language, enabling more intuitive and efficient communication. This control strategy is particularly valuable in situations where the operator's hands are occupied or when a direct physical interface is impractical. Moreover, speech recognition-based control allows for seamless integration with voice assistants and natural language processing technologies, enabling more sophisticated interactions and expanding the range of possible commands and functionalities. Nonetheless, challenges in speech recognition, such as handling ambient noise, variations in accents, or complex command recognition, require ongoing research and development efforts to improve the accuracy and robustness of speech recognition-based control systems.

4.4. Communication

Communication between humans and teleoperated robots is vital for effective control and seamless interaction. In teleoperation, two common approaches for communication are unidirectional communication and bidirectional communication [31]. This subsection aims to provide detailed insights into these communication approaches.

4.4.1. Unidirectional communication

Unidirectional communication involves one-way flow of information, typically from the human operator to the teleoperated robot. It is often used when the robot performs repetitive or predefined tasks that require minimal real-time feedback. It is characterised by the following aspects:

- Command-based Communication: In this method, the human operator sends high-level commands or instructions to the robot, specifying the desired actions to be performed. These commands can be in the form of motion trajectories, waypoints, or task-specific instructions. The robot then autonomously executes the received commands without further interaction with the operator.
- Programming Interfaces: Unidirectional communication can also be facilitated through programming interfaces, where the human operator writes scripts or programs that define the robot's behaviour. These programs are executed by the robot without the need for real-time interaction or feedback from the operator.

The **advantages** of unidirectional communications are: simplification of the control interface, reducing cognitive load on the operator; suitability for tasks that involve repetitive or predefined actions; clear separation of control and execution, allowing the robot to operate autonomously once the commands are received.

The **limitations** of unidirectional communications are: lack of real-time feedback limits the operator's situational awareness; inability to adapt to dynamic or unpredictable environments; limited ability to handle complex tasks that require constant interaction or adjustment.

4.4.2. Bidirectional communication

Bidirectional communication enables a continuous exchange of information between the human operator and the teleoperated robot. This approach allows for real-time feedback, enhancing the operator's situational awareness and providing better control over the robot's actions. It is characterised by the following aspects:

- Telepresence: bidirectional communication can involve video and audio streams, allowing the operator to perceive the robot's environment and communicate with the remote environment in real-time. This approach provides a sense of telepresence, where the operator feels present at the robot's location, facilitating intuitive control and decision-making.
- Haptic Feedback: another aspect of bidirectional communication is haptic feedback, which involves the transmission of forces, vibrations, or tactile sensations between the operator and the robot. By providing force feedback, the operator can perceive and interact with the remote environment more effectively, enhancing control precision and enabling tasks that require delicate manipulation.

The **advantages** of bidirectional communications are: real-time feedback enhances operator situational awareness and decision-making; enabling control in dynamic and unpredictable environments; facilitating complex tasks that require constant interaction and adjustment.

The **limitations** of bidirectional communications are: increasing complexity in terms of system design and integration; higher bandwidth requirements for transmitting real-time data; challenges in replicating haptic sensations accurately over a distance.

Both unidirectional and bidirectional communication approaches have their merits and applications in teleoperated robot control. The choice of approach depends on the nature of the task, the level of operator involvement, and the available resources. Advances in technology and communication protocols continue to improve the effectiveness and efficiency of human–robot communication, leading to more capable and immersive teleoperation systems.

4.5. Technology

4.5.1. Sensors

In HRI, sensors are typically incorporated directly on board of the robots themselves. This approach offers various advantages. Firstly, it enables the robots to obtain direct measurements and monitor their internal states and behaviours, including factors like position, orientation, velocity, and applied forces [32]. Secondly, onboard sensors provide localised perception of the robot's immediate surroundings. By integrating sensors into the robot's structure, it can gather real-time data about its environment, such as detecting objects, sensing proximity, or perceiving environmental cues [33]. This localised perception allows the robot to make prompt decisions and adapt its behaviour to the specific context encountered during HRI. Additionally, having sensors onboard facilitates seamless integration and communication within the robot's control architecture. By incorporating sensors directly into the robot, the collected data can be efficiently processed and utilised for control algorithms and decision-making. This streamlined approach ensures rapid response times and efficient computation as the sensor data is readily available within the robot's internal system. Moreover, the presence of onboard sensors contributes to the overall safety and reliability of HRI. With sensors integrated into the robot, it becomes capable of detecting potential collisions, obstacles, or hazardous conditions in its surroundings. This empowers the robot to take proactive measures and ensure the safety of both itself and the humans involved in the interaction. However, onboard sensors in HRI have some drawbacks to consider. They provide limited perception, have constraints in range and accuracy, increase system cost and complexity, are prone to failures, and lack scalability and adaptability. These factors can impact the robot's awareness, decision-making, and overall performance. However, proper system design, redundancy measures, calibration, and maintenance can help mitigate these disadvantages and ensure effective and safe HRI interactions.

Typically, sensors, such as encoders or position sensors are used to provide feedback on the actuators' position, velocity, and applied forces. This feedback is crucial for closed-loop control, where the operator can monitor and adjust the robot's actions based on real-time information [34].

Additional onboard sensors can be employed for teleoperation in HRI to provide the human operator with feedback and information about the robot's state. Force or tactile sensors measure forces and pressures experienced by the robot during interaction with objects or the environment [35]. These sensors can be integrated into robot grippers, end-effectors, or other robot body parts. By providing feedback on the contact forces, they enable the operator to perceive the physical interactions and make adjustments in real-time. Tactile sensors are particularly valuable in tasks that require delicate manipulation or tasks where force feedback is critical, such as surgery or handling fragile objects [36].

Inertial sensors, such as accelerometers and gyroscopes, measure the robot's acceleration, velocity, and orientation. These sensors are crucial for tracking the robot's movements and estimating its pose in space [37]. In teleoperation, inertial sensors can be used to track the operator's hand or body movements and transfer them to the robot. This allows for intuitive and natural control of the robot, where the operator's motions directly correspond to the robot's actions.

4.5.2. Actuators

Actuators play a crucial role in teleoperated robots by converting control signals from human operators into physical motion. These devices are responsible for executing the desired actions and movements of the robot in the remote environment. When considering HRI, where working steps are sequential, working spaces are separated, working tasks are not linked, and physical contact is impossible, rigid actuators are commonly used in teleoperated systems.

Rigid actuators are mechanical devices that generate motion through the application of forces or torques. These actuators are designed to provide robust and precise movement, making them suitable for a wide range of teleoperation tasks. Some common types of rigid actuators used in teleoperated robots include electric motors, hydraulic actuators, and pneumatic actuators.

Electric motors are widely used in teleoperated systems due to their high controllability and efficiency. They can generate rotational motion by converting electrical energy into mechanical energy. Electric motors offer various configurations, such as direct current (DC) motors, stepper motors, and servo motors, each with specific advantages in terms of torque, speed, and position control. These actuators are capable of providing precise and repeatable motion, making them suitable for tasks requiring accurate positioning or manipulation [38].

Hydraulic actuators utilise pressurised fluid to generate linear or rotary motion. They are known for their high force capabilities, making them ideal for applications that require heavy lifting or exerting substantial forces [39]. Hydraulic actuators offer excellent control over force and speed, allowing operators to perform tasks with precision. However, their complex hydraulic systems require additional components, such as pumps, valves, and fluid reservoirs [40], making them bulkier and more challenging to integrate compared to electric actuators.

Pneumatic actuators, similar to hydraulic actuators, use compressed air or gas to generate mechanical motion. These actuators are lightweight, cost-effective, and can provide high-speed movements [41]. Pneumatic actuators are often employed in applications that require quick and agile motions, such as robotic arms in teleoperated assembly lines [42]. However, they typically have lower force capabilities compared to hydraulic or electric actuators, limiting their suitability for tasks requiring heavy loads.

Regardless of the type of rigid actuator used, teleoperated systems must ensure effective control and feedback mechanisms. Actuators are typically integrated with sensors, such as encoders or position sensors, to provide feedback on the actuator's position, velocity, and applied forces. This feedback is crucial for closed-loop control, where the operator can monitor and adjust the robot's actions based on real-time information. The actuators, sensors, and interfaces for HRI are shown in Fig. 5.

4.5.3. Interfaces

Interfaces play a crucial role in facilitating effective teleoperation and HRI in various domains. One notable interface is the teach-pendant programming interface, commonly known as smartPADs. These handheld devices enable operators to program and control robots with ease and precision [43]. SmartPADs typically feature intuitive touchscreens that display a graphical representation of the robot's configuration and task-specific controls. For instance, in industrial manufacturing, a smartPAD interface allows operators to teach a robot arm specific movements and positions by physically guiding it through the desired motions. This tactile interaction enhances the ease of programming and enables rapid task reconfiguration.

Control panels are another prevalent interface in teleoperation HRI, primarily employed in complex robotic systems [44]. These panels consist of an array of buttons, switches, and dials that allow operators to control different aspects of the robot's behaviour. For example, in the field of unmanned aerial vehicles (UAVs), a control panel may feature buttons for initiating takeoff, landing, or specific flight manoeuvrers.

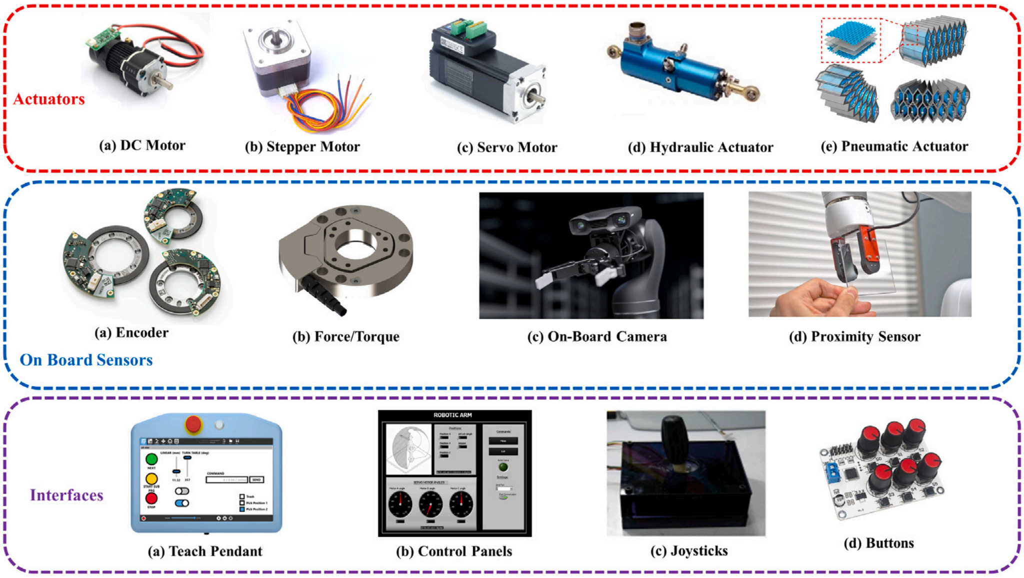

Fig. 5. Actuators, sensors, and interfaces for HRI.

By providing dedicated controls for specific functions, control panels ensure precise and reliable operation of the robotic system.

Screens also serve as prominent interfaces in teleoperation HRI, offering visual feedback and information exchange between humans and robots. These screens may display real-time video feeds from robot-mounted cameras, enabling operators to perceive the robot's surroundings remotely. In medical teleoperation, a surgeon might rely on a screen displaying high-definition images captured by a robot-assisted surgical system to perform intricate procedures with enhanced precision and visual clarity.

Furthermore, buttons are widely used as interfaces for teleoperation HRI, particularly for discrete command inputs. These buttons can be physical or virtual, depending on the specific context. For instance, in a teleoperated space exploration mission, buttons on a control console might allow operators to trigger different actions like sample collection, data transmission, or instrument deployment. Virtual buttons can also be implemented in touchscreen interfaces, where pressing on the screen emulates the function of a physical button.

Interfaces such as teach-pendant programming interfaces (smartPADs), control panels, screens, and buttons are essential components in teleoperation HRI. These interfaces enable intuitive control, visual feedback, and efficient information exchange between humans and robots in various domains, ranging from industrial manufacturing and UAVs to medical teleoperation and space exploration. Their design and implementation are crucial for enhancing teleoperation efficiency, user experience, and overall task performance.

Despite their advantages, interfaces such as teach-pendant programming interfaces, control panels, screens, and buttons in teleoperation HRI also have notable disadvantages. One significant limitation is that the majority of HRI primarily occurs during the programming phase, which often takes place offline. While these interfaces excel at sending commands and instructions to robots, they typically lack the ability to effectively convey detailed feedback from the robot to the human operator. This asymmetry in information flow can hinder situational awareness and compromise the operator's ability to make informed decisions or adjustments in real-time. For instance, in a teleoperated robotic surgery scenario, relying solely on a screen interface might limit the surgeon's perception of haptic feedback, making it challenging to gauge tissue texture or instrument force feedback. Such limitations can potentially lead to suboptimal task execution, reduced safety, and decreased overall performance in teleoperation systems. Therefore, addressing the deficiency in conveying real-time robot feedback to operators is a crucial area of improvement in teleoperation HRI interfaces.

4.6. Implementation of the running use case

During the infancy of HRI, human workers and caged robots worked together to fulfil customer orders in the warehouse. Caged robots are usually big, stationary devices that execute specific tasks inside a constrained space. To ensure the safety of human employees and to prevent accidental contact or collisions, these robots are physically contained in protective cages identified as safety enclosures.

In this case, the workflow is adapted as follows:

- Order management:
  - human workers receive orders electronically or via a centralised system;
  - human workers schedule/prioritise orders, assign resources, and set up picking procedures;
  - human employees identify the goods required for each order and devise the most effective order fulfilment strategy.
- Order picking:
  - human workers are responsible for navigating the warehouse aisles and locating the necessary goods;
  - human workers identify the correct goods and quantities by using handheld devices or pick-to-light systems [45], which use light indicators installed on shelves or storage locations. When a certain product needs to be picked, the corresponding indicator flashes, directing the human employee to the needed goods;
  - once the goods have been identified, human personnel manually remove them from the shelf and arrange them in bins or containers.
- Goods Handling and Transportation:
  - robots that are caged, fixed to specific areas or guided along predefined paths, assist human workers with goods handling and transportation;
  - human personnel or a centralised system order the caged robots to collect the bins or containers enclosing the selected items;

- caged robots transfer the bins or containers to a centralised packing station using built-in conveyors, elevators, or specialised grippers;
- caged robots follow predefined routes or respond to directions from human operators to guarantee correct and efficient transportation.

• Packing and Shipping:

- human employees receive the carried bins or containers from the caged robots at the centralised packing station;
- human workers verify the products for quality, correctness, and completeness before beginning the packing process.
- human employees secure the goods for transportation by employing the proper packing materials, paperwork and labelling standards.

• Quality Control and Inventory Management:

- human personnel execute quality control inspections at various phases of the order fulfilment process. They check the selected products to guarantee accuracy, product quality, and the identification of any damaged or faulty items. During the packaging step, human personnel also do final inspections to verify that the products meet the needed requirements before delivery;
- human workers update the inventory system to reflect the items picked, packed, and shipped. They undertake physical inventory counts on a regular basis to resolve any inconsistencies between system records and real stock levels;
- human workers replenish the shelves when necessary, ensuring an appropriate supply of goods for future orders.

4.7. Limitations of HRI

The restricted nature of HRI and the caged-robot is highlighted by studies into the human perspective of and quality interactions. Interactions are evaluated through different metrics [46–48]: the usefulness of the robot; the ease of use in interacting with the robot; the adaptability of the robot within the environment; the perceived intelligence of the robot by human collaborators; the perceived control over the robot's behaviour; the level of anxiety towards the robot; the human enjoyment of using (or collaborating with) the robot.

Although these studies focus on the HRI sub-domain of social robotics, which are embodied systems explicitly designed to provide social interactivity with people, these metrics are expandable beyond to HRI in general. Ultimately, a robot system intended for collaborating with people that fails to satisfy all of the above categories is less likely to be used in practice. That is, a collaborative robot must be perceived as useful, easy to work with, able to adapt to each task, believed to be independently intelligent but permitting a human to retain control over the robot, all invoking minimal anxiety and ultimately an enjoyable platform with which to engage.

A recurrent theme that impacts whether collaborative robots satisfy these criteria is the "sociability" of the robot and the robot's physical presence to co-exist with human partners [46]. That is, the overall use of the robot improves the more "social" the robot appears and the more it physically interacts. Regular interaction improves the acceptance of the robot, along with utilitarian factors such as a shared 'important or meaningful' goal, along with the robot providing useful feedback or information [47]. Studies of the quality of interactions in applications that overlap with our running use case, including internal office delivery robots [49], the collaborative manufacturing Baxter robot [50], and service robots for aged-care [51], all show the importance of moving beyond simple HRI. With regular embodied interaction, human collaborators establish a view that the robot has a personality, or "their-own mind" with their own agency and intent. The more a person interacts with the robot, the more the human perception and acceptance improves, to the point that the interactions take on a feeling of being "human-like". Conversely, limited engagement can introduce a misalignment between the goals of the human and robot, and in some circumstances, lead to a perception that the robot takes unwanted precedence over humans co-existing with the same space [49].

Thus, the limitation of HRI is clear. To obtain metrics of robot acceptability and long-term use, the design of the human–machine interface must move beyond "the cage", to embodied systems that co-exist with humans in the same space.

Table 3
Human–Robot Collaboration (HRC) components, separating sensors/actuators from interfaces specifically for interactions.

Sensors	Actuators	Human–Robot Interfaces
Camera	Gripper, Robot Arm	Voice command
Force/Torque Sensors		Gesture recognition
Depth Sensors		Touch screen
Microphone		

5. Human–robot collaboration (HRC)

5.1. Definition and characteristics of HRC

Definition 2. Human–Robot Collaboration (HRC) involves the exchange of forces between humans and robots through physical contact. This necessitates ensuring the safety of the robot, requiring monitoring and control of forces and torques. It is crucial to consider the minimum standard requirements outlined in ISO 10218-1 [4].

Referring to Fig. 3, working steps are still separated, working spaces can be synchronised and timely separated, working tasks are linked, and physical contact is possible, but not necessary (i.e., controlled collisions, impedance and admittance control). Concerning minimum requirements according to the standard ISO 10218-1 [4], speed and separation monitoring, power and force limiting are achieved. Robot speed is limited.

5.2. Modelling

As described previously, when considering HRI, a teleoperated robot system is commonly formed by two different scenarios: the operator site where the master and the human operator are located, and the remote site where the robot performs the remote task. It clearly shows that the human is "isolated" from the working environment and is to be safe at every moment. However, for the case of HRC, a relatively new concept of robot teleoperation, called "proprio and teleoperation", introduces a scenario where sometimes both areas, the operator and remote environment are the same, but not at all times [52], as shown in Fig. 6. The human operator teleoperates the robot whose working environment includes themself. This paradigm enables the possibility of adopting teleoperated robotics in a home environment or a work environment. When considering HRC, dynamic modelling is necessary, as humans and robots exchanges forces between each other. Dynamic modelling of HRC involves capturing the dynamics and interactions between humans and robots [53]. This includes understanding the forces exchanged between the human and robot, the motion of both entities, and the control strategies employed to achieve effective collaboration. To model the dynamic interaction between humans and robots, we need to consider the dynamics of both the human and the robot, as well as the forces exchanged during their interaction. Table 3 lists the components of a robot that are required for implementing HRC, separating sensors and actuators from interfaces that are specifically designed for supporting human–robot interactions.

In the following, we will focus on the physical modelling of a robotic arm. We will discuss the forward kinematics and dynamics of the system, providing mathematical equations to describe its behaviour.

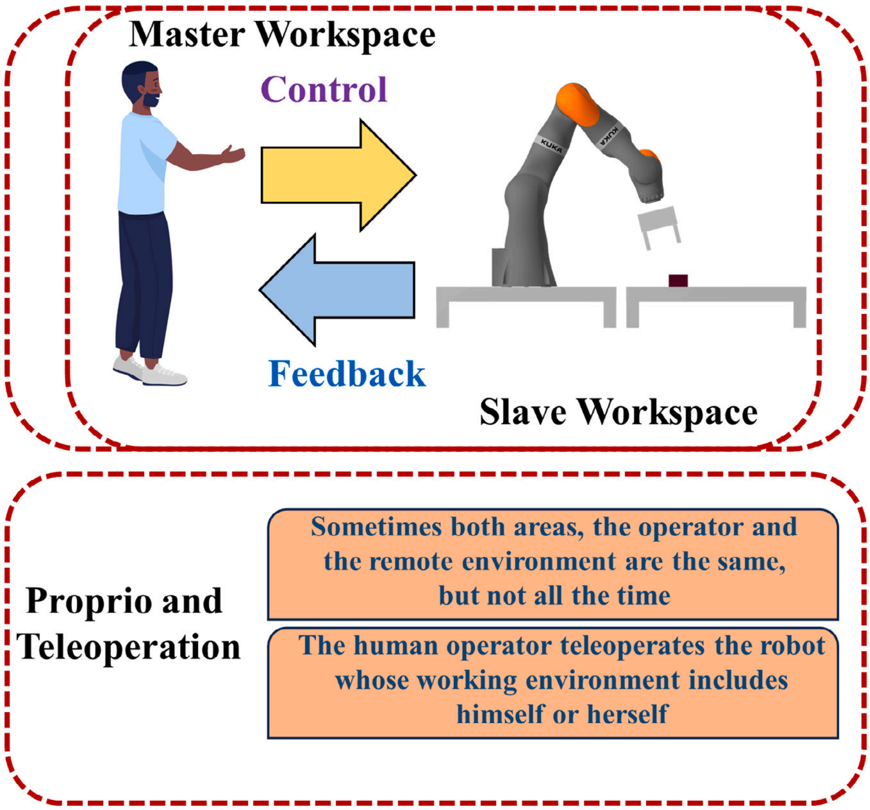

Fig. 6. Proprio working environment.

5.2.1. Forward kinematics

The forward kinematics relate the joint angles to the position and orientation of the end-effector.

These relations determine the position x of the end-effector based on the joint angles q. For an in-depth overview of the formulation of these equations, the reader is referred to [54].

5.2.2. Robot dynamics

The dynamics of the robotic arm involve understanding the forces and torques acting on the arm segments. We can use Lagrange's equations of motion to describe the dynamics of the robotic arm.

Let q be the vector of joint angles, q' be the vector of joint velocities, q'' be the vector of joint accelerations, τ be the vector of joint torques, $M(q)$ be the mass matrix, $C(q, q')$ represent the Coriolis and centrifugal forces, and $G(q)$ represent the gravitational forces. The dynamics equations can be written as:

$$M(q) \cdot q'' + C(q, q') \cdot q' + G(q) = \tau \quad (6)$$

By solving these equations, we can determine the joint torques required to achieve desired motions or respond to external forces.

5.2.3. Human dynamics

Human dynamics refers to the motion and forces exerted by the human during the interaction. The human can be considered as a complex system with its own dynamics and control mechanisms. The dynamics of the human body can be represented using biomechanical models or simplified models depending on the level of detail required.

Let us denote the joint angles of the human's limbs as $\theta_1, \theta_2, \ldots, \theta_n$. The dynamics of the human body can be described using equations similar to those used for robot dynamics, such as the Euler–Lagrange equations:

$$M_H(q_H)\ddot{q_H} + C_H(q_H, \dot{q_H})\dot{q_H} + G_H(q_H) = \tau_H \quad (7)$$

where q_H represents the vector of human joint angles, $\ddot{q_H}$ represents the vector of human joint accelerations, $\dot{q_H}$ represents the vector of human joint velocities, $M_H(q_H)$ is the mass matrix of the human body, $C_H(q_H, \dot{q_H})$ represents the Coriolis and centrifugal forces on the human body, $G_H(q_H)$ represents the gravitational forces on the human body, and τ_H represents the joint torques or forces exerted by the human.

The human's dynamics model can be further extended to include more detailed representations of the human body segments, such as arms, legs, and torso, as well as their interactions.

5.2.4. Interaction forces

In a dynamic human–robot interaction, forces are exchanged between the human and the robot. These forces depend on the contact interactions between the human and the robot, as well as the control strategies employed.

Let us denote the interaction forces exerted by the human and the robot as F_H and F_R, respectively. These forces are typically determined based on the contact models and control strategies used in the specific application.

The interaction forces can be influenced by various factors such as the stiffness of the robot's end-effector, the impedance control strategy employed, the compliance of the human's limbs, and the force/torque sensors integrated into the system.

Mathematically, the interaction forces can be represented as:

$$F_H = f_H(q_H, \dot{q_H}, q_R, \dot{q_R}, F_R, F_{ext}) \quad (8)$$

$$F_R = f_R(q_H, \dot{q_H}, q_R, \dot{q_R}, F_H, F_{ext}) \quad (9)$$

where f_H and f_R represent the interaction force models for the human and the robot, respectively. These models take into account the joint angles, velocities, and the forces exchanged between the two entities, as well as any external forces F_{ext} acting on the system.

The interaction forces play a crucial role in determining the collaborative behaviour of the human and the robot. They influence the stability, comfort, and overall performance of the interaction.

5.3. Control

5.3.1. Control strategies

Control strategies are employed to govern the behaviour of both the human and the robot during the interaction. These strategies aim to achieve smooth and coordinated motion, force regulation, and task completion.

For the human, control strategies can involve feedback mechanisms based on sensory inputs, such as visual feedback, proprioceptive feedback, or force/torque feedback. These feedback signals can be used to adjust the human's joint angles, velocities, and forces exerted during the interaction [55,56].

Similarly, the robot employs control strategies to regulate its motion and interaction forces. These strategies can include impedance control, force control, or admittance control. The control signals are generated based on the desired behaviour, sensory feedback, and the interaction forces [57,58].

The specific control algorithms and strategies employed in human–robot interaction depend on the application, safety considerations, desired task performance, and user preferences.

5.3.2. System equations

The system of equations can be further extended to include the interaction forces with the environment, represented by F_{ext}, if applicable:

$$M_H(q_H)\ddot{q_H} + C_H(q_H, \dot{q_H})\dot{q_H} + G_H(q_H) = F_H + F_{ext} \tag{10}$$

$$M_R(q_R)\ddot{q_R} + C_R(q_R, \dot{q_R})\dot{q_R} + G_R(q_R) = F_R + F_{ext} \tag{11}$$

These equations provide a comprehensive representation of the dynamic interaction between the human and the robot, accounting for the internal dynamics of each entity as well as the forces exchanged during their interaction.

Solving these equations allows us to analyse and predict the behaviour of the human–robot system, design control strategies for achieving desired collaboration, optimise performance, and ensure safety.

It is important to note that the specific formulation and complexity of the system equations may vary depending on the level of detail required, the type of interaction, and the specific modelling approach employed.

5.4. Communication

HRC involves a dynamic interplay between humans and robots, characterised by the exchange of forces through physical contact. This form of interaction requires sophisticated communication mechanisms to ensure seamless and effective collaboration. Communication in HRC is inherently bidirectional, enabling both parties to share information, respond to changes, and adapt their actions accordingly [59].

5.5. Bidirectional communication

In HRC, communication is not merely a one-way transmission of commands from the human to the robot, as seen in traditional HRI. Instead, it involves a continuous loop of feedback and response between the human and the robot. This bidirectional flow of information is crucial for several reasons:

1. **Real-Time Feedback:** both the human and the robot need to provide and receive real-time feedback. For instance, when a robot detects an increase in the force applied by a human during a task, it can adjust its movements to assist or accommodate the human's actions.
2. **Adaptive Interaction:** bidirectional communication allows for adaptive interaction. The robot can modify its behaviour based on the human's actions and vice versa. This adaptability is essential for tasks requiring precision and coordination, such as lifting and assembling components.
3. **Safety Monitoring:** continuous bidirectional communication is vital for ensuring safety. Robots must constantly monitor the forces and torques applied during interaction to prevent injuries. This requires real-time data exchange and processing to adjust movements and avoid harmful scenarios.

5.6. Modes of communication

Communication in HRC can take place through various modes, including:

- **Physical Signals:** the exchange of forces and torques provides tactile feedback, allowing both the human and the robot to sense and respond to physical contact. For example, a robot arm can sense resistance when a human applies force, prompting it to either assist with additional force or reduce its own exertion to prevent strain.
- **Visual Signals:** robots equipped with cameras and sensors can interpret visual cues from humans, such as hand gestures, facial expressions, or body movements. This visual information can be used to infer the human's intentions and adjust the robot's actions accordingly.
- **Auditory Signals:** speech recognition and sound detection enable verbal communication between humans and robots. Commands, alerts, and feedback can be conveyed through spoken language, enhancing the intuitiveness of the interaction.
- **Haptic Feedback:** advanced HRC systems incorporate haptic feedback, allowing robots to provide tactile sensations to humans. This feedback can simulate textures, forces, and vibrations, enhancing the realism and effectiveness of the collaborative task.

5.7. Ensuring safety

Ensuring the safety of both humans and robots in HRC requires rigorous monitoring and control of the forces and torques involved. Several strategies are employed to achieve this:

- **Force/Torque Sensors:** robots are equipped with force/torque sensors that continuously measure the physical interactions with humans. These sensors provide real-time data that the robot uses to adjust its movements and ensure safe collaboration.
- **Compliance Control:** robots use compliance control algorithms to modulate their stiffness and flexibility based on the detected forces. This allows the robot to yield when excessive force is applied, preventing injuries and facilitating smooth interaction.
- **Predictive Modelling:** advanced HRC systems employ predictive modelling to anticipate human actions and adjust robot behaviour proactively. This involves using machine learning algorithms to predict human movements and intentions based on past interactions and current sensory inputs.

5.8. Technology

5.8.1. Sensors

Environmental sensors provide information about the physical parameters of the robot's surroundings [60]. These sensors can include temperature sensors, humidity sensors, gas detectors, or even radiation detectors, depending on the application context. By monitoring the

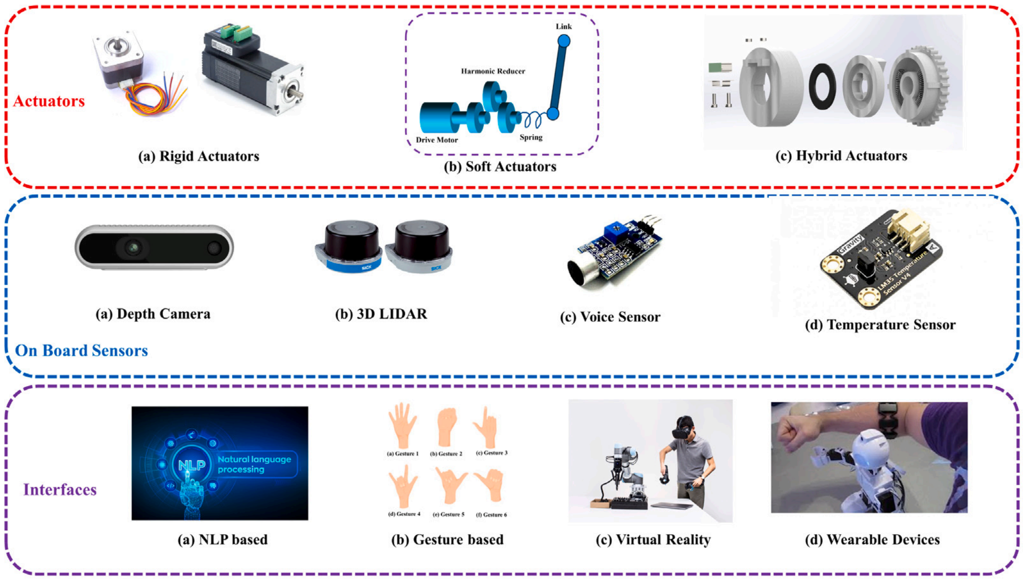

Fig. 7. Actuators, Sensors and Interfaces for HRC.

environmental conditions, the operator can ensure the safety of the robot and adapt its behaviour accordingly. For example, in teleoperated exploration of hazardous environments, such as nuclear facilities, environmental sensors can alert the operator to dangerous levels of radiation or toxic gases.

Vision sensors, such as cameras, provide visual feedback to the operator. High-resolution cameras capture real-time video or images of the robot's surroundings, allowing the operator to perceive the environment as if they were physically present [61]. These cameras can be monocular, stereo, or even 360-degree panoramic cameras, depending on the application requirements. Advanced vision systems may incorporate features like object recognition, tracking, and depth estimation, enhancing the operator's situational awareness.

Depth sensors, such as depth cameras or LIDAR scanners, provide depth information about the robot's surroundings. They utilise technologies like time-of-flight or structured light to measure the distance to objects in the environment. Depth sensors are particularly useful for tasks that require accurate 3D perception, such as object manipulation or navigation in cluttered environments [62]. The depth information enhances the operator's understanding of the scene and helps in making informed decisions during teleoperation.

Audio sensors, such as microphones, enable the operator to perceive and communicate with the remote environment. By capturing sounds and transmitting them to the operator [60], these sensors facilitate auditory feedback, allowing the operator to react to auditory cues or communicate with people in the robot's vicinity. Audio sensors are particularly useful in teleoperation scenarios that involve social interaction or tasks where sound plays a significant role, such as search and rescue operations.

The integration of various sensor technologies in teleoperation enables human operators to interact with robots remotely and perform tasks with precision and situational awareness. By providing visual, depth, force, inertial, environmental, and audio feedback, these sensors enhance the operator's perception, control, and decision-making capabilities, making teleoperation a powerful tool for a wide range of applications in industry, healthcare, exploration, and many other fields. The details of the sensors and actuators are shown in Fig. 7.

5.8.2. Actuators

One of the key factors influencing successful collaboration is the design and implementation of actuators within robots. Actuators are devices that convert energy into mechanical motion, enabling robots to interact with their environment. Two main categories of actuators used in human–robot collaboration are rigid actuators and soft actuators [63].

Rigid actuators are traditional mechanical components that generate motion using rigid materials, such as metals and plastics. They have been extensively used in industrial robots and various other applications. These actuators are known for their high precision, repeatability, and ability to generate high forces and torques. They typically consist of motors (electric, hydraulic, or pneumatic) combined with mechanisms like gears, linkages, and belts to transmit and amplify the generated motion. In HRC, rigid actuators are well-suited for tasks requiring high accuracy, forceful interactions, and structured environments. For example, they are commonly found in manufacturing scenarios where robots assist humans in assembling intricate parts, lifting heavy objects, or performing precise operations. However, the following challenges are associated with using rigid actuators in collaborative settings [64]: **safety**, the rigid nature of these actuators can pose a risk to humans due to their potential for causing injury upon contact; **limited flexibility**, rigid actuators might struggle with tasks that require adaptation to non-structured environments or interactions with delicate objects.

Soft actuators, on the other hand, are a relatively newer technology inspired by biological systems such as muscles. They are made from flexible and elastic materials, such as elastomers and polymers, and can achieve motion through mechanisms like inflation, bending, or contracting. Soft actuators offer the following advantages in HRC: **safety**, the inherent compliance of soft actuators makes them safer for interactions with humans, as they are less likely to cause harm upon contact; **adaptability**, soft actuators can deform to fit various shapes and handle unstructured environments better than rigid actuators. This adaptability allows them to navigate cluttered spaces and interact with objects of varying sizes and shapes; **natural interaction**, the compliant and biomimetic nature of soft actuators enables more natural and intuitive interaction with humans. This is particularly beneficial in applications like rehabilitation and assistive robotics.

The applications of rigid and soft actuators include [65]: **Manufacturing**, rigid actuators excel in precision tasks, such as assembling small components with tight tolerances [66]; **Healthcare**, soft actuators find application in wearable exoskeletons for rehabilitation, providing gentle assistance to patients during physical therapy [67,68]; **Assistive Robotics**, soft actuators can be integrated into robotic prosthetics or assistive devices to provide more comfortable and human-like movement [69]; **Search and Rescue (SAR)**, soft actuators allow robots to navigate through rubble and tight spaces during disaster scenarios [70,71].

The challenges and future directions include: **control**, soft actuators often require advanced control strategies to achieve desired motions due to their nonlinear behaviour and complex deformation patterns; **durability**, ensuring the longevity of soft actuators in real-world applications, especially when subjected to repeated deformations, remains a challenge; **integration**, both rigid and soft actuators need seamless integration with sensors, AI algorithms, and control systems to enable effective collaboration with humans.

5.8.3. Interfaces

In the context of HRC, various interfaces serve as crucial conduits for communication and interaction between humans and robots. These interfaces are designed to facilitate seamless cooperation, ensure safety, and enhance overall collaboration efficiency. This article structurally outlines the prominent interfaces that empower bidirectional communication and heightened adaptability between human operators and robots. For a more detailed review, the reader is referred to [59,72].

5.8.4. Natural Language Processing (NLP)

Natural Language Processing (NLP) [73] has bridged the semantic gap between human language and machine understanding, enhancing the communication spectrum between humans and robots. This innovation permits operators to articulate complex instructions and preferences using natural language [74], thereby imbuing the communication process with an intuitive quality. Robots equipped with NLP can accurately decipher these linguistic cues, transforming them into actionable tasks and responses. NLP, as a catalyst for adaptability, empowers robots to comprehend nuanced directives and swiftly align their actions with human intent. For a more in-depth review on this topic, the reader is referred to [75].

5.8.5. Gesture and body language recognition

Incorporating visual perception capabilities through cameras and sensors, robots have acquired the remarkable ability to interpret human gestures and body language [76]. This dimension of communication introduces a layer of nonverbal interaction, enabling operators to communicate commands and indications through physical gestures. For instance, a robot adept in gesture recognition can promptly identify a "stop" gesture from an operator, initiating an immediate halt in its operations. This interplay of gestures enhances not only operational efficiency but also safety in collaborative scenarios. For a comprehensive review on this topic, please refer to [77].

5.8.6. Haptic feedback

The integration of haptic feedback mechanisms has transcended the realm of virtual experiences to encompass human–robot interaction [78–80]. Through touch and force sensors, robots can provide tactile feedback that mimics physical sensations, enabling operators to gain a tangible understanding of the robot's interactions with the environment [81]. This sensory dimension fosters situational awareness, elevating the adaptability quotient by affording operators insights into real-time dynamics and potential challenges encountered by the robot.

5.8.7. Virtual reality (VR), augmented reality (AR), and Mixed Reality (MR)

VR, AR, and MR interfaces immerse operators in a virtual environment where they can visualise, control, and interact with robots and their surroundings. These interfaces enhance spatial understanding and enable remote operation, training, and maintenance [82].

5.8.8. Shared control

The paradigm of shared control interfaces epitomises a harmonious collaboration where human expertise synergises with robotic autonomy. This approach empowers operators to provide high-level guidance, articulating overarching objectives and strategies, while robots undertake intricate low-level tasks. The fusion of human insights and robotic precision ensures that tasks are executed efficiently while capitalising on human cognition for complex decision-making scenarios. For a more detailed review of this paradigm, the reader is referred to [83].

5.8.9. Context-aware

Context-aware communication systems imbue robots with the capacity to discern and respond to real-time environmental cues. By amalgamating sensor data and user inputs, robots can engender informed decision-making processes that seamlessly adapt to the prevailing circumstances. This contextual acumen enables robots to dynamically adjust their behaviour, catering to the fluid and ever-changing collaborative context. Examples of this approach are presented in [84,85].

5.8.10. Adaptive learning and artificial intelligence (AI)

The integration of adaptive learning and artificial intelligence empowers robots with the capability to evolve in response to dynamic situations and user preferences. This continuous learning framework equips robots with the propensity to refine their communication skills over time, leading to heightened comprehension of operator intent and the ability to anticipate actions [86]. As a testament to adaptability, robots progressively align their behaviours with evolving collaboration needs. A more extensive perspective of this approach is presented in [87].

5.8.11. Multi-modal interfaces

Multi-modal interfaces represent a convergence of diverse communication modalities, encompassing speech, touch, and visual cues. This synthesis of sensory inputs enriches the communication landscape, accommodating individual communication preferences and enhancing the bidirectional information flow. The incorporation of multiple communication modes amplifies the depth and versatility of human–robot interaction. For a more in-depth overview, the reader is referred to [79,88,89].

5.9. Implementation of the running use case

In this case, the workflow is adapted as follows:

- Order management:
  - human employees process order information, prioritise tasks, and allocate resources accordingly;
  - HRC is used to determine the most effective order fulfilment strategy, i.e., intelligent algorithms [90].
- Order picking:
  - human employees navigate the warehouse and employ technology aids to find the products they need. For instance, handheld devices can be employed, such as smartphones, tablets, or specialised barcode scanners [91];
  - robots having sensors and localisation capabilities assist in the identification and retrieval of goods [92];
  - humans and robots work together to pick products and place them in designated containers [93].
- Goods Handling and Transportation:
  - humans and robots collaborate to handle and carry products across the warehouse;
  - robots assist humans with material handling tasks by utilising sophisticated sensing and manipulation skills [94];
  - robot may navigate the warehouse on their own or with human assistance [92,95];

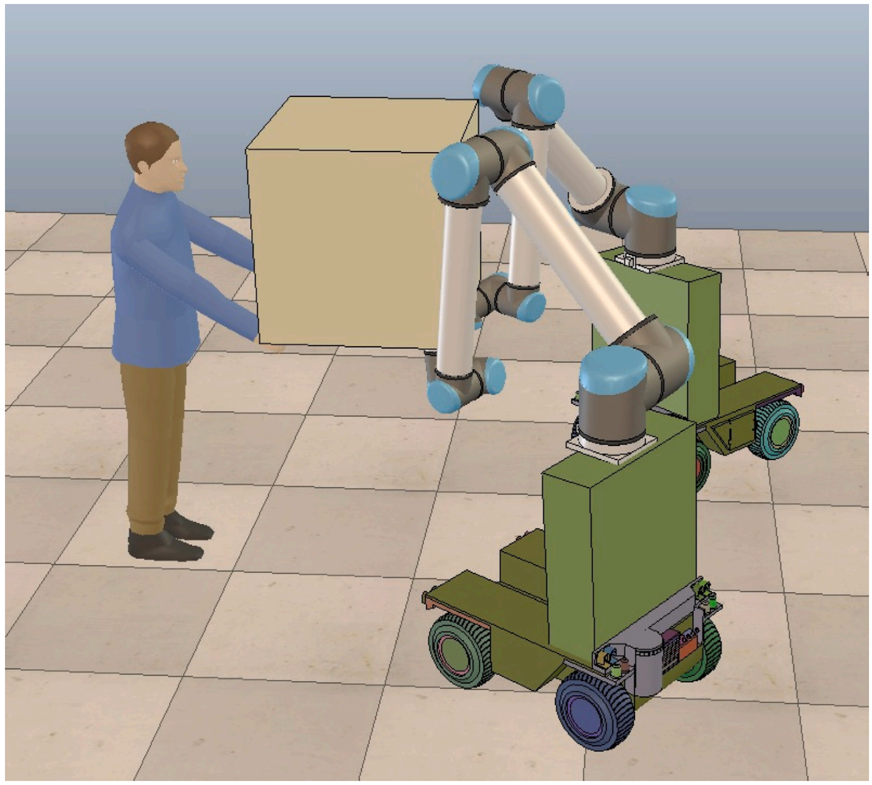

Fig. 8. Simulation composed of two homogeneous cooperative robots team-up with a human operator to grasp and manipulate an object.

  - humans and robots collaborate to load and unload goods into conveyors, lifts, or other forms of transportation systems.

- Packing and Shipping:
  - humans and robots work together in the packaging and shipping procedures. This only happens sequentially;
  - humans check products to verify their quality and correctness;
  - robots can help humans with packing tasks by providing packaging materials or securing goods;
  - humans and robots collaborate to package products, add labels, and prepare them for shipping.

- Quality Control and Inventory Management:
  - humans and robots collaborate on quality control tasks;
  - inspections are carried out by humans to ensure the correctness and quality of selected products;
  - robots may be used in automated quality control procedures that use computer vision systems or other comparable technology;
  - humans and robots work together to discover and resolve any flaws or abnormalities during quality control inspections.
  - humans and robots work together to manage inventories;
  - humans update inventory systems to reflect goods that have been picked, packaged, and shipped;
  - robots aid humans in automated inventory tracking by monitoring stock levels with sensors or RFID technologies;
  - humans and robots collaborate to do physical inventory counts and resolve any differences.

Table 4
Human–Robot Teaming (HRT) components, separating sensors/actuators from interfaces specifically for interactions.

Sensors	Actuators	Human–Robot Interfaces
Camera	Gripper, Robot Arm	Natural language Processing
Force/Torque Sensors	Mobile base	Gesture recognition
Depth Sensors	Collaborative Robots	Touch screen
Microphone		Wearable devices

6. Human–robot teaming (HRT)

6.1. Definition and characteristics of HRT

Definition 3. Human–Robot Teaming (HRT) is the concept of collaborating with a robot as an equal teammate, rather than viewing the robot merely as a "tool" [96]. This implies that humans and robots work together towards a shared goal with both parties able to make decisions to achieve this goal.

6.2. Modelling

The concept is shown in as shown in Fig. 8. The mathematical models for the human arm endpoint, robots, and manipulated object to develop the control framework for human-multi-robot teaming is presented below [97]. Table 4 lists the components of a robot that are required for implementing HRT.

6.2.1. Human arm endpoint model

The human arm endpoint is modelled as a damped mass–spring system, with the applied force F_h dependent on the endpoint position p_h, velocity $\dot{p}_h$, and the desired position $p_{h,d}$. Specifically, the human model is given by:

$$F_h = -D_h \dot{p}_h + K_h (p_{h,d} - p_h) \quad (12)$$

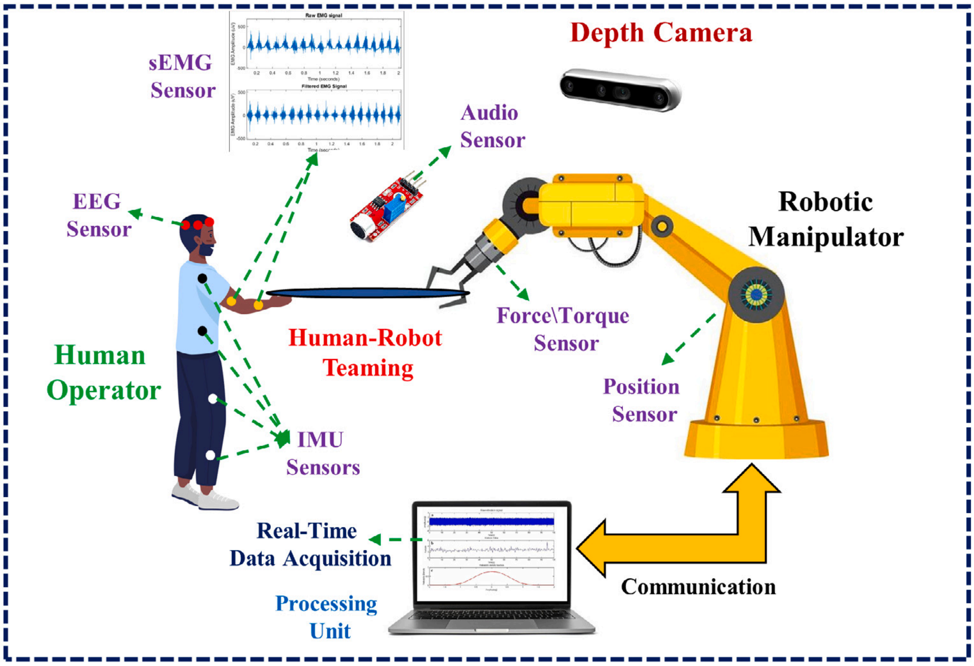

Fig. 9. Sensors and Interfaces for the implementation of Human–Robot Teaming (HRT) in industrial settings.

where D_h and K_h are the damping and stiffness matrices, which are assumed to be diagonal containing scalar elements d_h and k_h representing the impedance parameters in each direction. The damping d_h models the human stabilising actions, while the stiffness k_h relates to the human effort in deviating from the desired trajectory. Since these impedance parameters vary with muscle activation, they are considered time-varying and unknown.

To facilitate estimating these unknown parameters, the human model is reformulated in regressive form as:

$$F_h = Y_h(p_h, \dot{p}_h)\pi_h \tag{13}$$

where π_h contains the unknown parameter vectors d_h, k_h, and the desired position $p_{h,d}$.

6.2.2. Robotic manipulator dynamics

For each robotic manipulator, the dynamics are modelled in the operational space using the Euler–Lagrange formulation:

$$M_i(x_i)\ddot{x}_i + C_i(x_i, \dot{x}_i)\dot{x}_i + \eta_i(x_i, \dot{x}_i) = u_i - h_i \tag{14}$$

where x_i represents the robot end-effector configuration, M_i is the inertia matrix, C_i models centrifugal/Coriolis effects, η_i captures gravity forces, u_i is the control input, and h_i is the interaction force from manipulating the object.

Since the true robot dynamics contain uncertainties, an estimated model is used:

$$\hat{M}_i\ddot{x}_i + \hat{C}_i\dot{x}_i + \hat{\eta}_i = u_i - h_i - Y_i(x_i, \dot{x}_i, \ddot{x}_i)\tilde{\pi}_i \tag{15}$$

where $\tilde{\pi}_i = \pi_i - \hat{\pi}_i$ is the error between the actual and estimated dynamic parameters.

6.2.3. Object dynamics

The object dynamics are given by the Newton-Euler rigid body formulation, coupled to the human and robot interaction forces:

$$M_o\ddot{x}_o + C_o(x_o, \dot{x}_o)\dot{x}_o + g_o = \sum_{i=1}^{N} G_i h_i + F_h \tag{16}$$

where x_o is the object configuration, M_o, C_o, and g_o are its inertia, Coriolis and gravity effects. G_i and h_i are the grasp matrix and force from each robot i, and F_h is the human endpoint force.

This complete dynamic model, containing the human, robots, and object, will be used to develop the control framework for optimising physical collaboration between the human and multi-robot system.

6.3. Control

Here, a two-layer control architecture aimed at achieving optimal shared control between a human operator and a multi-robot system engaged in object manipulation is proposed.

6.3.1. Top layer

The top layer of the control architecture defines a virtual object dynamics equation:

$$M_v\ddot{x}_v = u_v \tag{17}$$

where M_v represents the virtual inertia matrix, $\ddot{x}_v$ denotes the virtual object configuration, and u_v is the virtual input. The design of u_v is focused on optimising a comprehensive cost function that takes into account both human and robot objectives:

$$\begin{aligned} J = {} & (\bar{x}_v - \bar{x}_{r,d})^T Q_{r,d}(\bar{x}_v - \bar{x}_{r,d}) + u_v^T R_v u_v \\ & + (\bar{x}_v - \bar{x}_{h,d})^T Q_{h,d}(\bar{x}_v - \bar{x}_{h,d}) + F_h^T R_h F_h \end{aligned} \tag{18}$$

Here, $\bar{x}_{r,d}$ and $\bar{x}_{h,d}$ represent the desired configurations of the robots and the human, respectively. Matrices $Q_{r,d}$ and $Q_{h,d}$ weigh the importance of various objectives, while R_v and R_h regulate the control effort. The term F_h accounts for the human force. The primary objective is to minimise this cost function to determine the optimal u_v, which subsequently generates the object's reference trajectory $\ddot{x}_v$. Notably, the impedance parameters of the human ($Q_{h,d}$) are estimated online using recursive least squares, enabling the adjustment of the weighting between robot and human objectives.

6.3.2. Bottom layer

The bottom layer of the control architecture focuses on generating control inputs u_i for each robot to enable the tracking of $\ddot{x}_v$ and the regulation of internal forces. An adaptive control law is formulated as follows:

$$u_i = \hat{M}_i\dot{\rho}_i + \hat{C}_i\rho_i + \hat{\eta}_i + K_s s_i + \Delta u_i \tag{19}$$

where ρ_i represents the command acceleration, s_i accounts for model uncertainties, K_s represents a feedback gain, and Δu_i encompasses force control terms. Δu_i is designed to compensate for uncertainties and regulate interaction forces. Moreover, the dynamic parameters of the robots ($\hat{\pi}_i$) are updated adaptively to enhance tracking using the equation:

$$\dot{\hat{\pi}}_i = K_\pi^{-1} Y_i^T (x_i, \dot{x}_i, \rho_i, \dot{\rho}_i) s_i \tag{20}$$

This adaptive control approach enables the coordination of the robots in a distributed manner to efficiently and effectively achieve the desired objectives.

6.4. Communication

Communication approaches and protocols for HRT are essential for coordinating the actions of multiple agents, ensuring the exchange of information, and enabling collaboration in complex tasks. A more detailed elaboration on these communication approaches and protocols is presented in the following.

6.4.1. Multi-agent coordination

- Centralised Control: in some teaming scenarios, a central control system or operator manages and coordinates the actions of all team members. Communication protocols, such as the Robot Operating System (ROS), facilitate information exchange between the central control unit and individual robots. The central controller can issue commands, monitor progress, and adjust strategies as needed [98].
- Distributed Control: in other cases, team members may operate more autonomously. In these situations, communication protocols enable peer-to-peer communication among robots and humans. These protocols support the exchange of information about tasks, positions, and goals, allowing team members to coordinate their actions collectively [16].

6.4.2. Sensor data sharing

- Live Video Feeds: robots equipped with cameras or other sensors can transmit live video feeds to human operators. This real-time visual feedback is crucial for remote monitoring and decision-making, particularly in scenarios like search and rescue or surveillance [99].
- Sensor Fusion: in teaming, robots may share sensor data, such as LiDAR scans, GPS coordinates, or environmental data. Sensor fusion techniques combine data from multiple sources to enhance situational awareness and provide a comprehensive view of the environment to both humans and robots [100].

6.4.3. Mission planning and execution

- Mission Command Protocols: high-level communication protocols are used to exchange mission plans and objectives among team members. These protocols allow for collaborative mission planning, where humans and robots can contribute their expertise and preferences. Mission commands might specify tasks, priorities, and waypoints.
- Progress Reporting: team members can provide updates on their progress, status, and any encountered obstacles. This information is crucial for real-time decision-making and adapting to changing conditions during mission execution.

6.4.4. Autonomous decision-making

- Inter-Agent Communication: robots in a team can communicate with each other to make coordinated decisions. For instance, drones might share information about their flight paths to avoid collisions or distribute tasks efficiently.
- Collaborative Decision Support: communication protocols enable collaborative decision support systems. These systems use shared information and algorithms to assist team members in making decisions, especially in scenarios where humans and robots must make choices based on uncertain or dynamic data.

6.4.5. Emergency communication

- Alerts and Requests: robots should have the capability to send alerts or requests for assistance in emergency situations. Communication protocols ensure that these alerts reach human team members quickly, allowing for a rapid response to unforeseen events, malfunctions, or safety issues.
- Semantic Data Exchange: in complex teaming scenarios, it is important for humans and robots to understand each other's intentions and capabilities. Semantic communication protocols use standardised vocabularies and ontologies to facilitate shared understanding, making it easier for team members to interpret and act upon information.

6.4.6. Adaptive communication

Communication protocols should be adaptable to changing conditions and requirements. They should support dynamic reconfiguration of the team, allowing for the addition or removal of agents as needed.

Communication approaches and protocols for human–robot teaming are diverse and tailored to specific applications and requirements. These protocols enable seamless coordination, information exchange, decision-making, and adaptability among human and robotic team members, ultimately enhancing the overall performance and efficiency of collaborative tasks.

6.5. Technology

6.5.1. Sensors

The effective functioning of human robot teams relies heavily on a sophisticated sensor ecosystem that enables robots to perceive, interact, and cooperate seamlessly with their human counterparts. This section delves into the scientific details of sensors crucial for human–robot teaming, elucidating their functionalities and significance in this emerging field. The detailed elaboration of the sensors required for HRT is shown in Fig. 10.

- Multi-Modal Sensors are instrumental in capturing data from various sources and modalities, including visual, auditory, and environmental data. These encompass technologies adept at integrating and processing information from diverse channels, such as cameras for vision, microphones for auditory input, and environmental sensors for capturing physical parameters of the surroundings [101]. Their significance lies in their capacity to amalgamate data from disparate sensor modalities, thereby facilitating astute decision-making and adept coordination with both humans and fellow robots.
- Communication Sensors encompass technologies dedicated to wireless data interchange and networking. Technologies such as Wi-Fi, Bluetooth, and 5G connectivity facilitate real-time data sharing, information exchange, and coordination among members of the team [102]. Effective communication forms the bedrock of human–robot teaming, and these sensors engender the seamless flow of information between robots and human team members, fostering coordinated actions and a shared situational awareness.
- Environmental Sensors encompass a diverse array of sensors that meticulously monitor the physical parameters of the environment. These sensors include temperature sensors, gas sensors, humidity sensors, and atmospheric pressure sensors. They supply invaluable data about the environment within which the team operates, including ambient temperature, air quality, humidity levels, and pressure conditions. In teaming scenarios, these sensors are particularly significant, especially when robots are deployed in environments marked by diversity or hazard. They inform decision-making, ensure safety, and aid in adapting to fluctuating environmental conditions.

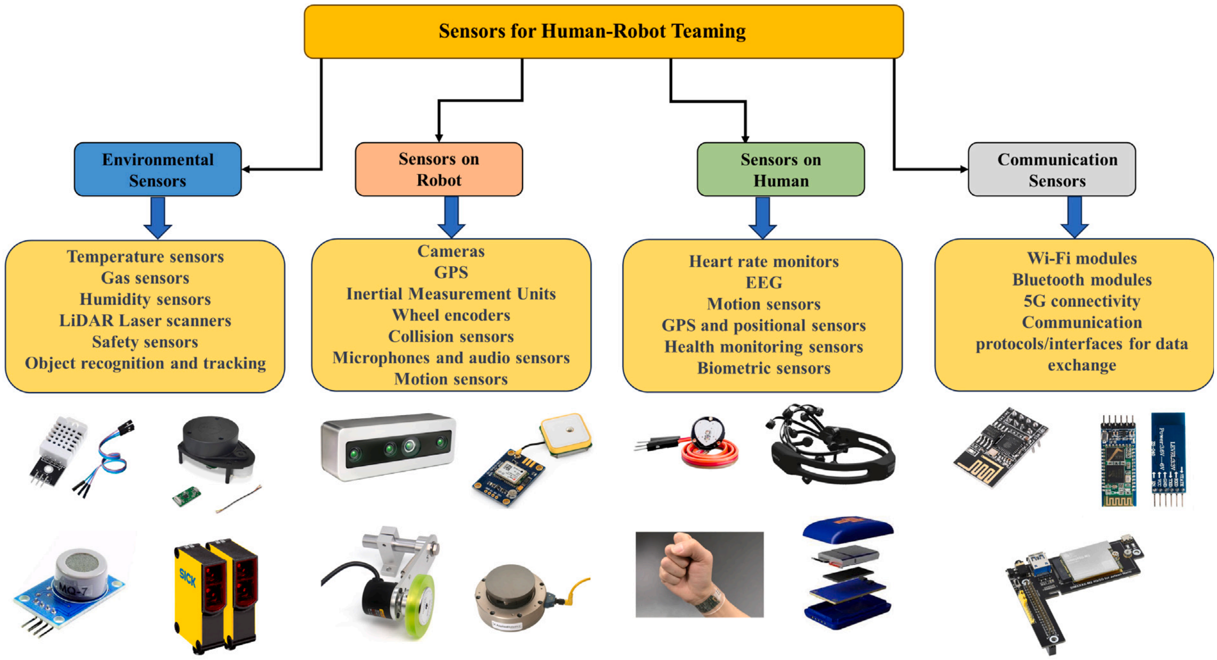

Fig. 10. Sensors required for Human Robot Teaming in different scenarios.

- Position and Localisation sensors play a pivotal role in ascertaining the precise location and orientation of robots within their environment. Technologies such as GPS, inertial measurement units (IMUs), and encoders provide the essential data for accurate positioning. Precision in positioning and localisation constitutes an indispensable element in fostering effective coordination within a team, supporting tasks encompassing navigation, path planning, and maintaining spatial relationships critical for collaborative endeavours.
- Object Recognition and Tracking Sensors harness advanced computer vision techniques to discern and track objects within the robot's field of view. Technologies like cameras equipped with image processing capabilities facilitate object recognition and tracking. In teaming scenarios, robots are often required to perceive, recognise, and track objects to facilitate collaboration. These sensors empower robots to trail, assist, and interact with humans and other objects in their surroundings.
- Human Biometrics Sensors are seamlessly integrated with robots to assess the well-being and physiological states of human team members. These include heart rate monitors, electroencephalograms (EEGs), and wearable health devices. Monitoring human biometrics assumes primordial significance in applications where human safety and well-being occupy the forefront. These sensors empower robots to take proactive measures in response to human stress, fatigue, or health-related conditions, ensuring the well-being of the human team members.
- Safety Sensors, such as bumpers, laser scanners, and emergency stop buttons, are engineered to detect and respond to unforeseen obstacles, hazards, or precarious conditions within the robot's operational milieu. They are indispensable in upholding the safety of human team members and precluding incidents, collisions, or accidents. These sensors endow the robot with the capability to react promptly to unanticipated situations, thereby ensuring a secure working environment.

Sensors for HRT are the sensory backbone of collaborative robotic systems. They empower robots with the ability to perceive, communicate, and interact effectively with humans and other robots in a wide range of applications. The detailed overview of the HRT with the sensors is elaborated in Fig. 9. As this field continues to advance, the development and integration of increasingly sophisticated sensors will play a pivotal role in realising the full potential of human–robot teams across industries such as healthcare, manufacturing, search and rescue, and autonomous transportation.

6.5.2. Actuators

In the realm of HRT, actuators are pivotal components that drive robotic systems, enabling them to execute precise movements and interact effectively with their human counterparts. These actuators play a crucial role in facilitating collaborative efforts and seamless coordination within the team. Here, we delve into the detailed scientific aspects of actuators employed in human–robot teaming and explore the innovative realm of hybrid rigid/soft actuators.

- Mobility Actuators: mobility actuators are essential in human–robot teaming scenarios where robots need to navigate diverse and dynamic environments. These actuators facilitate locomotion and include various types, such as electric motors driving wheels, hydraulic systems powering tracks, or legged systems employing electric or pneumatic actuators. The choice of mobility actuator depends on the specific requirements of the task and the terrain to be traversed. Precise control of these actuators enables robots to adapt to different terrains and maintain synchrony with human team members during cooperative tasks.
- Articulated Joints: robots participating in human–robot teams often require articulated joints to achieve a wide range of motion. These joints are actuated by electric motors, pneumatic systems, or hydraulic actuators. The design and control of these actuators are critical for achieving natural and flexible movements, allowing robots to adapt to various tasks and positions. For instance, humanoid robots employ articulated joints to mimic human-like motions and perform tasks collaboratively.
- Manipulation and Grasping Actuators: in teaming scenarios, robots are frequently tasked with manipulation and grasping of objects. Actuators employed for these tasks are meticulously designed to provide dexterity, precision, and compliance. Electric motors, especially servo motors, are commonly used in combination with sensors and control algorithms to achieve fine-grained

manipulation. Compliance and force feedback are integrated into these actuators to ensure safe interactions with both objects and humans.

- Sensory Actuators: sensory actuators are a sophisticated category that enhances communication and interaction within human–robot teams. These actuators can generate sensory feedback, such as haptic sensations, vibrations, or pressure. They facilitate information exchange between robots and humans, enhancing situational awareness and coordination. For example, a robot can use haptic actuators to convey information about the presence of an obstacle or the completion of a task to a human team member.
- Autonomous Actuation: autonomous decision-making and actuation are paramount in human–robot teaming scenarios where robots need to adapt to dynamic environments and changing objectives. Actuators are equipped with advanced algorithms that enable real-time adjustments based on sensory input and coordination with other team members. These algorithms may include path planning, collision avoidance, and shared control mechanisms. Autonomous actuators are critical for ensuring that robots can adapt to unforeseen events and evolving mission objectives.
- Hybrid Rigid/Soft Actuators: hybrid rigid/soft actuators represent an innovative approach in robotics that combines the benefits of both rigid and soft actuation. Rigid actuators, typically composed of metals or hard materials, offer precise control and structural integrity, while soft actuators, often made of elastomers or flexible materials, provide compliance and adaptability to complex shapes. In human–robot teaming, hybrid actuators find application in tasks that require a delicate touch, adaptability to varying environments, or safe interaction with humans. These actuators can transition between rigid and soft states, allowing robots to switch between tasks that demand precision and those that require compliance. For example, in medical applications, robots with hybrid actuators can perform precise surgical tasks while maintaining safety when interacting with delicate tissues. In collaborative manufacturing, they can handle objects of varying shapes and sizes, providing the necessary rigidity for manipulation and the softness for safe human interaction.
- Direct Drives: in the context of HRT, modern technologies such as direct drives are gaining prominence due to their superior performance and efficiency. Unlike traditional actuators that rely on intermediate components like gears and belts, direct drives couple the motor directly to the load, eliminating backlash and significantly enhancing precision and responsiveness. This direct connection allows for smoother and more accurate movements, which are crucial in applications requiring high degrees of coordination and cooperation between human and robot teammates [103]. Moreover, direct drives offer benefits in terms of maintenance and durability, as they have fewer moving parts and are less prone to wear and tear. These characteristics make them particularly suitable for advanced collaborative tasks in dynamic and unpredictable environments, where seamless interaction and reliable performance are essential. By integrating direct drives into HRT systems, robots can achieve higher levels of autonomy and adaptability, thereby improving their ability to work alongside humans as equal partners in complex workflows [104, 105]. This technological advancement represents a significant step forward in realising the full potential of human–robot teams, enabling more effective and efficient collaboration across various industrial and service domains.

As elaborated, actuators are fundamental components in human–robot teaming, enabling robots to achieve mobility, dexterity, and adaptability necessary for collaboration with humans and other robots. The integration of advanced actuation technologies, such as hybrid rigid/soft actuators, contributes to the versatility and safety of robots in diverse and dynamic teaming scenarios.

6.5.3. Interfaces

In the dynamic field of human–robot teaming, interfaces have undergone significant advancements to facilitate nuanced and efficient collaboration between humans and robots. These interfaces are pivotal in enabling complex teamwork, enhancing situational awareness, and optimising task performance. Here, we delve into the latest breakthroughs and elaborate on the interfaces designed for human–robot teaming:

- Multi-Modal Augmented Reality (AR) Interfaces: advanced AR interfaces have emerged to provide operators with an immersive and context-aware experience. These interfaces seamlessly merge the real world with virtual elements, offering operators real-time visualisations of robots' positions, intentions, and sensor data overlaid onto their field of view. This heightened situational awareness empowers operators to exert more intuitive and precise control over robot teams, particularly in scenarios where multiple robots collaborate in dynamic environments.
- Natural Language Understanding and Generation: significant strides in natural language processing (NLP) have empowered robots to comprehend and generate human language with greater accuracy and contextual relevance. In the context of human–robot teaming, this entails robots engaging in more natural and nuanced conversations with human counterparts. The result is improved coordination and communication, leading to enhanced team performance and adaptability.
- Advanced Gesture Recognition and Wearable Interfaces: gesture recognition systems have evolved to discern subtle movements, enabling operators to issue precise commands with minimal effort. In parallel, wearable interfaces, such as smart gloves and exoskeletons, have witnessed substantial advancements in terms of ergonomics and sensor technology. These developments grant operators the ability to exert fine-grained control over multiple robots, even in physically demanding and rapidly changing environments, thus fostering more efficient and intuitive teaming scenarios.
- Collaborative Virtual Environments: collaborative virtual environments (CVEs) have evolved to facilitate remote human–robot teaming. Within CVEs, operators interact with robots in shared virtual spaces, affording them the capability to visualise and control multiple robots concurrently. These environments play a pivotal role in collaborative decision-making, training, and simulations, empowering geographically dispersed teams to work harmoniously and effectively.
- Brain-Computer Interfaces (BCIs): while still in the realm of research and development, BCIs hold immense potential as futuristic interfaces for human–robot teaming. BCIs, if successfully developed, would enable direct communication between the human brain and robots, transcending traditional input methods. This breakthrough could revolutionise human–robot teaming by permitting operators to control robots through thought commands, ushering in a new era of precision and efficiency.
- Advanced Touch and Haptic Feedback: interfaces incorporating touch and haptic feedback have become more advanced and nuanced. Operators now experience a broader range of tactile sensations, enhancing their ability to understand the robot's environment and actions. This heightened tactile feedback not only facilitates delicate tasks but also fosters a deeper sense of immersion in remote teaming scenarios.
- Shared Autonomy and Machine Learning Interfaces: interfaces that embrace shared autonomy and machine learning algorithms empower robots to adapt and learn from human operators. Such interfaces enable robots to anticipate human intentions, adapt to operator preferences, and continually optimise task execution. This results in heightened efficiency, cooperation, and adaptability within the team.

- Networked Communication and Cybersecurity: in the era of the Internet of Things (IoT), interfaces have evolved to ensure robust networked communication while prioritising cybersecurity. Advanced encryption, authentication mechanisms, and network management technologies are integrated to safeguard data integrity and protect against cyber threats, ensuring secure and reliable information exchange.
- Human–Robot Teaming Dashboards: team leaders and operators now benefit from comprehensive dashboards that offer real-time data on robot status, mission progress, and performance metrics. These interfaces serve as decision support tools, empowering teams to make informed choices and adapt strategies instantaneously. Additionally, they facilitate centralised monitoring and coordination in complex teaming scenarios.

The ongoing evolution of interfaces in human–robot teaming is emblematic of the expanding complexity and capabilities of collaborative robotic systems. These advancements empower teams to operate more effectively across diverse domains, including disaster response, healthcare, manufacturing, and defense, where humans and robots work harmoniously to achieve shared objectives. As technology continues to progress, interfaces for human–robot teaming will remain at the forefront, shaping the future of collaborative robotics.

6.6. Implementation of the running use case

In this case, the workflow is adapted as follows:

- Order Management:
  - Human operators and robots work together to analyse order information, prioritise jobs, and effectively distribute resources;
  - Humans utilise VR, AR, and MR interfaces to easily visualise and manage order details, ensuring precise item specifications, quantities, and delivery timeframes;
  - Humans and robots efficiently coordinate order management tasks through synchronised communication (i.e., voice or gesture based commands) and shared workspaces.
- Order Picking:
  - human workers and robots work in coordination for order picking activities;
  - human operators wear VR and AR interfaces, which provide them with real-time instructions, item locations, and optimised picking routes;
  - humans use cognitive abilities and fine motor skills to handle complicated or fragile goods, whereas robots aid in their identification and retrieval;
  - force feedback interfaces are utilised to enhance human operators' control and precision by perceiving interaction forces.
- Goods Handling and Transportation:
  - humans and robots work as a team in shared workspaces to handle products and deliver them;
  - robots equipped with power and force limiting mechanisms ensure safe interactions with human operators;
  - human operators wear VR and AR interfaces, which provide them with dynamic information on optimal paths, item placement, and collaborative transportation;
  - Humans and robots team-up to load, unload, and use individual skills/capabilities for effective handling.
- Packing and Shipping:
  - human workers and robots work in tandem to effectively pack and ship things;
  - human operators receive real-time packing instructions, container specifications, and shipping labels via VR and AR interfaces;
  - humans use dexterity and judgement to arrange products securely, while robots help with larger loads and precise labelling;
  - humans and robots teaming up in packing operations manage to optimise density, reduce mistakes, and speed up shipping preparation.
- Quality Control:
  - humans and robots closely team up to assure quality control throughout the order fulfilment process;
  - human operators are provide with visual cues for quality control criteria and inspection procedures via VR, AR, and MR interfaces;
  - humans utilise perceptual and decision-making abilities for detailed inspections, whereas robots employ computer vision to assist with automated inspections;
  - human workers use integrated force feedback wearables to detect subtle quality issues through haptic feedback during inspections.
- Inventory Management:
  - human operators and robots effectively team up for inventory management tasks;
  - human workers employ VR and AR interfaces to achieve real-time monitoring of inventory levels, locations, and stock replenishment needs;
  - humans and robots team up to carry out physical inventory counts, ensuring accuracy and resolving discrepancies;
  - inventory management is streamlined with shared workspaces and synchronised communication between humans and robots for timely restocking and optimised warehouse organisation.

7. Ethical and philosophical aspects

Navigating the intricate realm of human–robot interaction (HRI), human–robot collaboration (HRC), and human–robot teaming (HRT) involves not only technological advancements but also a profound exploration of ethical and philosophical questions [106]. As these interactions progress from isolated tasks to synchronised collaboration and ultimately to seamless integration of humans and robots, fundamental ethical concerns come to the fore. In the early stages of HRI, ensuring safety, respecting privacy, and making informed decisions are at the ethical forefront [107]. Moving into HRC, equitable task allocation, accountability, and mitigation of biases become crucial to fostering a fair and accountable collaboration [108]. As collaboration advances further in HRT, trust, shared responsibility, and user autonomy emerge as vital ethical aspects [109]. In parallel, philosophically, questions regarding consciousness, moral agency, existential implications, and the nature of symbiotic relationships intertwine with these ethical considerations, enriching the discourse surrounding human–robot dynamics. Understanding and addressing these ethical and philosophical dimensions is essential to shape a future where human–robot interactions are not only technologically sophisticated but also ethically sound and philosophically grounded [106].

7.1. Ethical aspects of HRI/HRC/HRT

7.1.1. Ethics in human–robot interaction (HRI)

In the early stages of human–robot interaction (HRI), the collaboration between humans and robots is characterised by defined boundaries and separated workspaces. This stage marks the genesis of a complex relationship that intertwines ethical considerations with technological advancements [110]. Here, the fundamental ethical concern lies in ensuring the safety and well-being of both humans and robots engaged in interaction. Engineers and designers grapple with the responsibility of designing robots that do not pose any harm, be it physical, psychological, or emotional, to individuals. Alongside safety, the ethical framework encompasses issues of privacy and data security, given that HRI often involves the exchange and processing of personal data. Transparency, informed consent, and a clear understanding of the robot's capabilities form the bedrock of ethical decision-making in this stage of human–robot interaction.

- **Safety and Well-being:** Ethical considerations in HRI are fundamentally centred around ensuring the safety and well-being of both humans and robots [2]. Engineers and designers must prioritise creating robots that do not pose harm to individuals, whether it be physical, psychological, or emotional harm. Proper risk assessments, fail-safes, and compliance with safety standards are essential ethical practices.
- **Privacy and Data Security:** HRI often involves the collection and processing of personal data, raising concerns about privacy [111]. Ethical frameworks must be in place to regulate the storage, use, and sharing of data by robots. Transparency and informed consent regarding data collection and utilisation become vital to uphold individual privacy rights.
- **Informed Decision-making:** Humans interacting with robots should be adequately informed about the capabilities, limitations, and potential consequences of robotic actions [112]. Ethical considerations here include ensuring that users have a clear understanding of what the robot can and cannot do to make informed decisions during interaction.

7.1.2. Ethics in human–robot collaboration (HRC)

As human–robot interaction advances into the realm of collaboration, a nuanced ethical landscape emerges, necessitating a thoughtful examination of fairness, transparency, and accountability. In this stage, humans and robots move beyond simple interaction to synchronised tasks and shared spaces, requiring a deeper understanding of how collaboration impacts individuals and society at large. Ethical considerations extend to ensuring fair treatment, preventing biases, and promoting responsible actions within this evolving collaboration. Designing systems that respect human values and principles, distribute tasks fairly, and provide clear accountability becomes paramount, laying the foundation for ethical human–robot collaboration [113].

- **Fairness and Allocation of Tasks:** As collaboration deepens, ethical concerns shift towards ensuring fair task distribution between humans and robots [114]. It is crucial to avoid creating a power imbalance where robots are given preferential treatment or disproportionately assigned tasks. Fairness in allocation promotes a sense of equity and collaboration.
- **Accountability and Transparency:** In HRC, ethical frameworks should enforce accountability for actions taken by both humans and robots. Decision-making processes must be transparent and understandable, allowing individuals to know how and why specific decisions were made. This transparency aids in accountability and trust-building [115].
- **Bias and Discrimination Mitigation:** Algorithms and AI systems used in collaboration should be designed to mitigate biases and discrimination [116]. Ethical considerations involve addressing biases in data, algorithms, and decision-making processes to ensure that collaboration is free from unfair treatment or favouritism based on attributes such as race, gender, or socio-economic status.

7.1.3. Ethics in human–robot teaming (HRT)

As human–robot collaboration advances to the pinnacle of integration in human–robot teaming (HRT), a profound exploration of ethical dimensions is warranted [117]. In this advanced stage, where humans and robots work in shared spaces on interdependent tasks, ethical considerations transcend beyond task allocation and delve into trust, shared responsibility, and the preservation of human control [118]. Maintaining a symbiotic relationship and ensuring ethical conduct in this shared space is of paramount importance. Ethics in HRT encompass fostering trust, respecting user autonomy, and establishing transparent decision-making mechanisms to cultivate a cooperative and morally grounded human–robot team.

- **Trust and Mutual Understanding:** Establishing trust and mutual understanding between humans and robots becomes paramount in HRT [119]. Ethical frameworks need to focus on promoting trust through reliable performance, effective communication, and consistent behaviour, enabling a harmonious and productive team dynamic.
- **Shared Responsibility and Decision-making:** Ethical HRT involves ensuring shared responsibility and inclusive decision-making. Human team members must retain the ability to influence and make critical decisions, preventing scenarios where robots autonomously determine outcomes without human oversight [120].
- **User Control and Autonomy:** Ethical considerations emphasise that humans should maintain control and autonomy over critical aspects of the collaboration. Designing interfaces and control mechanisms that allow users to intervene, override, or modify robot actions fosters a sense of control and ethical autonomy [121].

Addressing these ethical aspects in HRI, HRC, and HRT is essential to cultivate a responsible and beneficial integration of robots into human environments. Ethical frameworks provide guidance to engineers, designers, and policymakers, ensuring that advancements in human–robot interaction, collaboration, and teaming prioritise the well-being, autonomy, and equitable treatment of individuals.

7.2. Philosophical aspects of HRI/HRC/HRT

7.2.1. Philosophical aspects in human–robot interaction (HRI)

In the realm of human–robot interaction (HRI), philosophical questions emerge concerning the nature of consciousness and autonomy. Discussions revolve around whether robots possess true consciousness or if their behaviours merely simulate it, raising debates on artificial consciousness and the extent of robots' self-awareness or intentionality [122]. Additionally, questions about moral agency and responsibility come to the forefront [106]. Delving into the ethical implications, considerations are made on whether robots should be held morally accountable for their actions, introducing complex inquiries about guilt, punishment, and the moral consequences of robotic actions. Furthermore, as HRI advances, existential and identity-related concerns are brought to light. The integration of robots into daily life prompts contemplations on the impact on human identity, relationships, and societal structures. Individuals ponder existential questions regarding the implications of relying on robots for companionship or support and how this affects human experiences of solitude, meaning, and purpose.

7.2.2. Philosophical aspects in human–robot collaboration (HRC)

As human–robot collaboration (HRC) unfolds, philosophical discussions delve into the notion of symbiotic relationships. Analogies with natural symbiosis lead to inquiries about the mutual benefits, dependencies, and ethical implications of such collaborations. Philosophers explore the characteristics that define a symbiotic collaboration and the implications it has on the individuals involved [123]. Additionally, HRC invites contemplation on the ethics of distributed cognition, where the collaboration forms a collective cognitive system [124]. Philosophical exploration navigates how distributed cognition affects our understanding of individuality, intelligence, and decision-making within collaborative contexts, reshaping notions of agency and intelligence.

7.2.3. Philosophical aspects in human–robot teaming (HRT)

In the advanced stage of human–robot teaming (HRT), existential questions are amplified as humans and robots work in shared spaces on interdependent tasks. Philosophical inquiry navigates the nature of collaboration, individual agency, and the existential meaning for humans in this technologically driven world [125]. Reflections encompass questions about purpose, autonomy, and fulfilment in the context of collaboration [126]. Moreover, HRT raises philosophical concerns about interdependence, questioning how reliance on one another for successful task completion and decision-making reshapes traditional ideas of self-sufficiency, autonomy, and freedom. Philosophical exploration centres on the ethical implications of this interdependence, exploring the evolving nature of relationships and responsibilities in collaborative teams.

The philosophical aspects in HRI, HRC, and HRT prompt deep reflections on consciousness, autonomy, moral agency, existential implications, and the nature of collaborative relationships. Philosophical inquiry is crucial for navigating the evolving landscape of human–robot interactions, collaborations, and teaming providing essential guidance for ethical considerations and societal implications in this rapidly advancing field.

8. Conclusions and future work

This paper offers a structured, position-oriented review delineating the progression from simple human–robot interaction (HRI) to more advanced human–robot collaboration (HRC), culminating in the advent of human–robot teaming (HRT). Initially, we introduced key concepts, motivations, and characteristics of human–machine interfaces, highlighting the increasing relevance of multi-modal communication for natural and intuitive interactions. Subsequently, a structured running use case of a warehouse workflow was described to illustrate the transforming journey across HRI, HRC, and HRT.

In HRI, caged industrial robots work in separated spaces from humans, interacting through limited commands and controls. HRC allows for synchronised tasks in shared spaces through monitored contacts, focusing on human-led initiatives. HRT represents the most advanced integration, with interdependent goals, close physical collaboration, and joint decision-making between human and robot teammates. Through the selected running use case, we elaborated on the modelling, control, communication, sensing, actuation, and interfaces for each paradigm.

The progression reveals increasing autonomy and shared control, wider adoption of soft robotics and haptics, multi-modal interfaces, and sophisticated coordination protocols enabling seamless teaming. Philosophical and ethical considerations were also discussed, underscoring the importance of trust, transparency, and human-centred values.

Key limitations and challenges were highlighted, including establishing robust recognition of dynamic human behaviour, developing intuitive interfaces and seamless information exchange, ensuring safety and resilience in physical collaborations, and addressing concerns regarding over-reliance, privacy, and accountability. Overall, our work aims to bridge the gap between theoretical concepts and practical applications, providing insights that can guide the design and integration of more advanced and intuitive human–robot systems. We believe that this structured review will serve as a valuable reference for future research and development in human–machine interaction paradigms. Further advancements in enabling technologies and a philosophical grounding can pave the way for synergistic teams where complementary human and robot abilities are fully leveraged.

CRediT authorship contribution statement

Filippo Sanfilippo: Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Muhammad Hamza Zafar:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology. **Timothy Wiley:** Writing – review & editing, Writing – original draft, Software, Resources, Formal analysis. **Fabio Zambetta:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation.

Declaration of competing interest

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

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