The collaboration scale: A novel approach for assessing robotic systems collaboration capabilities

Robotics and Computer–Integrated Manufacturing 96 (2025) 103062

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

The *collaboration scale*: A novel approach for assessing robotic systems collaboration capabilities

Federico Barravecchia, Riccardo Gervasi, Luca Mastrogiacomo, Fiorenzo Franceschini

Politecnico di Torino, Dipartimento di Ingegneria Gestionale e della Produzione Corso Duca degli Abruzzi 24, Torino 10129, Italy

ARTICLE INFO

Keywords:
Collaboration capability
Industrial collaborative robotics
Collaborative systems
Assembly
Human-robot collaboration
Industry 5.0
Manufacturing

ABSTRACT

In the transformative landscape of Industry 4.0 and the impending transition to Industry 5.0, the paradigm of collaborative robotics is emerging as a cornerstone, combining human and robotic distinctive abilities. This intersection is leading to a new era of 'human-centric' manufacturing, where the integration of human with robots is not just an option, but a need. In particular, the shift towards Industry 5.0 highlights the return of the human element to technological processes, emphasising adaptability, customization, and collaboration between humans and machines.

In this context, this study introduces the *Collaboration Scale,* a metric designed to evaluate the collaborative capabilities of robotic systems within this human-centred framework. This scale provides clear levels of collaboration across five foundational dimensions: *Situation awareness, Adaptivity, Communication, Learning,* and *Mobility*.

The proposed scale has three objectives: (i) establishing a common language for practitioners and researchers, (ii) promoting innovation and standardisation in collaborative robotics, and (iii) providing a practical tool for assessing and comparing the collaborative capabilities of different systems.

The framework aims to bridge the gap between current capabilities and future aspirations in robotics, while also promoting a human-centric approach for Industry 5.0.

1. Introduction

The evolution of industrial automation has embarked on a revolutionary path with the advent of Industry 4.0, marking the inception of smart factories and the seamless integration of cyber-physical systems [1]. As we stand on the cusp of transitioning into Industry 5.0, the focus shifts towards re-integrating the human element into the technological systems, emphasizing a human-centric approach in manufacturing processes [2–4]. This transition highlights the necessity for a novel manufacturing paradigm that is not only efficient but also adaptable and responsive to human requirements [5]. In this view, Human-Robot Collaboration (HRC) necessitates a redefinition where robots are not mere tools but partners capable of working alongside humans to achieve shared goals [6].

HRC has been extensively discussed in the literature, with numerous studies identifying different levels of collaboration between humans and robots [7–9]. These levels often focus on the interaction dynamics, task allocation, and the degree of autonomy shared between human and robotic agents. However, there has been comparatively less emphasis on the inherent capabilities of collaborative robotic systems and how they influence their ability to collaborate effectively [10,11].

The objective of this work is to present a collaboration capability scale for collaborative robotic systems. The concept of collaboration capability emerges as a critical factor for enhancing HRC. Collaboration capability refers to the intrinsic potential of a robotic system to be collaborative. By examining this concept, it can be better understood how cobots can contribute to collaborative tasks and how they can be improved to facilitate seamless and effective HRC. The focus on collaboration capability shifts the perspective from solely classifying levels of interaction to analysing the aspects that enable collaboration.

In this view, the following Research Question is addressed in this study: *What are the dimensions that define a robotic system's collaboration capability, and how can these be used to measure and quantify it?*

In order to address this research question, this paper introduces the *Collaboration Scale*, a novel framework designed to assess the collaborative capabilities of industrial collaborative robotic systems. This scale offers a multi-dimensional approach to quantify and evaluate the levels of collaboration between humans and robots. The *Collaboration Scale* is

E-mail addresses: federico.barravecchia@polito.it (F. Barravecchia), riccardo.gervasi@polito.it (R. Gervasi), luca.mastrogiacomo@polito.it (L. Mastrogiacomo), fiorenzo.franceschini@polito.it (F. Franceschini).

https://doi.org/10.1016/j.rcim.2025.103062
Received 21 December 2024; Received in revised form 1 May 2025; Accepted 13 May 2025

based on the analysis of five dimensions: *Situation awareness, Adaptivity, Communication, Learning* and *Mobility*. By discretizing these dimensions into multiple levels, the scale provides a systematic method to evaluate the collaborative potential of robotic systems, highlighting areas of strength and opportunities for improvement. This framework may serve as an initial approach towards a standardized assessment of collaborative systems.

This paper is structured as follows. Section 2 delivers a literature review, focusing on HRC, collaboration capability, and the key requirements for effective HRC systems. In Section 3, the methodology behind the development of the *Collaboration Scale* is detailed. Section 4 presents the *Collaboration Scale*, describing its dimensions, the levels within each dimension, and the criteria for assessing collaborative systems. Section 5 describes the different levels of collaboration capability as defined by the scale, providing a framework for categorizing robotic systems. A case study exemplifying a real-world application of the *Collaboration Scale* is also reported in Section 5. The broader implications of this *Collaboration Scale* for the field of collaborative robotics are discussed in Section 6. Finally, Section 7 offers concluding remarks, summarizing the paper's key points and suggesting directions for future research.

2. Conceptual background

2.1. Human-robot collaboration

HRC is a defining paradigm of Industry 5.0 in promoting human-centered processes [12]. HRC involves combining the skills of humans with those of robots to achieve a common goal (e.g., assembling a product) [13]. Robots involved in this type of interaction are called collaborative robots and are safety standardized according to ISO 15066 [14]. Unlike classical industrial robots, collaborative robots are designed to share the same workspace with humans and be able to physically interact with them thanks to the integration of safety devices that limit collisions (e.g., force limiters) [11,15]. Although the payload of cobots is usually smaller than that of classical robots, they allow the workstation layout to be more easily reconfigured, thus offering greater flexibility of production processes [16].

Over the years, collaborative robots have been implemented in various types of manufacturing activities. Most of currently available applications of collaborative robotics are concerned with performing tedious tasks, such as material handling, palettizing, machine tending, polishing, and welding [16,17]. Assembly is one of the processes where collaborative robotics usually finds the most potential [17]. The ability to work safely close to humans allows to provide greater support, both physical and cognitive, to the operator during the different stages of an assembly [18]. Another interesting area of application for collaborative robotics concerns quality inspection [19,20]. In this process, cobots equipped with suitable sensors can support the operator in identifying possible product defects. Working together with the cobot can cognitively support the operator and mitigate possible errors due to reduced vigilance [21].

2.2. Collaboration capability

Collaboration is an interaction paradigm where multiple entities work together to achieve a shared goal in a coordinated and accommodating manner [22]. In HRC, collaboration encompasses the actual process of joint work between humans and cobots, which is influenced by factors beyond the system's inherent abilities, such as environmental conditions, human factors, and organizational culture [23].

Collaboration capability represents the set of capabilities of an entity—whether an individual or a robotic system—to effectively engage in collaborative activities [24]. This includes the capabilities to understand shared objectives, adapt to changing circumstances, and harmonize skills and resources to work seamlessly towards common goals [25]. In the context of collaborative robotics, enhancing collaboration capabilities involves the implementation of a set of technologies: the development of intuitive interfaces that facilitate communication between humans and robots, the integration of sensors and algorithms that enable robots to perceive and respond to human counterparts, and the implementation of robot-behavior protocols to protect humans and proactively engage during the interaction [26]. By enhancing collaboration capabilities, collaborative robotic systems can improve human efficiency, enrich job satisfaction, and unlock new levels of productivity and innovation in manufacturing industries [27].

2.3. Collaborative system requirements

The ability of cobots to interact closely with humans marks a departure from traditional robotic applications, emphasizing safety, flexibility, and collaboration [28]. The broader concept of collaborative robotics extends far beyond its physical capabilities, necessitating a view of its integration within the manufacturing ecosystem [8].

To fully exploit the benefits of collaborative robotics, it is necessary to view cobots as integral components of a comprehensive "collaborative system" [11]. A *collaborative system* is defined as a system intended to directly interact with humans that may include collaborative robots and their supporting technology (e.g., external sensors, computer systems, and external devices). This section highlights the main studies that explored and identified critical requirements and evaluation tools for effective and efficient collaborative systems.

Villani et al. [16] proposed to focus on three main aspects for effective HRC in industrial settings:

- *Safe Interaction*. It encompasses the implementation of various collaborative operating modes, i.e., Safety-rated Monitored Stop (SMS), Hand Guiding (HG), Speed and Separation Monitoring (SSM), and Power and Force Limiting (PFL).
- *Intuitive Interfaces*. It involves developing natural and intuitive communication and programming interfaces such as walk-through programming and programming by demonstration, which allow non-experts to easily teach robots tasks.
- *Design Methods*. It includes task planning and allocation, the application of appropriate control laws to manage the robot's behavior and responses, and the integration of advanced sensors to provide real-time data and feedback.

Wang et al. [9] conceptualized Symbiotic HRC and delineated the prerequisites for Symbiotic HRC Systems (SHRCS):

- *Autonomy*. In SHRC systems, both human and robot agents should be capable of assuming leadership and roles, adapting dynamically throughout the collaboration process.
- Context-awareness. The robot ability to detect the status of the process and the working environment is crucial for successful collaboration.
- *Communication*. SHRC involves constant interaction between human and robot agents. Multimodal and bi-directional communication, encompassing verbal, non-verbal, and gestural cues, facilitates the exchange of information and understanding between agents.
- *Digital Twin*. A digital representation increases situation awareness, allowing both human and robot agents to coordinate their shared goals, roles, plans, and activities.
- *Learning*. Continuous feedback enables both human and robot agents to improve their performance and adapt their strategies based on new information or experiences, ensuring the system remains effective and efficient over time.
- *Safety*. The safety of the human operator within the shared environment is required for both predictable and unforeseen circumstances.

Gervasi et al. [13] presented a comprehensive framework to assess and compare different HRC configurations, highlighting the various latent dimensions that characterize the HRC. The framework is designed to provide a systematic approach to understanding the complexities of human-robot interactions and collaborations. In detail, Gervasi et al. [13] extended the model presented by Goodrich and Schultz [29], identifying the following dimensions to evaluate HRC:

- *Autonomy*. It is ability of a robot to sense its environment, plan based on that environment, and act upon that environment with the intent of reaching some task-specific goal without external control.
- *Information exchange*. It represents the manner communication between the human and the robot takes place.
- *Team organization.* It refers to the organization of the entities involved in the HRC.
- *Adaptivity and training.* It concerns the adaptability and instruction of cobots, as well as the operator training needed.
- *Task.* It contains information on the task to be performed (i.e.., field of application, safety, task organization, and performance).
- *Human factors.* It concerns the assessment of operator physical and psychological well-being and user experience.
- *Ethics.* It refers to evaluating potential ethical hazards derived from the introduction of HRC.
- *Cybersecurity.* It represents the ability of protecting information by preventing, detecting, and responding to cyberattacks.

Cohen et al. [30] identified various essential capabilities required to enable collaboration in collaborative systems. These capabilities include:

- *Safety.* It concerns the adaptive strategies implemented on a collaborative system to ensure human safety.
- *Input.* It represents the ability of the system to receive and process information from various sources such as sensors and other systems, but not from human inputs.
- *Mobility.* It is the ability of the collaborative system to move and navigate within its environment.
- *Actuation.* It deals with the ability of the system to perform physical actions and dynamically correct them.
- *Processing and Status Tracking.* The ability of the system to process information, make decisions, and keep track of the current state of the collaboration.
- *Intelligence.* It represents the awareness degree of the system concerning itself and the surroundings.
- *Interaction (connectivity).* It refers the ability of the system to communicate and collaborate with other systems, devices, and human operators.
- *Human Support.* It concerns with the ability of the system to support human operators in their tasks, both physically and cognitively, by providing appropriate clues or taking initiative when needed.

According to Barravecchia et al. [11], collaborative systems' technological feature that significantly enhance HRC are:

- *Sensing and Perception Systems.* These systems provide robots the capability to comprehensively perceive their environment, detect objects, and interpret the actions of human operators.
- *Adaptive Control Systems.* These systems empower robots to dynamically adjust their behaviour in response to evolving conditions and the actions of human operators.
- *Dialogue Systems.* These systems are instrumental in enabling intuitive and natural interactions and communication between humans and robots.
- *Safety Systems.* These systems include mechanisms to prevent accidents and protocols to handle any unforeseen events to ensure the safety during HRC.

In summary, the effective implementation of collaborative systems necessitates a holistic approach that encompasses a variety of dimensions. By integrating these critical requirements, industries can fully leverage the potential of HRC to enhance efficiency and productivity.

3. Collaboration scale development

The development of the *Collaboration Scale* was guided by a methodology aimed to create a multi-dimensional framework for evaluating the collaborative capabilities of robotic systems. The development was organised as follows:

1. Literature review. The initial phase involved a review of existing literature on HRC, collaborative robotics, and related technological advancements. This review allowed to identify the key dimensions that are critical for effective collaboration between humans and robots.

2. Expert consultation. Consultations with experts in the fields of robotics, automation, human factors, and industrial engineering were conducted to refine the dimensions of collaboration, ensuring they were comprehensive and aligned with current industry needs and future trends.

3. Identification of dimensions. Based on the insights gained step 1 and 2, five foundational and general dimensions were identified as essential to the collaborative capabilities of a system: *Situation awareness, Adaptivity, Communication, Learning* and *Mobility*. It is worth noting that different authors associate different terms for the same concept. Therefore, Table 1 provides a concise description of the identified dimensions of the *Collaboration Scale* and highlights their connections with those related to the collaborative system capabilities proposed in previous frameworks addressing HRC. It is worth noting that different authors may associate different terms for the same concept or decline the same concept with different emphases. A detailed description of the connection between the identified dimensions and those in previous frameworks is provided below:

- *Situation awareness*. It represents the capability of the collaborative system to perceive and interpret its operational environment. The "Design Methods" dimension of Villani et al. [16] emphasizes the need to integrate advanced sensors to obtain real-time data, which is a key aspect of understanding the surrounding environment. "Context-awareness" and "Digital Twin" proposed by Wang et al. [9] refer to the robot's ability to detect, represent, and understand the state of the process and work environment. "Autonomy" of Gervasi et al. [13] encompasses the ability of the collaborative system of sensing and interpreting without any external intervention. "Input" and "Processing and Status Tracking" of Cohen et al. [30] concern the system's ability to receive data from the environment and monitor the current state, while "Intelligence" represents the robot's ability to interpret this information, which is critical to maintaining accurate situational awareness. "Sensing and Perception Systems" by Barravecchia et al. [11] refers to the set of technologies that enables a collaborative system to sense its surroundings, detect objects and interpret human actions to enable situation awareness.
- *Adaptivity*. It refers to the collaborative system's capability to modify its actions in real-time in response to dynamic environmental changes or unforeseen circumstances. "Design Methods" and "Safe Interaction" of Villani et al. [16] encompass the laws controlling a robot's behavior, including those related to ensuring operator safety. "Autonomy" of Wang et al. [9] refers to the ability of the collaborative system to dynamically adapt and taking initiative during interaction, while "Safety" to collaborative system features and adaptive strategies to ensure operator safety.

Table 1
Dimensions of the Collaboration Scale and related connections with previous works in the literature.

Dimension	Description	References				
		Villani et al. [16]	*Wang* et al. (2019)	*Gervasi* et al. [13]	*Cohen* et al. [30]	*Barravecchia* et al. [11]
Situation awareness	The capability of the collaborative system to understand its operational context. This dimension assesses how effectively a collaborative system can perceive its environment and interpret the data.	• Design Methods	• Context-awareness • Digital twin	• Autonomy	• Input • Processing and Status tracking • Intelligence	• Sensing and Perception Systems
Adaptivity	The degree of autonomy with which the collaborative system can adjust to changes in the operational context. This dimension evaluates the collaborative system's capability to modify its actions in real-time in response to dynamic environmental changes or unforeseen circumstances.	• Safe Interaction • Design Methods	• Autonomy • Safety	• Adaptivity and Training	• Safety • Actuation • Human support	• Adaptive Control Systems • Safety Systems
Communication	The quality of communication and feedback between the collaborative system and the operator. This dimension focuses on the mechanisms and protocols through which collaborative systems and humans can exchange information.	• Intuitive Interfaces	• Communication	• Information Exchange	• Interaction (connectivity)	• Dialogue Systems
Learning	The capability of the collaborative system to learn, as well as receive and interpret instructions from human operators. This dimension measures the collaborative system's capability to learn new tasks and modify its performance based on experience or new information, enhancing its operations and interactions with human operators.	• Intuitive Interfaces	• Learning	• Adaptivity and Training	–	–
Mobility	The capability of the collaborative system to move within the environment. This dimension measures how well the collaborative system can navigate freely within an environment.	–	–	• Autonomy	• Mobility	–

"Adaptivity and Training" of Gervasi et al. [13] includes the capability of a collaborative system to autonomously modify its internal parameters to change its behaviour. "Safety" and "Actuation" of Cohen et al. [30] require that the collaborative system can adapt its actions to prevent accidents and collisions, while "Human Support" involves the adaptation to the needs of the operator, providing assistance when needed. "Adaptive Control Systems" of Barravecchia et al. [11] includes the technology set that allows the collaborative system to modify its behavior in response to changes in the environment or human actions, while "Safety Systems" focuses on action protocols to ensure operator safety.

- *Communication*. It refers to the capability of the collaborative system to interact and communicate with a human operator, i.e., to receive and send information. "Intuitive Interfaces" of Villani et al. [16] encompasses the implementation of natural and intuitive communication. "Communication" of Wang et al. [9] emphasizes the need for natural multimodal and bi-directional communication for continuous interaction with a collaborative system. "Information Exchange" of Gervasi et al. [13] represents the ways and means information is exchanged between a collaborative system and an operator. "Interaction (connectivity)" of Cohen et al. [30] involves the ability of the collaborative system to communicate and interact with other systems and human operators. "Dialogue Systems" of Barravecchia et al. [11] includes technologies that enable natural interactions and communications between human operators and a collaborative system.
- *Learning*. It represents the capability of the collaborative system to learn, as well as receive and interpret instructions from human operators. "Intuitive Interfaces" of Villani et al. [16] includes the way human operators can program a collaborative system intuitively to perform new tasks. "Learning" of Wang et al. [9] emphasizes the ability of continuously improving performance through new information and experiences. "Adaptivity and Training" of Gervasi et al. [13] encompasses methods to instruct a collaborative system and the ability to remember habits or preferences of an operator.
- *Mobility*. It is the capability of the collaborative system to move within the environment, i.e., how well it can navigate freely within the environment. "Autonomy" of Gervasi et al. [13] encompasses the ability of the collaborative system of acting without any external intervention, which includes autonomous manipulation and navigation capabilities. The dimension "Mobility" of Cohen et al. [30] explicitly refers to the ability of the collaborative system to move and navigate within its environment.

Note that although "safety" is undeniably a critical aspect in collaborative systems, it is not explicitly defined as a separate dimension in the *Collaboration Scale* as it is inherently integrated into the dimensions *Adaptivity* and *Situational awareness*.

4. Scale construction. Starting from the core dimensions characterizing collaboration capabilities, the corresponding scales were constructed. The choice of a six-level scale for the five dimensions was driven by the need to capture a progressive hierarchy of collaboration capabilities, moving from the complete absence of a capability (Level 0) to its most advanced form (Level 5). Moreover, this discretization was adopted to ensure consistency and comparability across different dimensions of collaboration. The *Collaboration Scale* underwent several iterations of refinement based on feedback from further expert consultations. This iterative process allowed for adjustments and improvements of the scale.

4. Collaboration scale dimensions

This section describes the core dimensions of the *Collaboration Scale,* which is designed to assess the collaboration capabilities of a robotic system. As anticipated, the framework is structured around five dimensions: (i) *Situation Awareness*, (ii) *Adaptivity*, (iii) *Communication*, (iv) *Learning*, and (v) *Mobility*. Each of these dimensions represents a fundamental aspect of collaboration,

enabling a systematic evaluation of a system's capability.

4.1. Situation awareness

The dimension of *Situation awareness* embodies the collaborative system's capacity to effectively perceive its operational environment [31]. This dimension is critical, as it forms the basis upon which robots can engage in collaborative interactions with human counterparts [32].

Situation awareness goes beyond mere sensory perception, encompassing a deep understanding of the context in which they operate [33]. Collaborative systems equipped with advanced *Situation awareness* can interpret a range of environmental cues, from recognizing the presence and actions of human workers to identifying and classifying objects and their states within the workspace [34]. *Situation awareness* is a key factor for enabling other collaboration capability dimensions (e.g., Adaptivity), facilitating a more intuitive and responsive collaboration [22]. When collaborative systems can understand the needs and actions of their human operators, they can adjust their operations to complement human efforts more effectively [35].

To assess the collaborative system's *Situation awareness*, six discrete levels have been established:

- *Level 0 - Absence of Perception*. At this level, the collaborative system is unable to detect objects or people within its operational range. It functions solely based on pre-programmed instructions, with no awareness of its immediate environment.
- *Level 1 - Basic Environmental Awareness*. The collaborative system has the capability to detect the presence of objects and people nearby but does not assign any interpretation or context to these detections. For instance, the cobot presented in Pini et al. [36] is only able to sense its surroundings through force, without assigning any interpretation.
- *Level 2 - Enhanced Environmental Awareness*. The collaborative system's perceptual abilities can distinguish between various pre-classified objects and recognize simple configurations of the workspace. For example, in Mendez et al. [37] the cobot is able to recognize different components through a vision system.
- *Level 3 - Advanced Environmental Awareness*. The collaborative system has the capability to identify moving objects and track their trajectory. Additionally, it can encounter unknown objects and categorize them into different classes. For example, Sharath Chandra et al. [38] presents a vision-based multi-object tracker to be implemented in cobots for enhancing HRC.
- *Level 4 - Basic Human Awareness*. The collaborative system's perceptual range encompasses the detection of human cues, such as body language and fatigue levels. This level marks the beginning of the collaborative system's capability to recognize human behaviours and emotional cues, albeit in a basic form. For instance, in Chand et al. [39] a system based on computer vision and physiological signals to assess the physical and cognitive fatigue of the real-time worker involved in HRC.
- *Level 5 - Advanced Human Awareness*. The collaborative system exhibits a sophisticated understanding of human emotional states, stress, fatigue, and even intentions. It can interpret a broad spectrum of human behaviours and conditions. An example approaching this level is the work of Bussolan et al. [40], which proposes a system for recognizing psychological stress during HRC combining physiological signals, facial action units, and voice features.

Table 2 details a distinction between each level, classification criteria, capability examples, and potential enabling technologies.

4.2. Adaptivity

The dimension of *Adaptivity* plays a pivotal role in defining the effectiveness and efficiency of collaborative systems [41,42], as well as the role that they can have during collaboration with humans [5,43].

Table 2
Levels of Situation awareness for collaborative systems.

Level	Description	Criteria	Example	Potential enabling technologies
Level 0	*Absence of Perception*	No obstacle detection	A collaborative system that does not detect environmental changes.	None.
Level 1	*Basic Environmental Awareness*	Detects obstacles	A collaborative system that in presence of objects and people within the collaborative system's range detects their presence without assigning any intepretation.	Basic sensors (e.g., infrared, ultrasonic, force sensor) for presence detection.
Level 2	*Enhanced Environmental Awareness*	Identifies pre-classified objects	A collaborative system that, when presented with a variety of pre-classified objects, can categorize them based on its programming. Additionally, when the workspace layout is altered, the system recognizes these changes.	Computer vision, basic machine learning for object classification.
Level 3	*Advanced Environmental Awareness*	Detects moving objects and classifies unknown objects	A collaborative system that, in an environment with moving objects, can track their trajectories and predict their future positions. Furthermore, when exposed to unknown objects, it can classify them into general categories based on learned characteristics.	Digital twin, advanced machine learning, motion tracking, object recognition algorithms.
Level 4	*Basic Human Awareness*	Recognizes human body language and stress indicators	A collaborative system that, in an interactive scenario with individuals, can recognize body language cues and signs of fatigue (e.g., hurried movements, expressions of frustration).	Affective computing for human affective state recognition.
Level 5	*Advanced Human Awareness*	Understands complex human behaviours and emotional states	A collaborative system that, in complex interaction scenarios involving actors displaying a range of emotional states and intentions, can accurately	Deep learning-based human behavior analysis, multimodal perception systems.

(*continued on next page*)

Table 2 (*continued*)

Level	Description	Criteria	Example	Potential enabling technologies
			perceive and interpret human conditions accordingly.	

This dimension measures a collaborative system's capability to autonomously modify its behaviour in real-time, including for safety issues, as it encounters varying conditions within its environment or shifts in its designated tasks [9]. The essence of *Adaptivity* lies in the robot's capability for self-regulation and in its ability to seamlessly integrate into human-centric workflows [44].

In industrial environments, the dynamic and often unpredictable nature of production processes requires flexibility and resilience [45]. Collaborative systems equipped with a high degree of *Adaptivity* can meet this demand, offering a versatile solution that supports a wide range of tasks and applications [46]. Whether responding to sudden changes in production requirements, adapting to new or modified components, or navigating alterations in the workspace, adaptive collaborative systems ensure continuity and efficiency in operations [47]. *Adaptability* extends also to the collaborative system's capability to recognize and accommodate the preferences and psychophysical state of individual human operators, further personalizing the collaborative experience [18].

The importance of *Adaptivity* in collaborative systems is underscored by its implications for productivity and job satisfaction [48]. From a productivity standpoint, adaptive collaborative systems can quickly transition between tasks without the need for extensive reprogramming, minimizing downtime and maximizing output [45]. Moreover, by taking on repetitive or ergonomically challenging tasks and adapting to optimize their performance based on real-time feedback, collaborative systems can alleviate physical strain on human employees, contributing to a healthier, more satisfying work environment [49]. The *Adaptivity* dimension is categorised into six levels:

- *Level 0 - No Adaptivity*. The collaborative system operates on fixed pre-programmed routines without any ability to adjust to new or changing conditions.
- *Level 1 - Reactive Adaptivity*. The collaborative system can react to specific changes in its environment but only in a very limited and predefined way. For example, it may stop its operation if it detects a human in its path but cannot alter its path autonomously for safety reasons. For example, in Pini *et al.* [36] the implemented cobot stops when it encounters obstacles and senses that it is applying a higher force than allowed.
- *Level 2 - Structured Adaptivity*. The collaborative system can adjust its behaviour based on a set of predefined rules when encountering variations in its operational environment. This might involve switching between different modes or routines. For instance, the cobot presented in Valente et al. [50] is able to change its behaviour to different predefined modes according to the environmental status.
- *Level 3 - Contextual Adaptivity*. The collaborative system can understand the context of changes in its environment, allowing it to make more specific decisions. For instance, it might plan a new path when approaching a crowded area or adjust the force applied to an object based on the characteristics. For instance, Zhang et al. [51] shows a cobot embedded with a method of trajectory adaptation based on impedance control for enhancing physical collaborative tasks.
- *Level 4 - Predictive Adaptivity*: the collaborative system not only reacts to immediate changes but can also predict future changes and prepare for them in advance. By analysing patterns of human movement and environmental conditions, it can anticipate operational interruptions and adjust its behaviour proactively. For example, Koppula and Saxena [52] presents a cobot embedded with a system to predict future human actions and perform reactive responses.
- *Level 5 - Full Adaptivity*: the collaborative system possesses complete autonomy and capability in adjusting its operations to any changes or new tasks. Based on past experiences, it adapts to novel situations without human intervention and makes decisions that optimize its collaboration with human workers. An example approaching this level is Cantucci et al. [53], which proposes a cognitive architecture for cobots based on the theory of social adjustable autonomy, in which the cobot can tune its behavior according to the user.

Table 3 details a distinction between each level, classification criteria, capability examples, and potential enabling technologies.

4.3. *Communication*

Communication represents the essential bridge that connects human and robotic agents within a shared workspace [54]. This dynamic flow of information is vital for orchestrating seamless interactions and fostering a collaboration that enhances the synergy between humans and robots [9]. The modalities of *Communication* are diverse, including verbal exchanges, non-verbal cues, visual signals, auditory prompts, and even haptic feedback [55,56]. Each of these channels plays a different role in conveying information, ensuring that collaboration is effective and adaptable to the needs of the task at hand [57].

Communication ensures mutual understanding and alignment of goals between humans and collaborative systems. This understanding encompasses the comprehension of intentions, anticipations of actions, and the exchange of feedback [58]. Crucially, effective *Communication* in HRC should be bidirectional [59]. On one hand, humans issue commands and provide guidance to collaborative systems to direct robotic actions. This Human-to-Robot communication is essential for handover tasks, adjusting operations, and imparting human knowledge and preferences to robotic systems [60–62]. On the other hand, collaborative systems also can play an active role in communicating with human operators [63]. Robot-to-Human communication can offer support and guidance to human workers. For example, a collaborative system might provide real-time information about task progress, suggest optimizations based on observed patterns, or even alert humans to potential errors or safety risks [64,65].

The *Communication* dimension is broken down into six distinct levels:

- *Level 0 - No Communication*. At this stage, the collaborative system operates without exchanging any information with the human. It just performs the pre-programmed operations without any human intervention.
- *Level 1 – Basic Unidirectional Communication*. The collaborative system can receive basic inputs/commands from the human (e.g. push button), but it does not provide feedback or responses. As an example, consider Gervasi et al. [66], where collaborative assembly tasks are structured through the use of a physical button that the operator presses to prompt the cobot to proceed with its next action.
- *Level 2 – Basic Bidirectional Communication*. The collaborative system can receive basic inputs/commands from the human, and can provide simple feedback (e.g., pop-ups or acoustic sounds) on the execution of tasks, the status of operations, and/or problems that may arise. As an example, in Capponi et al. [67] the robot interacts with workers through simple bidirectional feedback mechanisms, enhancing engagement and process flow.
- *Level 3 – Basic Multimodal Communication*. The collaborative system can receive information/commands from humans in multiple ways, including at least a natural communication medium (e.g., voice, gesture, gaze, and touch) and can provide detailed feedback regarding task execution, the operation status, and/or problems that may arise. For instance, Ekrekli et al. [68] introduces a co-speech

Table 3
Levels of Adaptivity for collaborative systems.

Level	Description	Criteria	Example	Potential enabling technologies
Level 0	*No Adaptivity*	Operates on fixed routines without adjustment	A collaborative system that, when a worker unexpectedly places an object in its workspace, continues executing its programmed task without detecting or responding to the change.	Pre-programmed task sequences, rigid automation scripts.
Level 1	*Reactive Adaptivity*	Reacts to specific changes in a limited, predefined way	A collaborative system that, when a crate is placed in its designated movement path, either stops or follows a pre-programmed avoidance protocol without autonomously rerouting its trajectory.	Fixed logic decision trees, predefined fail-safe responses, rule-based automation
Level 2	*Structured Adaptivity*	Adjusts behaviour based on predefined rules to environmental variations	A collaborative system that, when different-sized components are introduced on the assembly line, automatically switches to the appropriate handling mode based on predefined operational rules.	Predefined decision-making algorithms.
Level 3	*Contextual Adaptivity*	Understands context of changes, making appropriate decisions	A collaborative system that, when a worker moves unpredictably near its operating area, detects the motion and dynamically adjusts its speed or pauses operations to ensure safety.	Context-based adaptive behaviour algorithm.
Level 4	*Predictive Adaptivity*	Anticipates future changes and prepares in advance	A collaborative system that, when observing repetitive motions of a human operator (e.g., regularly placing tools in the same location), learns to anticipate the next step and adjusts its positioning in advance.	Machine learning algorithms, predictive analytics, pattern recognition, historical data processing.
Level 5	*Full Adaptivity*	Possesses complete planning autonomy and capability in adjusting to changes or new tasks	A collaborative system that, when relocated to a new workstation with unfamiliar tool placements, autonomously scans its surroundings, identifies the layout, and modifies its workflow to optimize efficiency without human intervention.	Reinforcement learning, autonomous decision-making AI, self-learning robotic control systems.

gesture model that allows humans to assign tasks to robots using both speech and gestures.

- *Level 4 - Advanced Multimodal Communication*. The collaborative system can receive information from humans through multiple communication channels simultaneously, merging the different information obtained. It has limited capability to understand deviations from pre-set commands (e.g., synonyms). The collaborative system can provide feedback also through natural communication mediums. Maurtua et al. [69] exemplifies this level by presenting a semantic framework that enables industrial robots to interpret and fuse human input from both speech and gestures, ensuring robust interaction even under adverse environmental conditions.
- *Level 5 - Natural Communication*. Communication with the collaborative system occurs as with another human being. The collaborative system can exchange information with the human through a variety of ways, including both verbal and non-verbal language, and can understand and respond to complex and unstructured requests. The collaborative system can interact with the human through natural communication mediums, as in human-human communication. Angleraud et al. [70] provide an example of *Natural Communication*, presenting a system in which robots learn action semantics and interact with humans using natural language to resolve ambiguities, enabling fluid and human-like collaboration.

Table 4 provides a distinction between each level, classification criteria, capability examples, and potential enabling technologies.

4.4. *Learning*

The dimension of *Learning*, within the realm of HRC, refers to the capability to be instructed, assimilate knowledge, and refine skills through external agent intervention or experience. Learning capabilities of a collaborative system range from the ability to receive instructions from external agents to self-learning [6]. Far beyond executing fixed tasks, *learning* enables collaborative systems to become more flexible, aligning more closely with the complex and ever-changing nature of human workspaces [58,71]. Receiving direct instructions by the human is the basic form of learning. It can be issued in a variety of forms, from the simplest of programming code that determines the collaborative system's movements, to learning-by-doing schemes, to voice instructions that the collaborative system needs to decode and implement [72].

Advanced *Learning* mechanisms within collaborative systems are powered by algorithms and data processing capabilities, often grounded in the principles of Machine Learning (ML) and Artificial Intelligence

Table 4
Levels of Communication for collaborative systems.

Level	Description	Criteria	Example	Potential enabling technologies
Level 0	*No Communication*	Operating without exchanging information	A collaborative system that, when assembling components on a conveyor belt, performs its task without interacting with the human operator, following only its pre-programmed instructions.	None.
Level 1	*Basic Unidirectional Communication*	Receiving basic commands without feedback	A collaborative system that, when a worker presses a start button, begins executing an assembly task without providing any feedback or status updates on its progress.	Push-button interfaces, simple digital inputs.
Level 2	*Basic Bidirectional Communication*	Receiving basic information/ commands and providing simple feedback.	A collaborative system that, when a worker presses a button to start an operation, acknowledges the input by displaying a confirmation message on a screen or emitting an audio cue to indicate task initiation.	Touchscreen interface, LED indicators, auditory feedback, human-machine interface panel.
Level 3	*Basic Multimodal Communication*	Receiving pre-set information/ commands through different ways, including natural communication mediums, and providing feedback.	A collaborative system that, when instructed by an operator through voice commands (e.g., "pick up the part") or gestures (e.g., pointing at an object), recognizes the command and executes the corresponding action while providing feedback (e.g., a light indicator or verbal confirmation).	Voice recognition, gesture recognition, haptic feedback, microphone, cameras.
Level 4	*Advanced Multimodal Communication*	Receiving information /commands from humans through multiple ways simultaneously, including natural communication mediums, and providing feedback also through natural communication mediums.	A collaborative system that, when a worker simultaneously issues commands via speech and gestures (e.g., saying "pass me the tool" while pointing at it), processes both inputs together, recognizing variations in phrasing (e.g., "hand me the tool" instead of "pass me the tool") and responding appropriately.	Multimodal sensor fusion (voice, vision, haptic), NLP (Natural Language Processing) for contextual understanding.
Level 5	*Natural Communication*	Exchanging information through natural communication mediums in an unstructured way, as in human-human communication.	A collaborative system that, when an operator speaks in natural language (e.g., "Can you grab that piece and hold it for a moment?") while making an indicative hand motion, interprets both the command and context, responding as a human collaborator would by adjusting its movements accordingly.	Deep learning NLP models, contextual AI, real-time scene analysis, emotion and intent recognition.

(AI) [73,74]. These technologies allow collaborative systems to analyse the outcomes of their actions, understand the implications of their interactions with human operators, and even predict future scenarios based on historical data [75]. As a result, a collaborative system that learns from its environment and experiences can optimize its task execution to complement human activities better, and avoid previous inefficiencies or errors.

To categorize and understand the extent of a collaborative system's learning capabilities, six distinct levels of *Learning* have been identified:

- *Level 0 - Traditional Programming*. The collaborative system operates following preset algorithms and procedures using internal programming language. There is no capacity for learning or adapting to new situations or errors without directly modifying the internal programming code.
- *Level 1 - User-friendly Programming*: The collaborative system operates according to preset algorithms and procedures, which can also be provided through a user-friendly graphical interface. This interface allows even less experienced users or those with limited information knowledge to reprogram the collaborative system. An example of *User-friendly Programming* is provided by Ionescu [76], which introduces a graphical, block-based programming environment that leverages GUI automation to simplify robot programming.
- *Level 2 - Programming by Demonstration*. The collaborative system is able to record and perform a sequence of actions and configurations (e.g., joint positions and end-effector status) demonstrated by a human manually guiding it. This instruction method is performed online and does not require programming language. Ravichandar

et al. [77] provides a comprehensive overview of techniques within the Programming by Demonstration paradigm.

- *Level 3 - Guided Learning*. The collaborative system can be instructed by a human operator that explains the various tasks to be performed through natural mediums of communication (e.g., voice, gestures, touch). Specific algorithms are necessary to process and interpret information provided by the human operator. For instance, Pires [78] shows an industrial robot that be commanded through human voice instructions, highlighting the use of natural communication interfaces and the necessary algorithms to interpret spoken commands for task execution.
- *Level 4 - Continuous Improvement*. The collaborative system can learn autonomously from previous situations or interactions, leveraging deep learning algorithms to improve and adapt its operation without direct human intervention. The collaborative system can learn from instructions or feedback provided by the human operator. This level of learning requires human supervision. An example is provided by Celemin et al. [79], which proposes hybrid learning strategies that combine reinforcement learning with human corrective feedback.
- *Level 5 - Autonomous Learning*: The collaborative system is equipped with a continuous learning capability and can dynamically adapt to novel situation. It is able to analyse feedback and past experiences with advanced algorithms to constantly refine its capabilities, predictions, and decisions. It proactively adapts its strategies and actions based on new information or experiences, ensuring optimal efficiency and effectiveness in the work environment. An example of *Autonomous Learning* is provided by Berscheid et al. [80], where a robot learns flexible pick-and-place tasks through one-shot imitation and self-supervised learning, enabling it to generalize to novel objects and adapt its actions based on experience without requiring predefined object models.

Table 5 provides a distinction between each level, classification criteria, capability examples, and potential enabling technologies.

4.5. Mobility

The *Mobility* dimension is a critical aspect of collaborative robotic systems, defining the robot's capability to move within its operational environment. *Mobility* enables collaborative systems to perform tasks at different locations and adapt to dynamic changes in manufacturing processes [81]. The ability to move within or across workstations can enhance the efficiency and versatility of collaboration, allowing robotic systems to respond flexibly to evolving tasks, layouts and operator needs. Mobility extends the functional capabilities of collaborative systems beyond fixed positions, facilitating tasks such as material handling, assembly, inspection, and maintenance in dynamic industrial settings [82]. Additionally, mobility enhances safety by enabling collaborative systems to navigate away from hazardous situations and maintain appropriate distances from human operators when necessary [83].

In detail, to assess the mobility of collaborative robotic systems, the following levels have been defined:

- *Level 0 – No Mobility:* The collaborative system is permanently installed in a fixed position with no capability to move or be repositioned. It cannot be relocated without significant disassembly or reinstallation efforts. The robot operates solely within the reach of its manipulator or end-effector.
- *Level 1 - Localized Adjustment Mobility*: the collaborative system is fixed in place but can be manually repositioned within the workstation area by human operators. These adjustments allow for limited movement within a defined, localized space, enabling fine-tuning of position and orientation as needed. A case of this level is the work by Palomba et al. [84], which shows a collaborative assembly station

Table 5
Levels of learning for collaborative systems.

Level	Description	Criteria	Example	Potential enabling technologies
Level 0	*Traditional programming*	Receives instructions through programming language.	A collaborative system that can only be programmed using an internal coding language, requiring explicit command sequences to define its actions. It does not allow adjustments or task modifications without reprogramming.	Text-based programming languages, low-level machine control, command-line interfaces.
Level 1	*User-friendly programming*	Receives instructions through graphical interface.	A collaborative system that can be programmed through a user-friendly graphical interface, allowing operators to configure actions and parameters without writing code.	Graphical User Interfaces (GUIs), block-based programming tools, drag-and-drop workflow editors.
Level 2	*Programming by demonstration*	Memorizes the operations to be performed after the operator's demonstration.	A collaborative system that can be programmed through physical demonstration, where an operator manually moves the robot's components (e.g., arm, gripper) to record a sequence of positions and actions, which the system then replicates.	Teach pendants, motion recording systems, trajectory learning through physical manipulation.
Level 3	*Guided learning*	Understands instructions for a new task given through natural communication mediums (e.g., voice, gestures, touch).	A collaborative system that follows step-by-step verbal instructions from an operator (e.g., "Pick up the screw") translating these inputs into executable actions.	speech-to-action frameworks, gesture-based command mapping.
Level 4	*Continuous improvement*	Modifies its behavior based on the feedback it receives.	A collaborative system that, during an assembly task, receives operator feedback to reduce the force applied when inserting a delicate	Reinforcement learning, real-time parameter optimization, adaptive control algorithms, human-in-the-loop training systems.

(*continued on next page*)

Table 5 (*continued*)

Level	Description	Criteria	Example	Potential enabling technologies
			component. In subsequent executions, it automatically applies the adjusted force without requiring manual reprogramming.	
Level 5	*Autonomous learning*	Autonomously improves its performance by developing appropriate strategies	A collaborative system that, after executing numerous pick-and-place operations, identifies patterns where objects frequently slip from its gripper. It then refines its grasping technique by adjusting grip force or approach angles to reduce errors.	AI-driven optimization, autonomous decision-making algorithms, real-time performance analysis.

where the cobot can be repositioned to improve ergonomics across multiple operators.

- *Level 2 - Manual Repositioning Mobility:* the collaborative system remains stationary during tasks but can be physically moved by human operators between tasks or shifts. Movement requires human intervention and is not automated. The robot can be relocated to different areas within the workspace to perform tasks in various workstations. Da Silva et al. [85] shows a plug-and-produce robotic assistants designed on a wheeled movable platform.
- *Level 3 – Constrained Mobility*: the collaborative system has the capability to autonomously move along a predetermined path or within a limited number of positions, such as a rail or a constrained guide. Its movement is restricted to specific trajectories defined by the physical constraints of its movement mechanism. For example, the robot presented by Grimstad et al. [86] is capable of navigating on a rail system.
- *Level 4 – Planar Mobility*: the collaborative system can autonomously move freely on a flat surface, such as an industrial floor. For instance, Moshayedi et al. [87] presents a mobile robot capable of navigating to various locations within a defined planar area, avoiding obstacles, and reaching specified targets.
- *Level 5 – Full Mobility*: the collaborative system possesses advanced mobility, enabling it to autonomously traverse uneven surfaces, navigate over obstacles, and move across complex terrains, including stairs or ramps. It can reach targets within an area with irregular surfaces, demonstrating high adaptability in diverse environments. As an example, Stasse *et al.* [88] presents a solution that allows a humanoid robot to dynamically navigate across substantial obstacles.

Table 6 provides a distinction between each level, classification criteria, capability examples, and potential enabling technologies.

5. Collaborative systems classification

Based on the dimensions and levels identified in the *Collaboration Scale*, collaborative systems can be classified into distinct categories,

Table 6
Levels of Mobility for collaborative systems.

Level	Description	Criteria	Example	Potential enabling technologies
Level 0	*No Mobility*	Fixed in place with no mobility, operates only within manipulator's reach.	A collaborative system that, when installed in a fixed position on an assembly line, operates solely within the reach of its manipulator, remaining immobile unless manually disassembled and reinstalled in a new location.	Rigid mounting system, fixed automation infrastructure.
Level 1	*Localized Adjustment Mobility*	Manually adjustable within a localized area for setup or calibration.	A collaborative system that, when positioned within a workstation, can be just manually adjusted within a predefined range (e.g., slight angle or position changes for calibration).	Manually adjustable platforms.
Level 2	*Manual Repositioning Mobility*	Stationary during tasks but manually movable between locations.	A collaborative system that, between production shifts, is physically lifted and relocated by workers to a different workstation, enabling it to operate in a new location.	Detachable fixtures, wheeled bases with manual locking, quick-connect power and data interfaces.
Level 3	*Constrained Mobility*	Moves autonomously along a predefined path or constrained guide.	A collaborative system that, when placed on a rail-mounted guide, autonomously moves back and forth along a constrained trajectory (e.g., transporting components along a fixed path), but cannot deviate from the track.	Rail-mounted systems, linear actuators, automated guided systems magnetic or optical guidance.
Level 4	*Planar Mobility*	Navigates autonomously on flat surfaces, avoiding obstacles.	A collaborative system in a fulfillment center navigates across a warehouse floor, transporting inventory bins. It autonomously	LiDAR, vision-based navigation, omnidirectional wheels, collision avoidance algorithms, indoor GPS.

(*continued on next page*)

Table 6 (*continued*)

Level	Description	Criteria	Example	Potential enabling technologies
			avoids shelves, forklifts, and workers while dynamically adjusting its path to reach designated picking stations.	
Level 5	*Full Mobility*	Traverses uneven terrains, obstacles, and stairs autonomously.	A quadrupedal collaborative system in an oil refinery moves across uneven terrain, climbs stairs, and adapts to slippery surfaces. It autonomously traverses hazardous environments to perform real-time equipment monitoring and detect leaks without human intervention.	Legged robotic locomotion, aerial mobility, dynamic stabilization algorithms, multi-surface traction control.

each reflecting a different stage of development in collaborative capabilities. These categories provide a structured way to evaluate and compare robotic systems based on their proficiency in the dimensions of collaboration capability.

The classification framework organizes systems into six progressive categories, ranging from the most basic systems with limited collaboration capabilities to fully autonomous systems that exhibit advanced collaborative capabilities. Essentially, six distinct categories of collaborative systems can be identified: *Dependent Collaborative System, Guided Collaborative System, Assisted Collaborative System, Balanced Collaborative System, Proactive Collaborative System, Autonomous Collaborative System*. Fig. 1 offers a detailed summary of these levels.

Each category corresponds to a level and possesses characteristics of that level in all dimensions. For instance, a collaborative system at Level 2 has at least all Level 2 characteristics in each dimension. Each level represents a distinct stage of collaboration maturity, from basic (e.g., Level 0 - Dependent Systems) to advanced systems (e.g., Level 5 - Autonomous Systems). This classification ensures that each level represents a coherent stage of development, where capabilities across all dimensions align. By ensuring that each level integrates all dimensions at the corresponding stage, the classification maintains a logical and scalable framework for collaboration capability maturity.

Collaborative systems may not fit perfectly into one archetype as they could be advanced in one dimension but limited in others. To classify a system at a particular level, it must possess all the level-related features across all dimensions (see Section 4).

5.1. Example of categorization of collaborative systems

To illustrate the practical application of the *Collaboration Scale* in categorizing collaborative systems, this section provides a real-world example of a collaborative system utilized in the assembly process of an electromechanical actuator for the aerospace industry. The system, depicted in Fig. 2, involves an actuator with a total length of 600 mm and a weight of 5 kg. This assembly process demands high precision and consistency due to the critical nature of aerospace actuators.

The scheme of the collaborative system employed in this assembly process is represented in Fig. 3.

Technological features of the system include:

Collaboration Scale Dimensions						
Situation Awareness	**Adaptivity**	**Communication**	**Learning**	**Mobility**		***Collaborative Systems Category***
Absence Of Perception	No Adaptivity	No Communication	Traditional Programming	No Mobility	→	*Level 0 - Dependent Collaborative System*
Basic Environmental Awareness	Reactive Adaptivity	Basic Unidirectional Communication	User-Friendly Programming	Localized Adjustment Mobility	→	*Level 1 - Guided Collaborative System*
Enhanced Environmental Awareness	Structured Adaptivity	Basic Bidirectional Communication	Programming By Demonstration	Manual Repositioning Mobility	→	*Level 2 - Assisted Collaborative System*
Advanced Environmental Awareness	Contextual Adaptivity	Basic Multimodal Communication	Guided Learning	Constrained Mobility	→	*Level 3 - Balanced Collaborative System*
Basic Human Awareness	Predictive Adaptivity	Advanced Multimodal Communication	Continuous Improvement	Planar Mobility	→	*Level 4 - Proactive Collaborative System*
Advanced Human Awareness	Full Adaptivity	Natural Communication	Autonomous Learning	Full Mobility	→	*Level 5 - Autonomous Collaborative System*

Fig. 1. Collaborative systems categories defined on the basis of the dimensions of the Collaboration Scale.

Fig. 2. Representation of the electromechanical actuator.

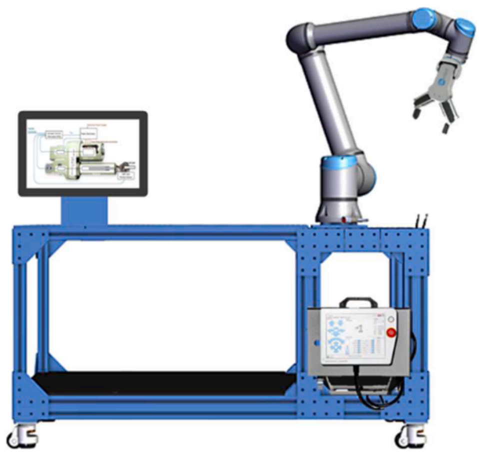

Fig. 3. Representation of the collaborative system used in the actuator assembly process.

- *UR10 cobot*: the UR10 cobot is equipped with a two-finger end effector designed for gripping and manipulating components during the assembly process. UR10 has a payload capacity of 10 kg, a reach of 1300 mm and ± 0.1 mm repeatability.
- *Proximity sensors*: these sensors allow the robot to detect the presence of objects and people in its immediate surroundings. If an obstacle or person enters the robot's workspace, the system automatically halts, minimizing the risk of collisions and adhering to safety protocols.
- *Human-machine interface*: the system is equipped with a user-friendly interface consisting of a touchscreen display where technical drawings of the actuator being assembled and the list of instructions are shown. The interface also includes touch commands that allow the operator to input instructions, such as starting, stopping, or repositioning the robot as needed. Additionally, the system provides simple feedback through audio alerts or messages displayed on the screen.
- *Simple programming interface*: the system is designed to allow operators to reconfigure the robot's tasks through a drag-and-drop programming interface. This feature enables quick and easy adjustments to the robot's operation without requiring advanced programming skills.

During the actuator assembly process, a collaborative robot assists by handling repetitive and physically demanding tasks, such as holding components in place. The robot operates alongside an automated delivery system that supplies components (e.g., actuator housing, gears, and fasteners) correctly positioned for easy access. While the robot contributes to streamlining certain aspects of the process, the collaboration remains basic, with the robot performing predefined tasks and the operator overseeing critical and complex operations, such as applying torque. The interaction is largely task-specific, with minimal dynamic collaboration or shared decision-making between the human and the robot.

Table 7 shows an overview of the performance of the collaborative system for the five dimensions of the *Collaboration Scale*.

Based on the criteria summarized in Fig. 1, the system meets the requirements for classification as a *Level 1 Guided Collaborative System*, due to its limited adaptivity and mobility, and user-friendly interface. Although the system's communication capabilities are at Level 2, the overall characteristics align with Level 1 (see Fig. 4).

Table 7
Performance of the collaborative system.

Dimension	Collaborative system performance	Level
Situation Awareness	The system detects objects and people in its workspace via proximity sensors	**Level 1 - Basic Environmental Awareness**
Adaptivity	The robot responds to environmental changes, such as stopping if an obstacle is detected, but cannot adjust behavior dynamically.	**Level 1 - Reactive Adaptivity**
Communication	The system allows the operator to issue commands (e.g., start/stop, reposition) and provides basic feedback through alerts.	**Level 2 - Basic Bidirectional Communication**
Learning	Operators can reconfigure tasks via a drag-and-drop interface.	**Level 1 - User-friendly Programming**
Mobility	The collaborative system is fixed in place but can be manually repositioned within the workstation area by human operators	**Level 1 - Localized Adjustment Mobility**

6. Implications

The introduction of the *Collaboration Scale* represents a contribution to the field of industrial collaborative robotics, with implications for both academic research and industrial practice. The proposed scale has the potential for a wide range of applications and can prove to be beneficial in multiple contexts:

- *Terminology and standardization*: the *Collaboration Scale* introduces a structured taxonomy that distinguishes between different types of collaborative robotic systems, proposing a common language and classification criteria. This framework aims to reduce and facilitate effective communication among stakeholders by establishing standardized terminology.
- *Acceleration of innovation*: by clearly outlining the levels of collaboration capability, the *Collaboration Scale* helps robot manufacturers and developers to better direct research and development efforts toward key areas that enhance HRC. The scale highlights critical dimensions: *Situation awareness, Adaptivity, Communication, Learning,* and *Mobility*, guiding technological innovation in these areas.
- *Guidance for policies and regulations*: policy maker can use the *Collaboration Scale* as a reference for developing guidelines and regulations that ensure the safe and ethical use of collaborative robots. The scale offers a structured framework for assessing different levels of collaboration capabilities, informing the creation of standards and certifications.
- *Promotion of human-centricity for Industry 5.0*: in the context of the evolution toward Industry 5.0, which emphasizes human-centricity, the *Collaboration Scale* helps organizations assess how their robotic systems align with these principles. By adopting robots with higher levels of collaboration capability, companies can create more flexible, resilient, and human-centered work environments. Moreover, the scale can be extended to evaluate individual robotic systems even within multi-human, multi-robot collaborative contexts.
- *Stimulus for future technological developments*: by identifying areas where current collaborative systems may be lacking, the *Collaboration Scale* stimulates research and development to overcome these limitations. For example, improving natural communication or autonomous learning in robots can become a research priority, driving technological advancement in the sector.

Situation Awareness	Adaptivity	Communication	Learning	Mobility		Collaborative Systems Category
Collaboration Scale Dimensions						
Absence Of Perception	No Adaptivity	No Communication	Traditional Programming	No Mobility	→	*Level 0 - Dependent Collaborative System*
Basic Environmental Awareness	**Reactive Adaptivity**	Basic Unidirectional Communication	**User-Friendly Programming**	**Localized Adjustment Mobility**	→	***Level 1 - Guided Collaborative System***
Enhanced Environmental Awareness	Structured Adaptivity	**Basic Bidirectional Communication**	Programming By Demonstration	Manual Repositioning Mobility	→	*Level 2 - Assisted Collaborative System*
Advanced Environmental Awareness	Contextual Adaptivity	Basic Multimodal Communication	Guided Learning	Constrained Mobility	→	*Level 3 - Balanced Collaborative System*
Basic Human Awareness	Predictive Adaptivity	Advanced Multimodal Communication	Continuous Improvement	Planar Mobility	→	*Level 4 - Proactive Collaborative System*
Advanced Human Awareness	Full Adaptivity	Natural Communication	Autonomous Learning	Full Mobility	→	*Level 5 - Autonomous Collaborative System*

Fig. 4. Classification of the collaborative system according to the Collaboration Scale.

7. Conclusions

In this paper, the *Collaboration Scale,* i.e., a comprehensive framework designed to assess and quantify the collaborative capabilities of robotic systems within industrial environments, has been presented. The *Collaboration Scale* addresses the growing need for standardized evaluation tools in the context of Industry 4.0 and the forthcoming Industry 5.0, where HRC plays a pivotal role in creating human-centric manufacturing processes.

By delineating five foundational dimensions: *Situation awareness, Adaptivity, Communication, Learning*, and *Mobility*, the *Collaboration Scale* provides a multi-dimensional approach to evaluating collaborative systems. Each dimension is discretized into specific levels, allowing for the distinction of a collaborative system's capabilities. This framework can provide support in identifying the current capabilities of robotic systems and in highlighting areas for improvement, guiding future technological developments.

The *Collaboration Scale* serves multiple purposes: (i) it creates a consistent vocabulary for professionals and researchers to describe and discuss collaborative capabilities, facilitating clearer communication and collaboration across disciplines; (ii) by providing clear criteria and benchmarks, the scale encourages innovation in the development of collaborative robots; (iii) the scale provides a practical means to evaluate and compare different robotic systems, assisting organizations in selecting appropriate technologies that align with their operational needs; (iv) the scale could serve as a reference for standardization efforts by organizations such as ISO commissions or certification authorities, supporting consistency and interoperability in collaborative robotics.

The *Collaboration Scale* represents an initial attempt to structure and assess collaboration capabilities in robotic systems. Harmonizing the *Collaboration Scale* with established international standards for robotics and automation is an essential step toward broader adoption. Moreover, future research will focus on developing a framework that integrates the *Collaboration Scale* to evaluate performance and productivity in different HRC contexts.

CRediT authorship contribution statement

Federico Barravecchia: Methodology, Formal analysis, Conceptualization. **Riccardo Gervasi:** Methodology, Formal analysis, Conceptualization. **Luca Mastrogiacomo:** Supervision, Methodology, Conceptualization. **Fiorenzo Franceschini:** Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

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

References

[1] J. Lee, B. Bagheri, H.-A. Kao, A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems, Manuf. Lett. 3 (2015) 18–23.
[2] F. Barravecchia, L. Mastrogiacomo, F. Franceschini, A general cost model to assess the implementation of collaborative robots in assembly processes, Int. J. Adv. Manuf. Technol. 125 (11–12) (2023) 5247–5266.
[3] J.M. Rožanec, I. Novalija, P. Zajec, K. Kenda, H. Tavakoli Ghinani, S. Suh, E. Veliou, D. Papamartzivanos, T. Giannetsos, S.A. Menesidou, D. Mladenić, J. Soldatos, Human-centric artificial intelligence architecture for industry 5.0 applications, Int. J. Prod. Res. 61 (2023) 6847–6872.
[4] M.H. Zafar, E.F. Langås, F. Sanfilippo, Exploring the synergies between collaborative robotics, digital twins, augmentation, and industry 5.0 for smart manufacturing: a state-of-the-art review, Robot. Comput.-Integr. Manuf. 89 (2024) 102769.
[5] L. Wang, X.V. Wang, J. Váncza, Z. Kemény, Advanced Human-Robot Collaboration in Manufacturing, Springer, 2021.
[6] A. Weiss, A.-K. Wortmeier, B. Kubicek, Cobots in industry 4.0: a roadmap for future practice studies on Human-robot collaboration, IEEE Trans. Hum.-Mach. Syst. 51 (4) (2021) 335–345.
[7] A. Kolbeinsson, E. Lagerstedt, J. Lindblom, Foundation for a classification of collaboration levels for human-robot cooperation in manufacturing, Prod. Manuf. Res. 7 (1) (2019) 448–471.
[8] A.C. Simões, A. Pinto, J. Santos, S. Pinheiro, D. Romero, Designing human-robot collaboration (HRC) workspaces in industrial settings: a systematic literature review, J. Manuf. Syst. 62 (2022) 28–43.
[9] L. Wang, R. Gao, J. Váncza, J. Krüger, X.V. Wang, S. Makris, G. Chryssolouris, Symbiotic human-robot collaborative assembly, CIRP ann. 68 (2) (2019) 701–726.
[10] F. Barravecchia, M. Bartolomei, L. Mastrogiacomo, F. Franceschini, Designing symbiotic human–robot collaboration in assembly tasks, Prod. Eng. (2025) 1–33.

[11] F. Barravecchia, M. Bartolomei, L. Mastrogiacomo, F. Franceschini, Advancing Human-Robot Collaboration: proposal of a methodology for the design of Symbiotic Assembly Workstations, Procedia Comput. Sci. 232 (2024) 3141–3150.
[12] M.C. Zizic, M. Mladineo, N. Gjeldum, L. Celent, From industry 4.0 towards Industry 5.0: a review and analysis of paradigm shift for the people, organization and technology, Energies 15 (14) (2022) 15145221.
[13] R. Gervasi, L. Mastrogiacomo, F. Franceschini, A conceptual framework to evaluate human-robot collaboration, Int. J. Adv. Manuf. Technol. 108 (3) (2020) 841–865.
[14] International Organization for Standardization (2016) 'ISO/TS 15066:2016 - robots and robotic devices — Collaborative robots'.
[15] Z.M. Bi, C. Luo, Z. Miao, B. Zhang, W.J. Zhang, L. Wang, Safety assurance mechanisms of collaborative robotic systems in manufacturing, Robot. Comput.-Integr. Manuf. 67 (2021) 102022.
[16] V. Villani, F. Pini, F. Leali, C. Secchi, Survey on human–robot collaboration in industrial settings: safety, intuitive interfaces and applications, Mechatronics 55 (2018) 248–266.
[17] E. Matheson, R. Minto, E.G.G. Zampieri, M. Faccio, G. Rosati, Human-robot collaboration in manufacturing applications: a review, Robotics 8 (4) (2022) 8040100.
[18] R. Gervasi, F. Barravecchia, L. Mastrogiacomo, F. Franceschini, Applications of affective computing in human-robot interaction: state-of-art and challenges for manufacturing, Proc. Inst. Mech. Eng., B: J. Eng. Manuf. 237 (6–7) (2023) 815–832.
[19] N. Kozamernik, J. Zaletelj, A. Košir, F. Šuligoj, D. Bračun, Visual quality and safety monitoring system for human-robot cooperation, Int. J. Adv. Manuf. Technol. 128 (1–2) (2023) 685–701.
[20] E. Verna, S. Puttero, G. Genta, M. Galetto, A novel diagnostic tool for human-centric quality monitoring in human–robot collaboration manufacturing, J. Manuf. Sci. Eng. 145 (12) (2023) 121009.
[21] M. Bartolomei, F. Barravecchia, L. Mastrogiacomo, D.M. Gatta, F. Franceschini, Streamlining assembly instruction design (S-AID): a comprehensive systematic framework, Comput. Ind. 165 (2025) 104232.
[22] A. Hentout, M. Aouache, A. Maoudj, I. Akli, Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017′, Adv. Robot. 33 (15–16) (2019) 764–799.
[23] S. Robla-Gómez, V.M. Becerra, J.R. Llata, E. Gonzalez-Sarabia, C. Torre-Ferrero, J. Perez-Oria, Working together: a review on safe human-robot collaboration in industrial environments, Ieee Access 5 (2017) 26754–26773.
[24] C. Huxham, S. Vangen, Doing things collaboratively: realizing the advantage or succumbing to inertia? IEEE Eng. Manag. Rev. 32 (4) (2004) 11–20.
[25] M.J. Amon, H. Vrzakova, S.K D'Mello, Beyond dyadic coordination: multimodal behavioral irregularity in triads predicts facets of collaborative problem solving, Cogn. Sci. 43 (10) (2019) e12787.
[26] J.F. Castillo, J.H. Ortiz, M.F.D. Velásquez, D.F. Saavedra, COBOTS in industry 4.0: safe and efficient interaction, in: J.H. Ortiz, R.K. Vinjamuri (Eds.), Collaborative and Humanoid Robots, Intech-Open, London, UK, 2021.
[27] A. Colim, R. Morgado, P. Carneiro, N. Costa, C. Faria, N. Sousa, L.A. Rocha, P. Arezes, Lean manufacturing and ergonomics integration: defining productivity and wellbeing indicators in a human–robot workstation, Sustainability 13 (4) (2021) 1–21.
[28] M. Faccio, I. Granata, A. Menini, M. Milanese, C. Rossato, M. Bottin, R. Minto, P. Pluchino, L. Gamberini, G. Boschetti, G. Boschetti, G. Rosati, Human factors in cobot era: a review of modern production systems features, J. Intell. Manuf. 34 (1) (2023) 85–106.
[29] M.A. Goodrich, A.C. Schultz, Human-robot interaction: a survey, Found. Trends Hum.-Comput. Interact. 1 (3) (2007) 203–275.
[30] Y. Cohen, S. Shoval, M. Faccio, R. Minto, Deploying cobots in collaborative systems: major considerations and productivity analysis, Int. J. Prod. Res. 60 (6) (2022) 1815–1831.
[31] M. Müller, T. Ruppert, N. Jazdi, M. Weyrich, Self-improving situation awareness for human–robot-collaboration using intelligent Digital Twin, J. Intell. Manuf. 35 (2024) 2045–2063.
[32] M. Faccio, Y. Cohen, Intelligent cobot systems: human-cobot collaboration in manufacturing, J. Intell. Manuf. 35 (2023) 1905–1907.
[33] M. Paliga, Human–cobot interaction fluency and cobot operators' job performance, mediat. role work engagem.: surv. Robot. Auton. Syst. 155 (2022) 104191.
[34] A. Dzedzickis, J. Subaciute-Žemaitienė, E. Šutinys, U. Samukaitė-Bubnienė, V. Bučinskas, Advanced applications of industrial robotics: new trends and possibilities, Appl. Sci. (Switz.) 1 (12) (2022) 135.
[35] R. Gervasi, M. Capponi, L. Mastrogiacomo, F. Franceschini, Manual assembly and Human–Robot Collaboration in repetitive assembly processes: a structured comparison based on human-centered performances, Int. J. Adv. Manuf. Technol. 126 (3–4) (2023) 1213–1231.
[36] F. Pini, F. Leali, M. Ansaloni, A systematic approach to the engineering design of a HRC workcell for bio-medical product assembly, in: 2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA), 2015, pp. 1–8.
[37] E. Mendez, O. Ochoa, D. Olivera-Guzman, V.H. Soto-Herrera, J.A. Luna-Sánchez, C. Lucas-Dophe, A. González, Integration of deep learning and collaborative robot for assembly tasks, Appl. Sci. 14 (2) (2024) 839.
[38] A. Sharath Chandra, M. Plasch, C. Eitzinger, B. Rinner, Context enhanced multi object tracker for human robot collaboration, in: Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction, 2017, pp. 61–62.
[39] S. Chand, H. Zheng, Y. Lu, A vision-enabled fatigue-sensitive human digital twin towards human-centric human-robot collaboration, J. Manuf. Syst. 77 (2024) 432–445.
[40] A. Bussolan, S. Baraldo, L.M. Gambardella, A. Valente, Multimodal fusion stress detector for enhanced human-robot collaboration in industrial assembly tasks, in: 2024 33rd IEEE International Conference on Robot and Human Interactive Communication (ROMAN), IEEE, 2024, pp. 978–984.
[41] R. Nogueira, J. Reis, R. Pinto, G. Gonçalves, Self-adaptive cobots in cyber-physical production systems, in: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), IEEE, 2019, pp. 521–528.
[42] S. El Zaatari, M. Marei, W. Li, Z. Usman, Cobot programming for collaborative industrial tasks: an overview, Robot. Auton. Syst. 116 (2019) 162–180.
[43] X.V. Wang, Z. Kemény, J. Váncza, L. Wang, Human–robot collaborative assembly in cyber-physical production: classification framework and implementation, CIRP ann. 66 (1) (2017) 5–8.
[44] S. Panagou, W.P. Neumann, F. Fruggiero, A scoping review of human robot interaction research towards industry 5.0 human-centric workplaces, Int. J. Prod. Res. 62 (3) (2024) 974–990.
[45] M. Soori, R. Dastres, B. Arezoo, F.K.G. Jough, Intelligent robotic systems in Industry 4.0: a review, J. Adv. Manuf. Sci. Technol. 4 (3) (2024) 2024007.
[46] F. Barravecchia, M. Bartolomei, L. Mastrogiacomo, F. Franceschini, Redefining human–robot symbiosis: a bio-inspired approach to collaborative assembly, Int. J. Adv. Manuf. Technol. 128 (5–6) (2023) 2043–2058.
[47] L. Vianello, S. Ivaldi, A. Aubry, L. Peternel, The effects of role transitions and adaptation in human–cobot collaboration, J. Intell. Manuf. 35 (2023) 2005–2019.
[48] F. Fraboni, H. Brendel, L. Pietrantoni, Evaluating organizational guidelines for enhancing psychological well-being, safety, and performance in technology integration, Sustain. (Switz.) 15 (10) (2023) 8113.
[49] A. Cardoso, A. Colim, E. Bicho, A.C. Braga, M. Menozzi, P. Arezes, Ergonomics and human factors as a requirement to implement safer collaborative robotic workstations: a literature review, Safety 7 (4) (2021) 71.
[50] A. Valente, G. Pavesi, M. Zamboni, E. Carpanzano, Deliberative robotics–a novel interactive control framework enhancing human-robot collaboration, CIRP Ann. 71 (1) (2022) 21–24.
[51] C. Zhang, J. Luo, C. Zeng, B. Tang, M. Pang, C. Yang, Trajectory adaptation with impedance control for Human-robot collaboration tasks, in: 2023 International Conference on Advanced Robotics and Mechatronics (ICARM), 2023, pp. 267–272.
[52] H.S. Koppula, A. Saxena, Anticipating human activities using object affordances for reactive robotic response, IEEE Trans. Pattern Anal. Mach. Intell. 38 (1) (2015) 14–29.
[53] F. Cantucci, R. Falcone, C. Castelfranchi, Human-robot interaction through adjustable social autonomy, Intell. Artif. 16 (1) (2022) 69–79.
[54] A. Bonarini, Communication in human-robot interaction, Curr. Robot. Rep. 1 (4) (2020) 279–285.
[55] K. Kassem, T. Ungerböck, P. Wintersberger, F. Michahelles, What is happening behind the wall? Towards a better understanding of a hidden robot's intent by multimodal cues, Proc. ACM Hum.-Comput. Interact. 6 (MHCI) (2022) 1–19.
[56] D.P. Losey, C.G. McDonald, E. Battaglia, M.K O'Malley, A review of intent detection, arbitration, and communication aspects of shared control for physical human–robot interaction, Appl. Mech. Rev. 70 (1) (2018) 010804.
[57] S. Gross, B. Krenn, A communicative perspective on Human–Robot collaboration in industry: mapping communicative modes on collaborative scenarios, Int. J. Soc. Robot. 16 (2024) 1315–1332.
[58] D. Mukherjee, K. Gupta, L.H. Chang, H. Najjaran, A survey of robot learning strategies for Human-robot collaboration in industrial settings, Robot. Comput.-Integr. Manuf. 73 (2022) 102231.
[59] D. Ferrari, F. Benzi, C. Secchi, Bidirectional communication control for human-robot collaboration, in: 2022 International Conference on Robotics and Automation (ICRA), IEEE, 2022, pp. 7430–7436.
[60] A. Castro, F. Silva, V. Santos, Trends of human-robot collaboration in industry contexts: handover, learning, and metrics, Sensors 21 (12) (2021) s21124113.
[61] M. Costanzo, G. De Maria, C. Natale, Handover control for Human-robot and robot-robot collaboration, Front. Robot. AI 8 (8) (2021) 672995.
[62] T. Kaupp, A. Makarenko, H. Durrant-Whyte, Human-robot communication for collaborative decision making - a probabilistic approach, Robot. Auton. Syst. 58 (5) (2010) 444–456.
[63] M. Fulton, C. Edge, J. Sattar, Robot communication via motion: a study on modalities for Robot-to-Human communication in the field, ACM Trans. Hum.-Robot Interact. 11 (2) (2022) 1–40.
[64] P. Robinette, A.R. Wagner, A.M. Howard, Assessment of robot guidance modalities conveying instructions to humans in emergency situations, in: IEEE RO-MAN 2014 - 23rd IEEE International Symposium on Robot and Human Interactive Communication: Human-Robot Co-Existence: Adaptive Interfaces and Systems for Daily Life, Therapy, Assistance and Socially Engaging Interactions, 2014, pp. 1043–1049.
[65] R. Salehzadeh, J. Gong, N. Jalili, Purposeful communication in Human-robot collaboration: a review of modern approaches in manufacturing, IEEE Access 10 (2022) 129344–129361.
[66] R. Gervasi, M. Capponi, L. Mastrogiacomo, F. Franceschini, Eye-tracking support for analyzing human factors in human-robot collaboration during repetitive long-duration assembly processes, Prod. Eng. 19 (1) (2025) 47–64.
[67] M. Capponi, R. Gervasi, L. Mastrogiacomo, F. Franceschini, Gamification in manufacturing: some insights in human–robot collaboration assembly and preliminary results, Int. J. Adv. Manuf. Technol. (2025) 1–29.
[68] A. Ekrekli, A. Angleraud, G. Sharma, R. Pieters, Co-speech gestures for human-robot collaboration, in: 2023 Seventh IEEE International Conference on Robotic Computing (IRC), IEEE, 2023, pp. 110–114.

[69] I. Maurtua, I. Fernandez, A. Tellaeche, J. Kildal, L. Susperregi, A. Ibarguren, B. Sierra, Natural multimodal communication for human–robot collaboration, Int. J. Adv. Robot. Syst. 14 (4) (2017).

[70] A. Angleraud, Q. Houbre, R. Pieters, Teaching semantics and skills for human-robot collaboration, Paladyn J. Behav. Robot. 10 (1) (2019) 318–329.

[71] X. Yang, Z. Zhou, J.H. Sørensen, C.B. Christensen, M. Ünalan, X. Zhang, Automation of SME production with a Cobot system powered by learning-based vision, Robot. Comput.-Integr. Manuf. 83 (2023) 102564.

[72] D. Fogli, L. Gargioni, G. Guida, F. Tampalini, A hybrid approach to user-oriented programming of collaborative robots, Robot. Comput.-Integr. Manuf. (2022) 73.

[73] S.H. Choi, M. Kim, J.Y. Lee, Smart and user-centric manufacturing information recommendation using multimodal learning to support human-robot collaboration in mixed reality environments, Robot. Comput.-Integr. Manuf. 91 (2025) 102836.

[74] M. Soori, B. Arezoo, R. Dastres, Artificial intelligence, machine learning and deep learning in advanced robotics, a review, Cogn. Robot. 3 (2023) 54–70.

[75] K. Jabrane, M. Bousmah, A new approach for training cobots from small amount of data in industry 5.0′, Int. J. Adv. Comput. Sci. Appl. 12 (10) (2021) 634–646.

[76] T.B. Ionescu, Leveraging graphical user interface automation for generic robot programming, Robotics 10 (1) (2020) 3.

[77] H. Ravichandar, A.S. Polydoros, S. Chernova, A. Billard, Recent advances in robot learning from demonstration, Annu. Rev. Control Robot. Auton. Syst. 3 (1) (2020) 297–330.

[78] J.N. Pires, Robot-by-voice: experiments on commanding an industrial robot using the human voice, Ind. Robot: Int. J. 32 (6) (2005) 505–511.

[79] C. Celemin, J. Ruiz-del-Solar, J. Kober, A fast hybrid reinforcement learning framework with human corrective feedback, Auton. Robots 43 (2019) 1173–1186.

[80] L. Berscheid, P. Meißner, T. Kröger, Self-supervised learning for precise pick-and-place without object model, IEEE Robot. Autom. Lett. 5 (3) (2020) 4828–4835.

[81] S. Bøgh, M. Hvilshøj, M. Kristiansen, O. Madsen, Autonomous industrial mobile manipulation (AIMM): from research to industry, in: Proceedings of the 42nd international symposium on robotics, VDE Verlag GMBH, 2011.

[82] G. Michalos, S. Makris, G. Chryssolouris, The new assembly system paradigm, Int. J. Comput. Integr. Manuf. 28 (12) (2015) 1252–1261.

[83] V.V. Unhelkar, J. Perez, J.C. Boerkoel, J. Bix, S. Bartscher, J.A. Shah, Towards control and sensing for an autonomous mobile robotic assistant navigating assembly lines, in: 2014 IEEE International Conference on Robotics and Automation (ICRA), IEEE, 2014, pp. 4161–4167.

[84] I. Palomba, L. Gualtieri, R. Rojas, E. Rauch, R. Vidoni, A. Ghedin, Mechatronic re-design of a manual assembly workstation into a collaborative one for wire harness assemblies, Robotics 10 (1) (2021) 43.

[85] E.R. da Silva, C. Schou, S. Hjorth, F. Tryggvason, M.S. Sørensen, Plug & produce robot assistants as shared resources: a simulation approach, J. Manuf. Syst. 63 (2022) 107–117.

[86] L. Grimstad, R. Zakaria, T.D. Le, P.J. From, A novel autonomous robot for greenhouse applications, in: 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, 2018, pp. 1–9.

[87] A.J. Moshayedi, G. Xu, L. Liao, A. Kolahdooz, Gentle survey on MIR industrial service robots: review & design, J. Mod. Process. Manuf. Prod. 10 (1) (2021) 31–50.

[88] O. Stasse, B. Verrelst, B. Vanderborght, K. Yokoi, Strategies for humanoid robots to dynamically walk over large obstacles, IEEE Trans. Robot. 25 (4) (2009) 960–967.