Advancing Human-Robot Collaboration: proposal of a methodology for the design of Symbiotic Assembly Workstations

Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 232 (2024) 3141–3150

Procedia Computer Science

www.elsevier.com/locate/procedia

5th International Conference on Industry 4.0 and Smart Manufacturing

Advancing Human-Robot Collaboration: proposal of a methodology for the design of Symbiotic Assembly Workstations

Barravecchia Federico*, Bartolomei Mirco, Mastrogiacomo Luca, Franceschini Fiorenzo

Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy

Abstract

The rapid advancement of robotics and artificial intelligence paves the way for collaborative robotics to revolutionise industrial operations. Collaborative robotics can bring significant improvements in productivity, efficiency, and safety. Recently, the concept of Symbiotic Human-Robot Collaboration (SHRC) has emerged within the field of collaborative robotics, emphasising the seamless and adaptive integration of human and robotic capabilities within a shared workspace to optimise overall production performance. However, existing collaborative systems frequently face difficulties in establishing dynamic relationships with humans and adapting to evolving conditions, ultimately restricting their overall potential. This paper investigates the essential features required for collaborative workstations to enable SHRC. Moreover, with the aim of fully harnessing the power of collaborative robotics, the paper introduces a design methodology that supports the development of symbiotic workstations for specific assembly operations. A real-world case study is provided, demonstrating the practical implementation and benefits of the proposed design approach.

Keywords: Collaborative robot; Symbiotic Human-Robot Collaboration; Assembly workstation; Design methodology.

1. Introduction

Collaborative robotics has emerged as a promising opportunity to enhance the efficiency, flexibility, and safety of manufacturing processes [1], [2]. In this contexts, Symbiotic Human-Robot Collaboration (SHRC) represents a paradigm shift from traditional automation solutions, as it promotes a more dynamic and interactive collaboration between humans and robots in manufacturing settings [3]. The concept of SHRC implies the exploitation of the specific capabilities and skills of human and robot agents to work together towards common goals [4],[5].

* Corresponding author. Tel.: +39.011.0905366
E-mail address: federico.barravecchia@polito.it

10.1016/j.procs.2024.02.130

The primary advantages of SHRC in assembly processes include (i) enhanced productivity and work quality [2],[6],[7]; (ii) improved safety measures [8]; (iii) mutual learning opportunities [9]; (iv) equitable distribution of workload robots [10]; and (v) fostering an inclusive workplace, particularly for individuals with physical disabilities or limitations [11], [12].

However, the practical applications of collaborative robotics still face several challenges that hinder their full potential [13]. Despite the recognized benefits, there is a clear research gap in addressing the adaptability and flexibility of these systems in dynamic manufacturing environments, thereby narrowing the use of collaborative robots to simple and rigidly pre-programmed tasks [3]. In this considerations, collaborative robots need to be endowed with additional technological equipment to meet SHRC requirements [14].

Considering these challenges, this paper proposes a methodology to assist designers in the development of collaborative assembly workstations. This methodology would pave the way for more effective human-robot collaboration in various work settings.

The remainder of this paper is organised as follows: Section 2 examines the technological features of assembly workstations that are essential for enabling SHRC; Section 3 presents a practical methodology to support the design of symbiotic assembly workstations, while Section 4 shows its application in a real-world context. The concluding section provides a summary of the key findings, outlines the implications and limitations of the proposed study, and offers insights into potential future research directions.

2. Symbiotic Collaborative Systems

To reap the benefits of SHRC [3], it is crucial to identify and address key requirements that enable an effective working relationship between humans and robots. A comprehensive review of the literature reveals a consensus on several key elements that underpin SHRC. Wang et al. [15] identified the following key requirements of a SHRC system:

- *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 ability to act and make decisions based on 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 allows both human and robot agents to coordinate their shared goals, roles, plans, and activities, creating a common ground for collaboration and decision-making.
- *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.

By meeting these requirements, both human and robotic agents can effectively leverage their unique skills and capabilities in collaboration. Contrasting this with existing systems, it becomes evident that the design of Collaborative Systems enabling SHRC requires the integration of specialized technologies. In detail, four main categories of technological features can be integrated to foster SHRC success: (i) *Sensing and perception systems*, (ii) *Adaptive control systems*, (iii) *Dialogue systems*, and (iv) *Safety systems*.

Sensing and perception systems are essential for SHRC, as they enable robots to perceive their surroundings, objects, and human operators' actions [16]. These systems can be divided into internal and external systems:

- Internal sensing systems refer to the sensors that are integrated into the robot's body, allowing it to perceive its own position, orientation, and movement. These sensors include encoders, accelerometers, gyroscopes, and force-torque sensors [17]. These sensors enable the robot to monitor its own movements and make adjustments in real time, enabling it to work collaboratively with human operators.

- External perception systems refer to the sensors, such as 2D or 3D cameras, that allow the robot to perceive its surroundings, including the objects, the location of the human operators, and potential obstacles [18].

A variety of sensors may also be employed for measuring the human factor:

- Wearable sensors, including motion and physiological sensors, can capture human movements and physiological responses [19].
- Vision-based sensors, such as cameras and depth sensors, track and analyse human behaviours, gestures and actions [20].

Adaptive control systems allow robots to adjust their behaviour in response to changing conditions and human operators' actions [21]. These systems can enhance the performance of the collaboration by adapting robot actions to environmental changes or task requirements [22]. Various adaptive control algorithms can be employed:

- Fuzzy Logic uses linguistic variables to describe system behaviour. In collaborative robotics, it has been used to control grippers and adjusts robot speed [23].
- Reinforcement Learning is an adaptive control system that learns through trial and error; it has been used to optimise robot movements based on human operator feedback [24].
- Neural Networks excel in tasks involving pattern recognition and decision-making. As an example, in collaborative robotics, Neural Networks enable the robot to recognise human gestures and learn from past interactions with the operator [25] .
- Model Predictive Control (MPC) uses system models to predict future behaviour and make decisions. In collaborative robotics, have been implemented to optimise robot trajectory using real-time vision from the operator [26].
- Kalman Filtering estimates system state based on noisy sensor measurements. In collaborative robotics, Kalman Filtering methodologies was employed to estimate the position and speed of the human operator [27].

Dialogue systems are essential for effective communication between robots and human operators, enabling intuitive and natural interactions. In collaborative robotics, natural dialogue systems are used to interpret verbal commands, ask clarifying questions, and provide feedback and instructions. Dialogue systems are employed across various communication modalities, encompassing a wide range of technologies, including:

- Speech Recognition, a natural language processing system that enables robots to recognise and interpret human speech. This technology uses algorithms to convert spoken words into text, which can then be processed by the robot's control system [28].
- Text-to-Speech technologies provide an artificial way of providing understandable audible output for human [29]. This technology uses algorithms to convert written text into spoken words. Text-to-speech is used, for instance, in assembly applications where robots need to communicate information about the process to the operator [28].
- Gesture Recognition enables robots to interpret human gestures and movements [30]. This technology uses cameras and sensors to detect and analyse human movements, which can then be used to control the robot's behaviour [31]. Gesture recognition is commonly used in applications where verbal communication is not possible or practical, such as in noisy environments [32].
- Graphical interfaces can also be employed to facilitate communication between humans and robots [33]. These interfaces can be designed for various devices, such as screen, tablets, or smartphones, allowing users to send commands, monitor robot status, and receive feedback.
- Emotion detection systems empower robots to recognize and respond to human emotions. This technology utilizes algorithms to analyse signals obtained from sensing and perception systems, enabling the interpretation of facial expressions, voice tone, and other physiological signs in order to discern the emotional state of the human operator. By harnessing these capabilities, robots can better understand and adapt to human emotions, leading to more effective and empathetic interactions[34].
- Haptic feedback enables robots to communicate with humans through touch, providing tactile feedback and allowing for more immersive and interactive communication experiences [35].
- Augmented/Virtual Reality have emerged as a powerful tool in enhancing the interaction between humans and collaborative robots. Augmented Reality (AR) and Virtual Reality (VR) have opened new doors for efficient human-robot collaboration. By overlaying digital information onto the physical environment, AR enables workers to visualise complex processes, receive real-time guidance, and monitor robot performance with greater ease [36].

Similarly, VR allows for immersive training and simulation, empowering workers to master cobot operation and maintenance in a safe, virtual environment [37].

Multimodal communication, which integrates multiple communication channels, allows for more seamless and comprehensive communication between humans and robots [38].

Safety systems play a pivotal role in collaborative robotics, where robots operate alongside humans in shared workspaces. Several technological solutions have been developed to address safety concerns in collaborative robotics:

- Sensor-based / Collision Detection Systems detect the presence of humans and other objects in the robot's workspace, enabling safe navigation and movement adjustments [39].
- Safety-rated Control Systems are specifically designed to ensure the robot's behaviour remains safe and predictable by implementing algorithms that monitor its movements and prevent exceeding predetermined speed or force limits [40].
- Force Limiting techniques are employed to prevent the robot from exerting excessive force on human operators or objects within the workspace[41].
- Emergency Stop systems serve as a crucial safety feature allowing human operators to swiftly halt the robot's movement in emergency situations, activated through buttons or levers, ensuring immediate response and human safety [42].

Table 1 reports the links between the *SHRC requirements* and the categories of *technological features* described above.

Table 1. Relationship between SHRC requirements and Technological features

		TECHNOLOGICAL FEATURES			
		Sensing and perception systems	Adaptive control systems	Dialogue systems	Safety systems
SHRC REQUIREMENTS [15]	Autonomy	X	X		
	Context-awareness	X	X	X	
	Communication	X		X	
	Digital Twin	X	X		X
	Learning	X	X	X	
	Safety	X			X

While many studies have examined the individual aspects of SHRC, this research holistically combines them, proposing an integrated approach to designing collaborative systems.

3. A methodology for designing symbiotic assembly workstations

Expanding on the insights presented in the previous section and taking inspiration from the principles of Quality Function Deployment (QFD) [43]–[45], a practical approach for designing collaborative assembly workstations that enable SHRC is presented. The proposed methodology comprises five main steps (see Figure 1):

1) *Identification of specific SHRC requirements* by gathering input from potential users to understand their expectations, needs, and preferences regarding the six categories of SHRC requirements: autonomy, context-awareness, communication, digital twin, learning, and safety.
2) *Translation of SHRC specific requirements into technological features*. This step involves recognizing and selecting relevant technological features from the suggested categories: sensing and perception systems, adaptive control systems, dialogue systems, and safety systems. It is important to consider how these features interact and complement each other to provide an integrated solution that addresses the complex nature of human-robot collaboration.
3) *Development of the relationship matrix and prioritization of technological features*. The relationship matrix helps determine which technological features have the most significant impact on meeting the SHRC specific requirements. Relationships can be identified using an ordinal scale, such as strong, medium, or weak. Based on these identified relationships and considering the importance of the corresponding specific SHRC requirements,

prioritization techniques like the Independent Scoring Method [43], [46], [47] are employed to prioritize the identified technological features accordingly.

4) *Translation of technological features into functional equipment*. To determine the functional equipment, the development team needs to analyze each technological feature individually and identify the type of equipment that can deliver that specific function.
5) *Development of the relationship matrix and prioritization of functional equipment*. This step involves identifying the functional equipment that has the greatest impact on implementing technological features. Similar techniques to those used for prioritizing technological features, such as ISM, can be applied in the prioritization process.

After identifying essential equipment for SHRC requirements, the main task is choosing and integrating the right equipment and collaborative robots. Given the many market options, this choice is vital and requires thorough market research. With technology's rapid evolution, new integrated solutions emerge, simplifying systems and reducing compatibility issues.

To finalise the development of a workstation, the team must integrate equipment with a collaborative robot, considering factors like the robot's type, payload, end effector, workspace layout, and ergonomics.

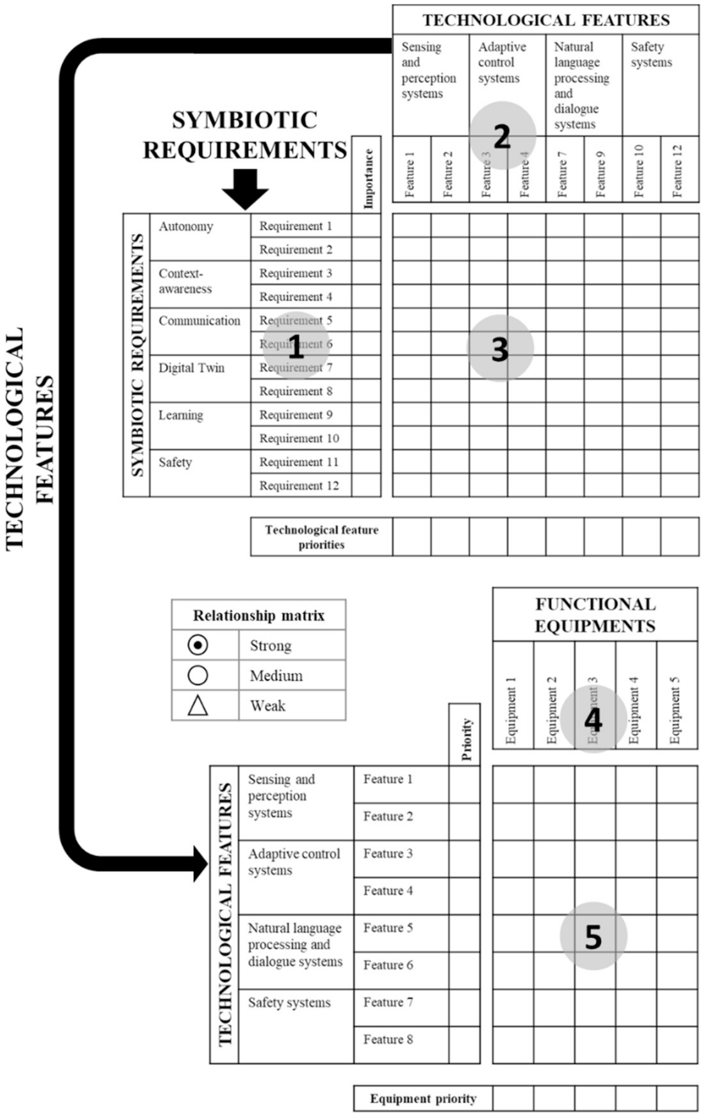

Fig. 1. Operational scheme of the proposed methodology for designing symbiotic assembly workstations.

4. Case study

In this case study the proposed design methodology is applied to create a collaborative workstation for assembling Printed Circuit Boards (PCBs). The assembly process demands both human dexterity and robotic precision. The goal is to design a symbiotic workspace where humans and robots can work together, allowing humans to focus on inspecting and handling delicate components while robots perform repetitive and precision-based tasks like component placement and soldering.

4.1. Identification of SHRC specific requirements

SHRC specific requirements were gathered through interviews with plant managers, operators, and other relevant stakeholders. These requirements categorised using the framework described in Section 2. Table 2 presents the identified SHRC specific requirements, along with importance values assigned to each one.
During the identification phase, one of the challenges was the diverse perspectives of the stakeholders. Balancing these perspectives was crucial. The insights gained were the importance of a holistic approach, considering both managerial and operational viewpoints.

4.2. Translation of SHRC requirements into technological features

After identifying the SHRC requirements for assembling PCBs, the next step was to translate SHRC requirements into technological features. The process involved mapping the SHRC requirements to specific technological features that could address those needs. The list of technological features that satisfy the SHRC requirements is presented in Table 3 as well as in the upper part of the scheme reported in Figure 2.
Translating abstract requirements into tangible technological features was not straightforward. The team realized the importance of iterative discussions to refine these translations.

4.3. Development of the relationship matrix and prioritisation of technological features

The team developed a matrix to show the relationship between SHRC requirements and technological features. Each requirement's connection to the features was assessed, categorizing them as strongly, moderately, or weakly related. The prioritization process was subjective and required multiple iterations. This phase underscored the importance of flexibility in the design process. The Independent Scoring Method (ISM) was used for prioritization, assigning values: Strong=9, Medium=3, Weak=1. The absolute level of priority for the j-th technological features was calculated as follows [43]:

$$w_j = \sum_{i=1}^{n} d_i \cdot r_{ij} \tag{1}$$

Where:

- d_i degree of importance of the i-th SHRC specific requirement, $i = 1,2,\dots,n$
- r_{ij} cardinal relationship between the i-th SHRC specific requirement and the j-th technological feature, $i = 1,2,\dots,n$ and $j = 1,2,\dots,m$
- w_j absolute level of priority of the j -th technological feature
- n number of SHRC specific requirements
- m number of technological features

The normalised relative priority for the j-th technological feature (shown in the lower part of the scheme in Figure 2) was calculated as follows:

$$w_j^* = \frac{w_j}{\sum_{j=1}^{m} w_j} \tag{2}$$

The results indicated that the most important technological features were the ability to visually perceive the process and human operator (17%), the ability to listen and interpret operator speech (15%), understanding the state of the task (11%), and the ability to store and update information on the assembly process (10%).

4.4. Translation of the technological features into functional equipment

The team analysed each technological feature to select the best equipment or technology for the desired function. They evaluated the integration feasibility of this equipment into the assembly workstation, considering space, power, compatibility, and interference. The equipment list is in Table 4 and illustrated in Figure 3's upper section.

4.5. Development of the relationship matrix and prioritization of functional equipment

The team evaluated the list of technological requirements and matched them with the corresponding functional equipment (see Figure 3). Independent Scoring Method (ISM) was used to prioritise the functional equipment. Functional equipment with higher priority were found to be: vision systems, including 3D and 2D cameras, with relative priorities of 15% and 14%, the information system for storing and updating the assembly tasks to be performed (12%), and the systems for communication and dialogue between humans and robots, including microphones, speakers, and voice command recognition systems (11%, 10%, and 10% respectively).

Table 2. Case study - SHRC requirements and related level of importance (1-5)

SHRC requirements	SHRC specific requirements	Importance level
Autonomy	Flexibility of use (only human, collaboration).	3
	Flexible to changing tasks and production requirements	4
Context-awareness	Collaborative system should be aware of the working environment	4
	Collaborative system should be aware of the status of the assembly process	4
	Understanding the stress level of the human	2
Communication	Ability to understand voice commands	5
	Ability to understand gestures	2
	Communicate information on the assembly process through multimedia material (video, images, etc.)	5
Digital Twin	Digital representation of the human in terms of position and stress	3
Learning	Capability to learn and adapt to changing working conditions, new components, and evolving assembly processes	3
Safety	Safety of human workers	5
	Real-time hazard detection	4
	Stop in case of emergency	5

Table 3. Case Study – Technological Features.

Categories of technological features	Technological features
Sensing and perception systems	Process and human vision
	Proximity object detection
	Human physiological status monitoring
Adaptive control systems	Assembly process activity storage and update system
	Role comprehension system
	Task comprehension system

Categories of technological features	Technological features
Dialogue systems	Speech recognition
	Speech message reproduction
	Gesture recognition
	Graphical interfaces
Safety systems	Emergency-stop function
	Human position tracking
	Activity classification based on hazard level

Table 4. Case Study – Functional Equipment

Functional Equipment	
3D camera on robotic arm	AI for speech message interpretation
Fixed 2D camera on work area	Microphone
Wearable bracelet with physiological sensors	Speakers
Assembly process feature storage information system	Screen display
AI for activity classification based on collected video data	GUI interface
AI for gesture classification and interpretation	Emergency physical button for activity interruption
Speech synthesiser	

Relationship matrix	
⊙	Strong
○	Medium
△	Weak

SYMBIOTIC REQUIREMENTS		Importance	TECHNOLOGICAL FEATURES: Sensing and perception systems – Process and human vision	Proximity object detection	Human physiological status monitoring	Adaptive control systems – Assembly process activity storage and update system	Role comprehension system	Task comprehension system	Dialogue systems – Speech listening and understanding	Speech message reproduction	Gesture recognition	Graphical interfaces	Safety systems – Emergency-stop function	Human position tracking	Activity classification based on hazard level
Autonomy	Flexibility of use (only human, collaboration).	3	○			⊙	⊙	⊙		○				△	
	Flexible to changing tasks and production requirements	4	○			⊙	⊙	⊙	○	○		○			
Context-awareness	Collaborative system should be aware of the working environment	4	⊙	○					△					○	
	Collaborative system should be aware of the status of the assembly process	4	⊙					⊙							
	Understanding the stress level of the human	2	△	△	⊙									△	
Communication	Ability to understand voice commands	5							⊙						
	Ability to understand gestures	2	⊙								⊙				
	Communicate information on the assembly process through multimedia material (video, images, etc.)	5								⊙		⊙			
Digital Twin	Digital representation of the human in terms of position and stress	3	⊙		⊙			○						⊙	
Learning	Capability to learn and adapt to changing working conditions,	3	○			⊙			⊙	△					
Safety	Safety of human workers	5	△	○		△	△							⊙	○
	Real-time hazard detection	4													⊙
	Stop in case of emergency	5							⊙		○		⊙		
	Technological feature priorities		17%	3%	2%	10%	7%	11%	15%	8%	4%	6%	5%	7%	6%

Fig. 2. Case study – Application of the phases 1,2 and 3 of the method

Relationship matrix	
⊙	Strong
○	Medium
△	Weak

TECHNOLOGICAL FEATURES		Priority	FUNCTIONAL EQUIPMENTS: 3D camera on robotic arm	Fixed 2D camera on work area	Wearable bracelet with physiological sensors	Assembly process and feature storage information system	AI for activity classification based on collected video data	AI for gesture classification and interpretation	Speech synthesizer	AI for speech message interpretation	Microphone	Speakers	Screen display	GUI interface	Emergency physical button for activity interruption
Sensing and perception systems	Process and human vision	17%	⊙	⊙	○			△			△				
	Proximity object detection	3%	⊙			△									
	Human physiological status monitoring	2%			⊙										
Adaptive control systems	Assembly process activity storage and update system	10%				⊙	○			○	○				
	Role comprehension system	7%		○			⊙			○	○				
	Task comprehension system	11%	⊙	○		⊙	○			△	△				
Dialogue systems	Speech listening and understanding	15%								⊙	⊙	⊙			
	Speech message reproduction	8%							⊙			⊙			
	Gesture recognition	4%	△	⊙				⊙							
	Graphical interface	6%											⊙	⊙	
Safety systems	Emergency-stop function	5%		△				△			○		○	○	⊙
	Human position tracking	7%	△	⊙	⊙										
	Activity classification based on hazard level	6%				⊙							○		
	Equipment priority		14%	15%	6%	12%	6%	3%	3%	10%	11%	10%	4%	3%	2%

Fig. 3. Case study – Application of the phases 4 and 5 of the method.

5. Conclusions

This paper delved into the concept of Symbiotic Human-Robot Collaboration (SHRC), emphasising the potential benefits of creating a mutually advantageous partnership between humans and robots in industrial settings.

The paper outlines requirements for enabling SHRC, such as *autonomy*, *context-awareness*, *communication*, *digital twin*, *learning*, and *safety*, showing that collaborative robots alone are unable to fulfil these conditions.

To meet these requirements, this paper has emphasized the need for the integration of various technological features. Seeking to give structure to the wide range of technological features that can be employed in conjunction with collaborative robots to facilitate HRC, this paper delves into four main categories of such features: *sensing and perception systems*, *adaptive control systems*, *dialogue systems*, and *safety systems*.

Based on these insights, this paper introduced a practical methodology for designing collaborative assembly workstations aiming at promoting SHRC. This methodology guides development teams in identifying and integrating essential technological equipment for successful SHRC.

The findings of this paper may have significant implications for the design and implementation of collaborative robotic systems in different manufacturing environments. However, it is important to note that the proposed method may not be directly applicable to all industries and contexts, as it has been primarily developed for assembly environments. Future research can build on the foundation laid in this paper to further explore the potential of SHRC and extend its applicability to a broader range of industries. Moreover, while this paper has laid the groundwork for the methodology, future developments will focus on establishing metrics and evaluation criteria to assess its efficacy and impact.

References

[1] Y. Cohen, S. Shoval, M. Faccio, and R. Minto, “Deploying cobots in collaborative systems: major considerations and productivity analysis,” *International Journal of Production Research*, vol. 60, no. 6, pp. 1815–1831, 2022.

[2] F. Barravecchia, L. Mastrogiacomo, and F. Franceschini, “A general cost model to assess the implementation of collaborative robots in assembly processes,” *The International Journal of Advanced Manufacturing Technology*, vol. 125, no. 11–12, pp. 5247–5266, 2023.

[3] F. Barravecchia, M. Bartolomei, L. Mastrogiacomo, and F. Franceschini, “Redefining Human–Robot Symbiosis: a bio-inspired approach to collaborative assembly,” *The International Journal of Advanced Manufacturing Technology*, vol. 128, no. 5, pp. 2043–2058, 2023.

[4] L. Wang *et al.*, “Symbiotic human-robot collaborative assembly,” *CIRP Annals*, vol. 68, no. 2, 2019, doi: 10.1016/j.cirp.2019.05.002.

[5] A. Kanazawa, J. Kinugawa, and K. Kosuge, “Adaptive Motion Planning for a Collaborative Robot Based on Prediction Uncertainty to Enhance Human Safety and Work Efficiency,” *IEEE Transactions on Robotics*, vol. 35, no. 4, pp. 817 – 832, 2019, doi: 10.1109/TRO.2019.2911800.

[6] K. Sowa, A. Przegalinska, and L. Ciechanowski, “Cobots in knowledge work: Human–AI collaboration in managerial professions,” *Journal of Business Research*, vol. 125, pp. 135–142, 2021.

[7] R. Bloss, “Collaborative robots are rapidly providing major improvements in productivity, safety, programing ease, portability and cost while addressing many new applications,” *Industrial Robot: An International Journal*, vol. 43, no. 5, pp. 463–468, 2016.

[8] A. Kanazawa, J. Kinugawa, and K. Kosuge, “Adaptive motion planning for a collaborative robot based on prediction uncertainty to enhance human safety and work efficiency,” *IEEE Transactions on Robotics*, vol. 35, no. 4, pp. 817–832, 2019.

[9] A. Hentout, M. Aouache, A. Maoudj, and I. Akli, “Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017,” *Advanced Robotics*, vol. 33, no. 15–16, pp. 764–799, 2019.

[10] M. Dalle Mura and G. Dini, “Job rotation and human–robot collaboration for enhancing ergonomics in assembly lines by a genetic algorithm,” *The International Journal of Advanced Manufacturing Technology*, pp. 1–14, 2022.

[11] E. Hüsing, C. Weidemann, M. Lorenz, B. Corves, and M. Hüsing, “Determining robotic assistance for inclusive workplaces for people with disabilities,” *Robotics*, vol. 10, no. 1, p. 44, 2021.

[12] R. Gervasi, F. Barravecchia, L. Mastrogiacomo, and F. Franceschini, “Applications of affective computing in human-robot interaction: State-of-art and challenges for manufacturing,” *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 237, no. 6–7, pp. 815–832, 2023.

[13] F. Vicentini, “Collaborative Robotics: A Survey,” *Journal of Mechanical Design, Transactions of the ASME*, vol. 143, no. 4. 2021. doi: 10.1115/1.4046238.

[14] M. Javaid, A. Haleem, R. P. Singh, and R. Suman, “Substantial capabilities of robotics in enhancing industry 4.0 implementation,” *Cognitive Robotics*, vol. 1. 2021. doi: 10.1016/j.cogr.2021.06.001.

[15] L. Wang *et al.*, “Symbiotic human-robot collaborative assembly,” *CIRP annals*, vol. 68, no. 2, pp. 701–726, 2019.

[16] F. Mohammadi Amin, M. Rezayati, H. W. van de Venn, and H. Karimpour, “A mixed-perception approach for safe human–robot collaboration in industrial automation,” *Sensors*, vol. 20, no. 21, p. 6347, 2020.

[17] R. Bogue, “Sensors for robotic perception. Part one: human interaction and intentions,” *Industrial Robot: An International Journal*, vol. 42, no. 5, pp. 386–391, 2015.

[18] Y. Cohen, S. Shoval, M. Faccio, and R. Minto, “Deploying cobots in collaborative systems: major considerations and productivity analysis,” *International Journal of Production Research*, vol. 60, no. 6, pp. 1815–1831, 2022.

[19] R. Gervasi, K. Aliev, L. Mastrogiacomo, and F. Franceschini, “User Experience and Physiological Response in Human-Robot Collaboration: A Preliminary Investigation,” *Journal of Intelligent Robotic Systems*, vol. 106, no. 2, p. 36, 2022.

[20] R. Nogueira, J. Reis, R. Pinto, and 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.
[21] C. Schmidbauer, B. Hader, and S. Schlund, "Evaluation of a digital worker assistance system to enable adaptive task sharing between humans and cobots in manufacturing," *Procedia CIRP*, vol. 104, pp. 38–43, 2021.
[22] C. Yang, Y. Wang, S. Lan, L. Wang, W. Shen, and G. Q. Huang, "Cloud-edge-device collaboration mechanisms of deep learning models for smart robots in mass personalization," *Robotics and Computer-Integrated Manufacturing*, vol. 77, p. 102351, 2022.
[23] M. N. Hidayati, D. Adzkiya, and H. Nurhadi, "Motion Control Design and Analysis of UR5 Collaborative Robots Using Fuzzy Logic Control (FLC) Method," in *2021 International Conference on Advanced Mechatronics, Intelligent Manufacture and Industrial Automation (ICAMIMIA)*, IEEE, 2021, pp. 162–167.
[24] T. Yu, J. Huang, and Q. Chang, "Mastering the working sequence in human-robot collaborative assembly based on reinforcement learning," *IEEE Access*, vol. 8, pp. 163868–163877, 2020.
[25] M. A. Simao, O. Gibaru, and P. Neto, "Online recognition of incomplete gesture data to interface collaborative robots," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 12, pp. 9372–9382, 2019.
[26] M. Krämer, C. Rösmann, F. Hoffmann, and T. Bertram, "Model predictive control of a collaborative manipulator considering dynamic obstacles," *Optim Control Appl Methods*, vol. 41, no. 4, pp. 1211–1232, 2020.
[27] J. Lim and S. Rhim, "Estimation of Human Position and Velocity in Collaborative Robot System Using Visual Object Detection Algorithm and Kalman Filter," in *2020 17th International Conference on Ubiquitous Robots (UR)*, IEEE, 2020, pp. 397–402.
[28] P. Gustavsson, A. Syberfeldt, R. Brewster, and L. Wang, "Human-robot collaboration demonstrator combining speech recognition and haptic control," *Procedia CIRP*, vol. 63, pp. 396–401, 2017.
[29] Y. Tabet and M. Boughazi, "Speech synthesis techniques. A survey," in *International Workshop on Systems, Signal Processing and their Applications, WOSSPA*, IEEE, 2011, pp. 67–70.
[30] C. Nuzzi, S. Pasinetti, M. Lancini, F. Docchio, and G. Sansoni, "Deep learning-based hand gesture recognition for collaborative robots," *IEEE Instrum Meas Mag*, vol. 22, no. 2, pp. 44–51, 2019.
[31] H. Liu and L. Wang, "Gesture recognition for human-robot collaboration: A review," *Int J Ind Ergon*, vol. 68, pp. 355–367, 2018.
[32] Z. Xia *et al.*, "Vision-based hand gesture recognition for human-robot collaboration: a survey," in *2019 5th International Conference on Control, Automation and Robotics (ICCAR)*, IEEE, 2019, pp. 198–205.
[33] D. Fogli, L. Gargioni, G. Guida, and F. Tampalini, "A hybrid approach to user-oriented programming of collaborative robots," *Robot Comput Integr Manuf*, vol. 73, p. 102234, 2022.
[34] A. Toichoa Eyam, W. M. Mohammed, and J. L. Martinez Lastra, "Emotion-driven analysis and control of human-robot interactions in collaborative applications," *Sensors*, vol. 21, no. 14, p. 4626, 2021.
[35] S. Grushko, A. Vysocký, P. Oščádal, M. Vocetka, P. Novák, and Z. Bobovský, "Improved mutual understanding for human-robot collaboration: Combining human-aware motion planning with haptic feedback devices for communicating planned trajectory," *Sensors*, vol. 21, no. 11, p. 3673, 2021.
[36] G. de M. Costa, M. R. Petry, and A. P. Moreira, "Augmented reality for human–robot collaboration and cooperation in industrial applications: A systematic literature review," *Sensors*, vol. 22, no. 7, p. 2725, 2022.
[37] S. B. i Badia *et al.*, "Virtual reality for safe testing and development in collaborative robotics: challenges and perspectives," *Electronics (Basel)*, vol. 11, no. 11, p. 1726, 2022.
[38] I. Maurtua *et al.*, "Natural multimodal communication for human–robot collaboration," *Int J Adv Robot Syst*, vol. 14, no. 4, 2017.
[39] A. Cherubini and D. Navarro-Alarcon, "Sensor-based control for collaborative robots: Fundamentals, challenges, and opportunities," *Front Neurorobot*, p. 113, 2021.
[40] Z. M. Bi, C. Luo, Z. Miao, B. Zhang, W. J. Zhang, and L. Wang, "Safety assurance mechanisms of collaborative robotic systems in manufacturing," *Robotics and Computer-Integrated Manufacturing*, vol. 67, p. 102022, 2021.
[41] N. Lucci, B. Lacevic, A. M. Zanchettin, and P. Rocco, "Combining speed and separation monitoring with power and force limiting for safe collaborative robotics applications," *IEEE Robot Autom Lett*, vol. 5, no. 4, pp. 6121–6128, 2020.
[42] M. Mihelj *et al.*, "Collaborative robots," *Robotics*, pp. 173–187, 2019.
[43] Y. Akao, "QFD: integrating customer requirements into product design," *Cambridge, MA*, 1990.
[44] Y. Akao, *QFD: Quality Function Deployment - Integrating Customer Requirements into Product Design*. New York City, United States: Productivity Press, 2004.
[45] F. Franceschini, *Advanced quality function deployment*. St. Lucie Press / CRC Press, Boca Raton, FL, 2002.
[46] L. M. V. de Oliveira, H. F. dos Santos, M. R. de Almeida, and J. A. F. Costa, "Quality Function Deployment and Analytic Hierarchy Process: A literature review of their joint application," *Concurrent Engineering*, vol. 28, no. 3, pp. 239–251, 2020.
[47] F. Franceschini and S. Rossetto, "Quality function deployment: How to improve its use," *Total Quality Management*, vol. 9, no. 6, pp. 491–500, 1998.