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An Overview of Human-Robot Collaboration in Smart Manufacturing

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***Abstract* — Industry 4.0, also termed smart manufacturing, has revolutionized the industrial world with cutting-edge technologies such as collaborative robots and artificial intelligence etc. Productivity and efficiency are two key factors that determine the success level of manufacturing. Therefore, many manufacturers have become so eager to adopt adaptive, intuitive, collaborative and smart techniques to improve the production lines, including key manufacturing machines and equipment. Therefore, robotic systems are playing an increasingly vital role in many industrial sectors, as they decrease the need for human labour and increase automation level. In addition, material waste can be also reduced since robots provide stability and accuracy during work. In turn, production times are reduced as well. Consequently, smart manufacturing areas need more advanced, flexible, and smart robotic systems to respond to market size changes and customization processes. As a result, currently, great research efforts are made to enrich the interactions between humans and robots in the work environment. This paper presents an overview of Human-Robot Collaboration (HRC) systems being employed in smart manufacturing to exploit the benefits of human experience and the capabilities of robotic systems. The research gaps, challenges and future work directions on HRC are highlighted and analyzed towards smart manufacturing.**

Keywords: Literature review; Human-Robot collaboration; Smart manufacturing; Cobot; Industry 4.0

I. INTRODUCTION

Human-Robot Collaboration (HRC) systems are increasingly used in the manufacturing sector such as the automotive and food industries. The trend of utilizing robots in manufacturing is changing. For now, researchers are making distinct efforts to exploit the human experiences, decision-making, and critical thinking abilities, with the robot's strength, repeatability, and accuracy to perform complex tasks [1]. In the long run, human execution of repetitive, low paid and risky tasks will be limited within smart factories as the human operators will shift into the work area where different and advanced role responsibilities may be required [2]. In the industrial world, manufacturers are focusing on transforming the working environments to be smarter and more adaptable to the changing market requirements and customized products. Therefore, the need for flexible solutions is increasing to adapt to these challenges [3]. By employing HRC systems in smart manufacturing areas, the chance of enhancing productivity and efficiency is becoming feasible.

This overview study aims to classify and highlight current Human-Robot Interaction (HRI) in manufacturing areas. Considering the collaboration interaction is the main interest of the research where collaborative robots are employed in HRC systems. Examples of industrial sectors are presented, as collaborative robots are implemented to highlight the difference between old and new production processes due to the change in the manufacturing environments toward smart manufacturing. Future work and estimated research directions are presented lastly in this paper.

II. HUMAN-ROBOT INTERACTION CLASSIFICATION

Industrial robots are playing a crucial role in the competition between companies to augment production. In 2019, the International Federation of Robotics stated that the robot production industry was likely to grow by 13% worldwide[4]. Additionally, many companies are focusing on special features to be offered in the robotic system they are interested in, such as requiring more human-friendly, adaptable, and safer robots [5]. With the emergence of collaborative robots ("cobots"), small and medium-sized companies can employ robots and boost productivity and flexibility. As a result, industrial enhancement can be influenced when the interaction phases between humans and robots are getting integrated.

The robot needs to be working with or collaborating with a human operator[6]. This interaction between the human operator and the robot depends mainly on a task to be performed, shared workspace, direct contact, and simultaneous and sequential processes. So, the interactions between humans and robots can be classified into four main types [7, 8]:

- Coexistence interaction: human operator and robot are working without intersecting each other workspace. They can work on the same task but at different times and places. Their connection is limited only by existing in the same facility [9].
- Synchronization interaction: Both human operator and robot might share the same workspace. Agents perform tasks by providing instructions to each

other. In this scenario, the human operator and robot are looking at the same target in sequential order.
- Cooperation interaction: operators and robots can access the same technological resources to obtain information about the work task. But both are intending to perform their own work interest. Overlapping workspace can occur but there is no direct connection between them.
- Collaboration interaction: both human operator and robot are working together to achieve the same task which can be complex. Direct contact between the system agents is possible and under their control.

Table 1 summarizes human-robot interaction features considering the shared contents of work tasks, direct contact, and simultaneous and sequential processes [10].

TABLE 1. HRI INTERACTION ON SHARED CONTENTS

	Interaction			
Shared Content	**Coexistence**	**Synchronization**	**Cooperation**	**Collaboration**
Work Task		×		×
Direct Contact		×		×
Simultaneous process	×		×	×
Workspace		×	×	×
Sequential process		×	×	

III. DEFINITION AND CLASSIFICATION for HUMAN-ROBOT COLLABORATION

In the HRC systems, the primary focus is to combine both human operator experience and robot abilities, while they should be physically separated during work [11]. However, collaboration interaction allows both operator and robot to always be in a direct connection and target the same task. The investment in developing collaborative working areas is increasing with specific interest given the ability of human operators to share and exchange information with robots to improve productivity and work efficiency [12]. This indicates the flexibility of creating a direct connection between the human operator and the robot [13]. HRC systems are designed to work intelligently as the production objectives are being delivered feasibly. Technological enhancements proposed in smart manufacturing areas allow the human operator to be working efficiently [14]. As a result, human operators will be able to influence the whole production process, especially in critical decision-making stages. On the other hand, collaborative robots can communicate with the human operator as they are built with intuitive interfaces and sensory systems. As such, they can support the operator in performing repetitive tasks, working in risky areas and other tasks that require high effort and stability [15]. Additionally, ordinary programming approaches are enhanced through the fourth industrial revolution. Therefore, non-expert operators can work and communicate with the robot simply. Gestures, speaking and eye blinking etc can be used instead of traditional tools to interact with the robot during the work. Therefore, the work is developed to be proactive instead of reactive [3].

Human-robot collaboration is determined by the agent's effort dynamics, the nature of work concerns, human operator satisfaction, and the ease of critical information transferring between operators and cobots [16]. Accordingly, the HRC system can be classified into four main aspects that are outlined in Fig. 1.

A. Collaboration levels

HRC system is based on the principle of collaboration between humans and robots. Thus, researchers have made considerable efforts to standardize the collaborations between humans and robots in the shared environment. In [16, 17], the latest levels of collaborations in the HRC system are classified as follows:

- Independent: Both humans and robots are focusing on different tasks separately.
- Sequential: Both human operators and robots execute sequential operations at different times focusing on the same work task.
- Simultaneous: Working at the same time, same work task but different processes.
- Supportive: Operators and robots complete a common process on the same workpiece in a synchronization manner.

B. Work roles

Depending on the type of task performed, human operators and robots have different roles in the industry [18]. In terms of [16], the HRC system can be examined by three different types of roles assigned to human operators or robots.

- Supervision: the relationship between human operator and robot is defined as master-slave. The human is the master.
- Peer: the human operator and the robot determine or maintain the work rate.
- Subordinate: the robot would be the master in this relationship type.

C. Safety control modes

For system safety, the protection of human operators is of paramount importance. In [19, 20], researchers identified the human operator faults, environmental

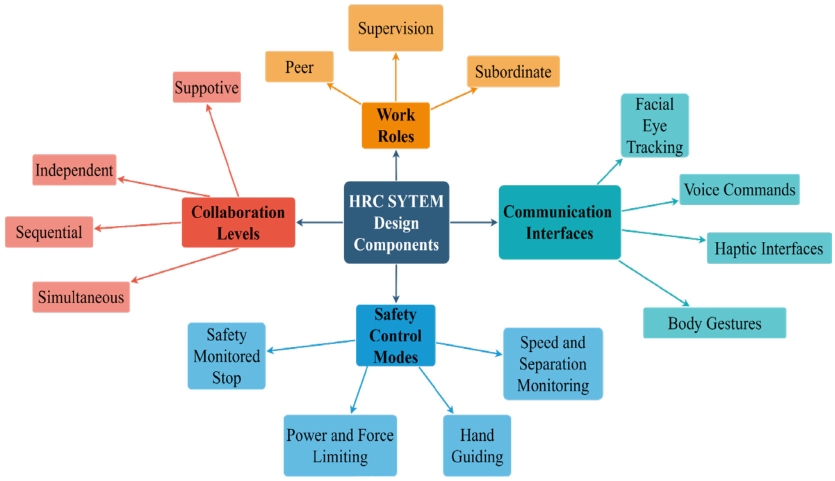

Figure 1. Structural components of HRC system

conditions and engineering errors as the main reasons why failure is likely to occur in the human-robot working area. The International Organization for Standardization (ISO) has therefore developed safety standards to ensure the safety of both system agents during the work process. For instance, ISO 10218-1 and ISO 10218-2 were established for parts installation and operations safety[21]. ISO 15066 was released in 2016 with special safety control modes to enhance the integration area especially when operation parameters are derived, such as force and speed [22]. So, mandatory safety modes for a safe working area are strongly recommended for HRC system installation. The safety tools classification is summarized as follows:

- Safety monitored stop: The robot stops moving once the human operator enters a specified safety area.
- Hand guiding: the human operator will be able to move the robot manually without the need for an external force source.
- Speed and separation monitoring: the robot's force and speed are limited to the safety zones regarding the human operator's location.
- Power and force limiting**:** the robot will be able to work within a certain range of force and torque. So, it will not be exceeding them to cause injuries.

D. Communication interfaces

In the HRC system, the communication and programming approaches are built more intuitively. The traditional programming and interfaces applied to control and drive robots are based on conventional coding [23]. Thus, the current HRC efficiency and flexibility require enhanced communication levels to adapt all the human movements and possible connection aspects with the robot during the work. Latest communication approaches are emphasized in [16, 24] to be developed and adopted. For instance: body gestures, facial/eye tracking, voice commands and haptic interfaces, etc.

IV. SMART MANUFACTURING

During Industry 3.0, automation solutions were focused on transforming the production processes to be automated and controlled with sensors and actuators, allowing the human operator to monitor the production and make improvements to the working environment [25]. However. with the digitalization of the industrial world, manufacturing processes are changing and being affected significantly [26]. Therefore, operating systems must be more intelligent to be able to work in collaboration and adapt to work conditions that are determined by market change [27]. The fourth industrial revolution is characterized by "smart manufacturing" where production has become more sustainable and digitally integrated [28]. Industry 4.0 enhancements have provided interesting terminologies outlined in Fig.2.

Currently, manufacturers are focusing on enhancing the production levels by employing these features. So, the company's strength will be increased against its competitors. Data exchange, value-added services, digitization and customized products and the green industry are the future of the industrial world [29]. These landscapes are enabled in smart manufacturing through four main approaches: Internet of Things (IoT), cloud computing, big data and analytics [30]. As a result, Industry 4.0 adoption can integrate the whole manufacturing system resulting in smart manufacturing, smart working, smart products and services [31]. In addition, these approaches are reducing the cost and energy waste of manufacturing processes.

Figure 2. Smart manufacturing technological terminologies

a) Smart manufacturing technologies

In smart manufacturing systems, there are more than ten intuitive technologies that are aiming to improve the work environment and the processes. Four technologies are highlighted to support the implementation of the HRC system in smart manufacturing. Through them, the system's efficiency and productivity are enhanced significantly.

- Artificial intelligence (AI): As a result of the vast data generated from connected machines in the factory, the two subsets of AI are playing a significant role in analysing and evaluating generated data to produce valuable information. Machine learning (ML) and deep learning (DL) are the main techniques representing the AI technology adopted in smart manufacturing [32].
- Augmented reality (AR): The remote assistant can be enabled to support the operator for improving the workplace as the production data are visualized [27, 33].
- Collaborative robots (Cobots): A new face of the industrial robots can be working in complex working situations with a human operator in the workspace safely.
- Digital twin (DT): The manufacturing system and its components can be designed in a digital environment. So, engineers can exploit gathered data to support human operators to conduct production without causing a gap in the production line as the digital twin is a virtual method that is used for validation while designing and implementing the HRC system [34].

b) HRC in smart manufacturing – Industrial cases

HRC system is implemented in many industrial sectors such as the automotive industry and food processing [35].

- **Food industry**

The food industry plays a key role in the European economy as some shops produce up to 10,000 meals daily [36]. In addition, the food industry involves a wide range of production processes, beginning with agriculture and extending to the production process (cooking, packaging) and ending with the ready meal to be sent to the market. Currently, the food industry is facing a major challenge of changing its business model from one based on supply to one based on demand. Noting that the supply chain resilience was impacted, especially at the beginning of the COVID-19 pandemic [37]. Therefore, the emergence of digitalization and industry 4.0 technological contributions are highly required to lead the transformation of food production to enhance the sustainability of this sector [38].

Robotics in agriculture is enhancing the collection of information about plants, soil and crop growth. In [38], it is stated that incorporating sensing approaches will increase the flexibility and sustainability of the robotic system, reflecting ultimately the entire production process. The use of Cobot in the food industry demonstrates the level of intelligence and automation that can be achieved in the food industry. The fruit can be picked by utilizing a cobot with a gripper attached to its end, so picking fruit is a smooth process and the labour reliance will be fulfilled using a robot. Additionally, the robot can move from one department to another easily [39].

According to [36], in catering facilities there are several processes (e.g., cooking, baking), and the production challenge lies at the end of the line. Food is processed in this area through manual steps, which are light and can be performed by humans, but they require a high level of repetitive ability, which the human worker lacks at this point. By utilizing the Cobot, the catering industry is becoming smarter and more advanced, especially since the Cobot is designed to assure flexibility and safety while working with a human operator. Working together is also important in catering facilities since some tasks can't be automated and require human expertise such as feeding machines with components to keep the work continuous.

- **Automotive industry**

Automotive is the largest industrial sector in the world. Considering the UK only, 3.7 million employees are working in the automotive sector and the economical contribution of the UK economy is about $26 billion [37]. In the automotive industry, assembly cells is playing an important role where 83% of production units involve assembly tasks [16]. However, some manual operations are still needing more flexibility and robustness to be performed efficiently; thus, relying on the industrial robot to perform these tasks alone may not be a practical solution as human abilities can't be fully replaced [40]. Therefore, the focus is to combine both abilities of humans and robots to work in collaboration while safety is assured to prevent any accident during the work [22].

From [8], in the assembly stage, the collaborative robot is responsible for the screwing task through the sensing integration with a human operator who will be able to share the work area and task. Also, installing the vision system is allowing the collaborative robot to collect information about the working environment and the human intentions that will be used for further improvements such as path planning and human movement predictions. As a result, the implementation of the HRC system is showing the needed capacity to perform complex tasks.

V. KEY FINDINGS AND FUTURE RESEARCH DIRECTIONS

In the age of industry 4.0, many opportunities are arising to get the benefits of emerging technologies [41]. AI, AR, DT and HRC approaches are employed in smart manufacturing to transform data processing into digital processing and controlling. Therefore, designing smart systems will lead to high-quality real-time data exchange, zero wasted efforts and better data management [42]. Focusing on HRC applications, HRC is the future alternative to conventional robotic and automation systems. As conventional systems require significant installation efforts and experts to program and control. In addition, old machines need to be upgraded so they can collaborate with HRC units in the production line [43]. HRC systems enable humans to work more efficiently and effectively with robots through intuitive interfaces [16].

The main target of employing HRC systems in the industry is to reduce the interaction complexity between humans and robots during work. Whereas, the implementation of collaborative robots in smart manufacturing systems is currently limited to simple and short-age production processes. In [36], the aim of employing a collaborative robot was only to increase the efficiency through automating the catering process. However, collaborative robot technology requires intuitive approaches to design and program. Therefore, the system complexity is limiting the opportunity of expanding the use of collaboration robots in industry. So, the human operator's confidence to be working with the new tools and technologies will be affected, especially when a work occasion occurs and requires the operator to share experience and take a critical decision. HRC system should be perfectly designed and built and human-robot roles need to be carefully designed and purely perceived [44]. In addition, existing HRC applications are designed mainly to increase productivity and efficiency levels with low safety insurance in the working areas [41]. Therefore, implementing collaborative robots in various industrial sectors is limited too. Consequently, the implementation of HRC in smart manufacturing requires a comprehensive design phase to enhance operational features. Future work should be focused on how to maintain safety and accessibility to reach the level of a flexible human-robot collaboration system in smart manufacturing. Additional effort relating to this research will be investigated to employ novel concepts and algorithms for better implementation of HRC systems in real world industrial applications.

VI. CONCLUSION

The presented overview has firstly covered the Human-Robot Interaction (HRI) and its definition and levels of interactions. The collaborative relationship between humans and robots was then discussed by defining, classifying and characterizing the Human-Robot Collaboration (HRC) as a complete working system. The structural components of the HRC system were also reviewed to emphasize the importance of the HRC system design. The overview has also highlighted smart manufacturing with the focus on analyzing the four important technologies that emerged in the age of Industry 4.0.

The food and automotive industries were discussed in this paper as examples of industrial sectors where the HRC is implemented in specific processes. The efficiency of employing HRC systems in these industries was able to showcase the significance of HRC in current industries.

The collaborative robots' approach is a promising technology that can leverage manufacturing efficiency. By exploiting the human operator's knowledge and the collaborative robot abilities, the production lines will take a new direction for further technical improvements. At the same time, it is very important to consider that the industrial world will require stable and intuitive solutions that can be adapted in many industrial areas. Therefore, the current challenges of HRC like complexity, rigidity, safety and interfacing need to be widely and deeply searched [45]. Adapting HRC in manufacturing with an assurance of the safety levels will be critical. The future HRC system to be explored must carefully design and identify the roles of human and collaborative robot to maintain constant levels of production if a technical issue occurs suddenly during work or working environments has to change abruptly.

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REFERENCES

[1] H. Liu, and L. Wang, "Gesture recognition for human-robot collaboration: A review," *International Journal of Industrial Ergonomics,* vol. 68, pp. 355-367, 2018/11/01/, 2018.

[2] J. Arents, V. Abolins, J. Judvaitis, O. Vismanis, A. Oraby, and K. Ozols, "Human–Robot Collaboration Trends and Safety Aspects: A Systematic Review," *Journal of Sensor and Actuator Networks,* vol. 10, no. 3, pp. 48, 2021.

[3] M. L. Nicora, R. Ambrosetti, G. J. Wiens, and I. Fassi, "Human–Robot Collaboration in Smart Manufacturing: Robot Reactive Behavior Intelligence," *Journal of Manufacturing Science and Engineering,* vol. 143, no. 3, 2020.

[4] I. IFR, "Executive summary world robotics 2020 industrial robots," 2020.

[5] V. Villani, F. Pini, F. Leali, and C. Secchi, “Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications,” *Mechatronics,* vol. 55, pp. 248-266, 2018/11/01/, 2018.

[6] M. A. Goodrich, and A. C. Schultz, *Human-robot interaction: a survey*: Now Publishers Inc, 2008.

[7] 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, 2019/08/18, 2019.

[8] L. Wang, R. Gao, J. Váncza, J. Krüger, X. V. Wang, S. Makris, and G. Chryssolouris, “Symbiotic human-robot collaborative assembly,” *CIRP Annals,* vol. 68, no. 2, pp. 701-726, 2019/01/01/, 2019.

[9] C. Gaz, E. Magrini, and A. De Luca, “A model-based residual approach for human-robot collaboration during manual polishing operations,” *Mechatronics,* vol. 55, pp. 234-247, 2018/11/01/, 2018.

[10] X. V. Wang, A. Seira, and L. Wang, "Classification, personalised safety framework and strategy for human-robot collaboration."

[11] R. Gervasi, L. Mastrogiacomo, and F. Franceschini, *Towards the definition of a Human-Robot collaboration scale*, 2019.

[12] M. Ronzoni, R. Accorsi, L. Botti, and R. Manzini, “A support-design framework for Cooperative Robots systems in labor-intensive manufacturing processes,” *Journal of Manufacturing Systems,* vol. 61, pp. 646-657, 2021/10/01/, 2021.

[13] J. de Gea Fernández, D. Mronga, M. Günther, T. Knobloch, M. Wirkus, M. Schröer, M. Trampler, S. Stiene, E. Kirchner, V. Bargsten, T. Bänziger, J. Teiwes, T. Krüger, and F. Kirchner, “Multimodal sensor-based whole-body control for human–robot collaboration in industrial settings,” *Robotics and Autonomous Systems,* vol. 94, pp. 102-119, 2017/08/01/, 2017.

[14] E. Matheson, R. Minto, E. G. G. Zampieri, M. Faccio, and G. Rosati, “Human–Robot Collaboration in Manufacturing Applications: A Review,” *Robotics,* vol. 8, no. 4, pp. 100, 2019.

[15] P. S. Parra, O. L. Calleros, and A. Ramirez-Serrano, "Human-robot collaboration systems: Components and applications." pp. 1-9.

[16] P. Segura, O. Lobato-Calleros, A. Ramírez-Serrano, and I. Soria, “Human-robot collaborative systems: Structural components for current manufacturing applications,” *Advances in Industrial and Manufacturing Engineering,* vol. 3, pp. 100060, 2021/11/01/, 2021.

[17] S. El Zaatari, M. Marei, W. Li, and Z. Usman, “Cobot programming for collaborative industrial tasks: An overview,” *Robotics and Autonomous Systems,* vol. 116, pp. 162-180, 2019/06/01/, 2019.

[18] X. V. Wang, Z. Kemény, J. Váncza, and L. Wang, “Human–robot collaborative assembly in cyber-physical production: Classification framework and implementation,” *CIRP Annals,* vol. 66, no. 1, pp. 5-8, 2017/01/01/, 2017.

[19] J. Carlson, and R. R. Murphy, “How UGVs physically fail in the field,” *IEEE Transactions on Robotics,* vol. 21, no. 3, pp. 423-437, 2005.

[20] M. Vasic, and A. Billard, "Safety issues in human-robot interactions." pp. 197-204.

[21] J. V. S. Teixeira, A. M. Reis, F. B. Mendes, and L. G. L. Vergara, "Collaborative Robots," *Occupational and Environmental Safety and Health*, P. M. Arezes, J. S. Baptista, M. P. Barroso, P. Carneiro, P. Cordeiro, N. Costa, R. B. Melo, A. S. Miguel and G. Perestrelo, eds., pp. 791-796, Cham: Springer International Publishing, 2019.

[22] M. J. Rosenstrauch, and J. Krüger, "Safe human-robot-collaboration-introduction and experiment using ISO/TS 15066." pp. 740-744.

[23] V. Villani, F. Pini, F. Leali, C. Secchi, and C. Fantuzzi, “Survey on Human-Robot Interaction for Robot Programming in Industrial Applications,” *IFAC-PapersOnLine,* vol. 51, no. 11, pp. 66-71, 2018/01/01/, 2018.

[24] D. Andronas, G. Apostolopoulos, N. Fourtakas, and S. Makris, “Multi-modal interfaces for natural Human-Robot Interaction,” *Procedia Manufacturing,* vol. 54, pp. 197-202, 2021/01/01/, 2021.

[25] K. Vinitha, R. Ambrose Prabhu, R. Bhaskar, and R. Hariharan, “Review on industrial mathematics and materials at Industry 1.0 to Industry 4.0,” *Materials Today: Proceedings,* vol. 33, pp. 3956-3960, 2020/01/01/, 2020.

[26] O. Givehchi, K. Landsdorf, P. Simoens, and A. W. Colombo, “Interoperability for Industrial Cyber-Physical Systems: An Approach for Legacy Systems,” *IEEE Transactions on Industrial Informatics,* vol. 13, no. 6, pp. 3370-3378, 2017.

[27] J. Zenisek, N. Wild, and J. Wolfartsberger, “Investigating the Potential of Smart Manufacturing Technologies,” *Procedia Computer Science,* vol. 180, pp. 507-516, 2021/01/01/, 2021.

[28] D. Jaspert, M. Ebel, A. Eckhardt, and J. Poeppelbuss, “Smart retrofitting in manufacturing: A systematic review,” *Journal of Cleaner Production,* vol. 312, pp. 127555, 2021/08/20/, 2021.

[29] J. Posada, C. Toro, I. Barandiaran, D. Oyarzun, D. Stricker, R. d. Amicis, E. B. Pinto, P. Eisert, J. Döllner, and I. Vallarino, “Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet,” *IEEE Computer Graphics and Applications,* vol. 35, no. 2, pp. 26-40, 2015.

[30] A. G. Frank, L. S. Dalenogare, and N. F. Ayala, “Industry 4.0 technologies: Implementation patterns in manufacturing companies,” *International Journal of Production Economics,* vol. 210, pp. 15-26, 2019/04/01/, 2019.

[31] B. Meindl, N. F. Ayala, J. Mendonça, and A. G. Frank, “The four smarts of Industry 4.0: Evolution of ten years of research and future perspectives,” *Technological Forecasting and Social Change,* vol. 168, pp. 120784, 2021/07/01/, 2021.

[32] T. Kotsiopoulos, P. Sarigiannidis, D. Ioannidis, and D. Tzovaras, “Machine Learning and Deep Learning in smart manufacturing: The Smart Grid paradigm,” *Computer Science Review,* vol. 40, pp. 100341, 2021/05/01/, 2021.

[33] J. d. A. Dornelles, N. F. Ayala, and A. G. Frank, “Smart Working in Industry 4.0: How digital technologies enhance manufacturing workers' activities,” *Computers & Industrial Engineering,* vol. 163, pp. 107804, 2022/01/01/, 2022.

[34] A. A. Malik, and A. Brem, “Digital twins for collaborative robots: A case study in human-robot interaction,” *Robotics and Computer-Integrated Manufacturing,* vol. 68, pp. 102092, 2021/04/01/, 2021.

[35] G. Michalos, P. Karagiannis, N. Dimitropoulos, D. Andronas, and S. Makris, "Human Robot Collaboration in Industrial Environments," *The 21st Century Industrial Robot: When Tools Become Collaborators*, M. I. Aldinhas Ferreira and S. R. Fletcher, eds., pp. 17-39, Cham: Springer International Publishing, 2022.

[36] R. Accorsi, A. Tufano, A. Gallo, F. G. Galizia, G. Cocchi, M. Ronzoni, A. Abbate, and R. Manzini, “An application of collaborative robots in a food production facility,” *Procedia Manufacturing,* vol. 38, pp. 341-348, 2019/01/01/, 2019.

[37] S. Bakalis, D. Gerogiorgis, D. Argyropoulos, and C. Emmanoulidis, "21 - Food Industry 4.0: Opportunities for a digital future," *Food Engineering Innovations Across the Food Supply Chain*, P. Juliano, R. Buckow, M. H. Nguyen, K. Knoerzer and J. Sellahewa, eds., pp. 357-368: Academic Press, 2022.

[38] J. Miranda, P. Ponce, A. Molina, and P. Wright, “Sensing, smart and sustainable technologies for Agri-Food 4.0,” *Computers in Industry,* vol. 108, pp. 21-36, 2019/06/01/, 2019.

[39] W. Grobbelaar, A. Verma, and V. K. Shukla, “Analyzing Human Robotic Interaction in the Food Industry,” *Journal of Physics: Conference Series,* vol. 1714, no. 1, pp. 012032, 2021/01/01, 2021.

[40] P. Tsarouchi, A.-S. Matthaiakis, S. Makris, and G. Chryssolouris, “On a human-robot collaboration in an assembly cell,” *International Journal of Computer Integrated Manufacturing,* vol. 30, no. 6, pp. 580-589, 2017/06/03, 2017.

[41] Y. Hu, Y. Wang, K. Hu, and W. Li, “Adaptive obstacle avoidance in path planning of collaborative robots for dynamic manufacturing,” *Journal of Intelligent Manufacturing*, 2021/08/18, 2021.

[42] K. Shin, and H. Park, "Smart Manufacturing Systems Engineering for Designing Smart Product-Quality Monitoring System in the Industry 4.0." pp. 1693-1698.

[43] T. Brito, J. Queiroz, L. Piardi, L. A. Fernandes, J. Lima, and P. Leitão, “A Machine Learning Approach for Collaborative Robot Smart Manufacturing Inspection for Quality Control Systems,” *Procedia Manufacturing,* vol. 51, pp. 11-18, 2020/01/01/, 2020.

[44] L. Wang, S. Liu, H. Liu, and X. V. Wang, "Overview of Human-Robot Collaboration in Manufacturing," *Proceedings of 5th International Conference on the Industry 4.0 Model for Advanced Manufacturing.* pp. 15-58.

[45] F. Sherwani, M. M. Asad, and B. S. K. K. Ibrahim, "Collaborative Robots and Industrial Revolution 4.0 (IR 4.0)." pp. 1-5.