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From Human to Robot Interaction towards Human to Robot Communication in Assembly Systems

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Abstract: The interaction between humans and robots has been a rapidly developing technology and a frequently discussed research topic in the last decade because current robots ensure the physical safety of humans during close proximity assembly operations. This interaction promises capability flexibility due to human dexterity skills and capacity flexibility due to robot accuracy. Nevertheless, in these interactions, the humans are marginally outside of the system, while the robots are seen as a crucial component of the assembly activities, which causes the systems to lack flexibility and efficiency. Therefore, this paper presents a study on Human to Robot communication in assembly systems. We conducted a systematic review of related literature and industrial applications involving human and robot interaction modes over the last decade to identify research gaps in the integration of collaborative robots into assembly systems. We believe that we are in a transformation phase from physical interaction mode towards cognitive interaction mode between humans and robots, where humans and robots are able to interact with each other during mutual working conditions and humans are able to guide robots. The main contribution of this paper is to propose a future mode of human-robot interaction in which a skilled operator performs not only physical cooperative tasks with robots but also work aided by smart technologies that allow communication with robots. This interaction mode allows for an increase in the flexibility and productivity of the assembly operation as well as the wellbeing of the human operator in a human-centered manufacturing environment.

Keywords: Human robot communication, Human robot interaction, Industry 4.0, Industry 5.0.

Introduction

Manufacturing has evolved over time, and the future vision is for a more sustainable, resilient, and human-centered manufacturing sector (Xun et al., 2021). Simultaneously, the market is demanding more customized products with improved final product quality and continuously decreasing production times, which challenges the manufacturing sectors to manage flexibility requirements in the assembly operations. The authors of the paper (Carsten et al., 2016) argue that the efficiency of managing these assembly flexibilities in production might be achieved by integrating humans and robots in the same assembly operation. Because, according to (Romero et al., 2016), assembly operations can benefit from capacity flexibility due to robot accuracy and speed and capability flexibility due to human dexterity skills.

Human-robot interaction (HRI) is growing automation trend in which robots are integrated into manual assembly operations (Tsarouchi et al., 2016), can facilitate safe interaction between human and robot resources. By integrating robots into the same assembly cell with human, robot can deal with heavy lifting, repetitive tasks, and tasks that require high accuracy, while the human focuses on tasks that need the flexibility skills of the human (Müller & Vette , 2016).

As a result, HRI systems have been one of the most widely debated topics in the last decade; however, research to date indicates that interactions between humans and robots are associated with physical interaction between resources and are focused on the human experience (Carsten et al., 2016). Consequently, it is time to investigate a new interaction mode in human-robot interaction systems, in which humans are viewed as an essential part of the assembly operations. We argue that this new mode of human-robot interaction opens up new possibilities for the assembly operation, enhancing its efficiency and flexibility. Therefore, this paper investigates the future mode of human-robot interaction as a smart and skilled worker who performs not only "collaborative tasks" with robots but also "work aided" by using aided technologies to interact with robots. In this paper, we analyzed the current state of the art in human-robot interaction in the past decade. After giving some background research topics covered by human robot interaction systems in the last decade, we simply narrow our focus to define the future human-centered human robot communication assembly system framework.

The outlines of this paper are the following. Section 3 provides a review of human and robot interaction modes over the last decade, additionally research topics covered by academia and industry, industrial applications, the opportunities and challenges of existing interaction modes. Then Section 4 starts to define HRI research gaps in assembly operations and concludes with a visualization of the current state. Section 5 highlights the vision of a future human robot interaction mode under human-centered assembly operations and suggests the framework of the new human centered human robot communication mode. Finally, it concludes and highlights the future research directions.

Literature Review

An assembly workstation that combines human and robot resources is known as a human-robot interaction system. (Abdelfetah et al., 2019). The systematic literature analysis showed that humans have excellent cognitive ability and adaptability skills, whereas robots are more efficient at executing repetitive and non-ergonomic tasks more efficiently and with a consistent level of accuracy (Chryssolouris et al., 2017). The following Table 1 summarizes the most valuable characteristics of humans and robots' resources when they work in close proximity during assembly operations.

Table 1. Human and robot characteristics

Advantages skills of human Special attention is paid to:	Advantages skills of robots Special attention is paid to:
High availability	Integrated process control
Handling of complex components	Handling heavy, sharp-edged components
Reliable execution of complex joining processes	Exact playback of defined paths
Simple magazine loading of components	Reliable performance of repetitive activities

The proper integration of robots into manual assembly systems opens many new possibilities. By integrating robots into manual assembly systems, new applications are enabled, and assembly processes can be built up more efficiently by integrating robots into manual assembly systems or by using assistive robots for repetitive and non-ergonomic tasks controlled by a human (Romero et al., 2016). Alternatively, the investment in automation equipment can be concentrated on the most important manufacturing steps, maintaining a high degree of flexibility with respect to reconfiguring of the production equipment and human dexterity, while still introducing a partial degree of automation. In assembly operations, combining the best abilities of humans and robots can improve productivity (Kuhlenkötte, 2016) and ergonomic factors (Chryssolouris et al., 2016).

Human and Robot Interaction Research Topics

The quantity of research studies has increased during the past decades on human-robot interaction in assembly operations, because current robots ensure the physical safety of humans during close proximity assembly operations. Nevertheless, a crucial question continues: how should a human-robot interaction system be designed in the assembly operations? The literature analysis showed that the recent human-robot interaction studies focus on the investigation of physical interaction between resources (Flacco et al.,2012). The goal of this research allows close proximity between human and robot during the assembly tasks that need the high characteristics of the robot in terms of accuracy, speed, and payload. Considered the above motivation of human and robot interactions in assembly processes, the following three main research categories in HRI can be divided, which are shown in Figure 1, can be identified an interaction mode related topic, safety interaction topics, and task distribution related topic.

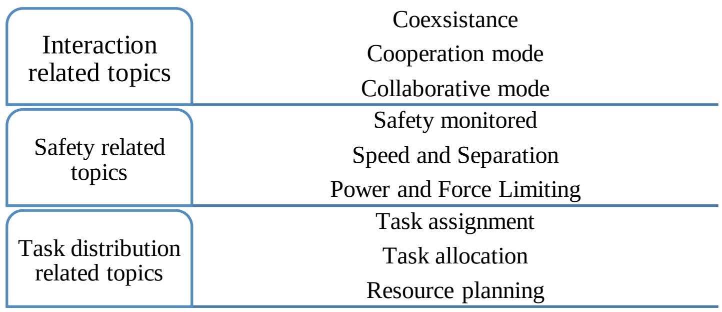

Figure1. HRI main research topics

Interaction Mode Related Research Topics

In recent years, the interaction between humans and robots has been divided into three main modes based on their shared workstation and tasks during assembly operations. These three classifications of human-robot interaction are explained as follows (Lihui et al., 2020):

- **Coexistence mode***:* the task is performed by humans and robots independently of each other;
- **Cooperation mode:** the task performed by humans and robots after each other, also known as synchronous mode.
- **Collaborative mode***:* the common task is performed by humans and robots at the same time.

Coexistence, cooperation, and collaboration are different types of interactions. The cooperation and collaboration modes are distinguished by the close proximity of resources. In coexistence mode, humans and robots work on different subtasks.

Safety-Related Research Topics

Today's robots can work closely with humans and perform assembly tasks in tandem with them (Waurzyniak, 2015). Furthermore, these developments result in violations of established safety standards and the removal of physical barriers between assembly workstations (Robla Gómez et al., 2017). The robots are able to move their bodies by force, very quickly, and always handle dangerous and sharp equipment. Therefore, the following safety and mode research topics are considered when designing human-robot interaction systems.

- **Safety monitored stop:** In this type of interaction, robots are defined by minimal interaction with humans. Usually, these types of robots are actually similar to industrial robots, with several sensors that stop robot execution when a human enters the work space. The coexistence mode is the best example of a safety monitored stop (Galin & Meshcheryakov, 2019; Maurice, 2014).
- **Speed and separation:** In this type of interaction, robots are embedded with more advanced vision technologies that slow their task execution when an operator approaches and decrease their speed when a worker is close to the robot. The cooperation mode can be an example of this type of interaction (Galin & Meshcheryakov, 2019; Maurtua et al., 2017).
- **Power and force limiting:** these types of collaborative robots are embedded with collision sensors to rapidly recognize human touch and slow execution. The collaboration mode can be an example of this type of interaction.

We argue that future research on safety and mode in human–robot interaction should not only focus on optimizing the performance of the robot but also include human wellbeing and focus on human-centered perspectives (Galin & Meshcheryakov, 2019; Khalid et al., 2017).

Task Distribution Related Research Topics

Task distribution during human-robot interaction is based on combining the respective strengths of humans and robots in close proximity during the assembly operation. Humans, with their flexibility and decision-making skills, are able to react to defective components or changing parameters of parts and assembly processes. Robots' advantages include their accuracy, repeatability, ability to handle heavy loads, and endurance (Thomos, Bjoem, & Kuhlenkötter, 2016). Finally, the following Table 2 summarizes the respective strengths of humans and robots in industrial applications for task allocation between resources.

Table 2. Human and robot characteristics

Human Characteristics Special attention is paid to	Robot Characteristics Special attention is paid to
Flexibility	Speed
Cognitive	Power
Dexterity	Precision
Creativity	Repeatability
Decision making	Endurance

The research activities performed on task distribution between human and robots during the last decade performed on the following key words which is summarized in the following Table 3.

Table 3. Task distribution research topics

Mode of task distribution	Focus
Task assignment	Process oriented (Muller et al., 2016), Economic and work capability aspects (Blankemeyer, et al., 2020), technical, qualitative, economic, safety indexes (Gualtieri et al., 2019), weight, displacement, accuracy requirements, dexterity requirements (Bruno & Antonelli, 2018).
Task allocation	Task complexity, Ergonomics Payload Repeatability (Dianatfar et al., 2019), task characteristics and agent capabilities (Liau & Ryu, 2020), task complexity (Malik & Bilberg, 2019), capability based (Ranz et al., 2017)
Resource planning	Resorce suitability, resource avalibality and process time (Tsarouchi et al., 2017)

In their research (Mateus et al., 2019), they subdivided the assembly tasks into the following a six-step hierarchy by using a CAD model. The first step is called operation, followed by subassembly, task, function, function stage, and motion levels. Then, in their research (Nikolakis et al., 2018), they distributed the collaborative tasks among resources into two step hierarchy models that collected data by task and operation. At that time, they applied a multi-criteria decision-making structure for offline task allocation and online rescheduling. Then, (Tsarouchi, et al., 2016) proposed the structure for task allocation using three cases; resource suitability, resource availability, and operation time.

Based on the above literature, we can conclude that the research highlighted above is mostly concentrated on task allocation based on criteria instead of the optimization of assembly performance. Nevertheless, (Bänziger et al., 2018) optimized queue time and moving distance within the hybrid workstation. Then (Dalle Mura & Dini, 2019) concentrated on cost reduction, the number of skilled operators, and energy load variance issues in an assembly system. In their investigations, both researchers used a genetic algorithm. Finally, the available studies concerning task assignment in a human-robot interaction system focused only on resource analysis-based task assignment or optimization of task assignment.

We believe that task allocation between humans and robots is one of the most important steps in the design of human-robot interaction systems. An efficient task allocation guarantees the safety and ergonomics of humans and the optimum performance in terms of cycle time and flexibility of the hybrid assembly system. Therefore, we think future task allocation between humans and robots needs more human-centered studies that explore the conditions under which human operators still feel responsible for the cognitive, decision-making, and supervision conditions of the overall assembly operation.

Method

A comprehensive review of the literature to synthesize the effects of HRI in assembly operations has been conducted. The review methodology is described in following subsections.

Search Criteria

We conducted a systematic review of the literature for papers published between 2010 and 2022 that used collaborative robots in assembly operations. Practical experiments and key words like "human and robot collaboration," "assembly, task allocation," "task assignment," and "resource planning" between humans and robots were included in the reviewed papers. An electronic search on databases to cover relevant publications in engineering from both academia and manufacturing (Scopus, Science Direct, IEEE Xplore, and Web of Science) was conducted. Data collection was preceded by deep learning of key research field input words between 2010 and 2023. We decided to look at research papers published after 2010, because HRI is a novel approach that emerged at the beginning of this decade. Both conference papers and journal articles were included. We finalized the search in April 2023. Keywords used for each criterion are presented in Table 4.

The search resulted in 739 papers: 178 papers from Scopus, 284 papers from IEEE Xplore, 155 papers from Science Direct and 122 papers from Web of Science.

Table 4. Keywords for each criteria

Criteria	Search phase
Involves human and robot	Collaborative, cooperation or coexistence
Studies about assembly and safety control	Safety monitored Speed and separation Power and force limiting
Refers to task distribution	Task assignment, allocation and resource planning

Study Selection

We filtered the studies using three main steps to eliminate papers that were not related to the focus of this review. The data collection methodology for this paper is depicted in Figure 2.

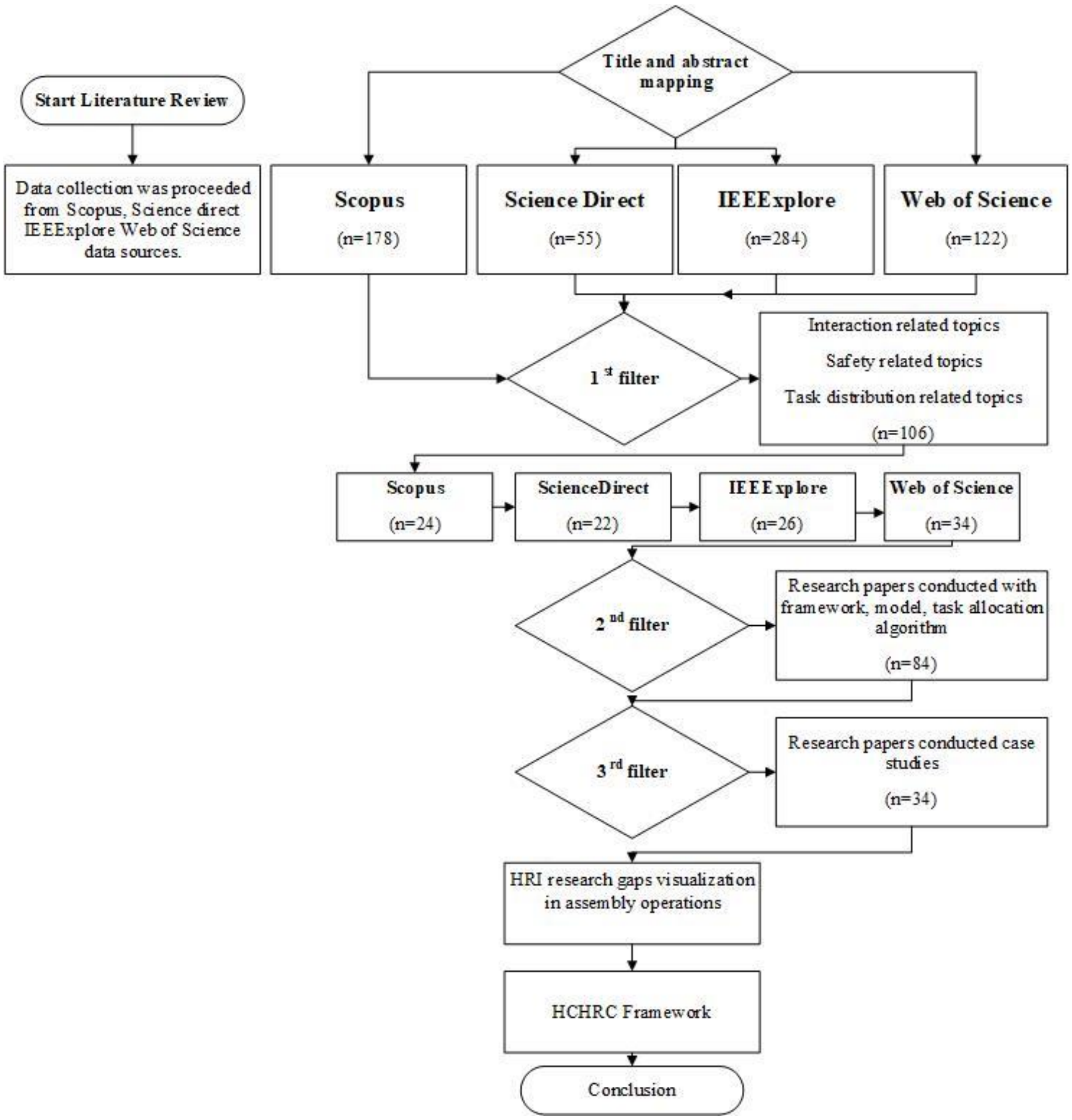

Figure 2. Methodology for data collection

Results and Discussion

Robots as a Central Part of the Interaction

The majority of HRI research topics to date has considered robots as the core of the assembly operations, while humans have been considered peripheral (Blankemeyer, et al., 2020). This interaction between human and robot was supposed to reduce the workload for the human operator through physical assistance by robots. When it comes to trust in robots, we defined that loss of trust happens over time in actual assembly operations. This led to the systems suffering from flexibility and efficiency. In addition to this, most studies are conducted in laboratory conditions and focus on short-term physical interaction between humans and robots, and there is little research on communication structures.

Lack of Larger Team Interaction

Another research gap is that recent human-robot interaction has been performed with a single operator and robots, and there has been no research on larger team structures with other factory workers or robot programming without the requirement of expert knowledge. Novel programming approaches, such as gestures or speech, and augmented reality must be introduced to avoid the bottleneck of traditional interaction modes.

HRI Design Methodology

Due to the fact that HRI assembly research is still in its initial stages, no mature integration methodology has been developed. HRI assembly systems involve much more human-related uncertainties than traditional assembly systems, where everything is pre-programmed and hence under strict control. Therefore, the integration of human operators and robots in the same environment remains a challenging research task. To achieve these goals, proper design methods must be addressed, which means control laws, sensors, task allocation, and planning approaches that allow the human operator to safely stand close to the robot, actively sharing the working area and tasks, and providing the interaction system with the required flexibility.

HRI Assembly System Efficiency

The current HRI assembly systems still suffer from low efficiency. Assembly efficiency may be lower than that of human assembly teams or robotic assembly teams. There is a critical capability missing from the current HRI assembly system. A very small number of sensors are installed, as well as intelligence algorithms. To improve current HRI assembly systems, we need to take full advantage of human cognitive skills. Therefore, we need to design a user-friendly interface so that human operators can easily communicate with the robot during assembly operations. In the following Figure 3 we summarized the visualization of identified research gaps in HRI in assembly operations.

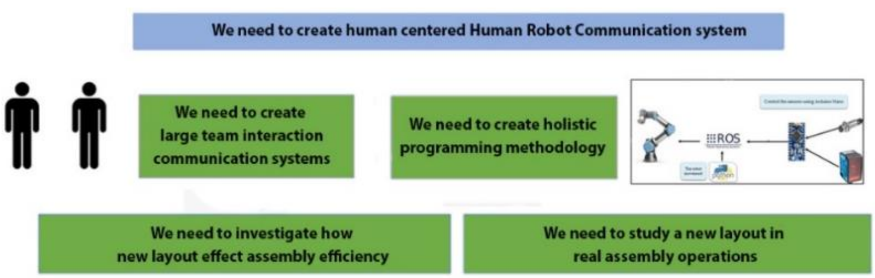

Figure 3. HRI research gaps visualization in assembly operations

Human Centered Human-Robot Communication (HCHRC) Framework

Designing a user-friendly interface that enables easy communication between human operators and the robot during assembly processes is essential to properly utilizing human cognitive capacities. On the one hand, providing inputs to the robot and programming it should be intuitive for the worker so that the operator is less concerned with how to communicate and can focus on the tasks and goals at hand. The information provided as feedback by the robot, on the other hand, should be sufficient to provide the user with the situational awareness required to comprehend the current system behavior and facilitate intervention in dynamic and unforeseen situations. To meet these objectives, actual design approaches must be taken, including control laws, sensors, task allocation, and planning strategies that permit the human operator able to works close with the robot in a safe manner while actively sharing the working place and tasks and giving the interaction system the necessary flexibility.

Generally speaking, future human and robot interaction in assembly systems should focus on how human operators supported by robots and advanced technologies in sociotechnical environment to satisfy human wellbeing in hybrid human robot interaction teams. The following Figure 4 summarizes the future human centered human robot communication (HCHRC) framework during assembly operations.

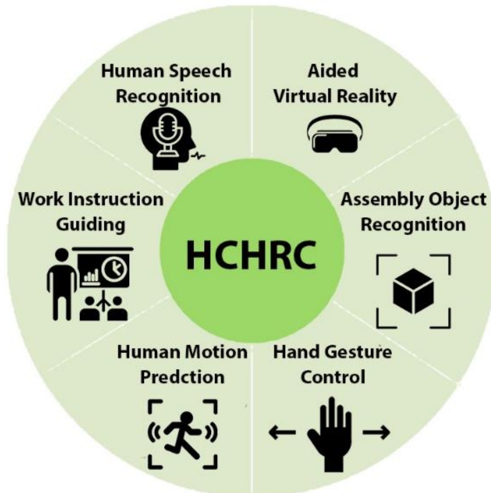

Figure 4. The future human and robot communication framework during assembly operation

The application of the Internet of Things (IoT) technology to assembly processes is the keystone of HCHRC systems. Every assembly workstation, storage location, piece of equipment, product, worker and robots embedded with sensors to communicate in real-time specific data. An assembly work instruction system leverages these data to implement proper models and methods to automatically manage and configure the assembly operations. This HCHRC framework eases the development of different applications which define the main characteristics of human centered assembly operation.

Aided Virtual Reality

Aided virtual reality training will be first step towards HCHRC, because VR technology can provide a combination of interactive virtual reality and advanced simulations of realistic scenarios for optimized decision-making and training for the smart operator during close proximity with collaborative robot. During assembly operation with collaborative robots, the worker is aided through augmented realty devices, as head-worn displays, which suggest the sequence of activities to complete an assembly task considering the customer personalization. Cobots automatically adjust their configuration in real-time to best fit with the worker physique and the assembly task features. Moreover, cobots provide to the worker an artificial force to perform hazardous activities reducing the ergonomic risk of strenuous tasks.

Aided virtual reality technology offer many significant benefits (e.g. decrease assembly cycle times, reliability, reduced failure rate and traceability of human) to support the smart operator in real-time during close proximity with robots by becoming a digital assistance system for reducing human errors and at the same time reducing the dependence on printed work instructions, computer screens and operator memory, which need to be interpreted first by a skilled worker (Romero et al., 2016).

Besides, aided virtual reality technology can comprise a new human-robot interface to manufacturing IT applications and assets, disposing real-time response about assembly processes and robots to the operator in order to improve decision-making (Gorecky et al., 2014). This can be applied at machine level using traditional Programmable Logic Controllers (PLCs) and Supervisory Control & Data Acquisition (SCADA) systems nonetheless also emerging Internet of Things (IoT) technologies for assets assembly sequences monitoring. In addition aided virtual reality technologies can be implemented also at mid-level operations like Manufacturing Execution Systems (MES), novel production line simulations and big data-driven quality controls and at higher levels such as the Enterprise Resource Planning (ERP) systems.

Assembly Object Recognition

Assembly operations involving both human operators and robots provide a unique co-working environment (Bjoen et al., 2016). As a result, object recognition is one of the building blocks of future HCHRC assembly systems. Within an operation, the object can include various physical information, such as assembly tools and assembly parts. A human operator can easily perceive all of the mentioned object recognition information in a communication assembly operation using cognitive skills, but robots can understand any of the mentioned context information using sensors and recognition algorithms. Furthermore, during close proximity with robots during assembly operations, a human operator can be guided by cyber physical systems (CPS), increasing the operator's productivity.

Hand Gesture and Haptic Control

Normally, human operators can use control codes to command an industrial robot with a programming-based user interface (Flacco et al., 2012). However, we believe future HCHRC workstations require a more flexible and intuitive way to control collaborative robots. A recent development in this direction is hand gesture control of the robots (Rafiqul & Noor, 2012). This control interface is designed for intuitive robot control. Hand gesture robot control can provide intuitive ways for human operators to control collaborative robots. Thus, the robot can dynamically adapt its task plan to collaborate with human operators in the same assembly operation. We believe that, it is important to identify and implement hand gesture and haptic control systems in order to jog/move the robot in different ways, covering all the movement types of a regular teaching pendant, and possibly adding more movement types and functionalities.

Human Motion Prediction

In order to address the human safety problems when it comes to close proximity with robots during assembly operations, we need design human motion prediction system that employs different cameras that tracks the human approach and gestures at different proximity of the user. This system allows improvement on safety of human operator and wellbeing during assembly operations.

Work Instruction Guiding

The human operator is crucial in assembly systems because they are in charge of the most flexible operations during the processes. Nevertheless, an operator faces some major problems during the assembly process. First, the management of hundreds of different product mixes, distinguished by different assembly cycles, as well as thousands of different parts, hundreds of tools, equipment, and several worker qualifications (Tsarouchi & Matthaiakis, 2017). Second, assembly tasks experience several challenges, such as the growing complexity of their processes and supply networks, cost pressures, and increasing customer expectations for quality, lead time, and customization (Bänziger et al., 2018).

The current problems may be solved by traditional assembly-aid methods such as paper, tables, and other drawings. However, these conventional paradigms have the drawback that employees have to look at different objects and search for the correct information by flicking through the work instructions, which is a time-consuming operation. Better suited technologies for displaying information would make manual assembly processes more efficient and less error-prone.

Thus, conventional operator support systems have to be substituted by digital and smart media systems to provide instructions in the most efficient way to the employees. The digital assistance system provides information about failures and information for the right execution of the process. However, displaying data and work instructions on a display is not the only suitable option for an assistance system. Furthermore, the second part is to check if an assembly process is executed properly or not. Consequently, assembly systems must be equipped with sensors and cameras to compare the target state and actual state of an assembly process.

Speech Recognition and Control

The quality of sensors for hand and voice control of robots still cannot satisfy industrial standards, and the recognition accuracy of the algorithms is also limited (Gustavsson et al., 2017). Hence, this communication between humans and robots is still at the laboratory stage and cannot be directly adapted in the manufacturing industry. Therefore, it is important to identify and implement appropriate speech recognition systems that can function in industrially noisy environments such as assembly manufacturing.

Conclusion and Future work

Human–robot communication is a new mode for assembly operations, and we believe that human centered human–robot synergy will constitute a relevant factor in industry for improving assembly operations in terms of performances and flexibility. However, we believe that, this will only be achieved with systems that are fundamentally safe and a user-friendly interface operator, intuitive to use, and easy to set up so that human operators can easily communicate with the robot during assembly operations. At glance, this paper has provided an overview of the current state of art research topics related to Human–Robot Collaboration, showing that it can be applied in a wide range of different modes. A literature analysis was carried out papers published between 2010 and 2022 that used collaborative robots in assembly operations.Within the context of assembly applications, we focused on the control systems, the collaboration methodologies, and the tasks assigned to the cobots in HRC studies.From our analysis, we identified that the majority of research is largely focused on robot centered applications and when it comes to trust in robots, we defined that loss of trust happens over time in actual assembly operations. This led to the systems suffering from flexibility and efficiency point of view.

We found that we are in a transformation phase from physical interaction mode towards cognitive interaction mode between humans and robots, where humans and robots are able to communicate with each other during mutual working conditions and humans are able to guide robots. Generally speaking, future human and robot interaction in assembly systems should focus on how human operators supported by robots and advanced technologies in sociotechnical environment to satisfy human wellbeing in hybrid human robot interaction teams. Therefore, we in this paper we proposed the future human centered human robot communication (HCHRC) framework during assembly operations. This HCHRC system boosted by assembly context recognition, hand gestures control, work instruction assistant and human activity prediction and other advanced technologies. We hope that by utilizing a human-centered human-robot communication mode, the flexibility and productivity of the assembly operation, as well as the human operator's well-being, will improve. Future work will identify and address the specific topics of the HCHRC framework types.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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