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Enhancing Safety and Collaboration in Human Robot Interaction for Industrial Robotics

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Abstract – This research evaluates the aspect of collaboration between humans and robots in industrial robotics. It highlights the advantages of using robots in non-ergonomic tasks while at the same time recognizing that there are challenges preventing them from achieving manipulation accuracy with precision. Collaborative robots also known as robots, have been proposed to address these limitations. Safety has been identified as one of the most critical issues in collaborative environments, which calls for a discussion on various strategies and practices to ensure the safety of operators. The study explores many facets of human-robot interaction and collaboration such as physicality and proximity, house sharing, and collaboration. Furthermore, this article argues that it is vital to consider human aspects of human-robot interaction such as trustworthiness, mental effort, and fear. The final part presents a case study on incorporation of humans and robots in assembly and sealing process of refrigerator. Finally, this case underlines safety measures that need to be included during robot type selection and assembly process equipment used should match robot's characteristics like size etc. This study suggests possible avenues for future inquiry including augmented reality methods and integrating safety constraints into design software and planning software.

Keywords – Collaborative Robots, Industrial Robots, Human-Robot Collaboration, Augmented Reality Techniques, Human-Robot Interaction.

I. INTRODUCTION

In contemporary times, the field of industrial robotics revolves on the substitution of human workers engaged in non-ergonomic tasks with robotic counterparts. For instance, notable instances of manipulation include handling of substantial weights, manipulation in physically strenuous postures, and engagement in hazardous operations involving poisonous or high-temperature substances. Robotic systems are often used in tasks that involve tedious manual activities characterized by repeated and highly precise demands.

In **Fig 1** presents the development of humans to consider applying full automation from manual manufacturing. Robots are very resilient, swift, and exceedingly precise mechanisms that exhibit superior efficiency, enhanced efficacy, and cost-effectiveness in comparison to human counterparts while executing assigned duties. Therefore, it is fundamental to consider the rationale of retaining the human aspect, despite its propensity for mistake, and engaging with collaborative robots. Certain activities may need to be modified in order to align with current situations. Robots lack the capacity for cognitive thought, since they only operate by executing predetermined orders and performing pre-programmed actions. In other terms, the capabilities of robots are constrained by the parameters set inside their programming. Manipulation robots are often engineered with seven or six degrees of freedom, representing the number of motion axes they possess. In contrast, around thirty degrees of freedom is exhibited by the human body`s upper limb.

Another disadvantage of these devices is the lack of precision manipulation capabilities with a wide range of motion. Consequently, two obstacles exist in task execution by human worker and a robotic counterpart. Collaboration effectively overcomes these constraints and thrives by leveraging the benefits of machines in demanding applications, while ensuring the presence of qualified individuals for operation. Collaborative robots, sometimes referred to as cooperative robots, cobots, or robotic helpers, are a kind of robotic technology. A robot designed for human collaboration does not always need a distinct design compared to conventional industrial robots (see Figure 2) that adhere to safety standard ISO EN 10218. However, it is necessary for the robot to be supplied with additional safety components. A technical standard ISO/TS 15066, published in February 2016, provides a summary of recommendations pertaining to collaborative robots, often known as robots and robotic devices [1].

Numerous research endeavors have focused on the construction of multimodal interfaces and control algorithms for the regulation of the movement of the component by both the robot and the operator [2, 3, 4]. As an example, the operator has the ability to manually manipulate the tool center point (TCP) of the robot, using standardized voices gestures or commands and force sensors, in order to do supplementary tasks. Simultaneously, the robot has the capability to transport the payload of the component while using virtual windows to guarantee a route that is free from collisions. Consequently, there has been an introduction of new initiatives and products aimed at harnessing the potential of flexibility and productivity in hybrid systems. Additionally, extensive research efforts have been undertaken to thoroughly examine the advantages associated with these systems [5, 6, 7].

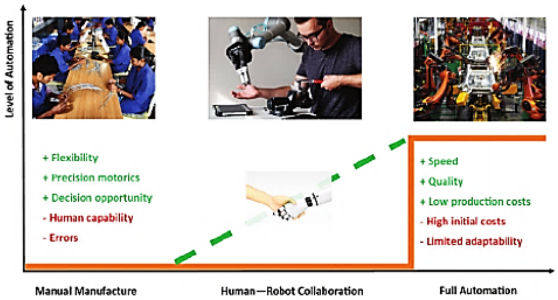

Fig 1. Foundation of Human – Robot Collaboration

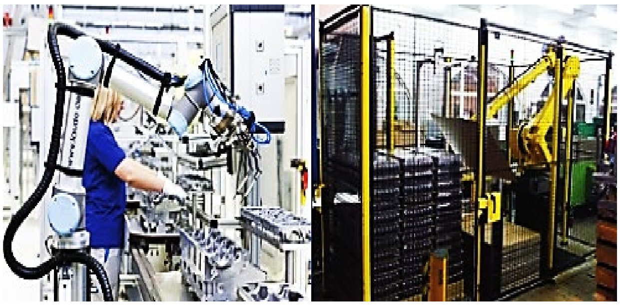

Fig 2. Robot Workplace with Collaborative (Left Image) and Conventional Robot

Nevertheless, there are certain limitations that hinder their widespread use in industrial settings. Despite successfully addressing the technological complexities associated with the design and implementation of such systems, the paramount consideration for attaining acceptability will always be the safety of the operators. The current applications use the practice of segregating the working spaces of robots and humans to guarantee the safety of operators. The current architecture does not effectively handle both sorts of production entities.

The purpose of this study is to examine the possibility of human-robot cooperation within the context of industrial robotics, while also addressing the safety considerations that are inherent to this practice. This study seeks to enhance cooperation and assure human operators' safety by examining the many elements that impact effective human-robot interaction, including environmental, robot, and human factors. The ultimate objective is to develop methods and technologies that may enhance this interaction. The subsequent sections of this article have been structured in the following manner: Section II presents a discussion of the human-robot interaction (HRI) and human-robot collaboration (HRC). Section III reviews the safety measures in HRC. Section IV discusses the human factors and consideration when dealing with robots. Section V presents a case study of HRI and HRC in relation to applications in the refrigerator's assembly. Lastly, Section VI draws a conclusion to the research and presents directions for future studies.

II. HUMAN-ROBOT COLLABORATION AND INTERACTION

The subject of human-robot collaboration (HRC) has been previously examined prior to the introduction of the first industrial manipulator capable of collaborative operation, known as the KUKA LWR 4, in 2008 [8]. Nevertheless, within both academic and industrial contexts, there exists a continuous discourse around the precise interpretation and meaning of the non-normative concepts of human-robot interaction (HRI) and HRC. Mukherjee, Gupta, Chang, and Najjaran [9] provided a comprehensive summary of the argument, which included many interpretations within the community. Additionally, the potential hazards and implications associated with the use of the phrase "collaboration" for branding reasons were emphasized. The issue under consideration was examined in [10], which delved into many perspectives by providing definitions and delineating several levels and subcategories of HRI and HRC. Salter, Michaud, Létourneau, Lee, and Werry [11] propose a categorization of Human-Robot into several categories. These categories include: (i) human-robot cohabitation, (ii) human-robot interaction, and (iii) human-robot collaboration. Within the category of human-robot collaboration, more subdivisions may be made, namely contact-less collaborations and physical collaborations.

Simultaneously, other perspectives pertaining to the classification that best encapsulates the highest level of engagement and direct engagement between people and robots are present within the academic research community. Krämer, Von Der Pütten, and Eimler [12] provided support for the classification system that relies on the physical closeness between a robot and human. This interpretation categorizes cooperative robot interactions as exhibiting a higher degree of closeness compared to collaborative robot interactions person-robot cooperation is seen when a person and a robot are in close proximity, whereas human-robot coexistence (HRCox) is observed when they are at a greater distance from each other. In contrast, Ferreira and Fletcher [13] assert that human-robot collaboration (HRC) revolves on the interaction and cooperation between people and robots within a shared workplace, including the division of duties. Consequently, the authors visualized human-robot collaboration (HRC) as a more immersive experience. Currently, most industry players maintain varying interpretations of HRC, whereby they assert that any robot capable of functioning without a physical barrier is deemed collaborative. Wang, Wang, Váncza, and Kemény [14] conducted a comprehensive study of many aspects of HRC in firm settings. Their analysis focused on three key areas: (i) safety concerns, (ii) communication interfaces for Human-Robot Interaction (HRI), and (iii) techniques for designing HRI processes.

This study used a finite state machine to describe both the human and the robot, while ensuring safety via the implementation of three separate levels. The levels included in this framework consist of the warning area, the safe area (re-planning and requiring collision avoidance of robot movements), and the dangerous region (resulting in the deactivation of robot motors). The HRI systems may be classified into two categories, namely “time and workspace sharing” and “workspace sharing”, based on their respective functionalities. Nevertheless, under both classifications, human operators and robots possess the capability to execute jobs alone or together. The configuration of an HRI cell, as outlined in [15], assigns several functions to the human operator. In addition to their primary role as an operator, the individual in question is also required to fulfill many other responsibilities, including acting as bystander, a supervisor, colleague, and mechanic. The systems of HRI may be further classified based on the degree of interaction. The robot and the human operator may engage in a workspace and task that is either separate or shared, or alternatively, they may participate in a task that is common while occupying distinct workspaces. In the second scenario, whereby both the robot and the human operator collaborate on activities inside a shared workplace, their relationship might be characterized as discrete.

In contemporary times, several industrial sectors want to incorporate Human-Robot Interaction (HRI) into their production processes, using the categories as guiding principles. The BMW automobile sector has implemented the usage of cooperative robots at its production facility in Spartanburg. These robots are designed to operate alongside human operators and assume jobs that have the potential to cause repetitive strain injuries among human workers. The Universal Robots UR10, which conforms to the ISO EN ISO 10218 standard, has been implemented at the BMW facility without the need of physical barriers [16]. This deployment included placing the robot near a human worker to undertake the task of door sealing. Furthermore, BMW has the objective of implementing collaborative robots inside the same manufacturing facility. These robots would function as aides to workers by providing them with components throughout the procedures. Moreover, the integration of a UR-5 robot has been seen in the area of assembly of the cylinder head of the Volkswagen (VW) factory located in Salzgitter.

Furthermore, Audi AG has implemented a collaborative KUKA robot at its primary facility in Ingolstadt with the aim of enhancing ergonomics and automating repetitive tasks. The robot collaborates closely with human operators and serves as an assistance in assembly operations [17]. Nevertheless, in the circumstances, the extent of cooperation between human operators and the robot is constrained, even though the former are permitted to physically navigate within the robot's vicinity and coexist inside the same workplace. Furthermore, most robots exhibit a lightweight design and possess a limited payload capacity, hence restricting their ability to do tasks that need strength augmentation, extremely accurate placement, and similar features. Current research trends, such as the ROBO PARTNER project [18], include exploring the potential for HRI in industrial settings, specifically in the context of simultaneous assembly activities. In this context, it is necessary for both parties to assume a more proactive role, equipping themselves with enhanced skills. These capabilities include the manual supervision of the robot in handling larger components, as well as engaging in interactive exchanges of information using multi-modal interfaces, among other tasks. The objective is to provide resolutions that enable enhanced levels of direct collaboration between robots and humans, while maintaining the safety of such collaboration with high-capacity machines.

III. SAFETY IN HUMAN-ROBOT COLLABORATION

According to Delgado, Ajayi, Akanbi, Akinadé, and Bilal [19], the prevailing tendencies in the industry are leaning towards the adoption of robotic configurations that are both fenceless and inherently safe. These settings consider various factors like as the robot's static force and speed, as well as the reaction actions of human operators. Tashtoush et al. performed a comprehensive study in [20] that provides a summary of the area of HRC and HRI. The study revealed that interactions involving physical touch between humans and robots may be broadly classified into two classes: unintended and intended contacts. Within this context, instances of unpleasant contacts are being categorized as collisions.

Long [21] conducted a comprehensive examination of several types of collisions and their corresponding critical contact force values. The scholars classified impacts into many distinct types, namely: (i) unconstrained effects, (ii) clamping inside the robot model, (iii) restricted effects, (iv) partly constrained effects, and (v) impacts resulting in secondary effects. The scope of this analysis was broadened in a subsequent study (reference [22]) to include a range of severity levels associated with different kinds of injuries, contingent upon the specific collision types. Therrien, Quatieri, and Dudgeon [23] conducted investigations to examine model-based algorithms that are specifically developed for identification, isolation, and real-time collision detection of physical human-robot interactions (HRIs). Additionally, Kluß, and Zetzsche [24] categorized contact types into unintended and intended contacts to emphasize the significance of interpreting and detecting contacts in order to ensure the safety of physical HRI.

Various measures have been used in recent years to safeguard the safety of human operators. These solutions are designed to address many aspects of safety, encompassing those in **Table 1.**

In order to facilitate the integration of safety measures into their systems, system integrators have been provided with national and international standards, directives, and legislation. Given the premise that a collaborative workplace encompasses not only human and robotic entities but also other supplementary equipment such as electric screwdrivers and electrical clamping devices, it becomes imperative to address the distinct hazards associated with each individual unit in a manner that prioritizes safety. Hence, it is essential to adhere to the prescribed norms and regulations pertaining to each category of equipment and operation.

Table 1. Measures to Safety of Human Operators

Measures	Literature	Explanation
Crash safety	Burgard, Brock and Stachniss [25]	To guarantee crash safety, it is essential to establish measures that restrict crashes to regulated and safe interactions between robots, people, and barriers. The primary purpose is to examine the constraints on the power or force put on individuals.
Active safety	Halme, Lanz, Kämäräinen, Pieters, Latokartano, and Hietanen [26]	Active safety systems are designed to promptly identify and anticipate potential accidents between people and equipment, and then halt the activity in a regulated manner. In order to achieve this objective, contact/force sensors, and sensors of proximity may be used.
Adaptive safety	Li, Pan, Gong, and Huang [27]	The implementation of adaptive safety measures involves interfering in the functioning of hardware equipment and implementing remedial steps aimed at preventing collisions, all while ensuring uninterrupted operation of the device.

Currently, there exists a considerable number of over 30 operational European Union regulations and around 600 distinct safety standards. In the context of robotic cells, **Table 1** outlines the first three requirements that include a wide range of measures aimed at ensuring safety. The most significant ones pertain to those shown in **Table 2**.

Table 2. Description of Measures Pertaining to Safety Assurance

Measure	Literature	Explanation
Safety-oriented control model performance	Su, Yang, Ferrigno, and De Momi [28]	The safety-related components of control systems must provide the ability to achieve tolerance in the presence of single defects, while maintaining safety integrity.
Robot Stopping Functionalities	Ajoudani, Zanchettin, Ivaldi, Albu-Schäffer, Kosuge, and Khatib [29]	Each robotic system must be equipped with a protective stop function. In addition, it is essential that they establish a connection to external safety apparatus.
Velocity Control	Lesort, Díaz-Rodríguez, Goudou, and Filliat [30]	It is important to have control over the velocity of both the TCP and the robot end-effector. In the context of collaborative work ecosystems, it is recommended that the velocity of the Transmission Control Protocol (TCP) should not surpass 250 millimeters per second.
Collaborative process requirements	Prati, Peruzzini, Pellicciari, and Raffaeli [31]	In order to facilitate effective collaboration, it is essential that robots intended for such purposes provide a visual indicator to signify their engagement in collaborative operations.
Limiting Robot Motions	He, Xue, Yu, Li, and Yang [32]	The inclusion of a safeguarded space with dimensions at their maximum capacity may lead to the large region`s enclosure. The restriction of the machine`s movement may be accomplished using the robot's integral systems, such as hard stops or space limiting and safety-red soft axis.
Defining minimal separation distance	Safeea, Mendes, and Neto [33]	The determination of the smaller distance of separation between the robot and the operator relies on a risk evaluation, which varies depending on the specific application. The evaluation considers two main factors: a) the potential risks posed by the end effector and the components it may manipulate, and b) the arrangement of the space of work. c) The responsibilities of the controllers and d) the usability of the system.
Collision identification	Sharkawy, Koustoumpardis, and Aspragathos [34]	The safety function must ascertain if the present locations and velocities of both the machine and the human have the potential to result in a reduction of the separation distance below the minimal threshold, therefore leading to a collision.
Mitigating potential collision	Villani, Pini, Leali, and Secchi [35]	This function enables the robot to control collision risks by using the following strategies: a) Decelerating its velocity or temporarily halting its movement; b) Reversing its trajectory along the current route; c) Navigating along an alternative path that ensures safety.
Ergonomical and technological requirements	Lorenzini, Lagomarsino, Fortini, Gholami, and Ajoudani [36]	In the event of a potential encounter between a person and a robot, it is advisable to take prudence to guarantee the absence of any rough, sharp, cutting edges, and pointed surfaces within the vicinity of touch. In addition, it is necessary to design the surrounding working environment in a manner that allows people to interact with collaborative robots without encountering any physical contact.

The standards organizations have assigned these functions to regulate distinct safety issues in a manner that avoids overlap. However, it is important to note that there may be instances of overlapping throughout the customizing process of each application. In such cases, it becomes necessary to thoroughly assess the extent to which the functional safety criteria are well addressed and covered.

IV. HUMAN CONSIDERATIONS

Charalambous, Fletcher, and Webb [37] conducted an evaluation to assess the effects of commonly studied human factors (HFs) on shared-space human-robot collaboration (HRC). They also documented the methods used to analyze these HFs and discussed their impact on various aspects of HRC, including utilization, teaming, and efficiency. The findings of this review provide valuable insights into the influence of HFs on HRC. The primary discoveries were:

a) The human factors that have received the most extensive research attention are trust, cognitive workload, and anxiety. Among the several evaluation techniques used in the field of human factors, subjective questionnaires have emerged as the most widely utilized.
b) The performance, efficiency, acceptance, and other aspects of human-robot collaboration (HRC) are significantly influenced by human factors. However, existing studies tend to focus primarily on examining how the robotic system affects human factors, while giving less attention to the reciprocal effect of HF on the system or the direct manipulation of human factors. There is a limited number of research that simultaneously examine the interplay between robot-to-human and human-to-robot factors in the context of closed-loop HRC systems.
c) Many studies have employed sample demographics that are not representative or have not provided relevant demographic information. These studies tend to have a higher proportion of male participants compared to female participants, a greater representation of younger individuals compared to older individuals, and often neglect to report the participants' prior experience and the methods used for experimental training. This lack of comprehensive demographic information may lead to an incomplete understanding of workforce development strategies in the context of collaborative robotics.

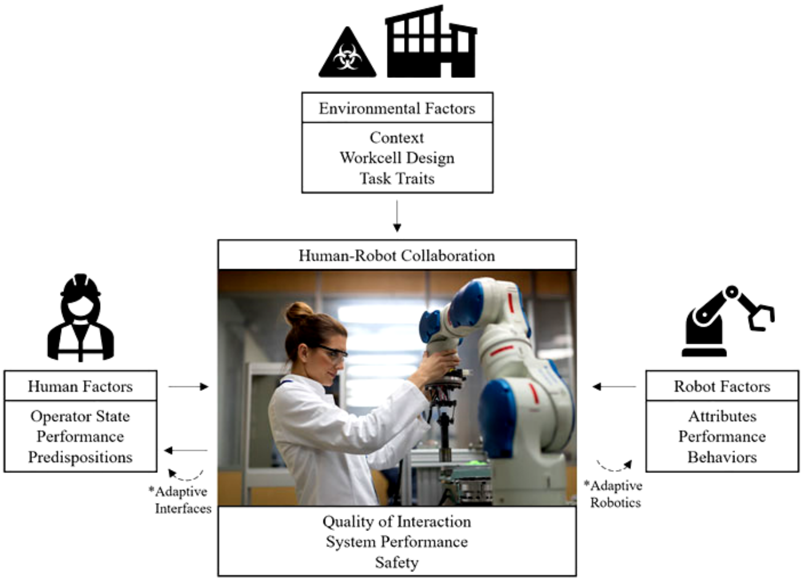

Fig 3. Collaboration-Centered Concept Map

Fig 3 depicts a concept map that focuses on cooperation, which is focused upon influences that have been discovered by a critical review of the existing literature. The definition of HRC may vary across different research, but, in this context, we describe HRC as including the whole of the human-robot system, as well as the environmental, robot, and human factors that contribute to it. Therefore, the HRC phenomenon is subject to the effect of several environmental factors (EF), including work cell design, task features, and context. Additionally, robot factors (RF), like automation and reliability, as well as human factors (HF), including experience, and qualities, also play a significant role in shaping HRC. According to [38], conventional manufacturing robots exert an impact on human-robot collaboration (HRC) without including feedback mechanisms. This implies that in traditional robotics, the responsibility for adapting to various elements of HRC falls on the operator rather than the robot itself. The incorporation of collaborative robots in the HRC system has been facilitated by the integration of supplementary sensors. These sensors provide valuable data on the system's condition, including real-time contextual information about human factors.

In contrast to cobots, which need deliberate programming and the incorporation of sensors to provide specialized feedback functionalities, human factors (HFs) include inherent cyclic properties as they impact the quality of HRC and adjust accordingly. The presence of this inherent feedback loop facilitates the use of operator sensing skills within Human-Robot Collaboration (HRC). However, it also signifies that the configuration of HRC systems has a direct impact on operator performance inside the system, as well as their inclinations towards trusting the machine, and other related factors. The impact of HRC systems on human aspects may be effectively regulated by using adaptive interfaces, including augmented reality technologies, sensor feeds, and other similar mechanisms. In contrast to human or robot variables, there is a lack of research that have specifically examined the adaptation of environmental parameters to the system of HRC state. This is likely due to the nature of shared-space robotics, where activities often involve monotony, and EF like emergency lights, are often attributed to the collaborative robot (cobot). Subsequent research endeavors might explore the possibility of adapting the HRC framework by including environmental aspects in addition to robot-centric considerations.

Considerable research has been conducted by Jevtić, Colomé, Alenyà, and Torras [39] on the phenomenon of unidirectional robot adaptation to human beings. Various approaches have been proposed in the literature for teaching robots' skills or specialized tasks. One such approach is the use of human experts who provide demonstrations. Robots have shown the capability to deduce human preferences in online settings via interactive engagements. Particularly, the application of Partly Observable Markov Decision Process (POMDP) models has facilitated the ability to reason about the ambiguity surrounding human intention. The POMDP formulation, as shown by Spaan [40], has exhibited notable computing and has been used in several applications of motion planning. In recent studies, Dani, Salehi, Rotithor, Trombetta, and Ravichandar [41] have successfully deduced human intention by breaking down a game task into smaller subtasks, specifically for the purpose of game artificial intelligence (AI) applications.

A research conducted by Kasmarik and Maher [42] examined the inference of human player intentions, enabling a non-player character (NPC) to provide assistance to the human player. In an alternative approach, Doucet, De Freitas, Gordon, and Smith [43] introduced a cooperative planning system based on partly observable Monte-Carlo methods. This system aims to infer human purpose in the context of a turn-based game. In their study, Stroud [44] introduced a formal framework for acquiring knowledge about human kinds via joint-action demonstrations. This framework enables the real-time inference of a new user's type and the subsequent generation of a robot policy that is in accordance with the user's preferences. Pezzato, Ferrari, and Corbato [45] have also shown the accomplishment of simultaneous intent inference and robot adaptability by using the transmission of state and temporal restrictions. An alternative method that has been used is the algorithm of human-robot cross-training, in which the human participant showcases their choice by exchanging objectives with the robot, so influencing the function of reward of the robot. While there is a potential for the human to modify their techniques throughout the training process, the algorithm lacks a mechanism for incorporating a human adaptability model that would allow the robot to freely affect the behaviors of its human partner.

Mitsunaga, Smith, Kanda, Ishiguro, and Hagita [46] investigated the phenomenon of human adaption to robots. The investigation has mostly concentrated on operator training in the domains of search-and-rescue, space, and military, aiming to minimize operator burden and mitigate operational risk. Furthermore, previous studies have examined the impact of recurrent engagements with a robot with human traits on the development of skills in kids diagnosed with autism. Additionally, investigations have explored the influence of such interactions on the language abilities of elementary school students, as well as on the spatial behavior of users. The phenomenon of human adaptation has been documented in a task involving assistive walking, whereby a robot utilizes input from humans to enhance its performance, thus affecting the level of physical assistance offered by the human counterpart. The incorporation of changes in human actions is a critical element of the learning process. However, the system does not explicitly analyze or consider the process of adaptation of human throughout the interaction. In contrast, the probabilistic model given by Sterzer and Kleinschmidt [47] pertains to the inference process undertaken by a human observer about the intentions of a robot. Additionally, they developed an algorithm for producing motion that aims to optimize this inference in the direction of a predetermined goal.

The suggested formalism aims to establish a reciprocal relationship between human-robot interaction and adaptability, therefore bridging the gap between these two areas of study. The use of the robot is based on a model of human adaption that is characterized by the parameterization of human adaptability. The system uses probabilistic reasoning to consider several potential modifications in the human's approach and adjusts its own actions accordingly, with the aim of assisting the human in adopting a more efficient strategy whenever feasible.

The phenomenon of mutual adaptation among agents has been the subject of substantial research in the domain of game theory, as shown by the work of Nourian and Caines [48]. The field of game theory often depends on making robust theoretical assumptions on the rationality of actors and their level of knowledge concerning reward functions. The suitability of these assumptions may be compromised in situations where individuals lack the ability or willingness to engage in rational deliberation over optimum tactics for themselves or others. This phenomenon is especially evident within the HRC context, because the human operator has uncertainty about the robot's behavioral patterns and is constrained by limited temporal resources to formulate an appropriate response. Fenichel et al. [49] provide a theoretical framework for understanding human adaptive behaviors, drawing on the concept of limited memory, and then incorporate this framework into the decision-making process of robots.

The successful or unsuccessful outcome of the HRC system's emergent elements, such as safety, level of performance, and acceptability, is contingent upon the combined examination of environmental factors (EFs), relational factors (RFs), and human factors (HFs) and their interactions within the system of HRC. The consideration of the reciprocal relationship between HFs and the HRC system is crucial due to the presence of the HFs-HRC loop. It is significant to examine the impact of HFs on the structure of HRC as well as the system`s impact of HRC on HFs. RFs have the potential to have an indirect impact on HFs by means of influencing a specific feature of the HRC. Eppner, Deimel, Jos, Álvarez-Ruiz, Maertens, and Brock [50] have extensively examined the modeling of the link between robot, environmental, and human elements, with a particular focus on trust. The research investigations often ignore the comprehension of the feedback component inside the HFs-HRC loop and the mechanisms of impact of HFs in the suggested model.

V. CASE STUDY: REFRIGERATORS ASSEMBLY

This case study examines the integration of human and robotic collaboration in the sealing processes and concurrent assembly of a refrigerator on a serial production line. The use of robotic systems in this scenario facilitates a decrease in tape application, hence mitigating a significant proportion of product rework. The use of a novel sealing procedure involving the application of a heated sealant may be proposed. The robotic system is situated in close proximity to the human operator and has the capability to function in either an autonomous mode or under manual control. Upon the arrival of the refrigerator to the station, the individual proceeds to prepare the various components, such as wire harnessing, while the automated robot begins the application of the sealant.

Wire harnesses are used to connect wires originating from various electrical devices. The assembly of wires and pipes has remained unchanged throughout the passage of time, despite developments in manufacturing technology. The process of wire harness assembly is a multifaceted manufacturing operation that is growing in complexity due to advancements in mechatronic and electronic devices. These products need an increased number of connections, sensors, controllers, and communication networking components. Furthermore, a significant portion of their assembly activities are performed by physical labor. According to Navas-Reascos, Romero, Stahre, and Caballero-Ruiz [51], it was shown that a significant proportion, namely 90%, of the jobs engaged in wire harness construction process are performed manually. The procedural instructions required to produce a generic wire harness are shown in **Fig 4.**

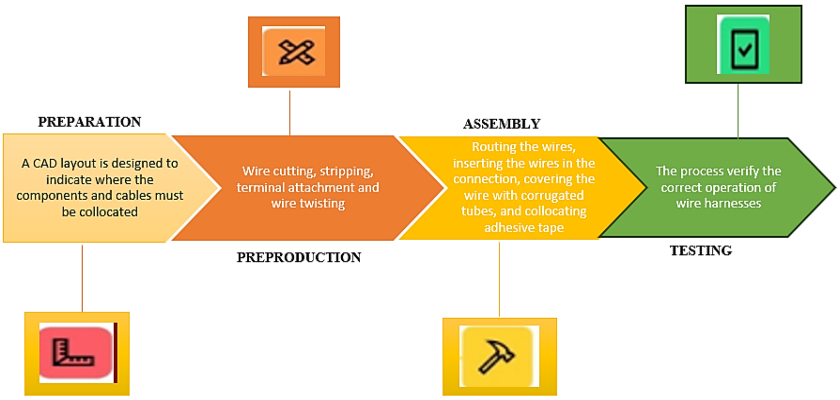

Fig 4. Phases in a Typical Wire-Harness Assembly Process

Due to the loose nature of the construction, there is a possibility that the sealant may not be uniformly distributed over the intended surface. Due to this rationale, individuals possess the ability to manipulate the robot by physically grasping it and guiding it along an alternative trajectory, using more sealant as needed. This serves as an illustrative illustration of how human intellect is integrated with the capabilities of a robot to facilitate a procedure of superior quality. In contrast to the preceding two case studies, the conditions for coexistence in this particular scenario do not permit spatial segregation. Due to the limited space available, it is impractical to rely on overhead cameras for surveillance in the context of HRC. In the present scenario, it is essential to use power and force restriction measures simultaneously with decreased velocity and vigilant monitoring of the speed and location of the robot. It is essential to consider the constraints of the tool orientation and operating envelope in order to prevent any potential contact between the operator's body and hot end effector.

Presently, firm robots have their own mechanisms to effectively restrict the workspace in order to ensure safety, as shown by [52]. The safety technique furthermore entails the utilization of various equipment, like capacitive or tactile skins that enable the immediate identification of touch with humans, as well as pressure-sensitive floor mats that possess the capability to monitor the whereabouts of individuals. Certain laboratory applications have successfully used sensors, such as the Kinect, to monitor and estimate human posture. However, it remains uncertain if these applications can be approved or guaranteed to have an unobstructed field of vision. The aforementioned techniques are applicable during the phase in which the robot is required to operate autonomously, without human intervention. In the context of manual guiding, the robot must either receive direct commands from the human operator or detect the physical touch of the hand of a human, prompting a transition to a more flexible control approach. This method enables the human operator to lead the robot using their hands, using techniques such as impedance or compliance control. **Table 3** presents a comprehensive overview of the various cooperation techniques and safety features associated with each individual scenario. Table 3 presents a concise overview of the safety functions associated with each instance.

The safety concept is formed by selecting and integrating several safety functions in accordance with the prescribed cooperation technique. The comprehensive examination and evaluation of the processes used to execute these duties beyond the boundaries of this work and need individualized investigation. The functions shown in Table 3 are guaranteed to be comprehensive by adherence to the TS 15066 application rules, which are further supported by a compulsory risk assessment for every implementation.

Table 3. Overview of the Collaborative Approaches and Safety Functions Used in The Case Study.

Element	Summary of sub-elements	Case Markups
Collaborative methods	Hand Guiding	*
	Force & Power Limiting	*
	Separation and Speed Monitoring	
Safety functions	Collision Avoidance	
	Collision Detection	*
	Force and Impedance Control	*
	Safe Tool Orientation	*
	IR: Cartesian Safe Limited Position	*
	IR: Cartesian Regions	*
	Deceleration Monitoring	*
	Space to Stop Monitoring	*
	Safety-Rated soft axis	*
	Safety-Rated Reduced Velocity	*
	Safety-Rated Monitored Velocity	*
	Enabling Device	*
	Safety monitored stop	*

VI. CONCLUSION AND FUTURE DIRECTIONS

The objective of industrial robotics is to substitute human workers with robotic systems to do jobs that are characterized as non-ergonomic, including but not limited to heavy lifting, unpleasant postures, and hazardous activities. Robotic systems provide many benefits in terms of enhanced velocity, precision, and cost-efficiency when juxtaposed with human counterparts. Nevertheless, robots have several limits, especially when it comes to executing precise manipulation tasks that need a wide range of motion. The integration of human-robot cooperation emerges as a solution to overcome these obstacles, enabling the use of robots in demanding tasks while coexisting with human operators. Collaborative robots, sometimes referred to as robotic assistants, are equipped with control algorithms and multimodal interfaces that enable joint control of motion by both the operator and the robot. Hybrid systems has inherent characteristics that provide them a considerable degree of flexibility and the capacity to enhance production. Nevertheless, there exist several limitations that hinder their widespread use in industrial settings, with safety emerging as the foremost apprehension. In contemporary practice, the segregation of human workers from the operational spaces of robots is implemented as a precautionary measure to safeguard their well-being.

The issue of safety in human-robot cooperation is increasingly being recognized as a significant worry, prompting endeavors to create robotic setups that are both fenceless and fundamentally safe. Several solutions have been used to assure the safety of human operators, including crash safety, active safety, and adaptive safety. Safety has been included into collaborative workplaces via the implementation of national and international norms, directives, and legislation. The significance of human variables in shared-space HRC is of utmost importance, including elements such as anxiety, trust, and cognitive workload. Nevertheless, most research endeavors primarily concentrate on examining the influence of the robotic system on human variables, while neglecting to adequately address the reciprocal effect of HFs on the system. There exists a need for conducting more extensive research endeavors that directly control human characteristics and consider pertinent demographic variables. The efficacy or inefficacy of human-robot cooperation is contingent upon the collective examination of environmental, robotic, and human elements. The feedback component of the human factors-human-robot collaboration (HRC) loop is often disregarded in research investigations. The successful incorporation of human and robot collaboration within diverse industrial operations requires meticulous deliberation about safety protocols, machinery selection, and spatial arrangement.

Several topics may be the focus of future research efforts in the field of industrial robotics and human-robot cooperation.

a) Safety: The issue of safety has significant importance in the context of human-robot cooperation. Future study may investigate novel tactics and technology aimed at enhancing the safety of human operators who collaborate with robots. This encompasses the development of sophisticated collision detection and avoidance systems, the implementation of adaptive safety measures, and the integration of safety-induced limits into design and planning tools.

b) Human Factors: It is significant to comprehend the influence of human factors on the cooperation between humans and robots in order to develop systems that are efficient and productive. Further investigation is required to explore human aspects, namely trust, cognitive workload, and anxiety, in the context of collaborative activities conducted in common spaces. The consideration of the reciprocal influence between human factors and the HRC system has significant importance. Furthermore, it is important for research endeavors to strive towards include a wide range of demographic groups within their participant samples. This approach is crucial to get a full comprehension of workforce development initiatives.

c) HRI: The sector of HRI is in a constant state of evolution. Subsequent investigations may prioritize the development of immersive and intuitive interfaces that facilitate human operators' interaction with robots. This study encompasses the examination of multimodal interfaces, manual guiding approaches, and augmented reality technologies in relation to the visualization of robot working regions.
d) Performance and Efficiency: Another area of future investigation is the augmentation of performance and efficiency within systems that facilitate cooperation between humans and robots. This may include the creation of adaptable interfaces that enable concurrent inference of user intent and modification of robots. Research might also investigate approaches aimed at enhancing the capacity of robots to adapt to human operators and vice versa, therefore fostering more efficient cooperation.
e) Integration of Robotics in Manufacturing Processes: As the proliferation of robots in industrial sectors expands, next research endeavors may concentrate on the seamless integration of robots inside assembly and production operations. This may include the advancement of novel methodologies and technology to facilitate activities such as meticulous manipulation, enhanced strength, and accurate placement.

In general, it is essential for future research endeavors in the sector of industrial robotics and human-robot cooperation to prioritize the resolution of safety apprehensions, the enhancement of human-robot interaction, the optimization of performance and efficiency, and the seamless integration of robots into manufacturing operations. By focusing on these specific areas, researchers have the potential to make significant contributions towards the progress and broad implementation of collaborative robots across diverse sectors.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

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