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Human-Robot Collaboration Systems: Components and Applications

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Abstract **-** Collaborative robots (cobots) have emerged as a technological solution for enhanced manipulation of objects while allowing safe interaction with a human counterpart. Although substantial developments in Human-Robot Collaboration (HRC) systems have taken place in the last decade, no conceptual framework of their composition is available. The literature provides an unclear process of how to integrate human-robot interaction levels and their roles with safety and communication technologies into HRC systems. To design an ergonomic HRC system (in its physical and cognitive dimensions) a clear identification and categorization of its components is required. This paper presents a literature review analysis that identifies the tendencies of HRC in the manufacturing sector. An initial distinction between application by type of industry and task is carried out. Afterward, interaction levels in HRC systems are examined, both individually and collectively, depending on the application area. Work roles of humans and robots, safety settings, and communication interfaces are also analyzed as part of the interaction levels in the primary composition of HRC systems. Their presence and distribution along 50 selected cases are also explored. The analyzed data, results, and observations presented in this paper demonstrate clear tendencies for specific components that were identified as necessary for improving future designs of human-centered HRC systems.

Keywords**:** Cobots, Safe Human Robot Interaction (HRI), Cognitive workload, Human Robot Cooperation.

1. Introduction

In recent years there has been an observed need for highly customized / personalized products. Despite past developments to reduce manufacturing production cost and production time—via agile manufacturing, just in time manufacturing, and other mechanisms—current manufacturing needs for high-mix and low-volume production cannot be satisfied with the so-called rigid automation [1]. Such deficiencies exist despite the use of state-of-the-art automation and robotic systems having the needed capabilities. Managing industrial and other robots (e.g., field robotics) can be time-consuming in key processes such as installation, set up, and programming leading to the decrease of the changeability capacity of an industrial organization. Alternatively, the utilization of legacy manual production systems makes use of the cognitive abilities of human operators that enable them coping with changes between tasks, tools, product specifications, and unexpected situations (e.g., errors) that challenge the sensing, planning, and movement envelopes. However, human performance in terms of speed, accuracy, and motivation tend to diminish as fatigue becomes visible.

Robots with collaborative capabilities or cobots (collaborative robots) have been developed with intuitive programming interfaces to support human operators in the physical workload of manufacturing tasks such as lifting heavy objects, handling materials with high precision, and executing repetitive actions with high accuracy. Furthermore, direct interaction between human operators and cobots has been enhanced via the use of sensors and software that enable safe physical Human-Robot-Interaction (pHRI), effective manipulation, and collision free activities. As a result, Human-Robot Collaboration (HRC) systems are being adopted as a suitable solution that blends both human operator and cobot capabilities into a shared workspace. As a result, at least in theory, HRC systems seem to be an appropriate strategy for manufacturing organizations seeking to reduce occupational risk incidence and cognitive workloads of humans while increasing efficiency and productivity [2]. However, due to numerous cognitive and pHRI complexities associated with HRC systems, one must note that, human operators' physical and cognitive wellbeing while working in HRC systems are not fully accomplished solely by complying with safety policies [3]. Although for some humans working with a cobot might be relatively easy and effective, executing a coordinated task with a cobot might be overwhelming for others. This is especially true for human operators that do not have a clear understanding of the machine's force, speed, acceleration, motion, and communication capabilities or simply do not trust robots as full fledged teammates. Furthermore, research has indicated that while physical ergonomics is particularly enhanced by cobots, the mental strain in humans might increase due to the high cognitive workload associated with effectively interacting with the HRC systems' components [4]. Thus, negatively affecting the efficiency of the entire system which in some way contradicts the intended goal.

This paper presents a detailed analysis about HRC systems and the factors that have been identified need to be improved to enable effective Human-Autonomy teaming [5]. The paper describes the methods used to collect and analyze the data, as well as a quantitative analysis of common practices regarding the selection of HRC systems' primary components that allegedly shapes the physical and cognitive workload of humans.

2. Outline of the Proposed Analysis

In recent years, an important number of HRC systems have been developed and proposed for academic and industrial purposes. In the research field, proofs of concept of different safety settings, virtualization tools, communication interfaces, and real time adaptation technologies have emerged as complementary solutions with the goal to improve the dynamics and performance of HRC manufacturing tasks. In what follows we describe the methodology performed to analyze HRC systems, their components, and the inclusion of supportive technologies. Then, the results of the analysis performed on the data collected from the papers reviewed is presented in Section 3.

2.1 Review Strategy

To focus on the practical aspects of HRC a literature review was performed which consisted in the search of HRC systems applied in laboratory and industrial environments. Proofs of concept, experimental work, and case studies in real manufacturing tasks were in the focus of this study and analysis. Simulated tasks made in a robust digital manufacturing software (i.e., Siemens Tecnomatix) were also performed to quantify and evaluate the observations reported in the literature. Based on the data collected, it was hypothesized that the simulated tasks are accurate representations of real manufacturing environments which involve human operators, robots, sensors, and complementary infrastructure in a desired industrial arrangement. HRC systems were deconstructed into four primary components (i.e., Interaction levels, Operator roles, Safety settings, and Communication interfaces). The integration of collaborative systems, work roles, safety settings, and communication interfaces was considered as the foundation for classifying and analyzing every collaborative scenario found in the literature.

The search for HRC systems was mainly carried out using the Scopus database. As a result, journals and conference proceedings were the primarily sources of information used in the review. The search terms (keywords) employed in this study were divided in two categories, "industry" and "task", depending on the HRC implementation details. On one hand, HRC industry category keywords such as automotive, metals, plastics, industrial and household appliances, and electronics were underlined in the search. On the other hand, the keywords used for HRC tasks in the manufacturing industry were assembling, welding, material handling & polishing, machine tending, and quality inspection.

2.2 Data analysis

The primary components comprising HRC systems of every possible collaborative workspace setting was used as the starting point of the data analysis. Complementary information (i.e., types of workstation, utilization of collaborative robots, inclusion of wearable devices, and real time adaptation technologies) was also included in the HRC composition. Based on the literature review and collected data, the most common practices and behaviors found in HRC systems were compiled and a quantitative analysis performed. The obtained results are presented via a series of charts. Individual trends by component was first analyzed, followed by an exploration of each collaborative system and their direct synergy with respect to the distinct work roles, safety settings, and communication interfaces combination possibilities.

3. Results Based On Sectors

The HRC systems review was carried out by registering both the primary components and the complementary technologies that were found to be involved in the implementation of manufacturing tasks. A quantitative interpretation of the collected data was made to discern the current panorama that academia has on HRC systems and its technologies. The proposed quantitative analysis was able to identify (forecast) the upcoming methods and tools for HRC industrial environments in future years. Thus, it is envisioned that the results will be used to revise and complement the operation norms and standards to be used in future HRC systems.

3.1 Selected Publications Origin And Classification

During the literature review 50 different HRC systems, contained in 44 research papers, were selected for analysis. From such publications, 59% came from conference proceeding, while 41% were obtained from scientific journals (Figure 1). It was noticed that the early advances shown in conference proceedings have been enhanced and implemented during the next 2 to 3 years after the technology was initially proposed. Based on such observations, it is presumed that HRC systems are still in their infancy, but the understanding and use of such systems is growing, as articles published in journals have been gaining ground recently and include the analysis of implemented HRC systems in industry which have been enhancing their produced throughput.

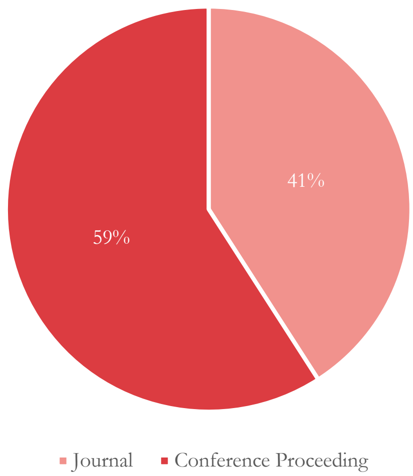

Figure 1: Selected research papers by type of publication.

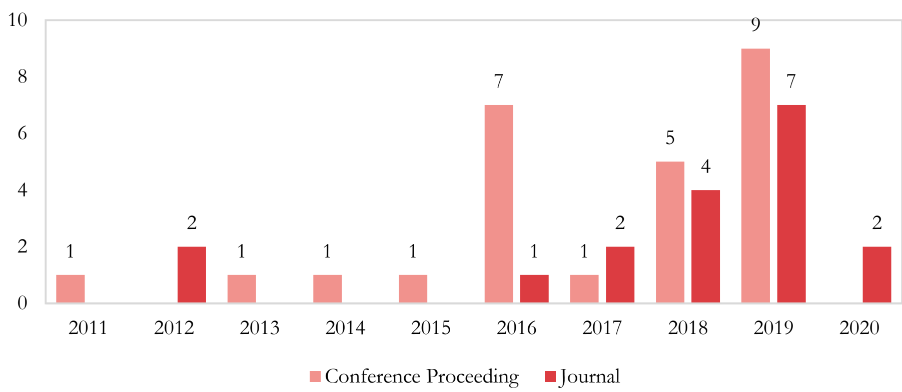

Figure 2: Selected research papers by publication year.

As a result, HRC systems can be considered as feasible alternatives for manufacturing production presenting dynamic growth. Proof of concept, laboratory reproduction of manufacturing processes, and case studies have provided the means to enrich and update this active field. Based on the literature review, it was observed that 80% of the advancements in HRC scenarios have been published throughout the last five years (2015-2020), Figure 2. Likewise, the study identified the number of publications by industrial sector. In the "industry" sector, manufacturing environments such as automotive, metals/plastics, and industrial research & testing (in collaboration with academia) were found to be the most common cases with 34%, 26% and 28% of the total papers reviewed, respectively (see Table 1). It was not surprizing to find that the automotive, metal / plastic related applications, electronics, and pharmaceutical represent a large proportion compared to other environments such as household appliances fabrication.

Such industries as the automotive sector have long-time experience on acquiring and implementing industrial robots in their production processes, so it is not surprising that such sectors are more likely to be advancing and implementing HRC systems.

During the study, assembling operations, was found to be the most repeated term with a 65% presence in all documents related to collaborative tasks. Material manipulation applications (e.g., handling, positioning, polishing) were also found to be the common tasks in the manufacturing industry with more than 20% of the total. It was also observed that these tasks are continuously being enhanced with HRC systems in a faster pace when compared to other tasks (e.g., packaging). This is due to the direct interaction dynamics that exists among humans, workpieces, and robots that are relatively easier to be performed via collaborative robots and supportive technologies.

Table 1: Results obtained by HRC systems category.

Industry	Publications	Task	Publications
Automotive	17	Assembling	33
Industrial Research	14	Material Manipulation	12
Metals/Plastics	13	General Machining	3
Other	6	Other	2

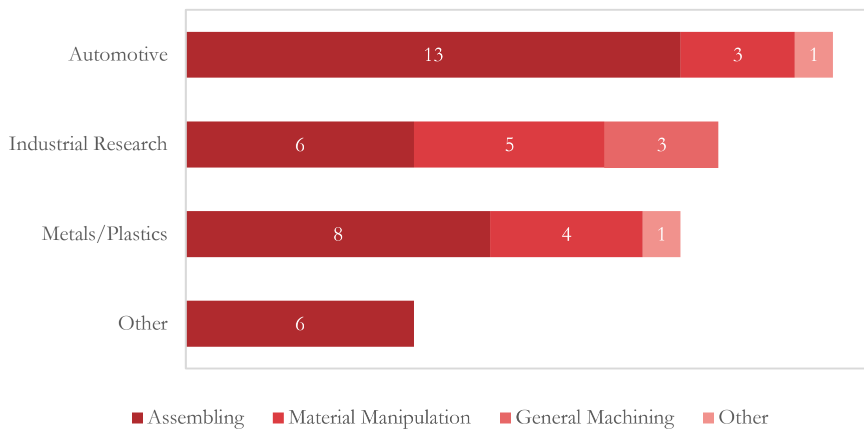

Figure 3: Distribution of common tasks by type of industry.

In Figure 3, the distribution of tasks by type of industry is presented. In the case of the automotive industry, a clear majority of 76% of the cases can be classified as assembling tasks. Support in screwdriving activities are the most common examples found in the literature not only for the automotive, but also in the metal/plastic industries. Material manipulation tasks are the second most repeated applications of HRC teams in manufacturing-related environments. This fact is due to the fact that cobots have been developed with the ability of lifting, holding, and positioning objects that can be labelled as risky or dangerous for human manipulation.

4. Results Based on Primary Components

The same 50 HRC systems contained in 44 research papers referred in Section 3 were used in quantifying the primary components comprising collaborative systems. The results include the working composition of the systems where the four primary components were considered as the building blocks in the design and implementation of HRC tasks. The analysis performed departs from the typical collaborative system components used by others. The proposed analysis was used as a base analysis where collaborative work dynamics, and technologies can be added upon while the affinity with other building blocks was examined.

4.1 Interaction Levels

A classification of HRC enterprises by the four basic human-robot interaction levels (i.e., Interdependent, Sequential, Simultaneous, and Supportive [6]) was performed with the associated components used in HRC (e.g., communication and safety) and the work roles, safety settings, and communication interfaces arrangements. Figure 4 shows the results obtained based on the distribution of HRC systems centered on the interaction level. It was observed that HRC systems with supportive interacting levels dominates the landscape with 50%. As reported in the literature, the manufacturing industry has only adopted co-existence work dynamics where removing physical safety guards has been the main reason for cobot implementation. This indicates that there is a clear attempt from the community to improve and simplify collaborative technologies to obtain broader industry adoption. Examples of HRC system using supportive roles between humans and robots include [7] and [8]. The second dominant interaction level was found to be the sequential systems which represent 26% of the identified HRC systems (Fig. 4).

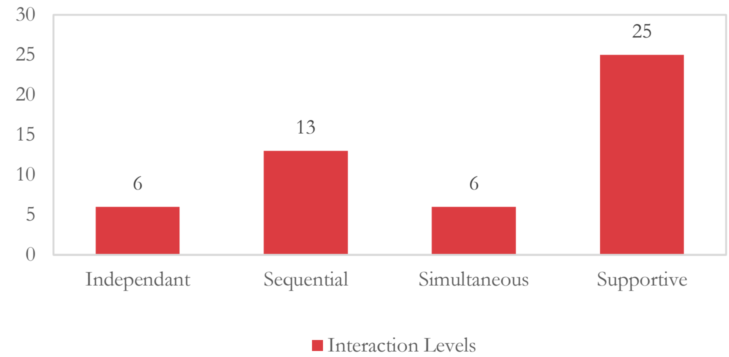

Figure 4: Distribution of HRC systems by Interaction Level.

Research on sequential systems has focused on optimizing work performance by harnessing task distribution and real time adaptation tactics. The last two levels of interaction, simultaneous and independent collaborative systems, jointly form 24% of the observed cases. The type of industries, tasks, and additional systems related to these two types of systems are varied and as a result a clear behavior on the use of such systems could not be identified.

The distribution of HRC interaction levels based on type of industry and task was also analyzed. Such findings are shown in Figures 5 and 6. In terms of the type of industry, HRC supportive systems were observed to be mainly allocated among the automotive, industrial laboratory research, and the metals/plastics environments. Despite the dominance of supportive systems, it was observed that HRC sequential systems are also evenly present in the automotive industry. In terms of the task, it was found that collaborative systems exhibit a large concentration of cases within the assembly related activities. It was found that both, supportive and sequential, HRC interaction levels often involve the utilization of screwdrivers (as well as other hand tools) and that the selection on either using a supportive or sequential HRC system might lie on activity allocation and tasks scheduling methods. Furthermore, these two types of HRC systems allow switching the work roles

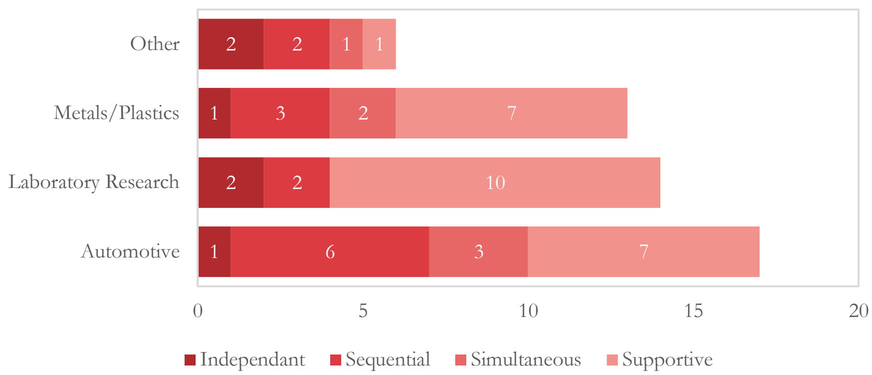

Figure 5: Distribution of HRC interaction levels by industry.

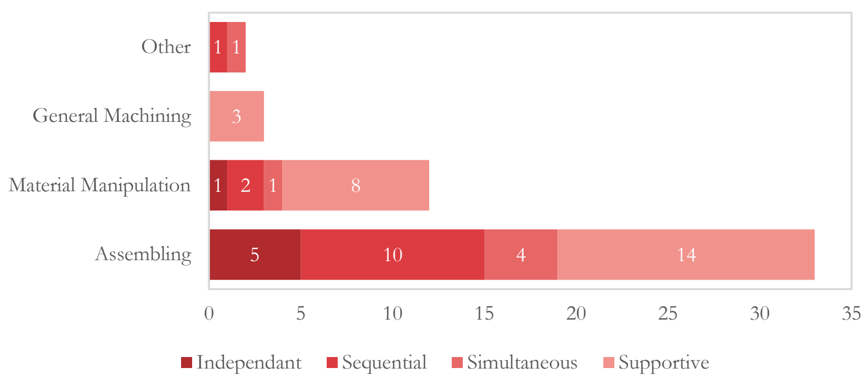

Figure 6: Distribution of HRC interaction levels by task.

between human and cobot depending on
the organization
necessities, prior HRC implementation experience, and available resources, thus enabling industry, a greater degree of adaptation to current and future manufacturing demands.

Coupled with the assembly tasks dynamics, HRC systems provide similar benefits to traditional human only material manipulation activities. Heavy object lifting, precise positioning of components (e.g., electronic boards assembly), and highly repetitive trajectories are the most frequently activities assigned to cobots in supportive and sequential type of HRC tasks.

4.2 Work Roles, Safety Settings and Communication Interfaces

Complementing cobots and humans as primary components for HRC, work roles, safety settings, and communication interfaces are required to improve process performance and operator wellbeing. The reviewed HRC systems found in the literature were classified based on the work role (i.e., subordinate, peer, or supervisor) that a human operator adopts with respect to his/her cobot companion while executing a collaborative task.
As presented in Figure 7, the obtained results show that 70% of the consulted cases belong to the peer work roles while the remaining cases accounted for 30% in the supervisor role (played by a human operator). Interesting, there were no cases found in manufacturing environments to belong to the subordinate role. It must be noted that implementing a subordinate role (played by a human operator) in any HRC system requires robots with substantial learning capabilities and vision systems to inspect, validate, and conduct a desired manufacturing process in physical collaboration with humans.

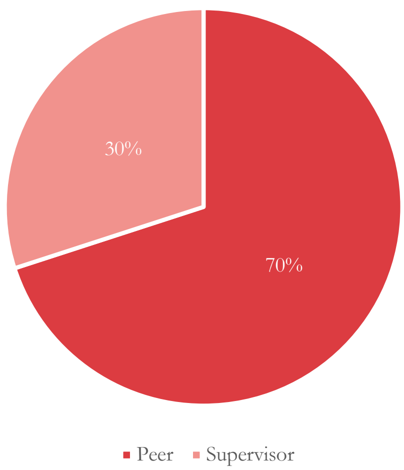

Figure 7: Distribution of HRC systems by Work Role.

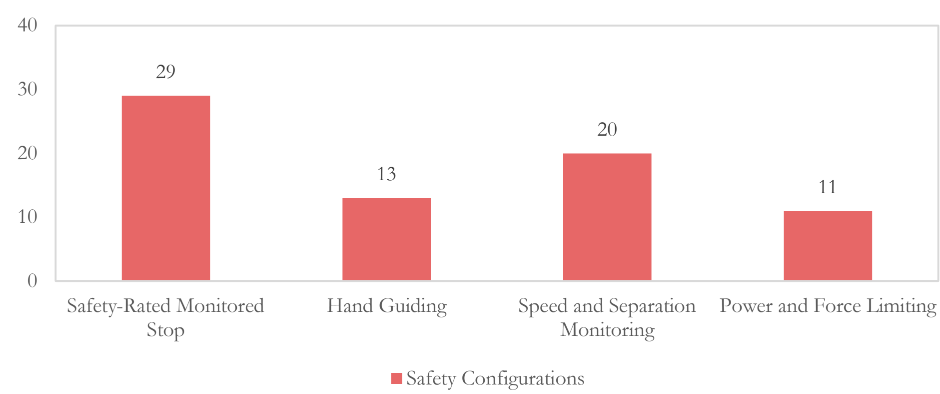

Figure 8: Distribution of HRC systems by Safety Setting.

In the area of HRC safety, where safety-rated monitored stop (SMS) controls were identified to be used in 29 HRC collaborative tasks, it was found that 39.7% of the reviewed HRC systems include this specific safety setting. Similarly, 27.4% of the reviewed collaborative systems were found to be related to speed as an important aspect to monitor. Settings like SMS are necessary to have safe execution of collaborative tasks. Figure 8 shows the numbers for the safety settings found to be present in HRC systems. In physical contact driven tasks where direct interaction is expected to occur between humans and robots, hand guiding (HG) and power & force limiting (PFL) controls were found to be often required to manipulate cobot trajectory features. The distribution of SMS safety settings where found to be 26% and 22% for HG and PFL controls, respectively. In total, 73 safety settings were identified to be used in HRC tasks. This suggests that collaborative systems tend to utilize more than one type of safety controls. In contrast, some HRC systems were observed to neglect the use of identifiable safety setting.

The distribution of HRC systems by applied communication interface was also analyzed. The obtained results are shown in Figure 9. It was found that traditional communication means including keyboards, mice, monitors, teach pendants, and buttons are the most utilized systems for information input with a 34% appearance. It also was found that advance communication tools such as body gesture communication represents 17% of the total cases reviewed. On the other hand, voice commands were found to appear in 13% of the HRC reviewed papers. Finally, mixed gestures or multi-modal communication that combines voice commands and body gestures for information input to HRC systems were also found to be used. The total number of applied communication interfaces found was 29.

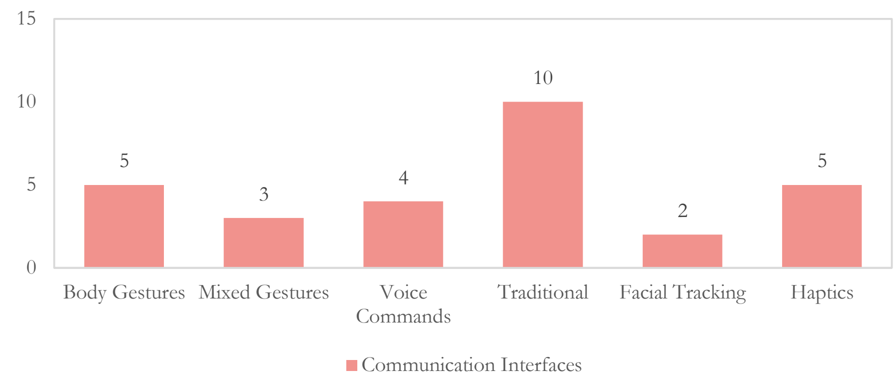

Figure 9: Distribution of HRC systems by Communication Interface.

In contrast to other primary components, the communication field presented the lower adoption. As a result, it can be concluded that further research and developments on communication methods and technologies is necessary to increase market acceptance of HRC systems.

6. Conclusions

The purpose of the presented work was to identify the presence of the so-called primary components and their different combinations in state-of-the-art HRC applications. It was found that such systems are being rapidly adopted in the automotive, metal, and plastic industries as these sectors have longer experience implementing industrial robots among other automation solutions in their shop floors. Furthermore, a clear tendency for performing assembly operations via HRC systems in every type of industry has been identified. Screwdriving activities appeared predominately in this type of operations. Similarly, material handling manipulation has also been observed to have a in every industry, but fewer cases were identified in the HRC literature. As expected, research institutions and manufacturing companies are rapidly taking advantage of the no-fences and safe-collision features that cobots offer for both assembling and material manipulation tasks alike.

In terms of the primary components comprising HRC systems, supportive HRC systems where identified as the most type used among the four types of HRC interaction levels. Having the deepest type of interaction, the safety settings and communication interfaces within supportive HRC were identified to be complex. This is especially true when peer-based work roles between human and robot are embraced. Safety-rated monitored stop is the safety control mechanism that appeared the most in the analyzed HRC systems. This safety control was found to be a suitable entry point for human operators that have little experience working with HRC systems. The reason for this is that collaboration with robots is executed only when the cobot is completely stopped during the collaboration (thus no real collaboration exists) or continuously monitored when the robot is enabled to operate when collaborating with humans. Finally, traditional communication means such as keyboards and mice where found to be the predominant devices for human-robot interactions.

No hand gesture and other sophisticated communication means have been identified to be in use in current manufacturing floors. However, intense research and development being performed on such novel types of communication will most likely enable such systems to be used in the coming years, and most likely become critical aspects.

Future research should focus on generating novel conceptual models for HRC components, integrated systems, and support technologies if HRC systems are to be embraced and adopted by the manufacturing sector. Additional analysis is needed to be conducted with the support from the industrial sector and team-autonomy psychology in areas of cognitive and physical ergonomics. From a cognitive ergonomics point of view, the execution of time-sharing activities (that compete for limited information processing resources) frequently result in the increase of the overall cognitive workload. A higher level of cognitive workload on the human has negative effects on performance, work quality, robot's acceptance in the workplace, and on the overall mental wellbeing of human operators. Analyzing the transition dynamics from manual to collaborative work schemes might bring valuable information to promote the adoption of human-centered HRC systems.

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