Human Robot Collaboration: Taxonomy of Interaction Levels in Manufacturing

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Abstract

As the demand for robotics grows and the evolution of technology continues to thrive, alongside the shortages of operators and increasing cost of labour, human robot collaborative teams will inevitably become more commonplace. However, the terminology used to describe this field of work in both academic research and industry is ambiguous and confusing. The terminology used in human robot collaboration (HRC) are reviewed in this paper and a coherent HRC taxonomy of interactions is developed. The levels of interaction and terms used are defined based on a comparison of the previous literature and the International Organisation of Standardisation's (ISO) definitions. The functionality inherent in the definitions of collaboration, coordination and cooperation are determined along with the decompositions of the levels of interaction between human and robot. The importance of safety is also highlighted, and safety measures appropriate for each level of interaction are detailed. Finally, case studies are reviewed demonstrating levels of interaction from the developed HRC taxonomy. The goal of the research outlined in this paper is to facilitate improved communication and enable co-ordinated research collaboration across academic researchers and industry in the implementation of HRC installations.

1.0 Introduction

Since the unveiling of the first industrial robot in 1961 (1), robots have been embraced and installed globally by large manufacturing firms. In 2020 there were 3 million industrial robots in operation worldwide, with 384,000 units shipped globally with installations expected to have increased by 13% in 2021 as economies began to recover from the Covid-19 pandemic (2). Industrial robots (and industrial automation systems) have traditionally been kept separate from humans, behind fences and cages to minimise safety risks(3). Traditional industrial robots have brought industry benefits of high speed, precision, with increased reliability, quality and load carrying capabilities. However they are typically targeted at repetitive tasks and applied only within high volume manufacture due to being expensive and difficult to program (especially by non-specialised manufacturing engineers) and are not well suited to increasingly adaptable manufacturing systems (3).

To remain competitive, businesses must be able to produce a range of product variants, deliver complex assembly operations and manufacture variable quantities (4,5). The drive for efficient human robot collaboration (HRC) is to enable more flexible and efficient production lines, supporting human operators by reducing physical requirements (6). Human robot collaboration aims to maximise the combined capabilities of humans and robots to create adaptable manufacturing systems with improved productivity and product quality (7,8) . The strengths of the human include dexterity, flexibility and problem solving with robotics providing efficiency, repeatability and accuracy (8–10).

1.1 Cobots

The concept of a "cobot" was originated in 1996 by Colgate & Peshkin, with the term being conceived by Brent Gillespie (11). However, it wasn't until 2008 that the first commercially available cobot (the UR5 by Universal Robots (12) was sold. This was followed by similar offerings by companies such as ABB, Kuka, Fanuc, Staübli and Rethink Robotics in subsequent years. In 2015 Fanuc announced the launch of the first "collaborative industrial robot" with built in safety features such as power and force limiting (PFL) and a payload of 35kg (13). Cobots are robots designed specifically for sharing their workspace with humans as they have advanced safety features (e.g. power and force limiting – PFL) built in as standard (14). Cobots have been described as the "new generation of industrial robots" (5). Cobots typically are typically lower cost and easier to program but have lower payloads and operating speeds (3,10). The low cost, ease of programming and integrated safety systems makes them a flexible option that SMEs can integrate into their production lines (10), as they can easily be reconfigured and moved around factories to support variable production demand.

1.2 Human Robot Collaboration

The goal of HRC is to establish an *appropriate level* of collaboration to complete a task effectively (4,7,15). An understanding of the tasks to be completed and the skills of the operators is therefore necessary to maximise productivity (7,16). Effective HRC has the potential to reduce task errors (9,17) and increase productivity (6,8,18,19) adapting to demands such as shorter product lifecycles, variable production demand and customisation (3,18). Furthermore, HRC can be designed to support human operators, reducing physiological and psychological stress (6,18,20) and

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supporting operational changes such as social distancing (21).

The differences between what was traditionally defined as an "industrial robot" and a "collaborative robot" (or "cobot") are reducing due to technological advances in the design of robots. The International Organisation of Standardisation (ISO) committee ISO/TC 299's Working Group 1 for Vocabulary and Characteristics removed the definition of a "collaborative robot" in the 2021 revision of ISO 8373. The standard now defines only an "industrial robot" and "collaboration". Collaboration is defined by the ISO as "an operation by *purposely designed robots* and person working within the same space" (22). The evolution of robotics technology and safety systems are transforming industrial robots, enabling them to be used for collaborative applications. Any industrial robot can be used in a collaborative operation provided it includes one or more of the following safety methods: 1) safety-rated monitored stop (SMS), 2) hand guiding (HG), 3) speed and separating monitoring (SSM) and 4) power and force limiting (PFL) (23).

This continuing evolution of robots and their function and use has resulted in a myriad of definitions, many closely related or nuanced resulting in a confusing landscape of definitions. The use of terminology related to HRC is therefore ambiguous and confusing. Terms are used interchangeably throughout the literature, at times with overlapping and opposing meanings affixed (15,24). The ISO recognise the importance of consistent robotics vocabulary to facilitate application in industry (22). Without precise and widely accepted definitions, misunderstanding can arise.

There is a need for a common language to define the interaction levels in human robot teaming to bring clarity to discussions and explanations of applications in both academic research and industrial applications. The purpose of the research presented in this paper is to clarify the meanings of the terminology used in HRC. Following a review of the literature, a coherent taxonomy of HRC, interaction levels and safety measures for collaborative applications are presented.

The definition of HRC and the terms used to describe the levels of interaction between human and robots will be reviewed in this paper and a coherent taxonomy to enable comprehensible discussion of collaborative interactions defined. The importance of safety is also highlighted, and safety measures appropriate for each level of interaction are detailed. Case studies demonstrating each level of interaction illustrate the benefits of the developed HRC taxonomy.

2.0 Terminology

2.1 Collaboration Terminology

Collaboration and coordination are terms commonly used to describe human-robot interaction levels which have similar meanings and are often used interchangeably (14,24). Collaboration has been described as a continuum with stages of increasing interaction from cooperation to coordination and collaboration (25–27). However, there is disagreement across the literature concerning where the various terms used lie on the continuum (26,27). In some papers, cooperation is described as having a higher degree of interaction than collaboration (16,28).

The definitions for the terms associated with the continuum of collaboration are show in **Figure 1**. The terms coexistence, cooperation and collaboration are arranged along the X and Y axis, demonstrating the increasing requirement for communication and coordination at each stage. The key difference in the definitions is that collaboration entails working towards a shared vision to *create something new* via a *collective team effort*, whereas in cooperation although the team shares information and resources to support each other's goal, the *achieved result arises from the individual's effort* (25,29). Collaboration involves team members sharing knowledge, intention and goals and is dependent on communication and coordination (30).

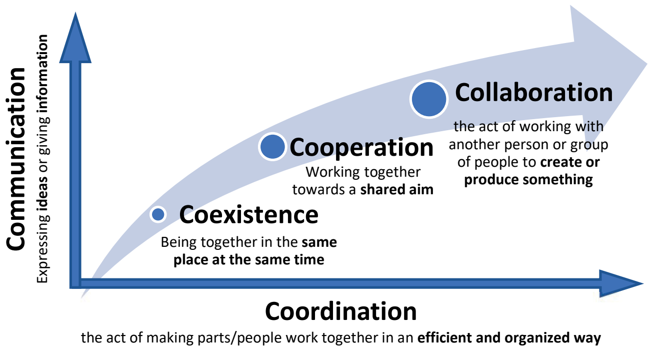

Figure 1: Terms associated with collaboration along with their definitions (31) arranged in increasing level of collaboration. Communication and Coordination on the X and Y axis demonstrates the increasing levels of communication and coordination required.

Coordination and communication are key components to enable effective HRC (30). Coordination is described as the "harmonious functioning" of a group working together (30) and requires: 1) Shared situation awareness and understanding of goals, 2) Sharing resources, 3) Co-ordination of action, i.e. a workplan, 4) Shared mental model of responsibilities and requirements and 5) Mutual understanding (32). As the levels of collaboration interaction increase, the requirement for efficient coordination increases.

These terms traditionally associated with human-human interaction in teamwork are now also used to describe work by human-robot teams. Regardless of precise definitions, the consensus is that coexistence, cooperation, collaboration and coordination are all important aspects of effective teamwork (30).

2.2 HRC Terminology

Most commonly HRC refers to human robot collaboration (8,10,17,33,34), occasionally to human robot cooperation (7,9,35) and infrequently to human robot coordination (36). Academic papers also use terms such as HRI for human robot interaction (19,37) and may refer to human robot teaming (38).

With the similarity in meanings between collaboration, cooperation, and coordination, it is not surprising to see the range of terms used in literature. However, the ISO 8373:2021 specifically defines *cooperation* as "information and action exchanges between *multiple robots* to ensure that their motions work effectively together to accomplish the task" (22). Cooperation should therefore not be used to describe human-robot interactions to avoid confusion with the ISO definition.

Consistent with, ISO 8373:2021 (22) and academic authors (14,39), the term "collaborative robot" should not be used to define a robot. Collaboration status can never be assumed based on a description of a robot as each installation is unique and requires its own risk assessment. Provided the correct safety measures are in place, any type of robot can be used in a collaborative application, operating alongside humans and not requiring physical fencing or guarding to keep human and robot separated. Rather it should be referred to as a robot working on a collaborative application. Each collaborative application must involve a risk assessment considering safety aspects such as the workpiece properties, forces, speeds, trap points, potential contact points with operator and put appropriate safety measures in place. The term, "cobot", is used universally for robots with built in safety features to enable collaborative applications.

Human robot collaboration should be adopted for the abbreviation HRC in this paper because: 1) it is the most frequently used (14,28) and 2) the focus is on HRC for manufacturing and the dictionary definition of collaboration centres on the *creation of something* by a team (31).

2.3 Classification of Interactions

Numerous frameworks have been created with three or four terms to classify the levels of interaction of human and robot teams (14,15,19,24,28,39–45) . These 3 or 4 degrees of collaboration increase in levels of interaction between the human and robot, in terms of the proximity sharing of workpieces and sharing of tasks. **Table 1** summarises terms used for each of the various degrees of interaction.

There is no uniform and internationally agreed taxonomy (15) and much ambiguity in the terms used. Several authors use cooperative to mean a higher level of interaction than collaboration (15,28) whereas others apply opposite meaning to these terms (24,40,43–45). While some have avoided these terms altogether (14,19,41).

The explanations used to describe the ranges of interactions were not mutually exclusive across all authors. However, they do follow a broad base of defining whether the workspace, workpiece and task are shared by human and robot. Following a review of HRC literature containing definitions of the levels of interactions, the terms used have been organised and categorised based on which elements were shared. The range of terminology used and how different conditions are applied to the same terms is illustrated in **Figure 2.**

In the diagram the terms have be arranged by determining whether the workspace, and /or task and /or workpiece are shared. The lack of clear definitions of the terms such as collaboration, cooperation and coexistence and opportunities for misunderstanding are further illustrated. For example, the terms collaboration, supportive, cooperative, and assisted are all terms used to describe operations where task and workpiece are shared simultaneously in a shared workspace.

Table 1 Terms used in Literature for various degrees of interactions

Authors	Terms for levels of interactions				
	No/low degree of interaction ⟷ High degree of interaction				
Aaltonen et al, 2018 (24)	No coexistence	Coexistence	Cooperation	Collaboration	
Bauer et al, 2016 (40)	Cell	Coexistence	Synchronised	Cooperation	Collaboration
Cesta et al, 2016 (39)	Independent	Synchronous	Simultaneous	Supportive	
El Zaatari et al, 2019 (14)	Independent	Sequential	Simultaneous	Supportive	
Haddadin & Croft, 2016 (28)	Supportive	Collaborative	Cooperative		
Helms et al, 2002 (41)	Independent	Synchronised	Simultaneous	Assisted	
Marvel et al, 2015 (42)	Independent	Synchronous	Simultaneous	Supportive	
Marvel et al, 2020 (19)	Separate	Sequential	Simultaneous	Supportive	
Pichler et al, 2017 (43)	Coexistence	Assistance	Cooperation	Collaboration	
Schmidtler et al, 2015 (44)	Coexistence	Cooperation	Collaboration		
Webb & Fletcher, 2020 (15)	Supportive	Collaborative	Cooperative		
Wang et al. 2020 (45)	Coexistence	Cooperation	Interaction	Collaboration	

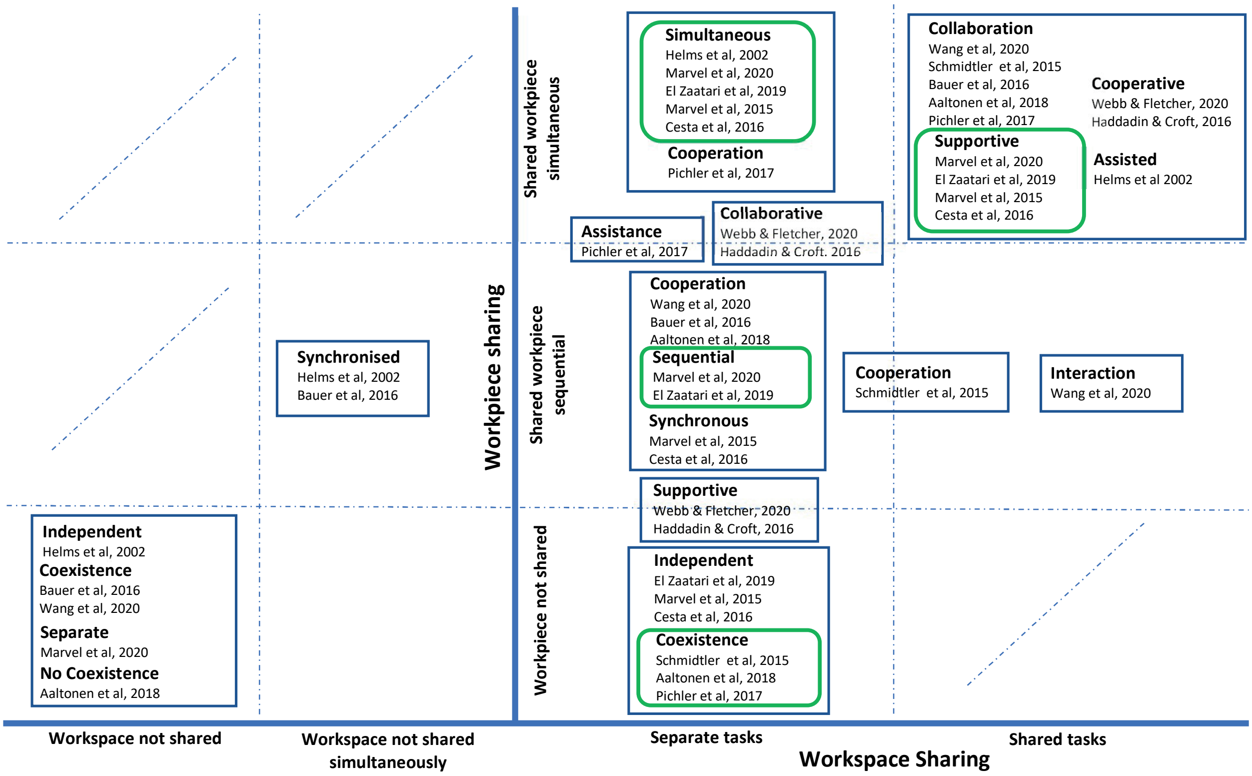

Figure 2 Range of terms used for HRC Levels of Interaction. Boxes group terms with similar descriptions based on workplace, workpiece and task sharing. The green boxes with curved corners identify the terms selected for the developed taxonomy.

3.0 HRC Taxonomy of Interactions

The proposed taxonomy classifies the logical and frequently defined interaction levels according to increasing level of interaction as: 1) Workspace shared but task and workpiece not shared, 2) Workspace shared, task not shared and workpiece shared sequentially, 3) Workspace shared, task not shared, and workpiece shared simultaneously and 4) Workspace, task and workpiece shared. Interactions where workspace is not shared were excluded from the taxonomy as they should not be deemed collaborative interactions considering the definitions of a collaborative operation by the ISO, "*purposely designed robots* and person working within the same space" (22). Collaborative workspace is defined as "space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation"(23)

The terms proposed for the taxonomy are Coexistence, Sequential, Simultaneous and Supportive, selected to reduce ambiguity of interpretation and shown in **Figure 3**. The diagram shows the four degrees of interaction each involving a robot and operator sharing a workspace. In *Coexistence*, only the workspace is shared and the robot and operator work on separate tasks and workpieces. In *Sequential*, the robot and operator work on separate tasks and the workpiece is shared sequentially. *Simultaneous* also involves separate tasks, however the work is done on the same work piece and simultaneously. *Supportive* involves shared task and workpiece.

The majority of HRC applications in industry can be classified as *coexistence* applications. Bauer et al (40) carried out a survey of industrial applications and found

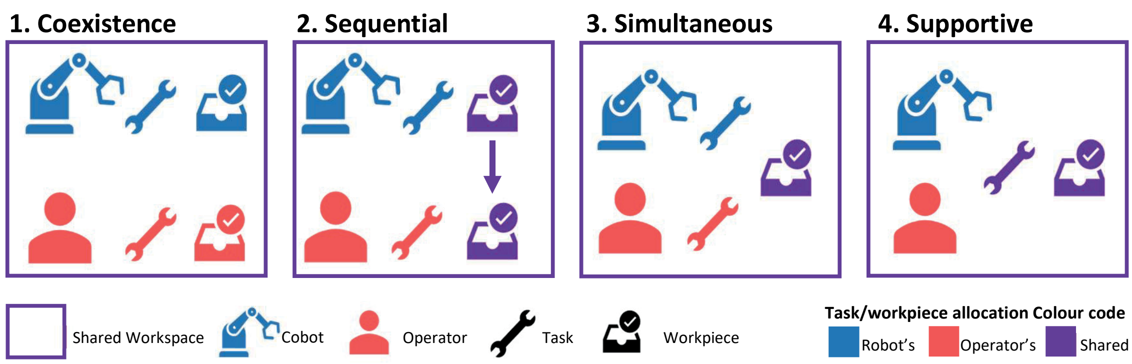

Figure 3: HRC Taxonomy of Interaction

60% of HRC installations to be *coexistence*. In contrast, academic research tends to be focused on the higher levels of interactions which are not commonly seen yet in industry (46,47). The limited implementation of HRC with higher interaction levels could be due to the extensive planning and configuration effort required for each installation (4). **Table 2** provides an overview of selected literature with case studies which correspond to the degrees of collaboration detailed in the proposed HRC taxonomy.

Table 2: Literature examples of HRC interaction levels

Author	Case Study
Coexistence	
Müller *et al*, 2016 (4)	Automotive leakage inspection
Sequential	
Malik *et al*,2021 (11)	Ventilators assembly
Morato *et al.*, 2014 (18)	Chassis assembly
Tsarouchi *et al.*, 2017 (48)	Hydraulic pump assembly
Malik & Bilberg, 2019 (49)	Electronic linear actuator assembly
Simultaneous	
Pellegrinelli *et al*, 2016 (35)	Pallet assembly
Luxenburger *et al*, 2019 (50)	Rivet sealing & quality checks
Malik & Brem,2020 (5)	Battery pack assembly
Supportive	
***Michalos et al*, 2018 (51)**	Automotive assembly
Mueller *et al.*, 2019 (52)	Riveting process
Pérez *et al.*, 2020 (53)	Rib subassembly for aerospace

3.1 Safety and HRC

Safety remains a critical aspect of HRC installations, regardless of interaction level. It is expected simultaneous and supportive classifications will pose the highest risk of injury for the human operator (42). However, this should not reduce emphasis on the other interaction levels as injuries are still a high risk without appropriate safety measures. The classification of interaction could give some basic guidance on potential safety issues, however each HRC installation must be treated as unique and detailed risk assessments carried out. **Figure 4** suggests the most suitable safety measures for each level of interaction. However, there are many variables to be considered: the robot's payload and force it can apply, the part's geometry and weight, the type of robot and whether this is a dual or single arm robot, safety mechanisms, the process and end effector being used (6). A risk assessment is required for all robotic installations as detailed in ISO 10218-2:2011 (54) with further information in ISO 15066:2016 (23) which details collaborative application design factors such as maximum permissible forces to impact on various body parts.

A detailed risk assessment of the HRC application will assist with the selection of the necessary safety systems. A vast range of technologies are available to implement the required safety methods, such as laser scanners, safety mats and camera systems (51). **Table 3** contains two HRC case studies and details the tasks, safety systems implemented and the HRC interaction level. The automotive case study (51) details the change in speed of the robot dependent on the level of collaboration, when the operator is outside the collaborative workspace, the robot can move at full speed (2m/s for the - COMAU C5G) whereas it must slow to 250mm/s with the operator inside the workspace and to 20mm/s when carrying out a Hand Guided task. These changes in speeds need to be considered when allocating tasks to humans and robots, as not all elements of a task will require collaboration so relocating the human for some stages could be beneficial.

	Coexistence	Sequential	Simultaneous	Supportive
Safety Rated Monitored Stop (SMS)	✓✓	✓✓	✓✓	✓
Hand Guiding (HG) *				✓ ✓
Speed and separation monitoring (SSM) **	✓	✓	✓	
Power and force limiting (PFL)	✓	✓	✓	✓ ✓

Figure 4 : Suitability of ISO collaborative safety methods to HRC collaboration interaction levels. (*HG must be used in partnership with a SMS or PFL. **SSM requires a SMS system. (1))

Table 3 : Safety Measures for tasks in two case studies along with the relevant HRC interaction level

	Task	Safety Measures	
1 Automotive inspection - UR10	Robot inspects for moisture/ leakage, operators check damage, function and finish	*Power and Force Limiting* – using the force limitation and protective stop features built into the cobot.	**Coexistence**
2. Automotive assembly - COMAU C5G	Robot Loading axle and drum while operator inserts cables	A *Speed & Separation monitoring (SSM)* for initial steps along with Space Limiting function when operator is working inside the warning zone and a *Safety-rated Monitored Stop (SMS)* for the danger zone	**Simultaneous**
	Guiding robot to screwing position	*Hand Guiding* tasks which involve a *SMS* followed by a Safety Rated Reduced speed function of 20mm/s, Space Limiting function and Enabling devices to ensure the operator has both hands occupied to avoid crushing/trapping while carrying out the *HG* task	**Supportive**
	Operator screws drums, robot holds drum	*SMS* along with space limiting function to compensate for forces produced by operator carrying out task with a screwdriver.	**Simultaneous**

4.0 Discussion, Limitations and Future Work

A demonstration of the variety of terminology used, the range of meanings applied to terms and definition of a clear taxonomy for human robot collaboration are the aims of the research outlined in this paper. Without a consistent taxonomy issues in defining and applying the terms collaboration, coordination and cooperation and the lack clear agreement on meanings will remain (26).

In HRC, collaboration should be used as a generic term to describe how humans and robots can work together in a shared space on a shared overall goal. The terms collaboration, cooperation and coordination represent important aspects of human robot teams. However, they should not be used to classify specific levels of human robot interactions in order to reduce confusion and improve communication. Their definitions are not comprehensive or widespread enough to use them to categorise HRC operations (24). In addition, the ISO outlines a broad definition for collaboration identifying it as humans and specially designed robots working in the same space, whereas robot cooperation is defined as "*information and action exchanges between multiple robots...*"(22).

A HRC taxonomy has been proposed which details how specific tasks and workpieces can be shared in various manners whilst humans and robots share a workspace working collaboratively on the manufacturing goal. The developed taxonomy of HRC interactions classifies four levels of interaction: Coexistence, Sequential, Simultaneous and Supportive. It purposely uses descriptive language along with a simple diagram to assist in the communication of each level of interaction. The types of installations in industry and research have been reviewed, with industry applications being predominantly coexistence whereas academic research places greater emphasis on the higher levels of interaction: Sequential, Simultaneous and Supportive.

There are limitations of the proposed taxonomy that must be acknowledged. Due to the complexity of the research space, it is not possible to review all published work in all domains, however the use of ISO standards to aid term definition mitigates this problem.

The importance of safety was discussed and it was highlighted that it is dangerous to assume similar safety requirements even if installations are of similar interaction levels. The wide range of factors such as which end effector is being used, the shape/weight of the workpiece and the surrounding environment all raise unique risks which need careful consideration during the risk assessment process. Safety should never be assumed in relation to categorisation. There is scope for future work in developing a framework for safety systems in relation to the taxonomy of interaction to give more detailed guidance to industry on options available. Additionally, further developing processes to select the most appropriate level of interaction for various industrial tasks would be beneficial to the field of HRC. These should include consideration of allocation of tasks and the slower operating speeds for high levels of collaboration.

To enable HRC research and development to be effectively transferred and applied to industry, effective communication is vital. Understanding and applying research on this evolving field of HRC robotics will be easier when the level of interactions involved in previous research projects/case studies is clear. For example, task assignment for a *coexistence* versus a *supportive* solution will differ greatly, so conveying the intended interaction is key. Using a common language will enable researchers and engineers to communicate clearly about these installations. The starting point for this vision is concise, unambiguous terminology.

5.0 Conclusion

While automation brought a host of benefits to companies in manufacturing; the development of safety systems that facilitate human robot collaborative manufacturing enable the appropriate levels of automation to be chosen. Opportunities for the exploitation of research and development in this area has the potential to be lost due to the wide variety and inconsistent usage of terms used to describe the various degrees of interaction. The research presented in this paper clarifies the terminology used and defines a coherent taxonomy of the degrees of interactions commonly discussed in human robot collaboration. It is hoped that clear, concise language amongst the research and industrial communities will assist the development and transfer of knowledge on effective solutions from academic research through to industrial applications.

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