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Evaluating Safety and Productivity Relationship in Human-Robot Collaboration

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Collaborative robots can improve ergonomics on factory floors while allowing a higher level of flexibility in production. The evolution of robotics and cyber-physical systems in size and functionality has enabled new applications which were never foreseen in traditional industrial robots. However, the current human-robot collaboration (HRC) technologies are limited in reliability and safety, which are vital in risk-critical scenarios. Certainly, confusion about European safety regulations has led to situations where collaborative robots operate behind security barriers, thus negating their advantages while reducing overall application productivity.

Despite recent advances, developing a safe collaborative robotic system for performing complex industrial or daily tasks remains a challenge. Multiple influential factors in HRC make it difficult to define a clear classification to understand the depth of collaboration between humans and robots. In this article, we review the state of the art in reliable collaborative robotic work cells and propose a reference model to combine influential factors such as robot autonomy, collaboration, and safety modes to redefine HRC categorization.

Keywords: Safety, Reliability, Productivity, Human-robot collaboration, Robot Autonomy, Safety Standards

1. Introduction

Technological advances in Industry 4.0 focus primarily on improving the efficiency, quality, and productivity of an industrial cell through automation and interconnectivity. However, the development of a human-centric automation system has been overlooked in the initial formulation of I4.0. To further refine the interaction between humans and machines, Industry 5.0 was introduced, which allow humans to take supervisory roles and leave repetitive and monotonous tasks to the automation system (Sigga Technologies (2021)). HRC will play a pivotal role in enabling I5.0's idea to combine the cognitive and problem-solving abilities of humans with the precision and repeatability of robots to work alongside each other.

Typically industrial robots and related applications have been designed to achieve maximum performance and then adapted to safely work around humans. However, due to the lack of inherent safety in the design process and ineffec-

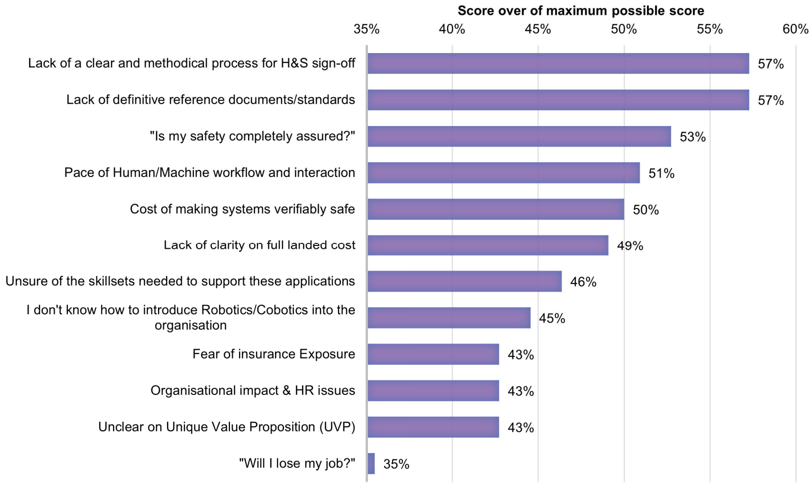

Fig. 1.: Ranked concerns over cobotics application adoption (Irish Manufacturing Research (2019))

tive communication modes, traditional industrial robots operate behind security barriers, thus defeating the main objective of HRC (Villani et al. (2018).

To ensure the safe and efficient execution of shared tasks, a category of lightweight robots, called collaborative robots (Cobots), has been introduced. Unlike industrial robots, collaborative robots are designed with inherent safety features like collision detection and force limitation, and the controller is adapted to output the required performance. This makes collaborative robots ideal for operating in close proximity or in conjunction with humans. Furthermore, the limitations mentioned above regarding industrial robots motivate the introduction of collaborative robots into industry to achieve the goal of *Level 6 Collaboration* (see Table 2).

In spite the advantages offered by collaborative robots, multiple issues still need to be addressed to enable seamless collaboration. Lack of- reference cases, knowledge of potential applications, understanding of safety, and standard metrics to classify collaboration are among the top barriers in adoption of collaborative robots (Aaltonen and Salmi (2019); Doyle-Kent and Kopacek (2021)). In 2019, Irish Manufacturing Research (IMR) conducted a similar study on the adoption of collaborative robotics applications in the manufacturing industry (Irish Manufacturing Research (2019)). As shown in Fig. 1 the two highest scoring concerns were the lack of a clear and methodical process for health and safety sign-off, and the lack of definitive reference documents/standards.

To design an effective collaborative team of humans and robots, a preliminary analysis of the depth of collaboration is necessary. The ISO/TS 15066 standard for collaborative robots is limited to the discussion of safety modes and technical safety solutions for HRC. Furthermore, the terminology used to describe collaboration is not standardized and often causes confusion, making it difficult to design these systems. The frequently used terms autonomy, collaboration, and interaction to classify HRC have acquired different interpretations, as discussed in Castro et al. (2021).

The aim of this paper is to investigate the state-of-the-art in HRC using a redefined reference model. A detailed taxonomy of these factors, robots autonomy, collaboration, and safety modes are described in Section 2. Subsequently, we discuss the relation between each of these influential factors and review reference cases and applications based on the proposed reference model in Section 3. Finally, in Section 4 the conclusions are drawn and future work is outlined.

2. Reference Model

From the perspective of R&D engineers and system integrators, it is not fruitful to categorize HRC only using safety modes and safety technology. A deeper understanding of the interaction is needed that covers not only safety but also the technical aspects of the tasks and the role of each agent. Therefore, we are proposing a refinement of the reference model by combining three influential factors: task allocated to each agent in the systems control cycle, nature of interaction between the agents during operation, and safety modes that can be incorporated. In the following sub-sections we will discuss the mentioned factors in detail.

2.1. *Levels of Robot Autonomy*

Multiple frameworks have been introduced to define HRC based on shared workspace, collaborative activity, and physical contact (Mukherjee et al. (2022); Yang et al. (2021); Gervasi et al. (2020); Beer et al. (2014)). Mukherjee et al. (2022) took inspiration from the preexisting standardized taxonomy of SAE's autonomous vehicle levels. Yang et al. (2021) defined levels of autonomy based on the decision-making methods of the robot during the interaction.

According to Gervasi et al. (2020), the concept of autonomy can be perceived in two ways when it comes to HRC. The higher level of robot autonomy could imply less frequent human interaction to accomplish a task. An alternative view is that a higher level of robot autonomy means that robots can perform complex tasks with frequent human interaction. In this article, the latter is preferred and, in the levels discussed below, being a manual cell or a fully autonomous robot does not alter the fact that agents are still interacting and sharing the same workspace.

Based on the idea of a richer and deeper level of collaboration as the field evolves, Beer et al. (2014) proposed Levels of Robot Autonomy (LoRA) for service robots. They categorize the interaction according to the robot control cycle and task allocation between humans and robots. Taking inspiration from LoRA, we adopted the following levels of collaboration in an industrial setting, which are discussed in Table 1.

2.2. *Levels of Collaboration*

In this article, the commonly used terms coexistence, cooperation, and collaboration (Aaltonen et al. (2018)) have been adopted to review the safety modes in LoRA. Collaboration is categorized on the basis of shared workspace and task sharing. The levels of collaboration (LoC) are defined as follows-

(i) **Coexistence**: human works in (partially or completely) shared space with the robot with no shared goals.
(ii) **Cooperation**: human and robot work towards a shared goal in (partially or completely) shared space.
(iii) **Collaboration**: both work simultaneously on a shared object in shared space.

2.3. *Collaborative Safety Modes*

The International Organization for Standardization (ISO) has published a comprehensive technical recommendation on risk analysis for collaborative robotics application, ISO/TS 15066: Robots and robotics devices - Collaborative robots (Directive (1989)). The primary goal of this standard is to ensure the physical safety of humans during intentional and unintentional contact with the robot. Standard provides four distinct types of safety modes, as shown in Fig. 2-

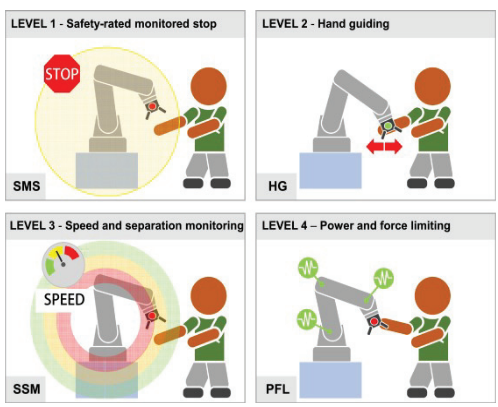

Fig. 2.: Collaborative Safety Modes (Villani et al. (2018))

Table 1.: Level of Robot Autonomy Beer et al. (2014)

Levels	Sense	Plan	Act	Description
L0-Manual	H	H	H	Human perform all aspects of the task- sensing the environment, generating and implementing plans.
L1-Teleoperation	H/R	H	H/R	Robot remotely assist the human mainly in the action implementation. In addition, robots can even help humans in sensing the environment and provide additional knowledge to assist in decision-making. However, planning is assigned to the human.
L2-Batch Processing	H/R	H	H/R	Both the human and robot monitor and sense the environment. The human, however, determines the goals and plans and robot then implements the task.
L3-Decision Support	H/R	H/R	R	Both humans and robots sense the environment and generate a task plan. However, the human chooses the task plan and commands the robot to act.
L4-Shared Control	H/R	H/R	R	The robot autonomously senses the environment, develops plans and goals, and implements actions. However, the human monitors the progress of the robot and may intervene and influence the robot with new goals and plans if the robot has difficulty. Additionally, if the robot encounters difficulties, it can ask the human for assistance in setting new goals and plans.
L5-Executive control	R	H/R	R	Human may give an abstract high-level goal. The robot autonomously senses the environment, sets the plan, and implements actions.
L6-Full Autonomy	R	R	R	The robot performs all aspects of a task autonomously without human intervention in sensing, planning, or implementing actions.

(i) **Safety-Rated Monitored Stop (SRMS)**: In this mode, Human can enter the robot workspace only when a safety-rated monitored stop is active and robot undergoes a “safe standstill”. Human can perform tasks in the shared workspace but not simultaneously.

(ii) **Hand Guiding (HG)**: In this mode, human can physically guide the robot to teach positions. Human is allowed to enter the workspace only after SRMS and then utilize a HG device to switch the states.

(iii) **Speed and Separation Monitoring (SSM)**: This mode allows free movement of human in the shared workspace only given that robot adjusts its speed according to the separation between the human and the robot itself.

(iv) **Power and Force Limitation (PFL)**: This is the only mode that allows physical contact between robot and human while the robot is in operation. This approach limits motor power and torque to regulate the forces applied to the human through touch or collision.

These collaborative modes may be used standalone or in conjunction with other modes. Robla-Gómez et al. (2017) provides a framework for industrial safety at all levels of interaction, using control and machine learning-based methodologies, as well as the design of materials and sensors for industrial robots. El Zaatari et al. (2019) compiled various existing safety standards and EU legislation and presented scenario-based case studies based on ISO safety requirements. Similarly, a literature review on the redefining of regulatory was carried out in the context of various safety aspects (Martinetti et al. (2021)).

However, determining which safety mode is optimal for a given level of autonomy, is challenging. The current standards and legislation do not explicitly define safety in terms of robot autonomy, level of collaboration, or prescribe which safety modes should be applied in the given application.

3. Safety and Productivity in HRC

In this section, we will discuss the correlation between each influential factor and present our position on the use of collaborative modes using reference cases. A brief review of the state of the art in safe HRC is presented in Table 2, in which the role of each agent and the sharing of tasks were examined to evaluate the mode of collaboration. Each LoRA has been divided into LoC.

The two basic design considerations for collaborative application in industry are the safety of the human operator and the productivity of the cell Arents et al. (2021). As the field progresses, the level of robot autonomy will increase, enabling seamless collaboration at *Level 6* with humans. The human and robot will work as a team without human interference in the robot control cycle (Nikolakis et al. (2019), thus reducing task execution time and increasing productivity. Similar relations could be seen in the level of collaboration, as the interaction between humans and robots becomes richer the productivity of the system rises, exceeding human-human collaboration.

However, removing the human from the decision-making loop poses a serious threat to operator safety. Uncertainties in sensing the environment and robot's reactive behavior to unexpected situations (Guiochet et al. (2017)) will be the main challenges in *L6- Full Autonomy* as the robot needs to adapt its behavior to the current human state. Likewise, a higher level of collaboration increases the likelihood of unintentional contacts.

The relationship between LoRA and LoC could be explained in terms of productivity and safety, shown in Fig. 3. As the level of robot autonomy and collaboration increases, the productivity of the collaborative system increases (see Fig. 3a), the control over the operator's safety decreases (see Fig. 3b). *Collaboration at L6* is the most productive but the riskiest combination for the operator. Similarly, *Coexistence at L0* is the least productive but safest combination for the operator. Both combinations are highly unlikely to be used in the industry as we need to maintain compliance with safety of machinery requirements alongside required productivity.

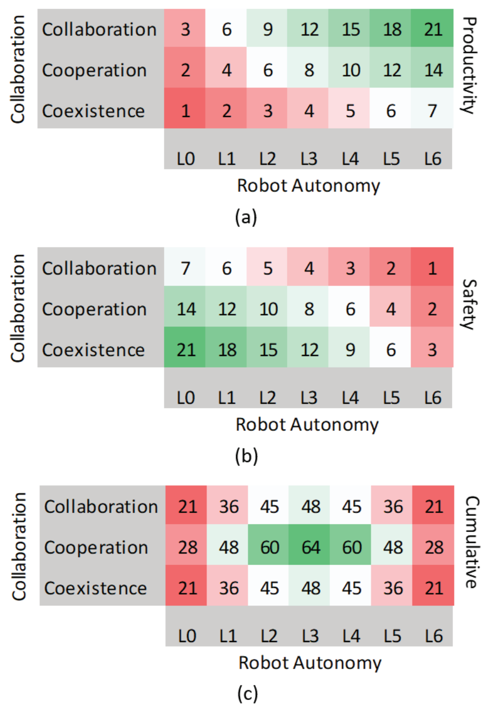

Fig. 3.: Relation between influential factors, where linear scoring is used to represent the trend. As the robot autonomy and collaboration increases, (a) productivity increases and (b) safety decreases. (c) Cumulative effect shows the desirable combinations in green.

A correlation between autonomy, collaboration, productivity, and safety should be the appropriate matrix to find the optimal level for HRC. Figure 3c shows this cumulative relationship, where we can easily conclude that the extremities of the matrix with the highest and lowest level are the

Table 2.: Recommended safety mode in terms of robot autonomy

LoRA	LoC	Safety Mode	References
L0	Coexistence/ Cooperation	SSM,SRMS	De Luca and Flacco (2012)
L1	Coexistence	SRMS, SSM, PFL	Tashtoush et al. (2021); Iossifidis (2014)
	Cooperation	SRMS, SSM	Vogel et al. (2020); Tashtoush et al. (2021)
	Collaboration	SSM, HG	Dianatfar et al. (2020)
L2	Coexistence	SSM, SRMS	Long et al. (2017); Heredia et al. (2020)
	Cooperation	PFL	Aljinovic et al. (2020); Tashtoush et al. (2021)
	Collaboration	PFL	Dombrowski et al. (2018)
L3	Coexistence	SRMS	Ko et al. (2021)
	Cooperation	SSM	Darvish et al. (2020)
	Collaboration	PFL	Murali et al. (2020)
L4	Coexistence	SSM, SRMS	Lee et al. (2020); Pichler et al. (2017)
	Cooperation	SRMS, HG	Weistroffer et al. (2014); Maurtua et al. (2017)
	Collaboration	SSM	Komenda et al. (2019)
L5	Coexistence	SSM, HG, PFL	Kousi et al. (2019); Iossifidis (2014)
	Cooperation	SSM, HG	Peter et al. (2020); Wang et al. (2020)
	Collaboration	SRMS, SSM, HG, PFL	Zlatanski et al. (2018); Mazhar et al. (2019)
L6	Coexistence	SSM,SRMS	Engemann et al. (2020)
	Cooperation	SSM	Kousi et al. (2019)
	Collaboration	SRMS	Melchiorre et al. (2021)

least desirable combinations in the industry based on current safety standards and methodologies. Combinations with white and green boxes are the preferred levels where optimal productivity and safety is achievable through safety modes.

The use of safety modes tend to differ according to the application and the interaction between human and robot. First, *Co-existence* being the lowest level of collaboration with no shared goals should employ SRMS or SSM to ensure safety and not hinder cell productivity. Second, *Cooperation* involves sharing workspace and goals without simultaneous action. SSM should be suitable in this scenario, as the operator reaches to load the workpiece or sequentially works on it, the robot should slow down and eventually undergo standstill. SRMS would decrease the productivity of cooperation and PFL is unnecessary, as the workpiece is not shared. Lastly, the highest level *Collaboration* will involve sharing workspace with simultaneous working on the shared object. PFL will ensure the highest level of safety at this level. It should be noted that dedicated force and torque sensors are required to enable PFL. However, certification of PFL is a tedious and error-prone process (Scibilia et al. (2021)) and relies on biomechanical tests validation (Behrens et al. (2021)) of force and pressure limits during collisions.

4. Conclusion

Recent evolution in the field of automation encourages humans to shift their roles toward collaboration and supervision, which poses major design and safety challenges. To overcome these challenges, in this paper, we have redefined a reference model in light of robot autonomy and collaboration, and reference cases are outlined for each level. Finally, the relationship between LoRA and LoC is explained in terms of safety and productivity. This relation motivates us to strive for the sweet spot somewhere in between rather than aiming for “lights out manufacturing”.

Through multiple surveys and authors experience while producing this work, it can be concluded that there is a lack of understanding and clear guidance to design and deploy safe HRC applications. This highlights the pressing need for harmonized European normative related to HRC to be published, which will enable the industry to adopt new technology with confidence. In future work, we will conduct a systematic review to present clear guidance to industries willing to adopt HRC.

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