Safety-Related Risks and Opportunities of Key Design-Aspects for Industrial Human-Robot Collaboration

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Abstract. For several years, sensitive robots are used in industry and in some cases perform collaborative tasks directly with humans on shared workplaces. At first glance, this type of human-machine interaction is associated with high risks. However, additional devices, advanced functionalities and risk mitigation activities can ensure that such collaborative scenarios are safe for humans. The essential aspects are the collaborative operation methods, workspace layout, end effectors, human machine interfaces and ergonomics. In this work we shed light on these important aspects of human-robot collaboration and discuss its facets. By adequately reducing and communicate potential indiscernible risks a robot is made trustworthy for a human being.

Keywords: Industrial human-robot collaboration · Safety
Collaborative robots

1 Introduction

Advanced Human-Robot Collaboration (HRC) is one of the key technologies to enable the current 4$^{\text{th}}$ industrial revolution, often called Industry 4.0 [6]. The strength of HRC lies in the flexibility and fast reconfiguration of the used collaborative robots. This flexibility is necessary in order to achieve small batch sizes as desired by Industry 4.0. Nevertheless, these new robots and the new technology associated with them not only present opportunities but also new risks.

Different aspects of collaborative robot applications, especially the contact between a human and a robot, are well studied. [5] describes possible injuries during collisions between humans and robots; [16] is about the detection of and reaction to contact situations and [17] describes a strategy to avoid the contact altogether. The system requirements from the operators point of view are addressed in [22]. Also the overall safety of such an application is discussed in [4, 18]. In this paper we focus not only on the risks, but also on opportunities of different technologies, while giving an overview of different practical approaches to develop and integrate a safe industrial HRC application. The key aspects, we focus on, are the collaborative operation methods, workspace layout, end effector, human machine interface and ergonomics.

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1.1 Norms and Standards

The relevant international standards regarding industrial collaborative robots are the ISO 10218 [8,9] and the Technical Specification ISO/TS 15066 [13]. While the field of collaborative robotics evolves fast, the available standards lack of guidance for the implementation of industrial mobile robots and also lack an effective method to verify the biomechanical loads for an operator during a collision with a robot in the field. For mobile robots in industrial environments an ISO draft [12] exists and the sub-committee R15.08 "Mobile Robot Safety" of the US RIA is currently working on a new standard. A method to verify the biomechanical load is described in [2], but it neither covers the transient contact nor considers the shape of the struck body part. An overview of relevant documents can be seen in Fig. 1.

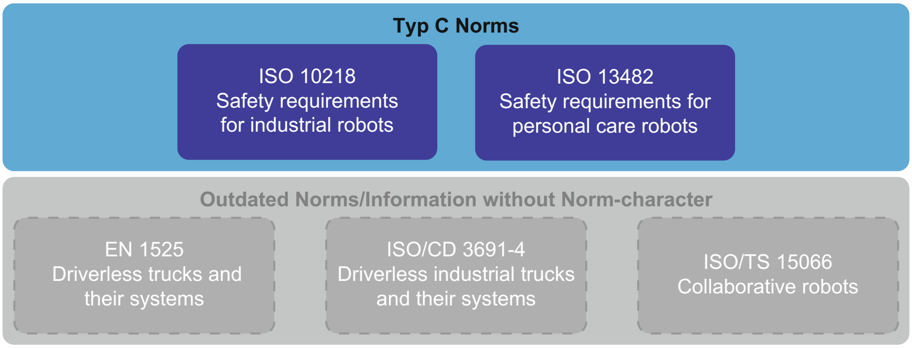


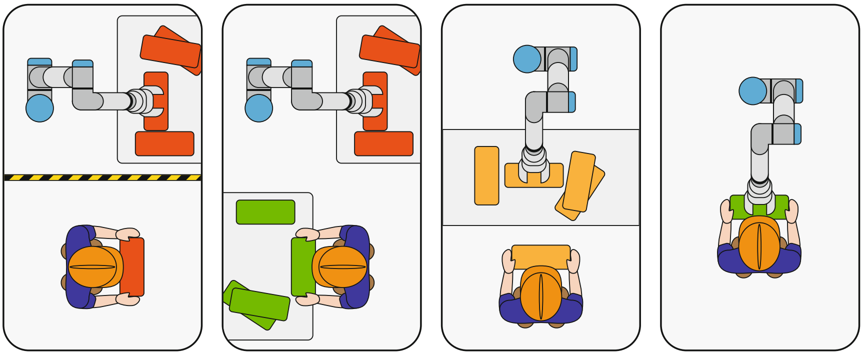
Fig. 1. Relevant norms and standards for HRC

1.2 Classification of HRC

Collaborative operation is defined in [10] as the *"state in which purposely designed robots [...] work in direct cooperation with a human within a defined workspace"*. This definition is rather general in the aspect of the degree of interaction. Therefore, we classify the HRC in 4 degrees of interaction, *"the 4 Cs"*, as shown in Fig. 2. The extent of interaction increases from Fig. 2(a) to (d), where *enCapsualtion* means no interaction at all and *Collaboration* allows the human and the robot to work simultaneously on the same workpiece.

2 Key Design-Aspects

In the following, design-aspects are presented, which are relevant for a safe industrial HRC application. Not only the risks of those aspects are presented, but also related opportunities to increase safety and add additional value for the operator.



(a) enCapsulation (b) Coexistence (c) Cooperation (d) Collaboration

Fig. 2. The 4 Cs: 4 degrees of interaction between a human and a robot

2.1 Collaborative Operation Methods

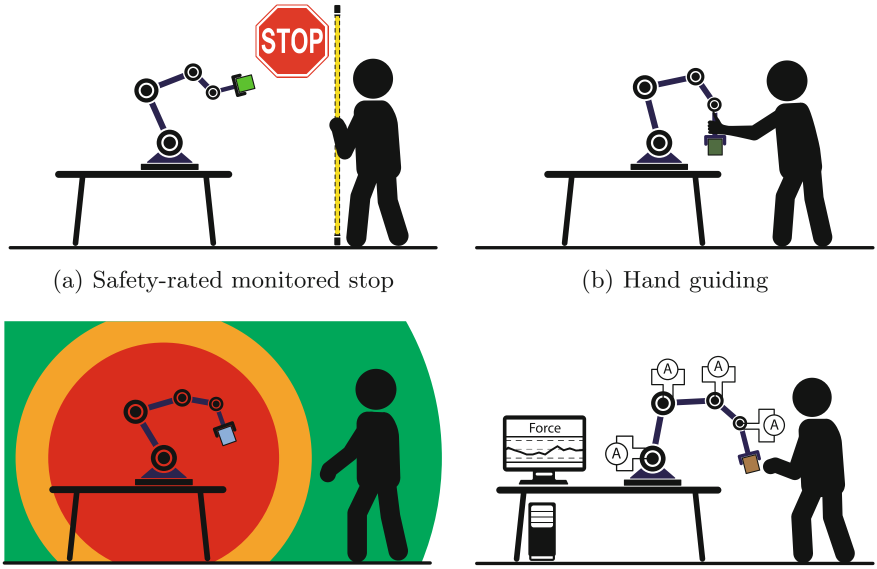
A collaborative robot can often solve a certain task in several ways. In the ISO/TS 15066 [13] and ISO 10218-2 [9], four collaborative operation methods (see Fig. 3) are defined, which can be applied to an HRC application.

(a) An application protected by a *safety-rated monitored stop* (Fig. 3(a)) is the most conservative collaborative operation method, because the interaction between human and robot happens when the robot stands still. The chance of hazardous situations is low compared to the other operation methods, but the possible benefits of collaboration are low as well.

(b) The *hand guiding* operation (Fig. 3(b)) can be safe, even though a direct contact between human and robot is necessary, because the robot acts passively. The interaction by hand guiding is intuitive and easy to learn. To increase the operators comfort during hand guiding, a compliant control strategy can be used. While this operation method is highly collaborative, the human attention and input is always necessary.

(c) During *speed and separation monitoring* (Fig. 3(c)) the robot keeps a safe distance to surrounding objects and humans at all times. Sensors provide the necessary information to adjust the distance dynamically, which can be placed directly on the robot. Alternatively, sensors can be mounted in the environment, monitoring fixed zones around the robot. Speed and separation monitoring prevents the contact between the robot and humans entirely, reduces downtime and thereby balances safety and productivity. Crucial design parameters are (i) the type of sensors, (ii) the sensor resolution (which determines the minimum object size, that can be detected) as well as (iii) the maximum reach and stopping time of the robot. The drawback of more advanced versions of such systems is their high complexity and the associated high computational demand.

(d) A Robot that is capable of *power and force limiting* (Fig. 3(d)) ensures the safety of a human during a contact, by complying with thresholds for the biomechanical load (force and pressure) presented in ISO/TS 15066 [13]. To achieve this compliance, the robot needs to be able to sense a contact. This increases the robots complexity but also eliminates the need for additional sensors in the environment. Two advantages, (i) no external sensors are necessary and (ii) the interaction can be intuitive, are confronted with the disadvantage that a collision between a human and a robot can not be prevented with this method. Therefore the risk is higher when using *power and force limiting* in comparison to the other collaborative operation methods. A second disadvantage is, that the compliance with the load thresholds must be validated in the field for all possible contact situations, which increases the integration effort.



(a) Safety-rated monitored stop (b) Hand guiding

(c) Speed and separation monitoring (d) Power and force limiting

Fig. 3. Collaborative operations according to ISO/TS 15066 [13]

2.2 Workspace Layout

The workspace layout design relates not only to the safety of the whole application, but also to the efficiency and the ergonomics (see Sect. 2.5) of an application. Many ergonomic problems arises from the layout design and can be solved by altering it slightly. In general a bigger workspace increases the number of probable hazardous situations, but also enables a greater variety of applications. Constrains are given by (i) the task (ii) the implemented collaborative operation methods and (iii) the capabilities of the used robot. Additionally the layout is influenced by the individual ergonomic requirements of possible operators. While in classical robot applications, the workspaces of humans and robots are strictly separated (see Fig. 4(a)), a collaborative workspace is needed in HRC applications. The collaborative workspace can be just an overlap (see Fig. 4(b)) of the two workspaces, the entirety of one becomes the collaborative workspace (see Fig. 4(c)) or all three are equal (see Fig. 4(d)).

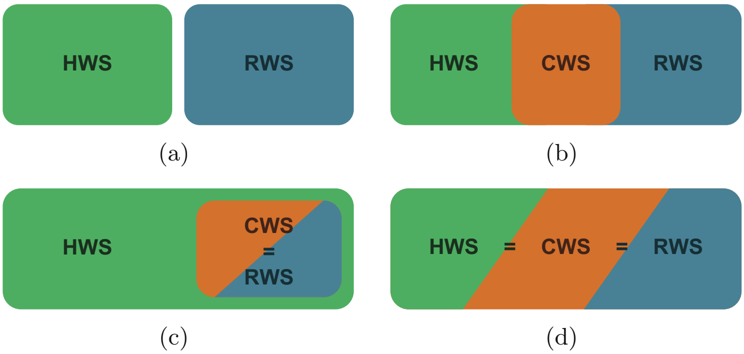


Fig. 4. Possible Workspace Layouts (H...Human, R...Robot, C...Collaborative, WS...Workspace)

Serious hazards that arises from the layout and geometry of the workplace are shear edges or pinch points, especially between the robot and its surroundings. Furthermore the operator can be indirectly at risk because of poor lightning conditions or constrained visibility of important areas.

To overcome these problems, the possible positions and movements of the robot should be considered. For stationary robots, the position of the robot base is crucial, and for mobile robots the possible working range respectively. In mobile applications, the workspace should exclude untrained personnel and hazardous objects. In stationary applications, the distance between the robots base and the collaborative workspace should be maximized, to reduce obstructive shadows around the workpiece and to prevent the robot from blocking the view of the operator. At the same time the movements of the robot should be as limited as possible to reduce the danger of an unwanted collision and to make the robot behavior more predictable.

2.3 End Effector

The end effector, typically a gripper, is usually the physical interface of a robot to its environment during normal operation and is therefore from great interest for the design of an HRC application. The gripper should in the best case, ensure a safe grip, flexible usage and needs to be safe for the human. To ensure safe gripping, form-fit should be preferred to force-fit, as form-fit is not prone to loosing the grip during higher acceleration, and also still grips the object after loss of energy. Another hazardous situation, the clamping of human body parts between the fingers of the gripper, can be prevented by minimizing the clearance to the gripped object or by monitoring the gripping force. There are specialized gripping solutions, which can improve the safety in some cases. For example soft grippers, suction cups and electromagnetic grippers. In general an inherent safe design is preferable. Most mentionable thereby is a lightweight construction, to reduce the mass; and maximizing the radii of corners, to enlarge the surface area and thereby reducing pressure during a contact. In cases where the gripper-design is inherent unsafe and can not be changed, due to limitations of the application, shielding the gripper and also the gripped object [21] can increase the safety dramatically.

2.4 Human Machine Interface (HMI)

The HMI, or user interface is the *"means for information and action exchange"* [10]. A good HMI for industrial applications ensures, that operator and robot share the same knowledge on the applications status and work together in an intuitive and productive way. With increasing complexity of a robot system, a good HMI becomes crucial. To ensure a safe application, also the security risks of the applied technology should be considered, especially the confidentiality, availability and integrity of the transferred information.

The communication between humans and robots is possible in both directions, from human to robot and from robot to human respectively. Different technologies are available to implement the HMI, depending on the addressed sensory stimulus and whether the action/information originates from the human or the robot. Table 1 categorizes possible interaction technologies according to the mentioned dependencies.

Augmented Reality (AR) and Projections. AR, as an interface technology, can evoke or reduce risks. A common AR-device, the smartglasses, can be used to highlight dangerous areas or guide the operator to prevent a faulty operation. At the same time the operators field of view is limited and the situation awareness could decrease. The use of virtual reality devices results in motion sickness for some users [15]. Although this issue seams to be less likely to occur in AR, it can decrease the usability and acceptance.

Projections are another technology to enrich the real world and can be used to display graphics in the collaborative workspace [20]. The displayed information can be used to show the robots next actions or to highlight risks in order to prevent contact situations between the human and the robot. In contrast to smartglasses, the operator is not constrained by additional gear, but the projections are limited to certain areas.

Table 1. Classification of HMIs

		Input originates from....	
		Robot	Human
Sensory stimulus	Visual	Gestures, Signal lamp, Display, Projections (Projector, AR-Glasses)	Gestures, Gaze
	Acoustic	Speech, Sounds	Speech, Sounds
	Haptic	Contact, Haptic device	Contact, Haptic device, Joystick, Keyboard/Mouse, Touchscreen

Data Representation. An important aspect in the interaction design is the representation of data, especial but not limited to Graphical User Interfaces (GUIs). In todays applications a lot of data accumulates, which can be used to monitor and control the application. With this increasing amount of data, processing it becomes crucial, as the operator simply cannot monitor every parameter at all times. Instead only meaningful information should be provided incidental to the operator [19]. According to [1] information should be *event-based*, *future-oriented* and *structured*.

(a) If providing information *event-based*, the user is only disturbed, when the information is relevant to the actual context. An example is to display the reason for a safety stop, right after it occurs or the information that a monitored parameter leaves its usual range.
(b) The information provided, should be *future-oriented*, so the operator has the chance to prepare for upcoming events and plan his/her actions accordingly. A future-oriented information would be the trend of a parameter or the remaining lifespan of a component.
(c) To quickly find a specific information or value, the collected data should be *structured*. This can be achieved by classifying the data in a searchable hierarchical structure or by visually separating and grouping the data.

2.5 Ergonomics

The ergonomics of an industrial HRC application is crucial for the operator. Even if the application is harmless, its success depends also on the acceptance by the operator.

According to [3], there is a connection between the operators stress level and his/her situation awareness. This situation awareness can be influenced by stressors of physical (e.g. noise, lighting conditions, boredom) or psychological (e.g. fear, uncertainty, consequences of events) nature. A reduced situation awareness leads to an increased probability of hazardous situations. In [14], hazards related to manual manipulation of heavy objects are addressed; general ergonomical hazards are listed in [11].

The following design errors in industrial robot applications in relation to ergonomics should be taken into account:

- misleading communication between human and robot, especially due to
  - unsuitable designed control- or programming-pendant,
  - poorly marked control elements or
  - unsuitable designed loading/unloading post;
- unsuitable localized lightning conditions or
- unsuitable height of the work surface, control elements or loading/unloading post.

If an existing workstation is upgraded with a robot, ergonomics is particularly important, since the existing design was usually not planned with a robot in mind and the temptation is great to leave the workstation design as it is in order to reduce effort.

These failures could lead to invalid programming or control inputs by the operator, which again lead to hazardous situations. Repeated and unintentional contact situations between the operator and the robot are also more likely, which increases the strain and fatigue of the operator. If safety devices disturb or annoy the operator, the risk of manipulation of these safety devices is high. In order to avoid such hazards, the workplace design should meet the requirements of the operators and their individual physical characteristics and habits. Future operators should be involved in the planning process from the outset in order to prevent the bypassing of safety devices [7].

By mitigating the presented ergonomically hazards, not only a reduction or elimination of the hazards can be achieved but they can even be turned into opportunities to create a welcoming environment for the user, where he/she likes to work and is at ease.

3 Conclusion

Right now robots enter more fields of applications beside industrial ones (e.g. households, elderly care, agriculture) and the number of people, interacting with robots, increases. The ease of use of robots and therefore their interfaces is quite important, as not all operators have a technical background and are able to understand the technology, especially children and the elderly.

In industrial applications, the high degree of freedom enables serial manipulators to extensive and complex sequences of movement, which are not always predictable for humans and may not be intuitive. In combination with the close human interaction, this can result in hazardous situations. To combat that, an appropriate communication interface between man and machine (HMI) is essential. A good interface can reduce the induced stress, which ensures good health of the operator in the long run. Another factor for the need of a good interface, is the high complexity of collaborative robots in combination with the demand for ease of use.

Certainly, robots will change our workplaces and homes, but design-factors like the interaction between humans and robots will decide, whether it is a good or a bad place to work and live. Additional factors like the workspace-layout, end-effector design or the collaborative operation methods will not only affect the acceptance of such systems but also the safety of the operators. Guidelines for those factors, in form of norms, are already available, at least for stationary applications. Norms for mobile robots, on the other hand, are still in their draft phase. Which means more thought has to go into the development of such systems.

Only when all the conditions that were stated in this work are met, the way will be paved for trustworthy robots.

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