A Risk Reduction Framework for Design of Physical Human-Robot Collaboration

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Abstract

As robots designed to physically interact with humans become common in various application areas, shared workspaces and force exchange between human and robot lead to new challenges in terms of safety. Often, a variety of safety techniques is necessary, and deciding what methods to include in a comprehensive safety framework is not an easy task. This paper is concerned with the design of robotic co-wokers that involve physical Human-Robot Collaboration (pHRC), with humans and robots in continuous direct physical contact and exchanging forces. A hierarchical risk reduction framework is presented for guiding the design of robotic co-workers to reduce the risk associated with hazards commonly found in pHRC tasks. A case study is presented to demonstrate the use of the framework in designing an Assistance-as-Needed roBOT (ANBOT) which has been extensively tested in practical industry applications.

1 Introduction

Human presence in the robot workspace makes physical Human-Robot Interaction (pHRI) one of the most challenging research topics [Bicchi *et al.*, 2008], and the use of robots that physically interact with operators in industrial applications is gaining a lot of interest. In a literature review about exoskeletons used in industrial applications, out of the 40 papers selected, 18 were published in 2010 or later, showing the current interest in pHRI for industrial applications [de Looze *et al.*, 2016].

In the past few years the necessity of regulations and standards regarding pHRI has risen due to the increasing popularity of such robots. The International Standard ISO 10218 presents standard requirements for industrial robots and consists of two parts: “Robots” is mostly designed for manufacturers, while the second part, called “Robot systems and integration”, focuses on potential safety issues that integrators have to keep in mind [International Organization for Standardization, 2011a; 2011b]. This standard represents the main document about safety related to industrial robotics, but it is quite generic and only partially addresses collaborative robots. Since collaborative robots are spreading in the market, a Technical Specification was released in 2016 to extend specific requirements presented in ISO 10218 about collaborative robots [International Organization for Standardization, 2016]. International Standards are meant to give a general direction and used as a guide. They have to be integrated with a risk assessment, which strongly depends on the specific application.

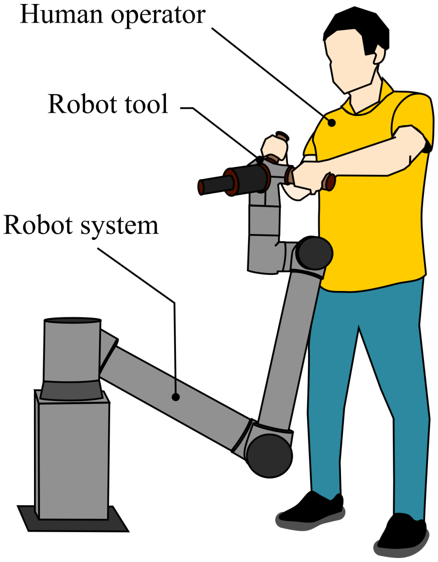

Figure 1: Example of an application involving pHRC

We adopt the definition of the Québec WHO Collaborating Centre for Safety Promotion and Injury Prevention, which states: “Safety is a state in which hazards and conditions leading to physical, psychological or material harm are controlled in order to preserve the health and well-being of individuals and the community" [World Health Organisation, 1998]. A way of improving safety is to develop hardware specifically designed to have a safe, and usually compliant, interaction. The International Standard ISO 10218-2 presents general hardware requirements for collaborative robot operations, such as ergonomic design, no sharp-edges, no protrusions, accessibility of the guiding device and location and function of protective devices [International Organization for Standardization, 2011b]. Extensive work has been done to develop hardware that is safe to collaborate with [Ham *et al.*, 2009; Hoshi and Shinoda, 2006; Vanderborght *et al.*, 2013; Kühne *et al.*, 2015]. In the last decade, several robotics manufacturers have developed industrial robots designed to operate in proximity with humans: for example, UR3, UR5 and UR10 by Universal Robots [Universal Robots], Baxter and Sawyer by Rethink Robotics [Rethink Robotics], the ABB Yumi [ABB], and the KUKA LBR iiwa [KUKA AG].

Even if the hardware is considered safe, the integrator is also responsible of the overall system safety, including the application and possible additional components integrated in the system [International Organization for Standardization, 2011b]. A more flexible way to ensure safety is to address the problem at a system design and integration level, taking advantage of modern control techniques and sensors. A recent survey focusing on studies in this field presents a wide variety of possible approaches [Lasota *et al.*, 2017].

Some industrial applications involve complex and dynamic environments, which itself presents several hazards and challenges to the human operator. Consequently, ensuring safety leads to many implementation challenges. In fact, the system designer has often to compromise, due to the cost of safety-related technology, or software implementation limits, such as computational power. The design of a new system is usually a time-demanding process. Deciding which safety methods a system will feature is paramount, and can jeopardize the success of the technology. A guideline for which safety methods are worth investing into will definitely benefit system integrators working with collaborative robots.

This paper is aimed at collaborative systems that involve pHRI, with human and robot in direct physical contact and willingly exchanging forces to accomplish a common task. We refer to this type of interaction as physical Human-Robot Collaboration (pHRC). In Fig. 1, an example of pHRC is shown, with a human controlling a robot manipulator through physical exchange of interaction forces.

We present a safety framework, that gives as an output a system of modules that are organized into a three level hierarchy: approaches, strategies and methods. Each module represents a way to reduce the risk associated to a hazard, with each module having its own advantages and drawbacks. Which module to be used in the system design and integration depends on the risks associated with the specific application, therefore a procedure to systematically analyze risks and design a safety solution is suggested. Finally, a case study is described as an example of how this methodology can be used to design a safety framework.

2 Framework

Often, hazards cannot be eliminated, but the associated risk can be reduced to an acceptable level. This is achieved through a process called risk management. In 2010, the International Organization for Standardization published the ISO 12100 to specify techniques of risk assessment and risk reduction to help designers achieve satisfactory safety in the design of machinery [International Organization for Standardization, 2010].

We define a safety framework as a process which reduces the risk associated to hazards and hazardous situations, and is the result of the following design steps:

1. Identify hazards and hazardous situations;
2. Assess the risk associated with each hazard;
3. Identify which modules help reduce the risk;
4. Select safety modules;
5. Evaluate whether the resulting risk is acceptable.

The resulting solution is always a compromise between achieved risk, system performances and cost, in terms of money and time.

2.1 Hazard identification and risk assessment

In Table 1, hazards common to pHRC are listed, organized by topic. These hazards are not the only ones to be considered and the topics are not exhaustive, but can be treated as a guideline.

Generally, the application, and the environment where the interaction will take place, are pivotal to identify potential hazards and hazardous situations. The application-related hazards reported in Table 1 are examples that may commonly be encountered.

Some of the listed hazards can also be generated by fully automated robots, however they become critical when a human is physically interacting with the system. For example, kinematic singularities and jerky movements also affect industrial robots in traditional non pHRC applications, but during pHRC the potential loss of control caused by them will have a large impact on the safety, due to the proximity of human and robot.

As stated in the ISO 12100, the risk related to a hazard is a function of the severity of harm that can result from that hazard and the probability of occurrence of

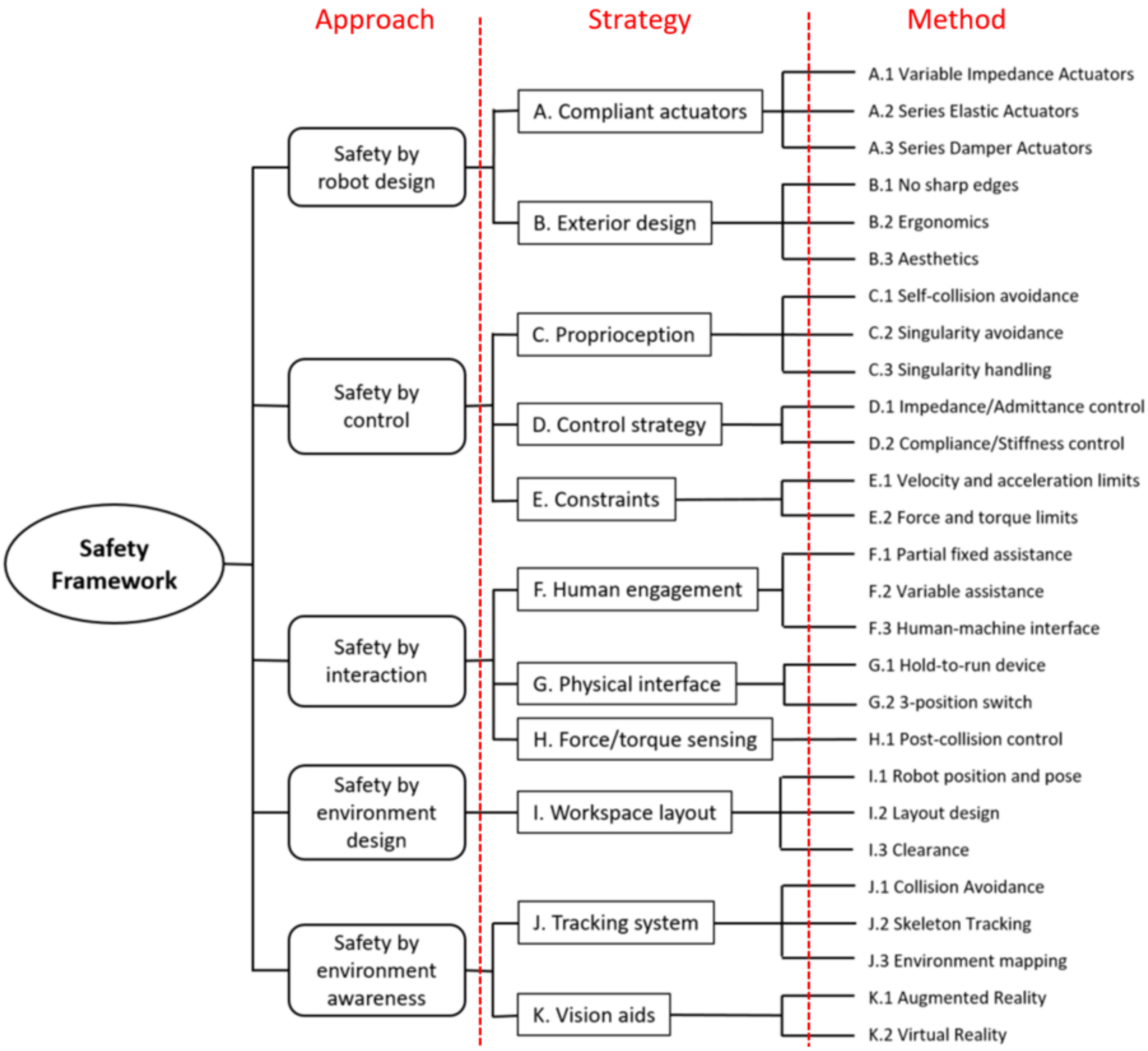

Figure 2: Safety framework for risk reduction in applications involving pHRC

that harm [International Organization for Standardization, 2010]. Risk matrices are a visual tool to quickly assess the risk level given the likelihood and the consequences. For example, a collision between the robot and the environment will be less critical than an undesired collision between the robot and a person, and even less critical than a person being pinched between the robot and fences.

Once a risk level has been selected for each of the identified hazards, each risk has to be reduced to an acceptable level by using appropriate safety modules.

2.2 Safety modules

In order to reduce the risk to an acceptable level, the likelihood or the severity of a hazard have to be reduced. In Fig. 2, possible means to reduce the risk in pHRC are listed, organized in three levels. Those safety modules, when combined, create a solution to decrease the overall risk of the system, improving the safety.

The three levels organize the modules approaches, strategies or methods. The integrator will use them to systematically decide which modules to include in their framework. For example, if the integrator is utilizing a robot manipulator available in the market, and it is undesirable to modify the robot design, then they would not utilize the modules within that approach, but they will have to obtain an acceptable level of risk from different approaches.

Safety by robot design

The mechanical design of a manipulator has a huge impact on system safety. In fact, one of the main sources of danger for humans is mechanical power, and actua-

Table 1: Common hazards in pHRC classified by topic

Topic	**Hazard**
1. Biomechanical limits	1.1 Forces over limit 1.2 Unergonomic interface 1.3 Uncomfortable posture
2. Human error	2.1 Unintended use 2.2 Psychological distress 2.3 Operator unengaged
3. Configuration	3.1 Kinematic singularities 3.2 Self-collision
4. Movement	4.1 Jerky movements 4.2 Vibrations
5. Collaborative workspace	5.1 Human-robot collision 5.2 Human pinched between robot links 5.3 Environment-robot collision 5.4 Workspace occluded 5.5 Human pinched between robot and object 5.6 Human trapped
6. Multiple human agents	6.1 Unexpected person in the workspace 6.2 Human-human interaction
7. Multiple robot agents	7.1 Robot-robot collision 7.2 Human pinched between robots
8. Application	8.1 Tool harming human agent 8.2 Tool damaging robot agent 8.3 Tool damaging objects or environment

tors play an important role in producing it. Vanderborght et al. [Vanderborght *et al.*, 2013] offers a good review and classifications of Variable Impedance Actuators (VIAs), including Series Elastic Actuators (SEAs) and Series Damper Actuators (SDAs). The design of these devices can be quite complex and the same review also mentions that it is possible to achieve the behavior of a VIA by software control. This has the advantage of not relying on the physical stiffness and damping factor of the actuator, but as a drawback presents a complex controller and no energy can be passively absorbed in the actuator, which means that shocks cannot be absorbed.

The way mechanical power is transferred from the robot to the human depends on the shape of the mechanical parts that contact the human. The whole system should have smooth surfaces and no sharp edges, so that, in case of impact with the operator, the collision force will be spread on a wider area, reducing the pressure on human tissues. When designing the exteriors of the system, ergonomics should play an important role. It should take into account not only the comfort of the operator, but also biomechanical parameters [Robotiq, 2016]. Furthermore, the aesthetic look of the robot will directly affect its acceptability among users and possibly make its usage more intuitive [Goetz *et al.*, 2003].

Safety by control

All modern robots are provided with proprioceptive sensors, so that their configuration can be always monitored and controlled. This makes it possible to solve issues generated by undesired configurations, such as the ones corresponding to self-collisions (collisions between parts of the same robot) and singularities. These configurations can be avoided, restricting the operating workspace, or can be handled using specific control strategies. During pHRC, to obtain a smooth interaction, the movement of the system should not be abruptly interrupted, but gently discouraged, for example by applying force fields [Dimeas *et al.*, 2018; Carmichael *et al.*, 2017].

Impedance and admittance control systems and their variants are the most common controllers used in pHRC [Rezazadegan *et al.*, 2015]. They focus on modeling the interaction in terms of impedance/admittance, as a combination of stiffness and damping. A direct or indirect measurement of the interaction force is required, which means having additional sensors or a good dynamic model of the system. Another option is to simplify the dynamic requirements by only taking the stiffness/compliance of the system into account and ignoring the damping term.

An easy way to improve the safety of a robot is to limit velocities and forces on both joint and Cartesian spaces, and this is in fact one of the first strategies being standardized in pHRC, but in some cases might be too restrictive. Due to new sensors, the limits on kinematic and dynamic parameters can be more flexible.

Safety by interaction

In pHRC, the human operator is always present and is the greatest unknown in the whole system because their actions can be unpredictable. Studies related to safety often focus on the physical aspect of safety, however, the way a machine or a task psychologically affects a person is also important. A scared or distracted operator will be more inclined to perform poorly and cause human errors. During pHRC, the robot assists the operator in performing a task. One way to keep the user engaged is to only provide partial assistance, requiring the operator to contribute to the task and hence promote engagement. A better but more complex strategy is to have a variable level of assistance. A dynamic feedback is more likely to keep a user engaged compared to a static one [Byrne and Parasuraman, 1996]. The human-machine interface in general is a powerful means that can greatly influence the level of engagement.

The physical interaction between humans and robots should happen through an interface specifically designed for this purpose. If the application introduces hazards that can be avoided by controlling the position of the operator, hold-to-run devices on the handles can restrict the position and pose of the user depending on the design of this interface. Safety measures such as 3-position switches can always be integrated and used to trigger protective stops, in case the device is released or squeezed too hard, due to an unexpected event.

In their survey, Lasota et al. [Lasota *et al.*, 2017] considers post-collision strategies to minimize the impact caused by collisions. Using a direct or indirect measurement of forces and torques is a common strategy of detecting unexpected collisions. Load cells and soft skin capable of sensing touch are some approaches used. How best to react to an impact is still an open question, but generally the reaction time should be as small as possible.

Safety by environment design

The workspace layout is an important feature of the system and it greatly conditions the interaction, the risk assessment and the safety measures. The location of the robot may impact the perception of the human towards the system. For example, having a big industrial robot above the level of the operator's head might cause them distress. Not only the operative environment, where the collaborative task takes place, but also the shared environment and the surroundings have to be taken into account. Where possible, clearance between the system and fixed objects, walls and fences, should be implemented. If working in restricted areas, collision avoidance is critical, to avoid humans being pinched.

Safety by environment awareness

A feature of collaborative systems is that they can work in flexible conditions, taking advantage of human adaptability. The use of vision systems and proximity sensors to obtain information about the area surrounding the robot allows unstructured and flexible environments. Tracking the distance between robot parts and the human or parts of the environment could prevent accidental collisions from happening. Lasota et al. [Lasota *et al.*, 2017] present in their study several pre-collision strategies applied in pHRI. Skeleton tracking can be used to track the pose of the human using digital human models. In the case of multi-agent systems, it could be crucial to monitor the location of each agent and share that information. Unfortunately, tracking systems may fail due to the limits of sensors and image processing algorithms. Moreover, during pHRC, it is likely that the human or the robot are partially occluded because of the small distance between them. The decision of mounting the sensors on-board of the system or around the environment may greatly affect performances and transportability. The big drawback of vision systems and algorithms is that, depending on the quantity and quality of data to analyze, this process may be computationally demanding.

Technologies such as Virtual Reality (VR) and Augmented Reality (AR) can also be integrated in a safety framework to help the operator gain information that might not be immediately available. For example, VR could help the user see parts of the environment that are occluded by objects or environmental constraints, while AR could help identify how to correctly manipulate an object during the collaborative task.

3 Development of the Proposed Safety Method

There is not a definitive way to achieve safety, and risk assessments and safety frameworks are influenced by the experience and knowledge of the people designing them. Table 2 presents a matrix with the hazards listed in Table 1 and the modules shown in Fig. 2, that could reduce the associated risk.

The purpose of this section is to provide a general guide to people who have identified one of the listed hazards and are looking for strategies to reduce the relative risk.

The reported level of risk is selected by considering the likelihood of the hazardous event and the severity of the harm/damage caused by it. The level of risk reduction is a result of how that safety method affects the likelihood

Table 2: Matrix with hazards and safety methods in pHRC. The risk related to a hazard and the risk reduction introduced by a safety method are also reported as an indicative measure. The risk associated to application-related hazards cannot be assessed.

		Risk	**Safety Methods**																										
			A.1	**A.2**	**A.3**	**B.1**	**B.2**	**B.3**	**C.1**	**C.2**	**C.3**	**D.1**	**D.2**	**E.1**	**E.2**	**F.1**	**F.2**	**F.3**	**G.1**	**G.2**	**H.1**	**I.1**	**I.2**	**I.3**	**J.1**	**J.2**	**J.3**	**K.1**	**K.2**
Hazards	**1.1**	++													×														
	1.2	++					×																						
	1.3	++					×																			×			
	2.1	++						×										×										×	
	2.2	+				×		×														×							
	2.3	+														×	×	×	×	×									
	3.1	++								×	×																		
	3.2	+							×																				
	4.1	+	×	×	×							×	×	×															
	4.2	+	×	×	×							×	×																
	5.1	+++	×	×	×	×						×	×	×	×						×				×				
	5.2	+++	×	×	×	×						×	×	×	×						×				×				
	5.3	++	×	×	×	×						×	×	×	×						×		×	×	×				
	5.4	++																				×	×				×	×	×
	5.5	+++	×	×	×																×		×	×	×		×		
	5.6	+																					×	×			×		
	6.1	++																					×				×		
	6.2	+														×	×	×					×						
	7.1	++							×																×				
	7.2	+++	×	×	×							×	×	×	×						×		×	×	×		×		
	8.1	?																											
	8.2	?																											
	8.3	?																											
Risk reduction			***	**	**	***	***	*	**	**	**	**	**	***	***	*	**	***	**	***	***	*	***	**	***	*	**	**	**

or/and severity of a hazardous event. The reported risk level will be subject to the knowledge and experience of the persons conducting the risk assessment.

The risk and risk reduction are expressed on a 3-levels scale. The risk can be low (+), moderate (++) and extreme (+++), with low corresponding to no direct harm to human or objects and extreme corresponding to life-threatening event. The risk reduction is classified as lowly (*), moderately (**) and highly effective (***), but it largely depends on how the safety method is designed and developed.

It may not be possible to suggest safety modules to reduce the risk introduced by hazards specific to the application. The tool, usually located on the robot end-effector, often introduces most of the application-related hazards. The operator is in fact often in its proximity and the interaction between robot and environment happens through the tool.

Something to consider when choosing which modules to implement is that the international standards ISO 10218-1 and ISO 10218-2 [International Organization for Standardization, 2011a; 2011b] state that every safety-related part of the control system has to comply with Performance Level (PL) = d with structure category 3 as detailed in ISO 13849-1:2015 [International Organization for Standardization, 2015]. This means that the method has to include cross monitoring to detect eventual faults in the module.

All these methods can be implemented to reduce the risk level associated to single hazards or to multiple ones. Some of them may affect the risk related to the same hazard, but sometimes such redundancy is considered beneficial in reducing risk. After a comprehensive framework is implemented, the risk should be reassessed to check if all the identified hazards present acceptable levels of risk.

Because safety modules generally have a price in terms of money, time, effort and performance, the integrator will always have to do compromises, depending on resources and priorities.

4 Case Study

We implemented the framework, using the above mentioned strategy, to achieve safety for a system operating in a highly challenging environment. The solution was developed keeping in mind the modularity of the solution and the benefits that redundant modules could enhance safety. The resulting robotic system is the ANBOT (Assistance-as-Needed roBOT), designed and developed by the Centre for Autonomous Systems (CAS), within the University of Technology Sydney (UTS) [Carmichael *et al.*, 2019]. In Fig. 3 an operator is shown while using the system in its industrial application.

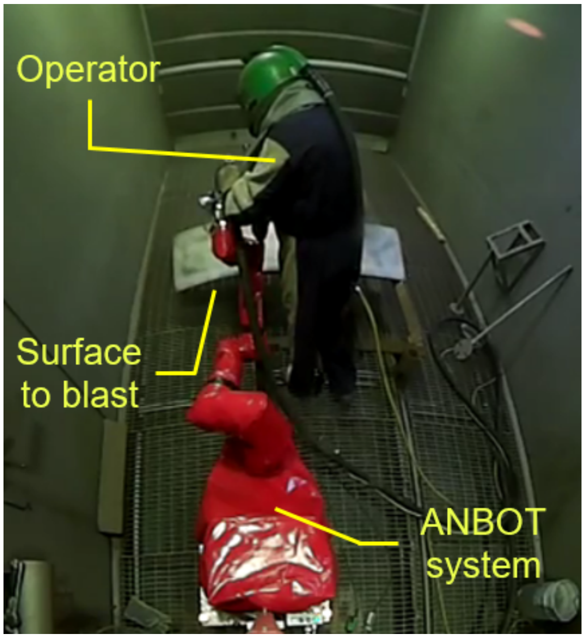

Figure 3: An operator performing grit blasting using the ANBOT system

4.1 Application

Abrasive blasting is an industrial process to clean surfaces from contaminants. Operators have to sustain loads ranging from 49 to 130 N during dry blasting tasks [Momber, 2008], along with the weight introduced by the nozzle and the hose. Operators get easily fatigued and their performances deteriorate quickly during their shifts. This makes abrasive blasting a physically demanding job and a good candidate for an assistive system.

There are several types of abrasive blasting depending on the material used. We use grit blasting as a case study, because of the additional challenge introduced by the environment. This kind of blasting takes place in blasting chambers. During operation the chamber becomes filled with airborne particles which reduce visibility.

4.2 Risk assessment

The presented risk assessment is not a comprehensive one, but just an example of the hazards, and associated risks, related to pHRC in a grit blasting application.

We identified the hazards listed in Table 1, excluding the ones relative to multiple human and robot agents, since our system is meant to be operated by one operator and only one robot manipulator is used. The application introduces the following additional hazards:

- 8.1 Operator is in the blasting stream (Risk: +++);
- 8.2 Nozzle is released from tool while blasting and hits the operator (Risk: ++);
- 8.3 Blasting material damages the robot (Risk: ++).

To simplify the process of designing a safe system for pHRC, a UR10 by Universal Robots was used as a manipulator. This robot arm is certified for collaborative operation, and, even if the integrator has to reassess the risks of the manipulator as a component of a system, this robot features safety-related options that makes it easier to achieve high safety levels. It is in fact possible to easily set force and velocities limits, and the controller issues a protective stop in case of singular configuration or collision.

4.3 Resulting safety system

Table 3 lists the identified hazards and the modules implemented to target the relative risk.

Table 3: Identified hazards and implemented safety methods

Hazards	**Safety methods**					
1.1	E.2					
1.2	B.2					
1.3	B.2					
2.1	B.3	F.3				
2.2	B.1	B.3	I.1			
2.3	F.2	F.3	G.1	G.2		
3.1	C.2	C.3				
3.2	C.1					
4.1	D.1	E.1				
4.2	D.1					
5.1	B.1	D.1	E.1	E.2	H.1	
5.2	B.1	D.1	E.1	E.2	H.1	
5.3	B.1	D.1	E.1	E.2	H.1	J.1
5.4	I.1	J.3				
5.5	H.1					
5.6	J.3					
8.1	B.2	G.1	G.2	SP		
8.2	SP					
8.3	SP					

Each control interface includes an emergency stop, and sharp edges are avoided in the mechanical design. The system features an admittance controller, which takes into account interaction forces and torques through a load cell located between the tool and the manipulator. Limits for velocities, accelerations, forces and torques are hard-coded in the control system and we use the UR10 to control forces in the eventuality of an unintended collision as a redundant safety measure. The tool is where the physical interaction happens. It has been designed in a way that is not only comfortable for the user, but also constrains the human position relative to the tool. It has two handles equipped with 3-position switches, working as hold-to-run devices. In case the user releases or squeezes them as a reaction to an unexpected event, the controller issues a protective stop. To be able to blast, the operator has to hold both the handles and the switches have to be in the middle position. A plastic shield is placed in front of the handles, protecting the operator's hands from bouncing particles and preventing the user from holding the tool in the wrong direction. As a consequence, this forces the operator to be behind the tool and out of the blast stream.

The constraints set on the dynamic parameters decrease the severity of the consequences in case of collision. To reduce the likelihood of impact with the environment, four Kinect 1 cameras are used to scan the workspace and create a virtual 3D grid which generates force fields around the detected obstacles. The robot is attached to a base that can be moved with a pallet jack and to improve the transportability of the system the integrated vision sensors are on-board. We also use force fields to avoid self-collisions and singularities, and in case a problematic configuration is reached a protective stop is issued. To engage the operator in the task and enhance their awareness a variable level of assistance is provided. The implemented method is a model-based assistance-as-needed algorithm and uses the pose of the upper body to calculate the assistance to provide the user [Carmichael and Liu, 2013]. As specific safety methods implemented for this application, the nozzle is attached to the tool with a mechanism that cannot be unintentionally released and the system has an inner and outer cover to protect components from airborne particles.

Some of the implemented methods are used as redundant safety means, to reduce an already acceptable risk level.

5 Conclusions

Safety is a topic undergoing intense study in the field of robotics and it is especially challenging in applications involving pHRC, due to the proximity of humans and robots. To improve safety, many techniques have been developed, but choosing which one to implement can be challenging. In this paper, a framework to help select those techniques is suggested: after identifying hazards and assessing the associated risk, the described methods can be evaluated, depending on their effectiveness in reducing the risk versus available resources. The resulting safety solution is a set of modules that together reduce the overall risk to an acceptable level. To validate the framework, this methodology has been applied to a grit blasting application of pHRC, with promising results.

As technological advancements continue, new safety methods will be designed and developed. In fact, only a few decades ago, people would have not been able to safely physically interact with robots. Safety techniques can be used to reduce the risks of technologies that can potentially improve quality of life, and a systematic methodology to integrate them will make the process more objective and fast. This framework is specially useful to highlight the direction that researchers should pursue to achieve safety in a robot system that physically interacts with humans.

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