Safety of Collaborative Industrial Robots

Certification possibilities for a collaborative assembly robot concept

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Abstract— **Industrial requirements for automation of small parts assembly operations are driving technology into the direction of scalable robotic automation, suitable for operation in shared environments with human workers and exhibiting highest flexibility and ease of use. One of the challenges is developing solutions for personnel safety under these conditions. This paper discusses both the presently viable approaches to risk assessment for collaborative robots and a more detailed future methodology that will be better able to resolve the relevant low-level injury risks.**

Keywords- human-robot collaboration; shared workspaces; personnel safety; ISO 10218; risk assessment

I. Introduction

Industrial robots have seen an extended period of huge success in the area of discrete manufacturing. The deployment of robotic applications has led to sustained advantages in product quality and economic efficiency. In many cases, unhealthy or hazardous work places are today operated by robots rather than human workers. With the possibility to freely program industrial robots for a large variety of applications, investments in robotic automation for flexible manufacturing environments have been very attractive.

On the other hand, flexibility requirements on manufacturing enterprises continue to grow even further, for example in the area of electronic consumer goods, which is characterized by very short product lifetimes and frequent production changeover. Complete automation of product assembly under these boundary conditions is economically prohibitive. In order for robotic automation to offer productivity benefits even in this environment, it must exhibit a new level of versatility. Among these new aspects is the need to operate robots in this environment without any traditional safeguarding measures.

The past decade has seen growing interest in the technology for and economic relevance of bringing humans and robots closer together in the manufacturing working environment [1], [2]. As flexibility requirements continue to increase, the optimal degree of automation will turn out to be less than 100% and the role of the human worker remains important [3], [4]. Due to their contributions to product quality and their inherent flexibility, industrial robots will also retain an important role in the manufacturing environment of the future.

Thus, for highest flexibility, we envision humans and robots working in a shared manufacturing environment, situated side-by-side or face-to-face with numerous interaction points between both (Fig. 1). Individual work places may be operated either by a robot or by a human worker, depending on the details of the current set of manufacturing tasks. There are no separating safeguards, neither of physical nor of sensory type, to guard against physical contacts between human workers and robotic workers. The collaborative industrial robots deployed in this environment must be harmless to the human worker in all situations. This means that they are characterized by a combination of design and control means to avoid or eliminate any risks of injury to their human colleagues.

In a focused effort, ABB has developed a robot concept addressing this vision [5]. This concept features inherent safety for its human co-workers, highest flexibility and ease of use in deployment and programming, and dexterity of handling skills making it suitable for assembly of small parts [6]. The concept system comprises a two-arm robot with its controller integrated into its torso (Fig. 2). Each arm has seven joints, allowing for collision-free access to objects even in a constrained working environment. Also, each arm includes a multi-tooled gripper, specially developed for the targeted applications [7]. The intended payloads are in the range of a few grams to a few hundred grams.

In this paper, we first summarize the safety concept we

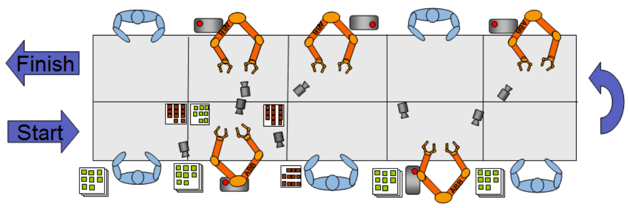

Figure 1. ROSETTA production scenario

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Figure 2. ABB dual-arm collaborative robot concept

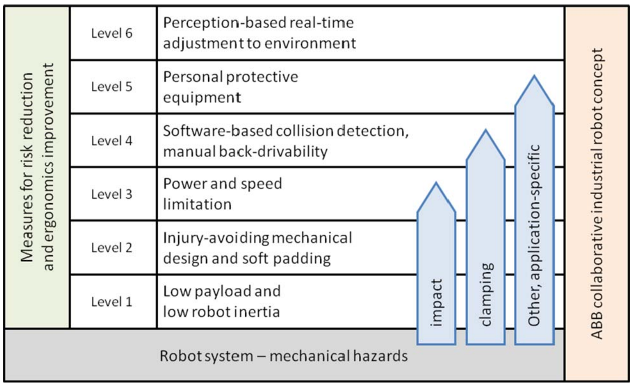


Figure 3. Structured safety of ABB collaborative robot concept

have chosen in the development of the harmless robot concept. Then, we describe our approaches to safety qualification of this industrial robot concept for assembly applications in shared workspaces.

This work consists of two separate efforts. First, as we are actively pursuing the safety certification of the robot concept according to present safety standards, we present our approach using common procedures for risk assessment. Second, in an effort to more carefully analyze the possible contact events between robot and human co-worker, we are participating in the EU-FP7 project ROSETTA [8], in which the classification and modeling of low-level injury mechanisms to soft tissues forms one of the main work packages. Once the results of this ongoing project are completed, more finely resolved risk assessments of collaborative robots and their applications will become possible.

II. Safety Concept

The safety concept rests on a combination of mechanical design principles for the manipulator and simple control measures to supervise the safe operation of the robot at all times. These design measures must eliminate the risk of injury to the human operator due to the following main hazards:

- Free impact between robot and operator, applies transient impact force to body part
- Clamping configuration where robot applies static holding force to body part
- Other application-specific hazards

The design measures and methodology we have applied in the concept design are the following (Fig. 3):

1) Mechanical measures
   a) Light-weight design giving a low-inertia robot, matched to the low intended payloads
   b) Ample padding on the surfaces of the manipulator arms combined with rounded surface geometries and joints without pinch-points
   c) Back-drivability of joints to enable operator to manually move manipulator, even against activated brakes
2) Control measures
   a) Control system functionality to limit power and speed of robot
   b) Model-based control function to detect collisions by monitoring motor currents
3) Other measures
   a) Special attention to specific hazards introduced by tooling and work pieces used in application (e.g. personal protective equipment such as safety glasses)

Fig. 3 also shows in a simplified way how the most relevant risks are reduced to harmlessness by the cumulative risk reduction effects of the measures applied. Note in particular that, while the major part of the risk reduction is handled by the mechanical measures of low-inertia design and padding, the last contribution comes from a controller-based supervision and limitation of the manipulator speed.

Using the structure of the safety architecture for our robot concept as shown in Fig. 3, we now turn to the issue of the risk assessment of the robot, as is required by the European Machinery Directive [9] and described in harmonized international standards [10], [11].

III. Risk Assessment for Collaborative Robots

The purpose of risk assessment is to supply guidance for the safety-related design of machinery. It is intended to derive in a systematic way the remaining safety-related shortcomings of a machine and focus attention on the most important points to address with measures for risk reduction.

For the development of our robot concept, we have considered risks as they have been identified by three main methods:

- A system-level analysis of failure modes and effects (FMEA) to identify safety-related failure modes

- A screening of all use cases established for our robot concept for safety-related issues
- Consideration of the standard risk lists for robots [12]

Fig. 4 gives a simplified view of the central role that the risk assessment plays in obtaining a safe design. The risk assessment evaluates the known and anticipated hazards associated with the operation of the robot and determines the severity of the associated risk for the operator. Whether or not a residual risk is acceptable is not a straightforward decision. The methodology used for this evaluation can differ and we present the two alternatives announced above.

A. Present Method of Risk Assessment

For the conventional approach, we follow the relevant guidelines in the standards ISO 10218 [12] and ISO 13849 [13] to determine the requirements on the implementation of the risk reduction measures used. To ensure a certifiable outcome, our development effort is accompanied by a notified body. We focus here on the main hazards named above.

The standard ISO 13849 offers a simple graphical method to determine the reliability requirements to be placed on risk reduction measures (i.e. safety functions) used in the design. It is based on assessing the basic properties of the hazard defined in Table I in a simple tree graph.

TABLE I. PROPERTIES OF HAZARDS FOR RISK ESTIMATION

Quantity in ISO 13849-1 Risk Tree	**Possible Values**
S – severity, with the possible values	S1 – slight, normally reversible injuries S2 – severe, normally irreversible injuries
F – frequency of exposure to the relevant hazards, with the possible values	F1 – rare F2 – frequent, constant
P – possibilities that the operator has for avoiding these hazards, with the possible values	P1 – possible under certain conditions P2 – scarcely possible

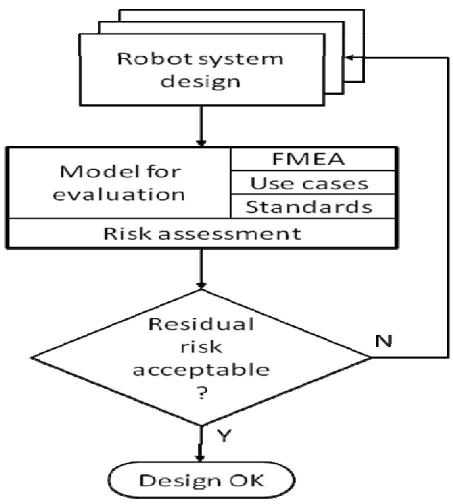


Figure 4. Simplified model of risk reduction in design

A traversal of a tree graph with the appropriate selections for S, F, and P will lead to a reliability requirement for a risk reduction measure. If the safety function used for the given case matches this reliability requirement, the risk is seen to have been adequately reduced.

1) Standard Industrial Robots

The reliability of the safety functions is referred to as the "safety performance level (PL)" and is ranked on a scale of PLa to PLe. Each of these levels corresponds to a certain range for the failure probability of the risk reduction measure [13].

For standard industrial robots, the above estimation generally results in a requirement of safety PLd, which corresponds to a probability of dangerous failure per hour in the range 10^{-7} to 10^{-6}, in other words once every 1142 to 114 years. This result mirrors the requirement for standard industrial robots as found in ISO 10218-1 in clause 5.4.2 [12] and is summarized in Table II.

TABLE II. REQUIRED SAFETY PERFORMANCE LEVEL FOR STANDARD INDUSTRIAL ROBOTS

Quantity in ISO 13849-1 Risk Tree	**Choice and Justification**
Severity of injury (S)	S2 – injuries are serious, normally irreversible
Frequency and/or exposure to hazard (F)	F1 – seldom and short due to safeguarding, fences
Possibility of avoiding hazard or limiting harm (P)	P2 – in general, little possibility of avoiding or limiting harm
Required safety performance level PLr	PL d – typical requirement for standard industrial robots (see also ISO 10218-1, clause 5.4.2)

2) Collaborative Industrial Robots

Our aim in the design of our robot concept was to obtain a harmless robot, i.e. one that cannot inflict injury on human operators. Assuming a single failure in our risk reduction measures, we have determined that the maximum possible injury severity corresponds to S1 in the risk evaluation tree.

Together with appropriate ratings of F and P, we obtain a result in our evaluation of the requirement on the safety performance level of risk reduction measures that is different from the case for standard industrial robots. This is summarized in Table III. Also, we illustrate this result as a traversal of the risk evaluation graph of ISO 13849 in Fig. 5.

Thus, the estimation for our collaborative robot concept results in a requirement for risk reduction measures of PLc. This corresponds to a probability of dangerous failure per hour in the range 10^{-6} to $3x10^{-6}$, in other words once every 114 to 38 years. This is compliant with ISO 10218-1 if we follow clause 5.4.3, which allows other safety performance levels than PLd if the risk assessment has shown that this is possible or required.

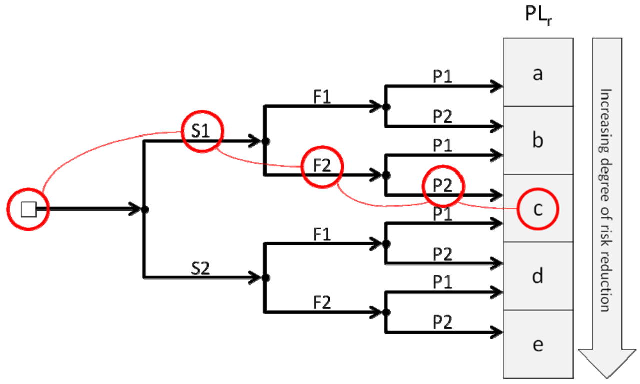


Figure 5. Traversal of risk graph for ABB robot concept

TABLE III. REQUIRED SAFETY PERFORMANCE LEVEL FOR ABB COLLABORATIVE INDUSTRIAL ROBOT CONCEPT

Quantity in ISO 13849-1 Risk Tree	Choice and Justification
Severity of injury (S)	S1 – injuries are slight, reversible, normally at most a contusion
Frequency and/or exposure to hazard (F)	F2 – frequent or continuous due to nature of collaborative application
Possibility of avoiding hazard or limiting harm (P)	P2 – in general, little possibility of avoiding contact events
Required safety performance level PLr	PL c – derived requirement for ABB robot concept (see also ISO 10218-1, clause 5.4.3)

An important consequence of this is that controller-based safety functions in the case of our collaborative robot concept require lesser implementation effort than is needed for PLd. Instead of fully dual-channeled safety functions, single-channeled implementations with a test function will suffice [13]. Existing controller architecture is more easily upgraded to the latter case.

It is very important to note that this reduction of safety performance level – when going from standard industrial robots to collaborative robots – hinges on the reliability of the estimation that possible injuries simultaneously go from S2 to S1 in their severity classification. Although this argument is solid from today's state of knowledge and it follows present standards, there is an obvious need to further substantiate the severity estimate. Some of the presently ongoing work in the EU-FP7 project ROSETTA [8] aims at providing exactly this increased level of understanding, as the next sections describe.

B. *Ongoing Work for Understanding Low-Level Injury*

Significant research effort has recently gone into the development of robots suitable for safe direct physical interaction with humans [14]-[17] and into methodology for understanding and classifying the possible physical effects of contact between these robots and their operators [18]-[20].

First approaches for rating a robot's hazardous potential by conducting crash tests with anthropomorphic dummy models consulted the Abbreviated Injury Scale (AIS) [21] to judge the severity of the relevant injuries. The AIS is a quick method for determining the severity and lethality of cases of serious trauma. It was originally developed for crash investigators to standardize data on the severity of motor vehicle related injuries. The AIS severity score, however, ranging from 1-6, is far too coarse to give any guidance for injury tolerance levels within human-robot collaboration scenarios. Any injury rated above a severity of AIS-1 is already far beyond what can be considered to be an acceptable residual risk.

Therefore, a new injury classification scheme and quantification method is needed to assess the low-level mechanical effects on the human body of the type that may occur with collaborative robots. Such a method, with the associated scale and threshold criteria for low-level injuries, such as contusions, could then be used to determine reliably if certain human-robot interaction cases pose an injury hazard. Research work in this direction is ongoing in the project ROSETTA [8].

C. *Structured Description of Human-Robot Interaction*

Before quantifying injury risks associated with collaborative robot systems, we need a systematic and comprehensive description of interaction scenarios. Such a description must focus on safety questions, i.e. for this analysis it is relevant how a robot moves in the vicinity of a human, but not which production task the robot actually carries out.

Starting with the risk analysis according to ISO 12100 [10] and ISO 14121 [11], the following items describe any human-robot interaction:

1) Limits of the machine
2) Lifecycle phases
3) Personnel involved
4) Activities carried out

When considering a contact situation, these additional items must be described:

5) Hazards encountered by the personnel involved
6) Contact areas on the human body
7) Injury scale to gauge the severity

In the following subsections we propose systematic descriptions of items 1 to 6. A conclusive result for a suitable scale on which to gauge low-level injury severity is not yet available.

1) Limits of the Machine

The limits of the machine consist of use limits, space limits, and time limits. Most parts of these descriptions are specific to the robot application, but are similar to those for traditional use of industrial robot cells. The important difference lies in the space limits: The physical workspace of the robot intersects the workspace of a neighboring operator (Fig. 1), who is continuously exposed to the moving robot, even if the robot motion does not directly interfere with the his production task. Consequently there is a higher likelihood of contact compared to traditional setups. Safety measures must therefore also consider means of softening collisions, since avoiding them will not always be possible.

TABLE IV. DESCRIPTION OF INTERACTING PERSONNEL

Role	Role Description	Worst unsafe interaction with robot
Visitor	internal or external visitors, coming to robot for single visit, uninformed about hazards	enters work range although advised not to, and is hit by robot resulting in any of the listed hazards (see below)
Other Worker	employees occasionally coming close to robot, without any particular assignment involving the robot	enters work range although advised not to, and is hit by robot resulting in any of the listed hazards; plus additional hazards such as electrical shock; his hazardous activities can be summed up under reasonably foreseeable misuse
Co-existing Worker	employees working physically in an overlapping workspace with robot; assignment does not comprise any interaction with robot	hits or is hit by the robot accidentally, resulting in any of the listed hazards
Collaborating Worker	interacts with robot (manipulator, end-effector, work pieces, fixtures, part tray, etc.) in regular operating mode	hits or is hit by the robot due to error in procedure or machine, resulting in any of the listed hazards
Service Engineer	interact with robot, reconfigure, repair and exchange and replace devices, reprogram, recalibrate robot and sensors, execute service routines	safety systems may be disabled, insulation protection may be removed; hit by robot resulting in any of the listed hazards; plus additional hazards such as electrical shock
Application Engineer	same as service engineer plus collaborating worker plus installation, introduce new production processes, decommissioning, retooling, switching on/off	interacts with robot when safety systems may be disabled; hit by robot resulting in any of the listed hazards; plus additional hazards such as electrical
Development Engineer	develop machine hardware and control, commission and test machine	safety system may be disabled or not working properly, unexpected behavior of robot is likely to happen during tests; hit by robot resulting in any of the listed hazards; plus additional hazards such as electrical

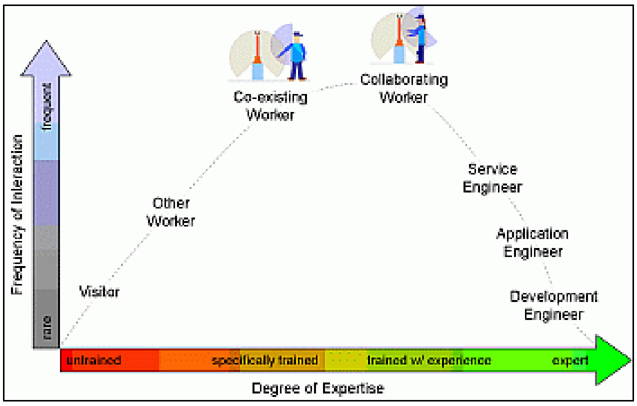


Figure 6. Roles of personnel, frequency of exposure and degree of expertise

2) Lifecycle Phases

The lifecycle phases of the collaborative robot application are considered to be the same as those for traditional robot applications. They range from setup, commissioning, production, decommissioning to dismantling. Production also includes retooling, maintenance and repair. Note that production of the robot and the cell equipment as well as disposal and shipping are not considered as lifecycle phases in the context of safety.

3) Personnel

An unfenced robot cell exposes personnel in the area to hazards associated with mechanical contact. In traditional robot cell setups, such a situation would be untenable and prevented by appropriate safeguarding. In a collaborative cell, however, we must consider this situation to be possible. Consequently we need a description of which person might be exposed to a hazard, what is his/her skill level and what is the frequency of exposure. A practical example of roles is shown in Fig. 6, with additional descriptions in Table IV.

4) Activities

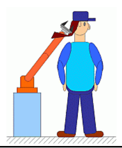
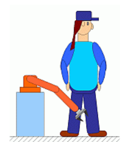
For our safety analysis, we have noted the worst unsafe interaction of each operator role with the robot in Table IV. Both intended use and reasonably foreseeable misuse are considered.

5) Contact Situations and Mechanical Hazards

Whenever there is a contact situation between the robot and a person, there is a risk of injury. Usually, there are additional mechanical hazards arising from the specifics of an application, e.g. tools and work pieces. We consider here, however, only the robot manipulator itself. In the ROSETTA project, these contact events between manipulator and human operator are studied using finite element models of the human body, optimized for the representation of the relevant injury types, to simulate such events.

Simplifying to the most relevant contact types and areas, we propose the classification shown in Table V. The risk assessment can now utilize an improved approach: Situations that can be studied by simulation are marked with 'S', others are marked with 'A'. The entry "n/a" indicates that this situation does not occur.

TABLE V. CLASSIFICATION OF CONTACT AREAS AND INJURY TYPES

Relevant Hazards, Injury Types	 Head and Neck	 Torso	 Upper Extremities	 Lower Extremities
Free Impact	S	S	S	A
Crushing, Trapping	S	S	S	A
Shearing	A	n/a	A	A
Cutting, Severing	A	A	A	A

The development of the simulation models for the behavior of soft tissue in the contact situations described is ongoing research. While the ROSETTA project has not yet brought forth criteria for judging these situations quantitatively, other approaches have already brought forth preliminary values in tabular or graphical form [22], [23]. Finally, although the present state of knowledge is highly dynamic, we must emphasize the importance of the ongoing efforts to develop a preliminary basis for the standardization of the safety requirements for collaborative robots [24].

Summary and Conclusions

Human-robot collaboration (HRC) in collaborative manufacturing settings requires a particularly detailed examination of injury risks. In this paper we have presented two approaches to the risk assessment for the relevant human-robot interaction scenarios. We consider these results as a first systematic step towards implementing safety in shared human-robot working environments and also as an input to new standards that will define HRC from the safety perspective.

Future work will aim at deriving the injury risk in contact situations from calibrated simulations, determining threshold values, and defining an injury scale. These results will be used for systematic assessment of the residual risk as well as for devising control and operation measures to ensure the safety of involved humans at all times.

Acknowledgment

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