Introducing a Morphological Box for an Extended Risk Assessment of Human-Robot Work Systems Considering Prospective System Modifications

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Abstract. *The concept of human-machine collaboration is regarded as key enabler for agile production systems as collaborative robots offer new forms of flexibility. Due to inherent safety functionalities, these robots can operate without physically separating safety devices and thus provide flexibility in task allocation and execution. However, changes on the work system require a new risk assessment due to the present normative regulations, which is a tedious task as feasible changes are usually not considered in the implementation phase. This paper presents the impact of modifications on collaborative robotic cells and how they influence the risk assessment. Furthermore, a method of considering work system variants based on desired future modifications is presented so that implications can be already identified in an early design phase of the system.*

1. Introduction

Robot safety constitutes a key factor in human-robot working systems [1]. Currently, every manufacturer or integrator of a collaborative robotic application must place its application on the market in accordance with Directive 2006/42/EC (Machinery Directive) of the European Parliament and of the Council Among other things, this stipulates that the basic safety and health protection requirements listed in Annex 1 of the Machinery Directive must be met. Annex 1 of the Machinery Directive, under *General principles*, and also the ISO 10218:2012 standard requires that the manufacturer of a machine or his authorised representative must ensure that a risk assessment is carried out. This ensures that the safety and health protection requirements applicable to the machine are determined and that the machine is designed and built taking into account the results of the risk assessment. In this process of risk estimation and risk reduction, the limits of the machine, the intended use and the reasonably foreseeable misuse are determined.

In practice, EN ISO 12100:2010 (Safety of machinery - general principles for design - risk assessment and risk reduction) is often used as a method of carrying out a risk assessment. Using this methodology, the hazards that can arise from the machine are identified. The associated hazardous situations and the risks are estimated by also considering their severity of possible injuries or damages to health and the probability of their occurrence. The risks are then assessed to determine whether a risk reduction measure in accordance with the objectives of the Machinery Directive is necessary. If so, the hazards are eliminated or reduced by applying protective measures while in some circumstances organizational measures might be necessary. However, ISO 12100 is a type A standard meaning that methodologies described in its content are applicable for a very wide range of machinery and not necessarily specific to the application of robotic applications. Thus, EN ISO 10218-2, a type C standard, is in place. Section 4 of this document gives a risk assessment scheme that is specifically refined for robotic applications (under consideration of ISO 12100 and other related standards). Topics such as the design, manufacture, installation, operation, maintenance and decommissioning of the industrial robot system or cell are addressed. The basic hazards and hazardous situations for these systems are identified and requirements are defined to eliminate or sufficiently reduce the risks associated with these hazards.

The structured process from the Machinery Directive down to the EN ISO 10218-2 shows that every safety-relevant change of the application requires a renewed risk assessment, unless this has already been considered in the original assessment. New risk assessments on an already existing work system might make required modifications impossible due to limited flexibility in the design or re-design. However, in order to consider safety-related changes in the original assessment, prospective modifications and thus system variants have to be considered in an early design phase. For this approach, however, the link between modifications and safety-related aspects is not yet clearly explored.

Even though, the Technical Specification for collaborative robotic applications, ISO/TS 15066:2016, presents a correlation of the applied robot's safety mode and the system's respective safety-related changes, the safety mode is only one of many safety-relevant modification dimensions within human-robot work systems [2]. Further, it shows drawbacks in applying the proposed safety measures, especially when integrating heavy industrial robots or sharp objects or estimating the human approach velocity [3]. Additionally, there is no advice considering the robot's movement predictability due to collision avoiding path planning or varying task allocation patterns.

As safety modes might not be an appropriate classification scheme for the identification of safety-relevant changes, new classifications schemes have been introduced, such as in [4, 5]. However, after an extensive literature review, [6] came to the conclusion that classification schemes for collaborative human-robot work systems are not applied consistently, which may lead to an incorrect identification of safety-relevant changes. To counteract this, model-based approaches have been developed either based on formal mathematical models, such as in [7], or based on simulation models, such as in [8]. A risk management simulator was for example introduced in [9], whereas [10] introduced a task-based characterization of human-cobot safety. Further, a metric depending on the distance between robot and human as well as the robot's structure was introduced in [11].

However, none of the proposed approaches considers a mutual influence of modifications on safety. In this sense, a structured procedure with the aid of an Morphological Box (MB) was developed and is described in detail in the following paper. The proposed approach should support manufacturers and system integrators in the consideration of safety-relevant changes in an early design phase of the planned collaborative human-robot work system including its prospective modifications.

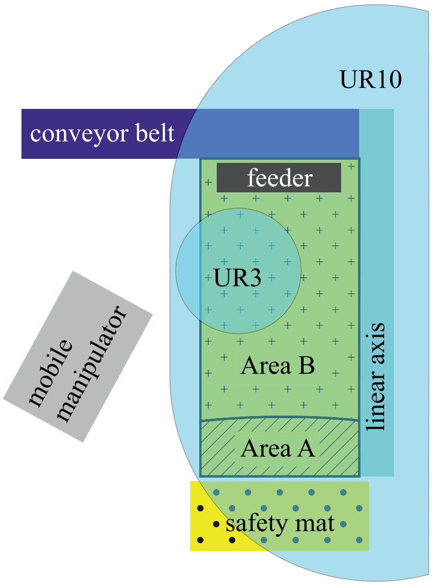

Figure 1. Structure of the workplace.

2. Impact of Modifications

Within the DR.KORS project on dynamic reconfigurability of collaborative robotic systems, 50 dimensions of modifications were identified directly influencing the safety of a human-robot system. The modification dimensions can be classified in workpiece, end effector, contact points (between human and robot), speed / acceleration, task / workflow and operating conditions / change of place. The impact of modification dimensions will be presented on a laboratory use case example for assembling rocker levers.

2.1. Use Case Description

In the laboratory use case rocker levers consisting of three separate components are assembled with a collaborative human-robot work system. Adjusting bolts are mounted on two separate rocker levers which are then assembled on a trestle. At this point, the positioning of the rocker levers on the trestle needs manual dexterity as the components tilt easily. Rocker levers and trestles are provided either by feeders or on a conveyor belt. The manipulation, screwing and storing tasks are allocated between four resources, i.e. human, two robots and a mobile manipulator. The work system is designed in a way, that the position of peripheral appliances is variable and safety devices can be changed. Hence, the collaborative work system consists of (a) a Universal Robot UR10 on a linear axis for workpiece handling, (b) a feeder and a conveyor belt for workpiece supply, (c) a Universal Robot UR3 for workpiece assembly, (d) a human operator for workpiece assembly and workpiece removal, (e) a mobile manipulator for workpiece manipulation and (f) external safety devices, such as light curtains and laser scanners, for person safeguarding. See Figure 1 for the layout sketch of the workplace.

2.2. Modification Dimensions in the Use Case

The laboratory use case offers the possibility of 13 modification dimensions, which either influence the layout, the task allocation or the motion parameters of the involved resources.

- **Product:** Two different products can be assembled on the work system - either in mixed or unmixed production. The change of the assembled product influences the workpiece supply, the task allocation as well as the motion paths of the robots.
- **Position during collaboration (end effector height):** The end effector height indicates the position where human and robot assemble the product at the same time. It can be changed according to the ergonomic height of the operator.
- **Position during collaboration (robot base position):** The Universal Robot UR10 is mounted on a linear axis so to easily change its base position. This might be necessary due to reachability reasons when the layout of the work system changes or when new collision points arise on the anticipated robot paths due to changes in the task allocation. A choice of the robot's base position during the collaboration is possible and influences the sensitivity and stiffness of the arm due to the according robot posture.
- **Resource allocation for trestle feed:** The supply of workpieces can either be implemented in terms of a feeder, directly coming from the previous manufacturing machine on a conveyor belt or by a human operator. The change of the supply unit influences not only the layout of the work system but also the robot paths and optionally the resource allocation (depending on the picking requirements).
- **Resource allocation for screwing:** The screwing process can be either done by the Universal Robot UR3, by the human or by the mobile manipulator. A change in resource allocation for a specific task influences the temporal and spatial proximity of humans and robots and thus may influence the safety concept.
- **Safety function:** The safety function can either be implemented as force limitation or as distance monitoring. Based on the safety function, the safety devices are defined as well as the layout of the work system in terms of space requirements and the motion behaviour of the resources.
- **Type of safety device for distance monitoring:** The distance monitoring can either be implemented by a separating safety fence or by non-separating safety devices such as light curtains, laser scanners, safety mats, software-based workspace limitations or a combination of those.
- **Position of safety device for distance monitoring:** Depending on the type of safety device and the space requirements of the work system, the mounting distance of the safety devices is defined and thus the velocity of the robots. In general these safeguarding distances are regulated by the standard ISO 13855:2010 - Positioning of safeguards with respect to the approach speeds of parts of the human body.

Modification dimensions lead to system variants of a use case which are necessary for the flexibility of a collaborative work system. In order to already consider desired variants of a human-robot work system in the planning and design phase, a Morphological Box is introduced.

3. Morphological Box

A morphological analysis is a creative heuristic method introduced by the Swiss astrophysicist Fritz Zwicky which is mostly applied for fully understanding complex problem areas and considering all possible solutions without prejudice [12]. The resulting

Modification dimension		Parameter value				
Product		A	B	A&B		
Position during collaboration - end effector height		$h_{\min} \leq h_{\text{col}} \leq h_{\max}$				
Position during collaboration - robot base		$p_{\min} \leq p_{\text{base}} \leq p_{\max}$				
Robot velocity		$v_{\min} \leq v_{\text{rob}} \leq v_{\max}$				
Resource allocation trestle feed		human	by UR10 from feeder	by UR10 from conveyor belt		
Resource allocation insert screw		human	screwdriver	UR10	CHIMERA	
Resource allocation tighten screw		human	screwdriver	UR3		
Area A	Safety function	force limitation	distance monitoring			
Area A	Type of safety device for distance monitoring	safety mat	light curtain	laser scanner	software	CHIMERA laser
Area A	Position of safety device for distance monitoring	$< d_{\text{safe}}$	$\geq d_{\text{safe}}$			
Area B	Safety function	force limitation	distance monitoring			
Area B	Type of safety device for distance monitoring	safety fence	light curtain	laser scanner	software	CHIMERA laser
Area B	Position of safety device for distance monitoring	$< d_{\text{safe}}$	$\geq d_{\text{safe}}$			

Table 1. Morphological box indicating modification dimensions in the lab use case.

solutions are aggregated in a so called Morphological Box (MB) representing specific attributes and their individual characteristics. This multi-dimensional matrix maps all possible solutions by combining one characteristic for each attribute.

With the assistance of a MB, a far-reaching risk assessment can be carried out to clarify whether a new risk assessment (or even a new risk estimation) must be carried out when modifying the robot system. To be able to make this decision, a distinction must be made between changes that have been considered in advance and changes that have not yet been assessed.

One possibility for a considered change can be, for example, the storage area, which was defined in advance as an area and does not focus on the required storage point as is traditionally the case. This enables the MB to check whether the changed placement point is within these defined limits by comparing coordinates and to provide the operator with clear information as to whether a new risk assessment is necessary. The maximum safe speed can be used as a further example. During the application definition, the considered speed is not the one required for the process, but the maximum safe speed. This has the advantage that a change can be evaluated using the MB with the additional parameters that are now available. These two examples show, that already during planning and integration the safety assessment must be implemented in the process via the MB to be able to make practical comparisons in everyday life. Furthermore, it becomes apparent that simple changes can be clarified clearly and efficiently, whereas complex changes require a thorough examination using mathematical models that support the MB. An example with a much higher degree of complexity is the change of a possible contact point between humans and robots. These must be verified and validated in accordance with ISO/TS 15066:2016 point 6 or tested and measured in accordance with EN ISO 10218-2:2012 Annex G.

Due to the complexity of such changes, the MB can be used to conclude that a new risk assessment is required. During such a reassessment, the MB can provide support by showing specific dependencies that need to be considered for the reassessment in the risk assessment, e.g. the system limits of the gripping technology, the change in the permissible force/pressure values due to the shifting of the contact between human and machine. When using the MB, such restrictions can only be prevented by determining all relevant modifications in the planning phase to cover the broadest possible range.

In this sense, the MB presented in this paper indicates desired and possible modification dimensions for a specific use case. Here, the modification dimensions represent the attributes while the parameter values represent the characteristics. By combining specific parameter values for each modification dimension, different system variants of the use case can be defined. In contrast to conventional morphological

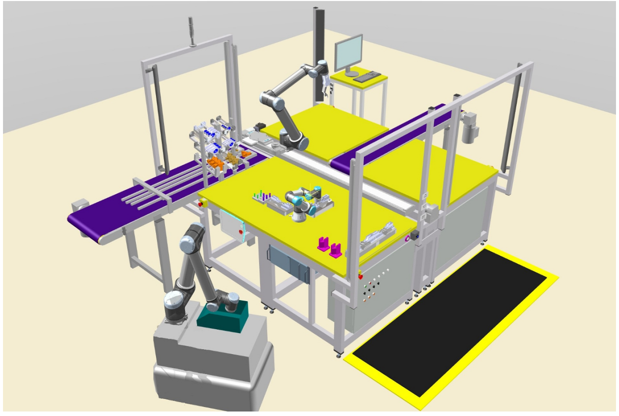

Figure 2. Simulation of the lab use case in ema Work Designer.

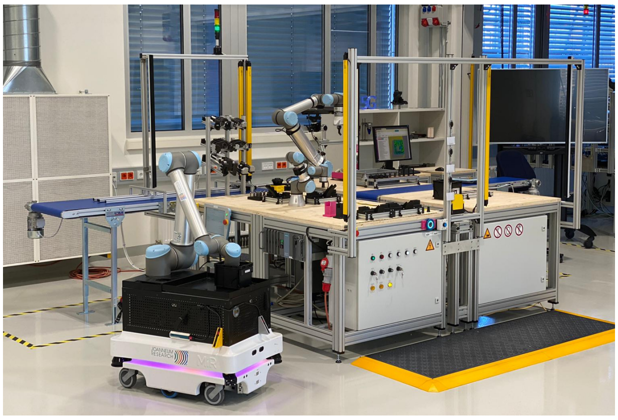

Figure 3. Setup of the use case in lab environment.

boxes, the MB in Table 1 allows for multiple selections within specific modification dimensions. In this example, the type of safety device for distance monitoring allows for combining different devices for one system variant.

For example, one use case variant could be defined as follows: The product type A of the rocker lever is assembled in the work system. The collaborative task of positioning the levers on the trestle is done in an ergonomic height for an operator. Trestles are supplied by a feeder and manipulated by a UR10. The insertion task of the adjusting bolts is carried out by the human while the tightening task is done by the UR3. The velocities of both robots is set to 500 mm/s. The safety function in both areas A and B is based on force limitation and distance monitoring by software-based workspace limitations. The distance between robot base and operator should be as large as possible during the collaboration.

3.1. Represented System Variants

The main effects on personal safety resulting from the selection of system parameters via MB are described in the following.

Impact of Resource Allocation The modification space related to the given resources spans all possibilities between manual processing to an almost fully automated scenario. Special safety considerations are relevant for those cases where a robot is allocated to a task. For this purpose, all boundary cases must be evaluated separately for e.g. critical contact situations, safety distances as well as force and pressure impacts on the involved body regions of the human. This can lead to restrictions which are stored as a set of rules for a partially automated assessment.

Impact of Safety Device Several extrinsic safety devices listed in Table 1 are exchangeable, e.g. whether a light curtain or a laser scanner is used for distance monitoring is usually irrelevant. However, the plane used to determine the safety distance has a significant influence on permissible distances and the velocity to the moving robot. Horizontal measuring safety devices, such as a safety mat or a laser scanner on a mobile manipulator, have a substantially different information content than vertical devices such as a light curtain. In contrast to horizontal safety devices, vertical safety devices have a higher uncertainty in determining the location of humans. However, a safety mat can be partially skipped by a human, whereas a laser scanner mounted on a mobile robot system, can be used in variable locations.

Impact of Workpiece Supply The feeding of the workpieces mainly influences mechanical safety characteristics, which can be determined by means of a risk assessment. Therefore, the type of the feeding system has no significant effect on the safety related system variant.

3.2. Simulated and Experimental Setup

The virtually designed and simulated laboratory use case is shown in Figure 2, whereas the physical setup of the use case is shown in Figure 3. All required modification dimensions were taken into account, which gives the impression that unnecessary redundancies exist especially for the listed external safety devices. However, these allow us to perform specific studies on meaningful combinations of safety devices and a direct and detailed comparison between them.

In order to assess the effects of modifications on the system, different configurations of the setup are analyzed. Quantitative differences, such as cycle and operating times of the resources are obtained by simulations in ema Work Designer. In order to validate the presented method for safe system modification, four different variants were implemented on the real plant to cover a wide range of variation possibilities. The parameters of six modification dimensions were varied, specifically the product, the resource allocation (trestle feed, insert screw, tighten screw), the position of end effector height and the robot base during collaboration. Significant safety-relevant influencing factors such as speed of the moving robot parts, safety distance, vulnerable human body parts, number and duration of exposure to hazards can thus be assessed.

4. Conclusion and Future Work

Collaborative work systems in an industrial context are currently limited if changes need to be taken into account regularly. Although robot programming of modern sensitive robots is aimed for users with limited programming skills and becomes more and more sophisticated, safety regulations limit this flexibility. An advanced structured approach for safety assessment, as described in this paper, enables safe implementation of modifications to a known extent. Future work will include an extensive comparison between simulated system modifications and modifications on the real experimental setup. Furthermore, qualitative differences, e.g. in terms of perceived physical workload for the operator will also be analyzed.

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