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Procedia CIRP 00 (2021) 000–000

www.elsevier.com/locate/procedia

15th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Gulf of Naples, Italy

A method to enhance the flexibility of collaborative human-robot workspaces through an extended safety perspective

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Abstract

For the adaptation of a process in a flexible production environment, robotic systems are basically a suitable option to ensure the required agility. In case of a human-robot work system, however, the flexibility of a robot is currently severely limited due to safety reasons; therefore, new tasks for the robot can only be implemented with significant additional effort. In this paper we present a method for the flexibilization of collaborative robot applications within the constraints of robot safety as defined by ISO/TS 15066. We will show how an in-depth analysis of foreseeable tasks during the start-up phase of a collaborative human-robot work system provides the basis for both, a flexible as well as safe use. An expert system and suitable mathematical models ensure these modifications of tasks and changes in the workplace can be automatically evaluated in terms of safety. As a result, even non-safety-experts can make modifications and operate the system without imposing additional risks.

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1. Introduction

Human-robot collaborative workplaces differ significantly from conventional industrial robot cells. To enable a temporally and spatially shared workspace between humans and machines, robot systems are operated without any physically protective safety devices (e.g. fence or light curtains). This enables direct interaction and cooperation, but at the same time exposes the worker to the risk of being injured by the robot system. Nevertheless, harsh requirements in robot safety standards still inhibit the acceptance of human-robot applications. According to the standard ISO 10218:2011 [1] for human-robot collaboration (HRC) four specific modes of operation are accepted. The goal of the collaboration mode "power and force limiting" is to reduce the risk-level of potential mechanical hazards caused by unintentional and sometimes unavoidable contact situations between a human body part and a moving part of the robot. To meet this requirement, robot parameters such as the programmed trajectory speed or the force threshold for triggering a protective stop are defined accordingly so that a person's pain onset threshold is not exceeded on contact at any time. On the other hand, this limitation also restricts the flexibility of the robot system decisively, which means that adaptation to a new task requires time and money. However, according to the EU machinery directive [2] risk assessment processes have to be revised whenever any modification of the robot system is performed, here the harmonized robot safety standard ISO 10218:2011 can be applied.

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This paper presents the research results from the DR.KORS[1] project. The project addresses the goal of using robot systems both without physically separating protective devices and as a flexible production system. This means that specific modifications are permitted in a collaborative robot system. Normatively and legislatively, any modification to the robot system requires a new revision of the existing risk assessment to validate that the specific machine modification has no comprehensive safety impact on operation. It is precisely this requirement that is to be relaxed by the research results obtained. Automated safety assessments in combination with clearly structured verification processes were conceptually developed in the project and evaluated in application scenarios by industrial project partners.

2. General approach

Since safety modes are not a suitable classification scheme to describe safety-relevant modifications within a human-robot work system due to the limited or even not considered mapping of system variability [3], a classification scheme was developed. In addition, classical classification schemes for temporal and spatial synchronization of both resources in human-robot work systems have often been used or interpreted incorrectly, leading to incorrect identifications of safety-relevant modification dimensions [4]. For the safety assessment of prospective modifications in human-robot work systems, what is needed above all is a form of representation that also considers all possible system variants, which can be created on the basis of a planned modification. In the perspective of risk assessment this means that according to ISO 12100:2010 [5] also all newly arising forms of intended machinery use as well as foreseeable misuse scenarios have to be considered.

2.1. Representation system variants

In this context, a method based on a morphological box was developed for this purpose [6]. A morphological box is a creative heuristic method developed by the Swiss astrophysicist Fritz Zwicky to understand complex problems and to consider all possible solution variants without prejudice. The morphological box thereby includes all solutions of a specific problem by representing individual attributes of the solutions with their respective characteristics. This representation then signifies all possible solutions by combining attributes and the respective properties.

The process model presented in this work is implemented in software and divided into two phases: the planning phase and the operational phase. In the planning phase, the morphological box is filled in by the manufacturer, integrator or marketer and thus sets the basis for the later evaluation and possible system boundaries. For this purpose, it is necessary to specify parameters describing the respective working system and to define known modification dimensions and their safety implications. This definition ensures that all possible decisions, e.g. how wide a workpiece/product storage area is selected, how comprehensive the product spectrum will be or which safety concept will be used, always conform to the corresponding directive and all required protection goals are met.

The next step is the operational phase, in which the manufacturer or plant operator defines the planned modifications and possible effects are evaluated by our software framework ADJUST (see 3.1). This process is divided into three sub-processes, i.e. recording of the desired modification via the morphological box, processing of the input values of this modification and output of corresponding instructions for action to ensure personal safety during the implementation of the corresponding modification. Within the scope of recording the desired modification, the manufacturer or plant operator selects the modification dimension from the morphological box and fills in the required test values, e.g. the new product weight, the new deposit position, the changed safety distance.

2.2. Risk assessment of prospective system variants

For the risk assessment of work systems with human-robot collaboration and for maintaining the inherent flexibility of such a work system, the consideration of prospective system variants in the context of a risk assessment is essential.

Model-based approaches for risk assessment of human-robot work systems have already been developed, based either on formal mathematical models [7] or simulation models [8]. A simulator for risk assessment was also developed [9]. However, the aforementioned approaches do not consider the mutual influence of relevant modifications on personnel safety. For this reason, a procedure model for risk assessment of prospective system variants based on the morphological box with the representation of prospective system modifications is needed.

In the evaluation phase, the input values of the morphological box are first checked using a stored logic for risk assessment of the desired modification and the existing dependencies. First, the modification dimension is determined and then the applicable variance. This leads to the comparison values, which were already determined during the approval. Many aspects are included in this evaluation, which concern, among other things, the individual application requirements, the change impact, the hazard potential, the conditions of use and the current life phase of the application. Accordingly, the measures taken can have an influence on the safety concept or, for example, the biomechanical limit values. The implementation of the action instruction by e.g. a risk analysis requires a large amount of expert knowledge.

[1] www.dr-kors.at (project website)

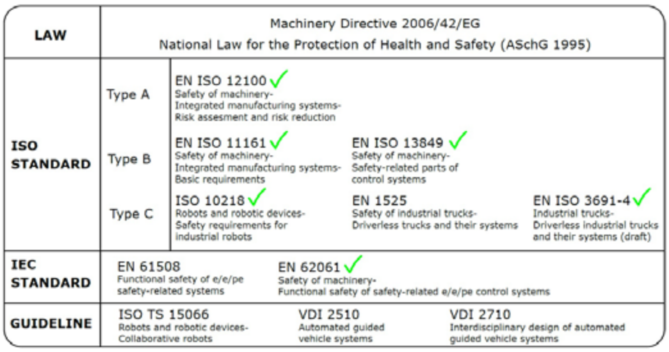

Fig. 1. Overview of standards within human-robot collaboration.

3. Automated assessment of modifications

An automated assessment of a modification to the robot system requires a suitable software, which must combine the digital twin of the plant and expert knowledge.

3.1. Software framework ADJUST

ADJUST is a framework for supportive safety assessment of human-robot applications. The ADJUST software basically has two main objectives. First, it determines whether the operation of a modified application is possible in a safe manner. In this context, safe means that the specifications from the corresponding standards for the respective robot application area, such as ISO 10218, ISO/TS 15066, ISO 13855, etc., are met (see Fig. 1), as well as the EU Machinery Directive. The documents indicated with a green check mark are harmonized with the EU Machinery Directive. This means that by complying with the standard, the requirements of the Machinery Directive (i.e. the law) are also automatically fulfilled. Furthermore, an insight into the quality of a modification, i.e. a specific comparison of a modified system with the current system state, is assessed.

The software framework is capable of evaluating modifications (note: selected modification dimensions) of an application for their permissibility on the basis of the stored models. This evaluation provides information on whether an application can still be considered safe (with regard to the considered modification dimensions) after a modification or not. Depending on the informative value of the stored models, in addition to the binary evaluation, further suggestions for improving safety and/or possible further modification suggestions can also be output in the evaluation.

To support the process of safety assessment during application changes, ADJUST is used throughout the lifecycle of an application. The basic process of an application modification follows the cycle: Plan, Test, Review. Hence, to move from an application in version N to version N+1, modifications must be planned, tested, and reviewed. In the planning step, models of the application are modified with respect to the modification requirements. These models are then subjected to tests, the results of which must be evaluated for safety-related aspects. This process can be performed iteratively until a planned modification is evaluated as (sufficiently) safe. Only after this approval the real application can be modified to the new version. The life cycle of a use case in ADJUST:

1. When the system is changed, the user modifies the input parameters (model inputs).
2. The configured continuous integration (CI) pipeline checks the modified inputs against the models.
3. If the check is successful, the modification can be implemented.
4. If the check fails, additional manual steps (e.g. adaptation of the change, process evaluation, risk assessment, etc.) must be taken. The results of these steps serve as input for the next run of the CI pipeline.

3.2. Continuous integration (CI)

In the context of software development, the process of continuous integration (CI) is well established. The aim here is not to integrate program changes collectively into an existing system after the completion of new or changed features, but to integrate them continuously during development. This process is based on the idea that small changes are easier to integrate into a system than large ones. Another advantage is that (integration) tests can be carried out not only at the end after a complete integration, but already during the development, so that errors can be detected earlier. However, for such a process of continuous integration to be accepted and designed efficiently, it must be possible to automate it as far as possible. Any CI platform can be used for this purpose and its environment typically consists of the following components:

Version Control System (VCS) In principle, any files can be versioned with such a system. For ADJUST, the VCS is used to version the model changes and also offers the possibility to manage different version strings (development branches) in parallel, see Fig. 2 for an example of a modification sequence with a valid version branch. Every change in this branch represents a stable, positively evaluated version of the application (purple). If an application modification is now to be made, a new version branch is opened (modification A or modification B). When all changes have been made and the evaluation is positive, the version branch can be merged with the stable branch and the next modification can be started.

Continuous Integration Pipeline The process is divided into several phases that build on each other. In each phase, any number (>0) of ADJUST software architecture tasks can be executed. The individual tasks can access data from previous

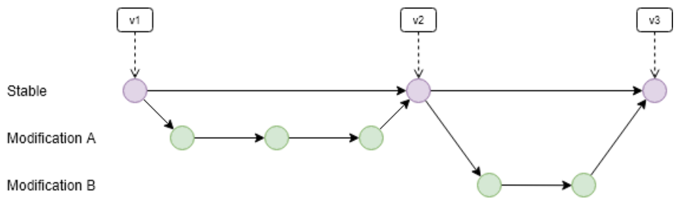

Fig. 2. Example of the use of development strands.

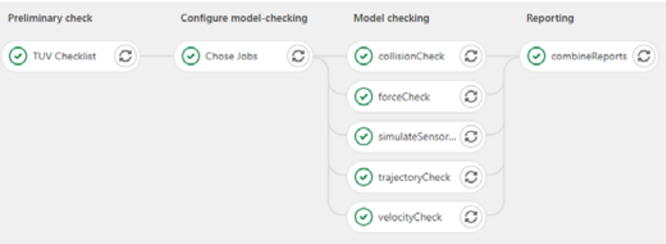

Fig. 3. Evaluation process of an application in GitLab.

phases and process them further. This generic structure, as shown graphically in Fig. 3, is as follows:

1. Preliminary Check: Decisions are made as to which subsequent steps can be carried out manually, and which can be automated.
2. Configure model checking: The results of the 1st phase are processed and it is determined which subsequent steps must actually be executed and which can be skipped (e.g. because the data have not changed or have changed to a more favorable case).
3. Model checking: Automated calculations are performed and models are checked.
4. Reporting: The results of all tasks are summarized and offered for download.

Each evaluation module of ADJUST is represented as a task. The only technical requirement for a task is that it can be executed (and thus automated) from a command line. Tasks have access to all data of the VCS. In ADJUST this means to all defined models (see Sec. 4). All data is available in the models so that the evaluation module can be executed. Each module defines for itself which models it needs and how they look like. It is up to the user to provide these models in the first steps of ADJUST. In order to avoid unnecessary complexity in the creation of a demonstrator and to remain flexible in the development of the evaluation modules, we refrain from defining a global model that could serve all evaluation modules. This can be done in a future development stage when the functionality of the assessment modules has been sufficiently tested and demonstrated. How the specific models should look like will be defined during the development of the respective evaluation modules.

In addition, there is also the possibility that tasks generate data and make it available to the tasks of the subsequent stages. This is necessary, for example, for the creation of the report. Each evaluation module makes its assessment report available to the task for creating an overall report.

Continuous Integration Runner The CI pipeline does not execute the tasks directly, but forwards the tasks to CI runners that are responsible for their execution. This allows the execution of tasks to be decoupled from the actual CI system and offloaded to systems with different hardware, operating systems, or software configurations. In ADJUST, this mechanism is used to offload computations to computers that, for example, have a required simulation program installed, or have hardware with graphics acceleration.

4. Modelling

The automated assessment of modifications to a robot system is based on mathematical models that represent an image of the influencing factors as realistic as possible. Essential models for an evaluation are:

- Risk assessment of prospective system variants
- Collision check between the robot arm and the environment during a movement
- Estimation of the contact force between a human and the robot during a collision
- Information content of external protective safety devices
- Motion path of the end-effector
- Verification of the velocity of all moving parts of the robot system

For some of the requirements above, useful methods are available in many simulation tools. However, the risk assessment of prospective system variants as well as mathematical models of external protection devices and possible contact forces between humans and robots are needed for an automated assessment of safe modifications.

4.1. External protective devices

In principle, a distinction can be made between two cases for ensuring personal safety. The first is the complete avoidance of a contact situation by safeguarding danger points with external protective devices or resource allocation. The other is to ensure that the contact forces and pressures do not exceed the specified limit values in the event of a collision between a person and a robot.

In order to prevent general contact between humans and robots, external protective devices are required to ensure that no human is present in the hazardous area or enters it. Modifications to the protective devices can open up opportunities to enter the danger zone without being detected. To clarify these cases, a virtual representation of the area to be monitored is created on the basis of geometric models and it is investigated whether the area can be monitored safely even after an adjustment of the sensor system (modification of the sensor parameters and its pose). Decisive for the assessment is the area covered by the sensor and the spatial and temporal resolution, resulting in an information content of the environment, indicated in Fig. 4. The modification of resource

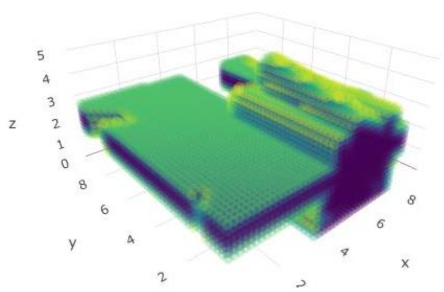

Fig. 4. Representation of the information density in the workspace.

allocation is relativeley simple if done within the context of safe reconfiguration limits. The human interaction with the system is reduced by the transfer of resources from the human to the robot, the potential for danger is drastically reduced. However, if a work step is transferred to the human, it must be ensured that the work area and the interaction between the human and the overall system is carried out safely.

4.2. Contact model for interaction of robots and humans

In order to obtain an analytical solution for the contact force between human and robotic system that relates the velocity of the contact point at the time of impact to the maximum or peak impact force, a nonlinear dynamic model is first replaced by a linearized model. The model obtained in this way is a system of linear ordinary differential equations. Then, this linear model is projected onto the direction of the contact force, resulting in a second-order inhomogeneous ordinary differential equation. An analytical solution for this model relating the impact velocity and the peak impact force. To validate the assumption that the linear models presented are good approximations for the nonlinear model, the predictions of the peak impact force for all models presented are compared for the case where the robot control is known. The latter assumption is crucial since this is often not the case. Finally, in order to predict the peak impact force for the case of a real robot where the control system and the mechanisms of contact detection and response are not known, a machine learning approach was chosen and an artificial neural network in terms of a boosted decision tree approach was used [11].

5. Multidimensional modifications

Safety assessments are generally performed by evaluating one or more characteristic system parameters. These are evaluated according to a fixed scheme (risk assessment process). The assessment is such that risks whose assessment level is above a defined acceptable residual risk must be mitigated by appropriate measures.

If changes and modifications are now generally permitted, their impact must also potentially be considered in the risk assessment. In the case of one-dimensional modifications, this is still feasible for applications with manageable complexity. The developed ADJUST framework narrows down the requirement of a reassessment and can specifically support the verification engineer in the reassessment of hazards associated with the modification.

If multidimensional modifications occur, the effect on the level of a hazardous situation to be reassessed cannot be traced back (or only with great effort). Especially under the presence of dependencies (in whatever form) the corresponding impact on the system behavior by multidimensional modifications often behaves dramatically. A corresponding formalization can only be done by strict modeling of the influence parameters and the determination/estimation of corresponding sensitivity coefficients. Potentially, approaches from system theory, which deal with the effect of multiple errors and the concatenation of errors, can be applied in the future and adapted for robot systems.

A multidimensional system modification arises from a non-unidirectional state motion in the parameter space of the system. The parameter space with respect to the modifiability (which also define the dimensions of the modification space) are to be seen as a subset of the complete parameter space of the system. Therefore, the modification space contains only those parameters which result in a reasonable variation of the original system, as defined according to the system specification. In the case of multidimensional modifications, several types can be defined.

Functional dependencies exist when modifications are directly or indirectly correlated with each other. This means that a change of a parameter in a modification dimension is directly connected with the change of one or more other parameter(s). The dependency is strictly deterministic and functionally unambiguous. In general, a modification parameter can be under control of the user or change independently directly by mentioned correlations.

Physical dependencies are given by physical regularities thus statically not changeable dependencies between parameters. However, the correlated parameter cannot be manipulated specifically from the outside. For example, the mass and dimension of a component manipulated by a robot are statically, physically dependent on each other (as long as the density and homogeneity of the component material does not change).

Dependencies due to parameter variations are smallest multidimensional modifications that are given by system variations and deviations from optimal system implementations. The effects of this influence can be evaluated by the sensitivity coefficients of the respective dependency.

Application specific dependencies are given by the technical functional specification of the considered system. These can be realized by corresponding hardware or software components. Parameter modifications in the defined modification dimensions are to be seen as inputs of the implemented functions and can be linked by the given functional dependencies.

Temporal dependencies are given by the temporal variability of dependency variables. Deterministic temporal variability can be formulated by complex modeling using temporal logical statements. The situation is more difficult, if the temporal variability, and in particular their dependence, is not constant and/or deterministic.

A distinction can be made between different types of correlations: Direct correlations, in which an event (in this case a system modification) directly influences another event or several values, and indirect correlations, in which effects can be chained but consequences are not directly related. A reciprocal correlation exists when an increasing expression in modification A results in a decreasing effect in modification B. For a correlation measure, the so-called Pearson product-moment correlation coefficient can be used. It is a normalized and dimensionless value between -1 and 1. The limits of this range represent total correlation (reciprocal or direct) or uncorrelated [10].

6. Experimental Results

To illustrate the effect of safety-relevant modifications, a lab use case was implemented (see Fig. 4). In this use case, rocker arms are assembled, consisting of three separate components. Adjusters are first attached to two individual rocker arms and then mounted to a trestle. Positioning the rocker arms on the trestle requires a high degree of manual dexterity, as the individual parts tilt easily. Rockers and trestles are supplied either by magazines or conveyor systems in the work area. The individual assembly, screwing and storage activities can be assigned to four different resources in the human-robot work system, i.e. a human, two serial robots and a mobile manipulator. The use case is designed in such a way that the positioning of peripheral devices as well as the active safety devices can be varied or changed. The lab use case consists of (a) a UR10 robot arm from Universal Robots mounted on a linear axis for part manipulation, (b) a magazine and (c) a conveyor for part provisioning, (d) a UR3 robot arm from Universal Robots for part assembly, (e) a human for part assembly and part removal (not shown in the image), (f) a mobile manipulator for part handling, and (g) external safety devices, such as light curtains, laser scanners, and safety mats.

The lab use case explores a total of 13 safety-related modification dimensions resulting from the alteration of the layout, task allocation, or motion behavior of the resource. These were recorded in a morphological box, a prospective risk analysis was performed and mapped in ADJUST.

Based on the simulated behavior of the laboratory use case, it was possible, for example, to determine influences of the task assignment and thus the temporal and local synchronization of humans and robots with regard to the number and duration of exposed body regions as well as distances to collision objects in the work environment. These data can then subsequently be validated by ADJUST on the basis of the dynamic robot model with regard to the permissible force and pressure limits according to ISO/TS 15066:2016 on the one hand, and with given standards, e.g., the minimum distances according to EN ISO 13855:2010 on the other.

Fig. 4. Lab use case for representing safety-relevant modification dimensions in human-robot work systems.

7. Conclusions

In order to ensure that robotic systems maintain their flexibility in collaborative applications, the safety issue and in particular the risk assessment effort must be drastically reduced. In this work, an approach was presented how risks of an adaptable system can a priori be considered in order to be able to make modifications safely using an automated assessment and without expert know-how. This should also provide a further step towards the democratization of collaborative robotic systems.

Acknowledgements

This work was funded by the Federal Ministry for Climate Protection, Environment and Energy, Innovation and Technology, BMK, and carried out within the framework of the program Production of Future and the project DR.KORS – Dynamic reconfigurability of collaborative robot systems (project number 864892).

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