Versatile Collaborative Robot Applications through Safety-rated Modification Limits

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Abstract. A robot is a flexible tool and handling device. However, by eliminating safety fences in robotic applications, flexibility is limited as regulations on personal safety must be followed. Any modification on the system or application will require a new risk assessment before the system can be put back into operation. This circumstance costs time and money and stands in contradiction to the nature of a robot as a versatile and adaptable device. By introducing safety-rated modification dimensions and determining admissible variations indicating the limits up to which the system or application can be changed in compliance with safety regulations, a potential solution to overcome this restriction is presented. A model-based strategy for estimating and validating the aforementioned modification limits is proposed, up to which changes on the system can be made without conducting a new risk assessment. The proposed approach gives rise to a novel safety concept for collaborative robotic applications, which ensures flexibility while taking into account safety standards.

Keywords: robot safety, mobile manipulation, reconfiguration, risk assessment

1 Introduction

The market for sensitive robot systems is already well established by numerous suppliers like Universal Robots, KUKA, Fanuc, ABB, Franka Emika, F&P Robotics, etc. A collision detection feature enables those so-called collaborative robots to work together with humans. By means of torque measurements in the joints or its estimation from measured actuator currents, collisions with the robot can be detected [2]. The decisive factor for this sensitivity in force and torque control is an accurate dynamic model of the robot that predicts the motor torques in the joints. The comparison of torque values for respective joints allows conclusions about any forces acting on the system from outside [8]. As a result of this functionality, protective fences are not required with sensitive robotic systems, as they can react to occurring forces. In this way, Human-Robot Collaboration (HRC) can be implemented and personal safety is ensured at a first level. However, operating robotic systems by identifying, measuring and validating potential contact situations with limit values stated in ISO/TS 15066 [10] is not trivial, as the real bio-mechanical load for the human during a contact situation depends on various parameters and can deviate from the predefined settings in the robot controller [3]. The high safety requirements, the complexity of the safety-related behaviour of a robotic system, and the lack of engineering tools for analysing those influences still inhibit their extensive application in industrial settings [6].

Especially one specific problem arises in the practical use of “fenceless” robots: Any change to the robot system or the application requires a new extensive risk assessment. By this substantial restriction, requiring the renewal of the risk and measurement assessment of the application after each modification, the essential flexibility of a classical industrial robot – to be adaptable at any time – is actually lost by a collaborative robot. In addition, collaborative robots (stationary and mobile) are preferably used in dynamic environments, which means that the robot must adapt dynamically to its changing requirements. This work focuses on the current need of companies for enhancing the flexibility of industrial HRC applications while at the same time ensuring the mandatory personal safety at any time.

In this paper, a new approach is proposed, where safe limits for modifying a basic application of a robotic system are defined. Thus, changes to the system and to the application can be executed in various dimensions, so-called *modification dimensions*, with limits known to the user. The safety assessment and approval of a desired modification is carried out automatically on the basis of the underlying safety system model. With this approach, we are pursuing two overarching objectives:

Goal one: Collaborative robots can be used flexibly and safely as fenced-in industrial robots.

Goal two: Sensitive mobile manipulators can be used in an industrial context.

This work is organized as follows. In Sect. 2, the proposed concept for the automated evaluation of modified collaborative robot applications is presented. The four main phases *Modelling*, *Analysis*, *Identification*, and *Operation* are described in more detail. The essential aspect of *Modification Dimensions* relevant to this work is explained in Sect. 3. The initial ideas for a necessary software framework is presented in Sect. 4 and we give conclusions of this work in Sect. 5.

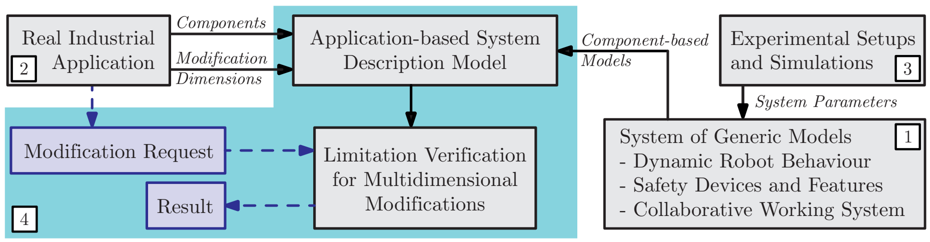

Fig. 1. The internal structure of the introduced safety concept for HRC systems. It contains of the four phases defined by (1) Modelling, (2) Analysis, (3) Identification, and (4) Operation.

2 Concept Description

In this work, we disengage ourselves from the usual approach of assessing the safety of collaborative robotic applications. We propose a use-centric concept that allows a user to apply a collaborative robot flexibly. Thus, the safety assessment concept (see Fig. 1) is introduced.

In the initial phase (Modelling), a set of generic system models is generated from which collaborative applications can be built. This includes the dynamic behaviour of the robot, the safety devices as well as the collaborative working system. The second phase (Analysis) focuses on investigating real industrial applications and identifying required industry-relevant modification dimensions which are integrated in an application-based system description model. Furthermore, the generic system models are optimized with specific parameters in the third phase (Identification), which are identified in experimental tests on individual components or in simulated environments. The final phase (Operation) describes the utilization phase, in which modification limits on the system are identified and validated. As a result of the safety model, a set of *safety-rated modification limits* is derived, describing the admissible changes in variability without the need of an additional safety assessment and measurement.

2.1 Modelling

The modelling of the system components is an essential part of the preliminary phase. The larger and more generic the set of predefined models, the faster a given use case can be replicated mathematically.

Dynamic Robot Model. The dynamic behavior of a robot is governed by the equations of motion (EoM) in the typical form of $\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{g}(\mathbf{q}, \dot{\mathbf{q}}) = \boldsymbol{\tau}_M + \boldsymbol{\tau}_{\text{ext}}$. Therein $\mathbf{q}$ are the minimal coordinates, $\mathbf{M}$ is the mass matrix, $\mathbf{g}$ represents Coriolis, centrifugal, gravity and friction terms and $\boldsymbol{\tau}_M$, $\boldsymbol{\tau}_{\text{ext}}$ are the motor torques and the external torques, respectively. In the presented approach, we focus on generic models that are valid for different robot types.

Safety Device and Feature Model. To guarantee human safety for HRC applications, different proprioceptive and exteroceptive sensors are used. In general, proprioceptive sensors measure internal values of the robot like the working speed of the robot's arm. In contrast to proprioceptive sensors, exteroceptive sensors acquire information about the robots environment, like distance measurements from the robot to an object [9]. The provided sensor data is used to statistically model the information density that can be achieved with a certain set of sensors. To develop these statistical models, the quality of the sensor data plays an essential role. To quantify the quality of sensor data, the sensitivity, the error and the precision of every single sensor are of particular importance [9]. A sensor with high sensitivity, high precision and low error should influence the statistical models more than a sensor with the opposite properties. That means, a weighted statistical model needs to be developed for each sensor type. By means of the developed statistical models, an estimation for the human safety will be possible, as the risk on the human changes by adding or removing sensors to or from the HRC system.

Collaborative Working System Model. Besides robots and safety devices, the collaborative working system is additionally defined by the physical equipment available, the tasks for execution, and the products that are subject to the task execution (see Fig. 2).

The physical equipment as well as the human model are represented by 3D volume models that use boundary representation. Thus, the model contains directly addressable and manipulable surfaces, edges, radii, etc., which are essential for evaluating safety issues regarding pinching areas (see also ISO 13854). The system-inherent work tasks are generated by a hierarchical task analysis, whereby a decomposition into subtasks takes place on the basis of superordinate objectives of the work system, as for example in [5]. These subtasks are characterized by completed actions, which cannot be divided further meaningfully and serve as allocation objects in the task division between humans and robots. They are modelled in motion-oriented synthetic process languages (MTM-1, MTM-

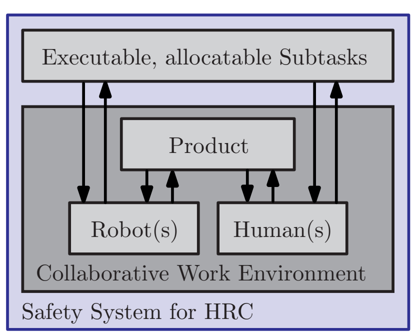

Fig. 2. Simplified work system model for HRC safety evaluation

MRK), as originally proposed by [7], and can thus be evaluated temporally as well as with regard to their influence on safety. The integration of the task allocation model into the overall safety-rated model is essential, as a variation in task allocation might lead to a new trajectory or rather workspace of the robot and thus new possible colliding points with the environment but also the human.

2.2 Analysis

Every given collaborative robot application consists of a finite number of components and parameters that define the whole system. Thus, the analysis of industrial use cases is essential to tackle the industrial need when it comes to defining an overall safety-rated approach. Based on the analysis, a set of generalized models is derived, which is used to map specific systems with relevant safety-rated aspects. Here, the focus was on processes in the field of manufacturing, assembly and logistics. The main objective was to identify required modification dimensions and their representations that are needed by industrial stakeholders in order to meet their entrepreneurial goals of time, cost and quality.

Handling Use Case. In the first use case, products need to be placed in testing units. The products are provided in magazines and need to be placed back in the magazines after testing. Specific types of products go to specific testing units. It is essential that the work system to be designed is applicable for both, human and robot. The idea was to place testing units in individual towers that can be turned facing either the operator or the robot, while the magazines are provided on a turntable. Human and robot can either work simultaneously or consecutively on the work system. By specifying the resource, i.e. robot or operator, for the handling process and thus the task allocation, the robot path changes dynamically. The identified modification dimensions in this use-case are task allocation as well as handling positions.

Post-Processing Use Case. In the second use case, products need to be post-processed. The products need to be handled to different post-processing stations in order to remove welding spatters, test a through hole, clean the inside of the product and place it in a magazine. Here, products can differ in size. Furthermore, the work system should again be applicable for an operator to work either simultaneously with the robot (e.g. when post-processing pre-serial parts) or consecutively and thus having again an effect on the robot's path. The identified modification dimensions in this use-case are task allocation and product size.

Machine Loading Use Case. In the third use case, a robot on a mobile platform should load and unload parts from a milling machine where parts can differ not only in size but also in material and thus affecting the weight of the part tremendously.The identified modification dimensions are product weight and the position of the robot base resulting in changes in the robot path.

Summarized Lab Use Case. By defining the lab use case, we wanted to combine the identified modification dimensions in the industrial use cases. In this sense, the lab use case consists of an articulated robot on a mobile platform with the task of loading and unloading a machine and gripping the raw material from a magazine while placing the processed parts on a conveyor belt. Thus, the lab use case covers the industry-relevant modification dimensions, i.e. change of workpiece in size and weight due to changes in product requests, change of pick and place positions on the individual station due to changes in station design and layout, and changes to the robot path due to changes in the robot base position and task allocation. Furthermore, the robot's velocity is subject to change when it comes to modification requests regarding production volume and/or cycle time.

2.3 Identification

The identification is used to determine the actual parameters of the real system. This can be done either on the real setup or on simulated laboratory setups. It is well known, that the dynamic robot parameters like link masses, inertia terms, friction coefficients etc. appear linear in the EoM. Therefore they can be rewritten to $\boldsymbol{\Theta}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}})\mathbf{p} = \boldsymbol{\tau}_M$, with the regressor matrix $\boldsymbol{\Theta}$ and the parameter vector $\mathbf{p}$. This linear form is employed for the identification using optimized persistent identification trajectories (e.g. Fourier series). These trajectories are used as desired values for the position controlled robot while the necessary motor torques are measured. Therewith an overdetermined system of identification equations is generated that can be solved for the unknown robot parameter $\mathbf{p}$ with a least squares error minimization, see [4] for details.

Additional measurements are done on a simulated laboratory setup to determine the relevant parameters during a collision between a human and the robot while modifying the modification dimensions. Contact forces are recorded in a simulated pick and place task while changing the position of the collision in few centimeter intervals within the entire robot workspace. Also the pose, speeds and velocities of the robot are changed systematically. To measure the contact forces, a special measurement device is used, which allows the biofidel properties to be configured according to ISO/TS 15066 [10] and DGUV information FB HM-080 [1].

2.4 Operation

During the use of a robot system, a need for adaptation may arise after a certain time. These changes can take multiple forms, but have a direct impact on the safety risk regardless of their complexity and magnitude. In this important phase, a modification request can be made, which will provide information on the guarantee of human safety in case of multidimensional variations on the system and/or application.

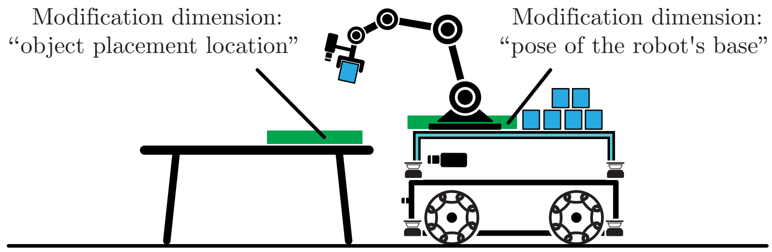

Fig. 3. Simplified representation of two exemplary modification dimensions

3 Modification Dimensions in Collaborative Applications

In order to motivate the need of modification dimensions and limits, they are defined by means of an illustrative example and by the findings of analyzed industrial applications. As analyzed in the previous chapter, the four most relevant identified modification dimensions are: (a) workpiece geometry and mass, (b) process sequence, (c) positions (robot's base, workpieces, workstations, workers), and (d) end effector trajectory regarding path, velocity and acceleration. In addition to those mentioned earlier, there are a number of other modification dimensions, such as robot type and structure, gripper geometry, type of safety function, and position of safety sensors.

For a better understanding two modification dimensions are illustrated in a scenario with a mobile manipulator, see in Fig. 3. The use of a mobile manipulator in industry is considered primarily in the logistics sector. For this reason, the focus is on the transport of goods of all kinds and require pick-up and drop-off at designated locations or areas. Because these locations are not always defined accurately and can vary over the lifespan of the application, one approach is to allow the variation of the object placement location. Also the position of the mobile base can be a modification dimension which corresponds to a modification of the pose of the manipulator on top of the mobile platform. The possibility of these changes during run time without the need of re-certifying the safety would enable plenty of applications and reduce the operational costs significantly.

Due to the fact, that the safety of this scenario depends on various parameters, like the environment of the object placement location, the handled objects, the presence of humans or the configuration and speed of the manipulator, the described approach doesn't aim for a universal safety, that can be guaranteed in any situation, but will define limits for the change within the modification dimensions, that are crucial for the application. In the illustrated example these limits could be a bounded surface on the table, where objects can be placed; and a bounded space relative to the mobile platform, where the manipulator can be mounted.

4 Proposed Software Framework

A software framework, called ADJUST, will be developed to support stakeholders in decision making during the operation phase. It integrates the dynamic robot model, safety devices and feature models (information density models) as well as a collaborative working system model – each covering different aspects of the collaborative robot application – into one software tool. The primary goal is to determine, if safe operation of a modified application is either possible, not possible or requires an updated risk assessment and re-certification. Based on a given application scenario, it can rate a desired application modification of defined modification dimensions regarding a possible safety violation. Thus, ADJUST supports the operator during design time of modifying an application. In addition to a boolean output, it also gives insight into the quality of a modification. This means that the framework does not only tell the user, if an application is safe or not, but also compares a modification to the status quo and assesses, if safety is improved or degraded by the planned modification. However, it is important to state, that automatic assessable modification limits are very narrow and exceeding these will require an updated risk assessment and re-certification of the application.

5 Conclusions

This paper presents a new and comprehensive safety concept for collaborative robotic systems. The proposed framework accounts for the variability of given HRC scenarios in industrial applications. This framework comprises three main models that need to be parameterized for a particular application and robot. Each of them covers a different aspect of the application, in particular (a) the dynamics of the robot, (b) the information density that can be achieved with a certain set of sensors, and (c) the impact of the work-flow and human factors. For a given data set of a particular application, the framework allows the determination of relevant modification limits and thus the boundaries of the workspace, where safe operations of the application are still guaranteed and the desired flexibility of the robotic system is retained without necessarily conducting a new risk assessment.

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