The 11th International Conference on Safety of Industrial Automated Systems

Safety Pilot: Digital Risk Assessment Integrated into Robot Programming

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KEYWORDS: digital risk assessment, power and force limiting, model-based validation of biomechanical limits

ABSTRACT

The CE marking process is mandatory for collaborative robot systems (cobots) in order to declare conformity with all harmonized safety standards and, thus, with the machinery directive. A crucial part of the process is the risk assessment, in which hazards are identified and evaluated according to their associated risks. A correct and comprehensive risk assessment is not an easy task. It usually requires long-term experience or external support that, given the associated costs, can be especially burdensome for small and medium-sized enterprises (SMEs). The author believes this is one reason why companies are currently hesitant to invest in cobots and associated technologies. Additionally, the risk assessment as done today is typically static and only applies to a particular configuration of a robot application as determined by trajectories, environment and task. Changes to the application require a review of the existing risk assessment documents.

In contrast to the risk assessment process, which has not changed much in recent years, the methods for cobot programming have dramatically improved. Most cobots on the market can be easily programmed without specific knowledge or training. A cobot can be deployed and programmed with relatively little effort, but the time-consuming and primarily manual executed risk assessment is done in the same way as decades ago. Anecdotal experience points to strong underrepresentation of cobots that run in operating mode power and force limiting (PFL), where physical contact is allowed as long as the robot does not exceed the biomechanical limit values of ISO/TS 15066. While PFL offers many advantages over other operating modes such as maximum flexibility, minimal footprint and reduced costs, the procedures associated with the validation measurements represent a high burden. Thus, most cobots that are in industrial operation are actually either installed with safety fences or with other operating modes such as speed and separation monitoring (SSM) instead of PFL.

In this article, we present the concept of a digitally-assisted risk assessment that directly addresses the aforementioned challenges, specifically the high effort, costs and uncertainty of the current procedure. The solution integrates the risk assessment directly into the programming environment of a cobot. This close integration allows for the identification of contact hazards for each robot movement by adding information about body parts at risk, contact type and contact point to the robot program. Once all hazard were described, an essential part of the risk assessment is completed. Additionally, this information is used in combination with a simulation to determine the maximum allowable speed whereby the robot still complies with the biomechanical limits of ISO/TS 15066. These calculated speeds are then used to determine how fast the robot may move in the respective hazard profile while complying with the limit values and are subsequently used for the robot movement. The digital risk assessment, simulation-based validation and hazard-based speed control of the robot movement was integrated as the *Safety Pilot* tool into a demonstrator. The results indicate a significant improvement over the current standard in terms of usability, time and costs.

We also see further advantages for cobot end-users. Whereas a risk assessment is traditionally executed by a safety expert who is responsible for a wide range of applications, in our case, the robot programmer who has clear and direct knowledge of the processes they are implementing is responsible for this task. This saves time and reduces misunderstandings. Another advantage is the granular view of the process and safety mechanisms involved. Typically, a worst-case situation for the whole process is used to determine maximum speeds. Our approach allows for different operating modes and different speeds for individual movements, and can offer an optimal balance between safety goals and cycle time needs. In conclusion, our concept will make the use of cobots simpler, especially for SMEs.

1 INTRODUCTION

Cobots are special robots, that meet the increased safety requirements for human-robot collaboration (HRC) to combine the strength and performance of robots with the dexterity, experience, and cognitive abilities of a human [1], [2]. Due to demographic change and emerging shortage of skilled workers, the demand for automation solutions for small and medium sized enterprises (SMEs) arises. Cobots, with their high flexibility, simple programming of task and low acquisition cost should actually be the ideal solution [3]. In addition, cobots enable market-oriented production [4], which is also crucial for SMEs. So, what is the reason that we don't yet see the cobot in the company next door?

Collaborative robotics is still one of the fastest growing sectors of the robotics market [5]. In a literature study, the increasing share in the manufacturing industry and in academic literature was made clear, thus illustrating that there is no reason for a decline in interest [6]. Nevertheless, there are only a few applications in which robots are used in collaboration and mostly cobots are still used behind fences and no real collaboration takes place [7], [8]. In an online questionnaire carried out by [9], lack of knowledge was identified as one of the most significant barriers for adopting cobots. Among many other relevant comments, safety, risk assessment and legislation are identified. Due to this lack of knowledge, the inherent safety design of cobots is often mistakenly considered as ready-to-use, but there is no absolutely safe design, as it depends on the application with end effector and payload. This perception of inherent safety can even have a negative effect, as it can create a false impression of safety and lead to further hazards [3]. A key problem is that, although there have been major developments in robotics in terms of usability and functionality, the legal requirements and standards have hardly changed. Especially for CE marking and risk assessment, because even robots that are specifically designed for collaboration with humans require a risk assessment [10], [11], [12]. Whereas a few years ago it was still difficult and complicated to operate and program a robot, today much emphasis is placed on useability, so that the entry barriers for using these machines have been lowered. The lower overall weight of the robots also makes it easier to integrate them into any existing structures. The cobots are therefore easy to program, uncomplicated to integrate, but the risk assessment relies on experience and expert knowledge and a safety expert is therefore required to put the machine into operation [13]. Thus, the image of cobots painted by robot manufacturers in advertisements and presentations as a plug-and-play solution for automation problems is incorrect.

The need to improve the safety process has already been identified in the literature and there are many approaches and publications. [13] distinguishes, for example, between system analysis, collision analysis and safety-guided design. [14] presents the SAFER-HRC, which is based on formal model and uses temporal logic and satisfiability checking to account possible behaviours of human operators and safety assessment team with experienced safety engineers for evaluation. This means that the humans are not taken out of the loop and the tool provides a supplementary and supportive tool for the current process. [8] presented a model-driven risk assessment for automatic hazard identification. Here, properties of the workspace are used to calculate resulting risk depending on material, geometry and weight. [15] proposed the simulation tool HIRIT for HRC applications, that describes and helps to understand complex correlations of safety issues and to find safety relevant distances between humans and robots. [16] presents an approach for robot control with a supervisory visual system and a variable joint impedance to improve safety for robots that must coexist with humans. [17] presents a real-time controller that limits the velocity of the end-effector based geometric primitives and is based on safety curves and an injury database from drop-testing on pig abdominals. [18] added a null space controller to this approach, where the effective mass is minimized depending on a point of interest with modifying the robot configuration and therefore allowing higher velocities. [19] describes the approach of a task-based assessment of risks for collaborative robots and relies on activity-based evaluation instead of an environment-based hazard analysis. However, of the many approaches from the literature, only a few are implemented in practice and production in the companies, as there is a trade-off between effort, benefit and time and money invested in safety promises no direct profit [13].

Risk assessment relies on experience and expert knowledge and this manual and heuristic approach stands in stark contrast to the dynamic and flexible requirements of SMEs [13]. In this article, we present the concept of a digitally-assisted risk assessment that directly addresses the aforementioned challenges, specifically the high effort, costs and uncertainty of the current procedure. The solution integrates the risk assessment directly into the programming environment of a cobot with the goal, to come closer to the promised plug-and-play solution and thus reduce the barriers to the introduction of robots into the company next door.

2 REQUIREMENTS

In this section, the requirements for an exemplary SME for a robotic solution are analysed and a solution is proposed that fit their needs. It is assumed that this company wants to automate part of its production, but has limited financial resources and the application is likely to change over time. In addition, there are environmental restrictions, as the solution is to be integrated under the existing conditions. This means, there is likely limited available space as well as blurred boundaries between work spaces. This makes it a prime target for HRC and the use of cobots. But how can the safety of the application be guaranteed in accordance with the applicable standards to enable CE certification of the application?

When the SME buys a cobot, they buy an incomplete machine for whose specific application a CE certification must be prepared, since there is no absolutely safe design as it depends on the application with end effector and payload [3], [9]. This also means that if the application, the end effector or the payload changes, the risks may also change and the original CE certification may no longer be valid. The CE marking process is mandatory for cobots in order to declare conformity with all harmonized safety standards and, thus, with the machinery directive. A crucial part of this is the risk assessment, which consists of the limits of the machine, the identification of hazards and the analysis of risks and countermeasures. Here, the risk of a collision and the resulting injury to the human is a decisive factor for HRC.

ISO/TS 15066 describes safety-rated monitored stop (SMS), speed and separation monitoring (SSM), power and force limiting (PFL) and hand-guiding (HG) as cobot operating modes to deal with the risk of collisions. The permissible safety measures result from the form of human-robot collaboration and it follows that only PFL and HG are suitable for a collaborative application where the contact between human and robot is permitted. However, HG can be neglected, as it is not applicable for most applications. With PFL, safety is achieved by ensuring that human biomechanical limits for all possible contact situations are not exceeded. The force monitoring of the cobots is used here, which triggers an emergency stop if the force limit value is exceeded and, in conjunction with the speed regulation, enables compliance with the limits. This means that no further safety measures are necessary, resulting in low acquisition costs as direct contact between human a machine is allowed. In addition, the application is still safe if the form of interaction changes and the workspaces can overlap, which leads to a high degree of flexibility. This makes the use of a cobot with PFL the ideal solution for the skewed requirements of the exemplary SME. How safety is achieved through PFL for cobots in the current process is described in the following section.

3 METHODOLOGY

The current process for PFL requires that contact hazards between human and machine must first be identified and then reduced to a manageable set of critical and risk-relevant hazards. For this purpose, the ISO/TS 15066 distinguishes between 29 body points for clamping and impact and in a human-subjected study [20] provides new and verified biomechanical limits, from whom the applicable limit values for force and power can then be derived. A measuring device must be used to ensure compliance with these values at the identified points with the respective geometries. If these values are exceeded, the speed of the robot needs to be reduced until the limits are no longer exceeded. The measuring procedure is defined by ISO/PAS 5672. The resulting process is time-consuming, expensive and cumbersome. In addition, adjusting the speed has the consequence that the performance of the entire application suffers, as many robots only distinguish between two safe speeds, the reduced and normal speed. This results in an optimization problem which, even with an optimal solution, is far from the performance of traditional robot applications. In addition, the regulatory measures cannot be estimated well in advance and therefore the question of the economic viability of automation cannot be answered. This means that when a company considers automation by a robot in collaborative operation, it faces a complex integration and validation process with uncertain speeds and cycle times, which overshadows the benefits of this process and, as a result, there are few true collaborative applications. This is a particular problem for SMEs, which, in contrast to the large industrial companies, often do not have their own safety experts and are therefore dependent on external services in addition to the costs incurred, creating an additional dependency. Even if the performance losses can possibly be compensated for by the other advantages, this complex validation process with its extensive requirements stands in the way of using cobots with PFL. The following section presents the approach developed to solve these problems.

4 APPROACH

The proposed method is based on the model-based validation of the biomechanical limit values for PFL. In a project with the BGHM, the online tool Cobot-planer [21] was developed. Here, a hazard model is created based on the information from the risk assessment and, in conjunction with a robot model, a collision model is created which is used to validate compliance with the biomechanical limit values. The parameters for the hazard model are endangered parts of the human body, collision type (impact or clamping), human posture (attached arm, extended arm) and possible collision points with according geometry on the robot. The result is a maximum safe speed that can be used to regulate the robot for safe movement. Compared to the current process, the Cobot-Planer tool with model-based validation replaces metrological validation using a measuring device and can be used to check the identified, representative contact situations. Although this replaces the complex, costly and time-consuming measurement, the relevant contact scenarios still have to be identified and there is still a separation of the risk assessment process and robot programming, which means that further advantages are lost.

The approach in this article envisages combining the risk assessment for collision risks with the robot system and integrating it into the robot programming. This offers several advantages. On the one hand, information about the robot that are not time-varying, such as type and serial number, are directly available and can be incorporated into the risk assessment. On the other hand, the status data of the robot, such as joint states and speeds, can be read out and used for the robot model directly. The status data is always up-to-date, even if changes are made to the program sequence, as it originates from the robot's real data. Only the hazard model is missing to enable model-based validation using the collision model. To make this possible, hazard sections have been defined which are used in robot programming to divide the program into different hazard profiles. A hazard section is characterized by the fact that hazards applying to this section are all the same. The necessary parameters for the hazard model are defined directly in the sections and the respective program sections are assigned to the sections. These parameters are the endangered parts of the human body, collision type, human posture, tool on the end effector and collision points on the robot. This makes it possible to calculate the maximum permitted safe speed of the robot for each state and to simplify the current process so that user input is only required for the parameters for the hazard sections, thereby significantly lowering the integration effort for robots. Changes to the robot program and the robot movement are also easier to implement, as this only requires an adjustment of these parameters, if necessary, which increases the flexibility of cobots. This can also increase the performance and cycle times of robot applications, as the maximum speed of the robot is not set for the entire application, but for each point in time. As a result, the requirements for SMEs outlined in section 3 for high flexibility, simple integration and no environmental dependencies can be met.

5 APPLICATION

The presented approach was implemented as the *Safety Pilot* tool as an extension of the hardware-independent robot controller voraus-core from voraus robotik [22]. Custom commands can be developed for this robot controller and can be used for the programming. A total of four custom commands were developed for the *Safety Pilot*. The “Init Safety Pilot” enables the initialization of the tool and establishes the connection to the database with the biomechanical limit values and the model-based validation. The existing “Move PTP” and “Move Linear” commands from voraus-core for programming the robot's trajectory were adapted so that they use the speeds set by the *Safety Pilot* for their respective sections. Finally, a command was developed for the hazard sections, which enables the description of the applicable hazards via a graphical user interface (GUI) which can be seen in Figure 1. The selection options were reduced from the 29 possible body parts from ISO/TS 15066 to 6 for the sake of clarity, as these were sufficient for application on a table. The hazard section command is a parent command that enables the subordination of other commands so that the robot program can be subdivided into hazard sections.

The developed tool was integrated into a demonstrator with an exemplary pick and place task. The task was simply to pick up an object with the gripper and place it at a different point and return to the starting position. For this, the robot first (1) moves in the +y direction to the intake location. Then the robot (2) lowers in the -z direction and, after the object has been gripped, there is a (3) movement in the +z direction to the previous point. This was followed by a (4) movement in the +x direction to the deposition location, and after that a (5) -z movement to where it was deposited and a (6) +z and (7) -y movement back to the starting point.

Four hazard sections were defined for these seven movements. For movements (1), (4) and (7), the risk of a free impact applied and the deltoid muscle and the forearm muscle were described as vulnerable body parts. The TCP on the robot was defined as the collision point. For movement (2), the risk of clamping was determined and the body parts were the back of the hand and palm and the tool was defined as the collision point. In movement (5), the clamping was also determined with the back of the hand and the palm, but the collision point differs from the previous section, as the gripped object represents the possible collision point. For movements (3) and (6), an impact with the deltoid muscle and the forearm muscle was assumed, but the collision point is at the top of the robot due to the ascending movement.

After the hazards were defined by the sections and the movement commands were assigned to the respective sections, the maximum speeds were calculated by the collision model and set in the Move PTP and Move Linear commands as a function of the higher-level sections. The robot application could then be executed with the calculated speeds. As the permitted forces are lower for clamping than for impact, the maximum speed in movements (2) and (5) was slow, as expected, but due to the differentiated consideration of the sections, the robot speed in the other sections was significantly higher. In addition to the considerable simplification of the current process, an optimized process runtime was also achieved.

The use of Safety Pilot can be summarized in the following steps:

1. Programming the robot with conventional move commands (Move PTP, Move Linear)
2. Initialize *Safety Pilot* with the "Init Safety Pilot" command
3. Definition of sections with the same hazards and subordination of other commands
4. Description of the hazards by custom command with GUI
5. Starting the robot in simulation mode, where the safe speeds are calculated and set
6. Operate the robot safely in automatic mode

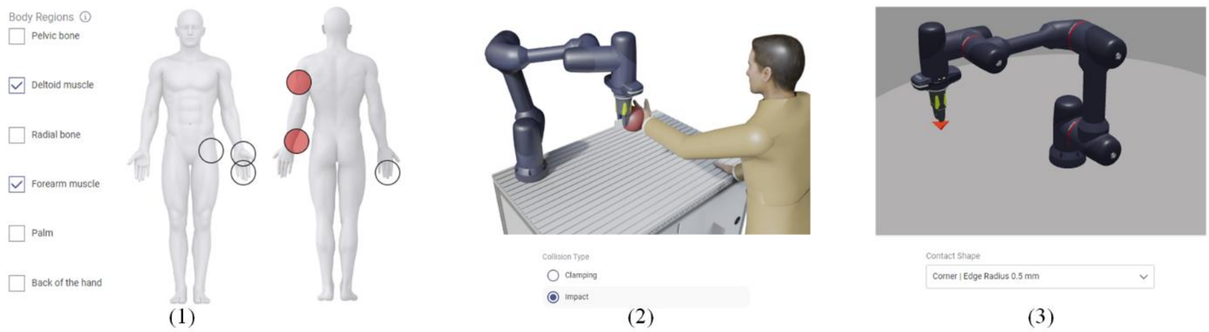

Figure 1. *GUI of the custom command for the hazard sections with: (1) body parts at risk, (2) collision type and (3) collision point on the robot.*

6 OUTLOOK

In this article, an approach for the simplified and improved integration of a cobot with the *Safety Pilot* tool was presented, which meets the derived requirements for SME and is based on the digitalization of risk assessment and the combination with robot programming. It is an improvement on the current process and, in the author's opinion, safety should not be more complicated than programming, as this gets in the way of the overall goal of safe machines. However, the advantages are not limited to SMEs, but also for Industry 4.0 or any other application that meets the outlined requirements. It must be mentioned, though, that the basic technology of model-based validation of biomechanical limit values is currently not covered by the standards and therefore cannot replace metrological validation. However, integration into the standards is currently in progress and the tool already offers the possibility of planning robotic solutions with PFL in advance in order to be able to estimate economic efficiency and performance. This was previously not possible and the speed and cycle times could only be determined after the robot had been purchased and integrated. The aim of the ongoing research is now to add further hazards to the *Safety Pilot* and to integrate the results into the risk assessment documentation for CE certification.

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