Safety in industrial applications: From fixed fences to direct interaction

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***Abstract*—Human-Robot-Cooperation will allow leveraging the capabilities of human and robot better through direct interaction, but requires new methods to ensure the safety of the worker. The article introduces a new methodology for the safety assessment in robotics by analyzing the collision risk of a robot. The concept for passive safety assessment, i.e. the approach to consider the collision potential of a robot system for analyzing its danger potential is presented. A test-setup to parameterize and validate models is presented. The test-setup can also be used for the verification of robot system installations with respect to adequate safety criteria**

***Index Terms*—Human-Robot-Cooperation, Safety, Safety assessment, Collision assessment, Injury mechanisms.**

I. Introduction

Conventional robot systems featuring separating safety equipment (fences) or non-separating safety equipment (light curtains and laser scanners) prohibit direct interaction of human and robot. Therefore the intelligence, knowledge and problem solving skills of the human worker cannot be combined symbiotically with the power, stamina and precision of robots. Human-robot-cooperation aims to bridge that gap by allowing direct physical interaction between human and robot, e.g. through hand-guiding or working independently in a common workspace. However, in order to allow direct interaction without separating safety equipment the safety of the worker in case of direct contact with the robot needs to be ensured at all times.

The development of new safety features and new methods for the hazard assessment of robot systems will change the way we interact with robots dramatically. Robots will become assistance systems in production that naturally and physically interact with the human operator. They will supply services to the operator, such as lifting parts, fine-positioning parts, repeating monotonous tasks and therefore relieve the worker from tasks where his cognitive skills are not required. This will free the worker for tasks that allow leveraging his experience and process knowledge. Furthermore, the reduced strain at the workplace and the improved ergonomics will allow keeping people on the job longer. In this respect human-robot-cooperation is a key technology for countering the demographic change.

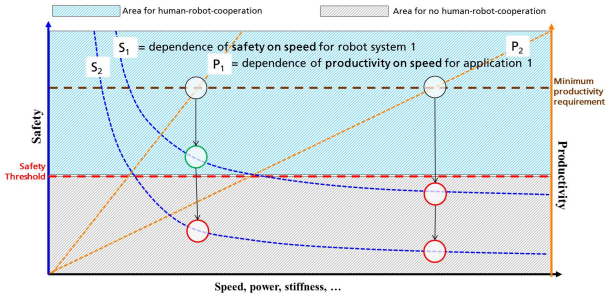

Figure 1. Balancing Safety and Productivity

Understanding the effects in case of a collision is essential to derive appropriate thresholds, to be considered for the safe design of robot systems for human-robot-cooperation. Classical robot systems that are purely designed for application in a specific process are defined by process characteristics such as payload, stiffness and speed. These characteristics promise feasibility in terms of fulfilling the needs for a specific process. Depending on the application this may result in non-flexible, hard and heavy machinery structure which may pose a significant hazard for a human, when put into contact which such a system.

Tuning such systems to a non-hazardous machine for its application in human-robot-cooperation definitely results in a short-cut of the systems' process characteristics. E.g. if the speed of the robot is reduced to limit its hazard potential during an impact many production tasks cannot be automated economically-feasibly, as the cycle time is also reduced.

But even if there is a common understanding on this safety - productivity trade-off (see Fig. 1) the level where to put this safety threshold is not yet a settled question. Only when these thresholds are known, the optimal robot design for efficient processes in human-robot-cooperation can be provided. In order to do so the lump-sum process performance characteristics (e.g. speed of robot, maximum force of robot, …) need to be put into relation to biomechanically motivated injury mechanisms during collision (e.g. body deformation, maximum pressure and maximum force on body extremity).

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II. Injury Thresholds as Result of Crashworthiness Analysis

Nowadays robotics research fosters a wide variety of approaches to not only avoid the contact between a human and a robot, but also to study the effects of unintended contact. Only when these effects are known, limits for safe contact between humans and a robot can be properly derived. In the area of service as well as of industrial robot systems inherent safety design is considered the paradigm for future systems. This chapter gives an overview on the current state of the art for injury criteria in robotics and the ongoing standardization efforts for safety thresholds in robotic.

A. Deriving Injury Criteria for Robotic Applications

The analysis of injury criteria for operator safety has mainly been developed within the area of the automotive industry. Thereby the main focus for accident research is the analysis of accident statistics as well as the experimental and computational evaluation of injury relevant factors for accidental reconstructions. Injury criteria are set up to establish the relation between a measurable physical value and the injury severity of a specific body region. The biomechanical research is thereby dedicated to derive the functional relation between a mechanical load case on the human body and the type and severity of the resulting injury [1].

Until now, the main work within the robotic society concerning the evaluation with crash test analysis was based on the transfer of the measurement devices and injury criteria from the automotive field. The most common criteria, e.g. the HIC (Head injury criteria), were analyzed for collision events with a robot arm and a human head model by simulation and in experiments during the last decade. Zinn et al. [2] were the first to publish estimations of the occurring HIC in case of a collision with a manipulator and a human head. The model has been enhanced by Bicchi at al. [3] to analyze the effect of damping as well as of compliantly controlled joints, to study their effect on intrinsic system safety, in case of a collision. Some years later additional studies, applying crashworthiness analysis using finite element simulation and experimental crash tests with anthropomorphic test devices (dummies) from the automotive industry have been reported by Haddadin et al., e.g. in [4], [5] and by Oberer-Treitz et al., e.g. in [6], [7]. All these research activities led to the conclusion, that crash tests are the right vehicle to understand the direct consequence on the human health in case of a contact and to derive appropriate safety enhancements thereof.

At the same time, the experiments revealed that the injury criteria studied in the automotive area are not corresponding to the injury mechanisms that are activated in case of a human-robot collision. The evaluation with dummy models yields on defining thresholds between death and survival, which is far away from relevant classification thresholds for human-robot-cooperation. Research in the robot society then started to focus not only on the evaluation of robot crash-tests, but also to adopt and derive new appropriate injury criteria to be used in the specific load cases relevant for robot systems. While first studies focused on blunt impact, such as [8], [9] and [10], Haddadin et al. also present work on sharp impact scenarios [11]. They present control strategies with post collision detection for a light weight robot reacting fast enough to not injure the skin in case of a collision with a knife for velocities up to 0.75 m/s, tested on pig cadavers. Finding the appropriate relation between the load cases applied by the robot on the human body in case of the collision and an injury severity, is still not a settled question and is therefore under research by different affiliations and projects worldwide.

While the injury thresholds evaluated by dummy models in the automotive field approach are too worst case to be applied in robotics, volunteer testing operates on the too low end of thresholds to derive a complete injury severity classification. Still the evaluation of pain tolerance is a relevant topic to be applied in robotics, when it comes to acceptability of robot system as well as setting up appropriate applications and functionalities for human-robot-cooperation. Povse et al. present their evaluation of impacts to the human arm with different impactor shapes and intrusion depths at varying speed [12]. Their aim is to validate a passive arm model for clamping by volunteer testing on its realistic damping behavior, concerning speed, acceleration and force of the intruding impactor as well as a linear relation of the impact energy density (energy received by the tissue divided by the contact surface area) to pain. This impact energy density is presented with a threshold at 2.52 J/cm2 for the mechanical failure of the skin in [13] and can thereby be used for the evaluation of soft tissue injury. Povse et al. will use this arm substitute for experiments of more severe collision constellations in their future research.

The direct modeling of injuries with numerical human models is a new approach to enable the applicability of the crash test methodology to a wider variety of load cases. The validation of the underlying models is done in analogy to the dummy models, while additionally organs and tissue structures are implemented into the models. Specific concern has to be taken on the validation of the relevant mechanical failure mechanisms and is done via numerical modeling of accidents with concrete injury protocols, as e.g. presented for a head model in [14]. The degree of detail and maturity of the available models significantly varies. For the implementation of fracture injuries of hard tissues, such as bones, widely accepted models and experimental data are available. For the representation of soft tissue injuries there is still a way to go.

B. Safety for Human-Robot-Cooperation in the Standards

The international committee for the standardization of robot systems (TC 184/SC 2) has realized the need for safety threshold independent from robot performance characteristics. For the first revision of the ISO 10218-1 [15] fixed values for velocities and power that might deceive a safe behavior without assuring operator safety have been dropped. Instead the requirements are to conduct a comprehensive risk assessment, taking into

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account all possible contact risks and evaluate them on their specific injury severity.
Tolerance values what is still allowed and where to set the limit cannot be found in the standard yet. The committee is currently drafting a technical specification (TS15066: Robots and Robotic Devices – Safety Requirements for Industrial Robots - Collaborative Robots) which should provide the user with additional support, when designing human-robot-cooperation in industrial applications. Ongoing efforts from the robotic scientific society are to transfer the latest results for injury severity classification into the discussion for operator safety in robotics. These topics are of high importance for the development of service robot standards as well as for the industrial robot standards when human-robot-cooperation is foreseen. The establishment of an exchange process with international experts in the standardization committee and research needs to be fostered.

III. Passive Safety Assessment in Robotics

The new safety paradigm in human-robot-cooperation introduces the method of "Passive Safety" to robotics in addition to the classical separation strategies. Passive Safety is defined for all means that are to reduce the effects in case of a collision, in contrast to those active safety measure that try to avoid the collision. It is impacted by the disciplines as depicted in fig. 2.

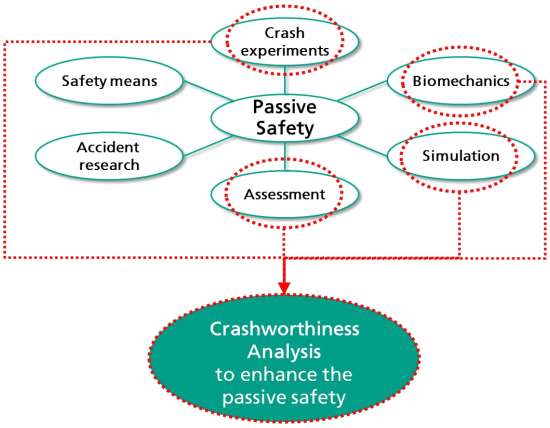

Figure 2. Impact Areas for Passive Safety

A. Injury model for robot safety assessment based on the collision potential

Deriving the appropriate input parameters that are relevant in case of a collision with a robot and a human is one of the essential tasks, to classify and to rate the potential injury risk in case of a collision. With known thresholds for the relevant collision types, parameter studies can be conducted in simulation or experiments offline to provide a specific injury severity to be used to apply adequate control strategies or reactions with a robot system during human-robot-cooperation.
It is well known that the possible loads that can be endured by the human body without an injury varies highly depending on a specific body part. Also the surrounding and the thereof resulting contact type considering a free impact or a clamping situation with a structural element has a significant impact on the loads the human body can bear. This could be already studied with the robot-dummy experiments, as presented in [9] and thereby requires a distinguished consideration of injury criteria for different contact types.
The procedure to identify safety thresholds via injury criteria, as motivated by the current research activities with a focus on passive safety, also needs to consider the different types of injury that might arise from a collision. The aim is to eventually provide an injury tolerance table to build the base of the injury model to be used for the safety assessment of a robot system in human-robot cooperation, as described in [16]. Fig. 3 provides an overview for a classification of robot accidents, as it should be provided by insurance authorities, to enable future usage of the injury criteria analysis according to standardized risk assessments.

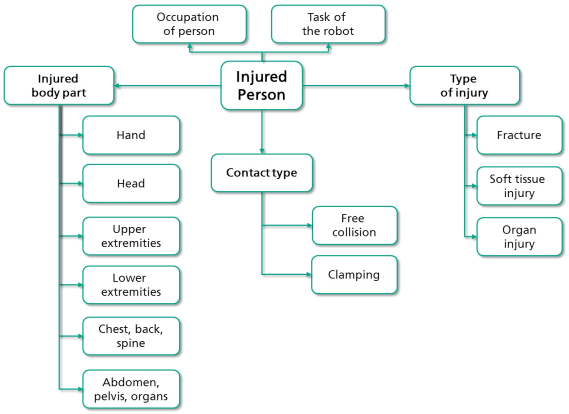

Figure 3. Scheme for accident research in HRC

IV. Experimental Collision Assessment

In order to validate collaborative robot systems with respect to their injury characteristics and to tune injury models a collision test-bed has been set up at Fraunhofer IPA (see Fig. 4).

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Figure 4. Collison testbed to assess the danger potential of a robot systems

The mechanism with two parallel guidances allows recording the forces and torques applied by the robot system as well as pressures and compressions induced to the system. For the pressure sensing high dynamic pressure foils (Tekscan) are mounted to the sensor head that allow as well for a recording of the contact area active during the collision. The testbed enables the analysis of collisions with a specific body part, due to an

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adjustable spring mechanism with a slider with which the gear ratio can be aligned for specific body stiffness.

The first consideration when interpreting the effect of the moving mass of the robot colliding with a human is whether to specify the event as a clamping scenario, in which the affected body part is trapped against a fixed object, or as a free impact, in which the body part can recoil freely in the direction of the impact after the collision. This distinction can be set for the measurement device by an electromagnet.

The benefit of the experimental evaluation of a robot system over a computational analysis is the implicit consideration of all structural and control specifics of the robot system and its current configuration.

V. Conclusions

The concept to consider passive safety assessment of robot systems, i.e. evaluating the collision potential of a robot system has been introduced. It was presented how the identification of injury mechanisms and appropriate tolerance levels need to be provided to dissolve the safety-productivity trade-off by optimally balancing the performance with the minimum safety threshold.

The current state of research for analyzing the danger potential of a robot system by means of numerical and experimental crashworthiness studies has been described. The article concludes with a short presentation of hardware setups that will be used to parameterize and validate injury models and to verify the injury properties of robot system installations.

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