INVESTIGATION OF ROBOT-HUMAN IMPACT

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Summary

Due to the introduction of assistant robot systems, the complete separation of the human from the robot's workspace is no longer the only option for operation. Therefore, the discussion on the safety assessment of robotic systems needs to be promoted. The injuries a human can suffer from in an unintended collision must be identified and evaluated together with possible enhancements in design and control, to minimise the hazardous potential of robot systems.

The aim of the reported research is to strengthen the awareness for the necessity of impact evaluations of robot systems, to assess the injury severity for a human. Whereas it is widely accepted in the automotive industry to take a standardised sample of crash tests scenarios that are evaluated on anthropomorphic test devices, so called crash test dummies, robotics science still lack uniform tests that can be carried out for different systems.

After the discussing the necessity for safety assessments in chapter 1, chapter 2 proposes a method to rate the safety performance according to scoring systems that are established by automotive authorities. They allow a relative measurement of the system safety based on injury indices. The knowledge from and the procedures of the automotive industry on injury evaluation from impact tests is introduced to robotics. This provides an important contribution for the safety assessment of robot systems for human-robot cooperation. In chapter 3 two simulation approaches for the quantitative computation of injury severity, including dummy models, based on the Finite Element Method and Multibody Dynamics are introduced. Their ability to conduct robot-human crash tests is presented. The impact studies are based on the evaluation of the head impacts, analysing the head injury criteria (HIC), to show its applicability to robotics. Also its limitations are presented by simulation results, so that in chapter 4 the further research direction for injury index evaluation in robotics is proposed.

1. Introduction

Nowadays robot systems, as they are established for conventional applications in the automotive industry, can be directly programmed for their specific task by highly educated robotics engineers to proceed with a predetermined operation throughout most of their product life. Due to the high lot sizes in the field of mass production no necessity for a regular reprogramming of the system arises [Craig03]. Entirely different requirements are given when robot applications are no longer restricted to mass production, but are to be offered to a wider range of customers from small and medium sized enterprises (SMEs) in industry and in crafts. Different operational tasks need to be fulfilled by one installed system to provide reasonable assistance to the worker and the systems needs to be scheduled and commanded directly by the worker to constantly respond changing requests. Not missing applications prevent the employment of industrial robots in SMEs, but the discrepancy of investment and operational costs against workload and downtime of the system. Recent research in the area of robot programming leads to more intuitive programming devices by the development of new methodologies and technical equipment. But there is still a long way to go with combined efforts of manufacturers, research institutions and users before all the issues necessary for the flexible production environment of SMEs can be addressed in an adequate way.

Safety issues are, and for obvious reasons will always be, one of the main struggling points for the introduction of new technology to the market. The joint efforts of national and international associations to set up new standards for the design and application of new systems reflect the concerns that accompany the introduction of systems that allow close human-robot-cooperation in industrial applications [Fryman03]. The new European certification standard for robot systems, the ISO 10218-1 (2006) is thereby divided into two parts: The first part deals with the technical specification of the robot that must be fulfilled by the robot vendors already during the development of the system. The second part focuses on the robot environment which must be adapted during the system setup, to secure a safe operation at a specific location for a specific task. Until now industry stays far behind its technical possibilities in robot control and programming. To overcome this lack of innovation, new liable safety technology and strategies need to be introduced and present safety regulations for industrial robot applications must be revised. For this only a quantitative measurement that can be repeatable applied within a certification process for different systems and applications can be taken into account by standardisation committees and certification authorities. Instead of completely separating the robot's workspace from the human, as it is foreseen for the state of the art robot systems in industry, the worker's and the robot's operation must be combined to profit from the synergy of the robot's and the human's abilities, therefore expanding the role of the worker in automation installations (see *Fig. 1*). This is one of the main issues that must be resolved to expedite the use of robots in SMEs, which demand for reliable systems to assure the safety for the human at any time during programming and during the production process. Stopping the robot in any occurrence of a collision is not sufficient to improve the safety, but new control strategies that can reliable fulfil an industrial tasks and allow human-robot cooperation are inevitable.

Danger measurements e.g. carried out by Kulic et al. in real time during the robot operation to avoid contact between the robot and moving objects in the environment significantly improve the safety operation of the robot [Kulic06]. Nevertheless there remains the question, whether the reliability of such a system can be sufficiently investigated without taking into account properly the resulting danger for the human in an impact with the robot. The approach of Ikuta et al. concerning human-care robots introduces a minimal impact force to make quantitative evaluations of the resulting safety advancement of different design and control strategies [Ikuta99], [Nokata02]. Combined with the knowledge of a study of potential human injury, a quantifiable scoring can thereby be further clarified. Pure knowledge of the robot's inertia and stiffness, together with the path and velocity of the robot's motion still lack the knowledge of the consequences for the human. A profound knowledge on the severity of possible arising injuries is essential to judge the risk that emanates from a robot during human-robot interaction. The necessity to set up a scoring system which can be used to grant or withdraw permission for or from the installation of a system for close human-robot cooperation will be stressed in the next paragraph, giving the basis for the impact studies carried out within this paper.

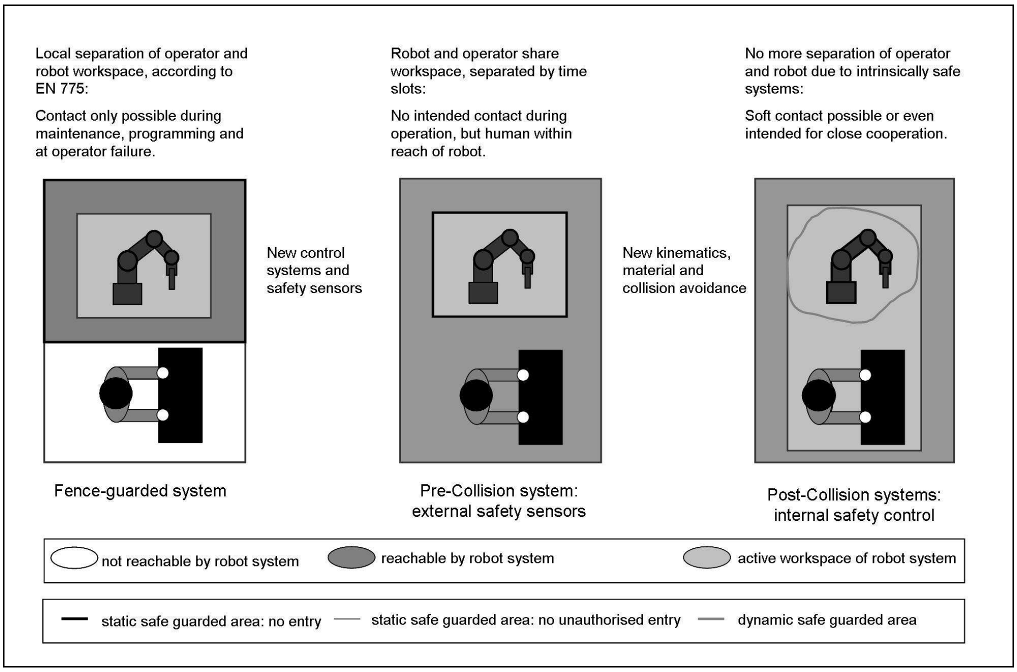

Fig. 1 Evolution of human involvement in automation systems

The approach for the study on the crashworthiness of industrial robots is based on the knowledge from the automotive industry, where a vast variety of crash-scenarios is investigated to improve passengers' safety. As a result of numerous studies about the humans' behaviour in a crash, concerning the biomechanical characteristics, dummy models are available both as hardware measurement devices and as software models for accompanying simulation. They relate the severity of a crash to the severity of a possible arising injury for the human involved in the crash. Even though only relative injury indices for the comparison of different impacts have been established so far, due to the ongoing research in biomechanics, however, there is a wide acceptance within the automotive community to rely on the rankings based on these indices.

Thus, it is the aim to adapt and investigate the procedures and indices from the automotive field to provide rankings for robot-human impacts. Hereby the paper introduces and proposes methods to estimate the consequences arising from a human-robot crash.

2. Evaluation of Impact Studies in Robotics

A wide variety of safety relevant features can be integrated in robotic systems, ranging from visual observation of the safe guarded area around the robot to collision avoidance algorithms implemented in the robot control [Helms95], [Kulic04]. But whenever a combination of highly technical equipment and software is included the systems reliability remains with a rest risk of failure, which can result in fatal hazards for the affected human.

Former studies on robotic accidents, like one carried out in Sweden in the 1980s, revealed the fact that human failure causes a high percentage of robotic accidents [Carlsson85]. Focusing only on the accidents arising from human-robot contact the majority of accidents did not happen during automatic operation, but during programming or maintenance. Thereby the outer safety equipment had been consciously deactivated or circumvented in another way. And it was mostly trained operators that should have been aware of the unpredictability of robot motion who became the victims [Carlsson85].

Aspects of human injury evaluation from crashes with robots are to be investigated for all kinds of robots that are in contact with humans during any time of their performance. Most systems that are introduced to the market for home environments such as Sony's Aibo[1] , NEC's PaPeRo [Nishizawa05], or Mitsubishi's Wakamaru [Kabe05] lack the danger of a hazardous potential due to their small size and low kinetic energy. The situation is different for industrial robot systems which can mostly be considered providing a hazardous potential during an impact, as they are designed to be used for work in industrial environments, thus requiring robustness and strength resulting in heavy masses and high velocities. The ongoing development of new kinematics such as parallel kinematics is one approach that will reduce the impact force due to the occurrence of lower inertia compared to serial structures, but does still not provide a state of the art for standard industrial applications [Brogardh02]. Lightweight structures, like the well-known LBR III from DLR[2], assure a better safety performance in case of a collision due to modern light materials in axes and links [Hirzinger02]. However they lack the power to replace the classical serial kinematics in automation task such as assembling or welding. Therefore, this paper focuses on crash evaluations for standard serial industrial robots as they are applied in traditional industrial applications.

To assess the hazardous potential of a robot system the three main issue that have to be evaluated can be classified as:

- Robot hardware and design
- Control software and algorithms
- Application environment of robot

To assess the safety performance of the overall system, a safety analysis covering these three categories must be conducted. Further classifications of hazardous potentials in robot systems can be found in [Heiligensetzer03]. Even if a pure numerical assessment of such complex domains does not seem to qualify as an exhaustive discussion of the possible variations that appear in a robot installation, each safety discussion must lead to a quantitative estimation. This arises due to the necessity to achieve standard requirements, to assure that supervising certification authorities such as the German Accident Prevention & Insurance Association or the American OSHA[3] can come into action and to open the basis for a widely accepted rating system.

2.1. Rating System

In *Fig. 2* a simple evaluation concept for the overall system performance is shown. Thereby the crash tests form the quantitative basis for judging the safety performance of a robot system, concerning the hazardous potential of the manipulator towards the human's health. The approach resembles the procedure as it is conducted by the European automotive safety organisation EuroNCAP [Griffiths99], adapted to the situation as it is predominantly found in robotics. In order to achieve a quantifiable measurement, predefined impact tests on different body regions need to be carried out. They will be evaluated on injury indices, as they are known from the automotive industry and are described in more detail

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[1] http://www.eu.aibo.com/

[2] DLR – German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt in der Helmholtz-Gemeinschaft)

[3] OSHA – Occupational Safety & Health Administration

in 2.3. Of course, the crash test will not remove the responsibility from the operator to assure maximum safety from the robot's peripheral like from equipment that supplies the robot with power or pressurised fluids as well as the surrounding walls and process tools. The crash test evaluation is limited to the hazards that arise from direct human-robot contact and the evaluation for the environment must be attached to the rating, which can only be done with a clear knowledge about the individual setup location of the robot.

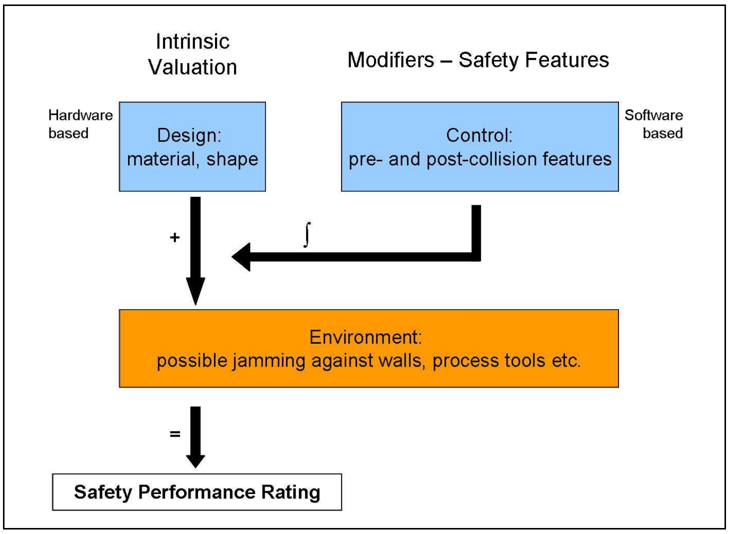


Fig. 2 Rating system for safety performance tests

In a first step, comparative impact tests for the structure, without any activation of further safety control features are conducted, to judge the static parameters from a manipulator, such as material, shape, configuration of the robot arm as well as mechanical passive safety enhancements such as padding. This is, because the valuation "intrinsically safe" can only be awarded to a reliable robot system that remains safe in any case of failure of electronic equipment or software. The results of impact evaluation must then be presented as a point scoring due to given limits for the injury indices derived by standardisation and medical associations.

Furthermore a different rating strategy for reactive safety equipment which is implemented either as post-collision (mainly with force/torque or tactile sensors) or as pre-collision safety (with contactless sensors) must be evaluated. Hereby, the proposed approach is introducing the implemented control strategy as so called "modifiers" to the rating scheme. Different control strategies result in variation of the robot motion leading to different impact scenarios, possibly changing speed and inertia of the robot arm. This outcome can again be measured at the evaluation of the arising crash and be included as a weighing to the points that are the outcome of the crash tests according to the reactive safety features that are included.

After conducting crash studies, the overall safety rating will result as the accumulated outcome of the scores from impact tests against different body parts and the evaluation of the environment, which focuses on jamming, hazardous equipment and process tools. Due to the lack of experience with injury data from accidents in robotics, for the injury valuation the data derived from experiences in car crashes will be consulted for analysis hereby. The awarding of scores for the environmental conditions will not be specified within this document.

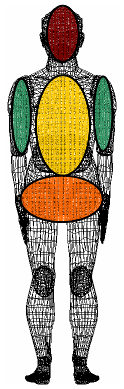
2.2. Crash test dummies as measurement devices

In the automotive industry various studies on crash-scenarios have been investigated to improve passengers' safety since the late 70s. Thereby the forces that would injure a human during a car crash are measured by anthropomorphic test devices, referred to as crash test dummies. Crash test dummies are full-scale replicas of human beings. They are available in different sizes, according to the age of the represented human. Even if they are not expressing the real biological matter or physiology of the human, they allow a good simulation of the behaviour of the human body. The are instrumented with load and acceleration sensors to record impact speed, forces, bending and torque the body is exposed to during a crash. The possible locations for the fitting of the sensors range from the head, neck, chest, pelvis, abdomen, hip, knee to the lower leg until down to the foot ankle. To receive reliable data on the response of the human body to extreme physical exposure cadaver testings have been conducted, providing data for the development of the dummies. The development resulted in the design of the "50th percentile male" Hybrid I in 1971. It still forms the basis for the present models Hybrid III, which is designed for frontal impact scenarios, and the ES-II, a side impact dummy both designed to meet the European safety standards. Models of the two above mentioned dummies will be used for the study within this paper. For further information refer to [EuroNCAP05], [Griffiths99], [GAO05].

To safe costs for crash testing by reducing the number of tests, different simulation tools provide software models of the available dummy technology. With the help of crash simulation, already during early stages of the car development phase, the design can be optimised for a better crash behaviour. Due to a close cooperation between the car manufacturers and the safety associations, nowadays, there is a good correlation between the simulated and real crash tests [Franz02]. Thus the study on the safety behaviour of robotics carried out in this paper is based on crashworthiness simulation results, to show the applicability of the automotive approach for crash studies on robot-human impact evaluations.

2.3. Injury indices

The most vulnerable impact region of a human during a robot-human impact has been identified as the head. The studies carried out in Sweden also reveal that in one sixth of the examined accidents the operator was hit against the head [Carlsson85]. Further body regions which are defined to be evaluated for the robot-human impact are the neck, the chest/thorax and pelvis/abdomen (see Fig. 3) This paper reduces its focus to the head impact evaluation. The resulting injury indices can be used to judge the severity of the injury with further consultation of biomechanical expertise, like e.g. the so called Abbreviated Injury Scale (AIS), revision 1990 from the AAAM[4], where then the body parts can be marked in accordance to the colour coding, to present the result of the evaluation.



AIS	SEVERITY	TYPE OF INJURY
0	None	None
1	Minor	Superficial Injury
2	Moderate	Recoverable
3	Serious	Possibly recoverable
4	Severe	Not fully recoverable without care
5	Critical	Not fully recoverable with care
6	Maximum Injury	Fatal

Fig. 3 Example colour coding for presentation of crash test results with the AIS90 scoring[5] of the AAAM

The most popular and well studied head injury index is the so called Head Injury Criteria (HIC), which is computed as the maximum integral of the resultant acceleration of the centre of mass of the head during the crash [Crash05]. Depending on the duration of the acceleration response, a maximum time interval is set to 15 or 36 milliseconds. Due to the highly stiff impact for a standard industrial robot, the acceleration signals duration stays far below the 15ms interval, therefore not affecting this difference. The HIC is computed as follows:

$$HIC = \max\left\{ (t_2 - t_1)\left(\frac{1}{t_2 - t_1}\left(\int_{t_1}^{t_2} a(t)dt \right) \right)^{\frac{5}{2}} \right\},$$

where the corresponding time interval is $I = [t_1, t_2]$ in $[s]$ and the resultant head acceleration $a(t)$ in $[g]$ [Crash05]. This formulation corresponds to the description of the Cerebral Concussion Tolerance Curve (WSU Curve), developed by the Wayne State University, that has been defined as the limit for life-threatening brain injury [Versace71].

For the evaluation of the resulting forces on the chest different injury indices are proposed, such as the so called Viscous Criteria (VC) and the Rib Deflection Criteria (RDB) [Crash05]. The VC is composed of the relative compression $c(t)$ and

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[4] AAAM – Association for the Advancement of Automotive Medicine

[5] http://www.trauma.org/scores/ais.html

the velocity of deformation $v(t)$ of the chest in case of a frontal impact and of the relative compression and the velocity of deformation of the ribs in case of a side impact.

$$VC = \max\left\{c(t), v(t)\right\} = \max\left\{\frac{s(t)}{0.5 * d} * \frac{d\left[s(t)\right]}{dt}\right\},$$

where $s(t)$ is the deformation of the thorax, d corresponds to the width or depth of the chest measured in the direction of the impact [Crash05]. For the existing safety regulations the velocity of deformation is computed as

$$v(t) = \frac{d\left[s(t)\right]}{dt} = \frac{\left(s(t+\Delta t) - s(t-\Delta t)\right) - \left(s(t+2\Delta t) - s(t-2\Delta t)\right)}{12 * \Delta t},$$

where Δt is the time interval between two measurement steps in $[s]$ [Crash05]. For each body part one or more indices are available which will be not discussed further here.

3. Robot-Human Crash Simulation

For the simulations that are carried out within this research, two different mathematical approaches are dealt with for the impact investigation. These are the Finite Element Methods (FE) and the Multibody Dynamics (MBD) whose profit and differences for the robot-human crash evaluation will be outlined in the following.

The Finite Element Method is based on the discretisation of spatial structures, to provide a set of partial differential equations. Their solution can be achieved more easily with given boundary conditions than a solution for the full models mathematical description. The geometry, the characteristics and exterior forces on a body are approximated by finite element approximations. Surfaces are represented as meshes, so that solutions on the surface are given just on the interconnecting nodes on the mesh. To investigate the deformation of individual body parts of the human, where highly non-linear material laws are involved FE is widely applied in the biomechanical field, especially for the evaluation of injuries concerning passive occupant safety or pedestrian accidents analysis. A commercially available simulation tool for crashworthiness that is widely used within the automotive industry is LS-DYNA[6].

In the case at hand, this yields to the discretisation of the equation of motion of the dummy body parts, that are impacted by the robot arm. Thereby, motion and deformation of the body can be retrieved from the elements' performance which can be computed with commercially available FE solvers, as done here with LS-DYNA. Due to the high complex structure of bones and muscles, a full human modelling with FE data is rarely possible, full models only exist for body parts for specific applications, e.g. for modelling implants in the jaw. But as described above, representations of the human body are given by crash test dummies and these can be completely implemented as FE models.

Compared to the computational effort that is required for dynamic FE analyses with all relevant material parameters a MBD model can be realised in far lower dimensions. This is applied in most cases for complex active full body motion, where the body is realised as a kinematical chain of rigid bodies (usually identified with the word "links"), that are connected by joints as it is here for the behaviour of the controlled robot. On these individual rigid bodies, forces and moments can be applied, which is done mostly for industrial applications, but is also used in some cases for biomechanical behaviour. Usually links are rigid, but sophisticated computational tools also deal with flexible links. MADYMO e.g. is a simulation tool especially designed for injury simulation in car crashes, with the focus on investigation the human body movements in the car due to the seatbelt, or for investigating pedestrians behaviour involved in a crash. This is thereby realised with a coupling between FE and MBD simulation.

The MBD tool that is used for the kinematics simulation is the popular ADMAS[7] software. LifeMOD[8] is a plug in to this package to provide a complete modelling environment refining the task of creating passive and forward-dynamics for biological models which interact with the environment, tools and equipment. Crash dummy strength characteristics are available for passive-type dummies to be used in simulations. The strength model can be scaled to the particular body size and gender. The strength algorithm includes joint friction, non-linear stiffness/damping and limits with hysteresis using

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[6] LS-DYNA by Livermore Software Technology Corporation: http://www.lsdyna.com/

[7] ADAMS by MSC.Software Inc., http://www.mscsoftware.com/products/adams.cfm

[8] LifeMOD by Biomechanics Research Group, Inc., http://www.lifemodeler.com/

data derived from the physical dummy. The possibility to create simulations as damage appraisals in case of injuries is given for operators, used by assurances and personal injury investigators [McGuan95].

With the joint effort studying FE and MBD simulation for robot-human crash tests the authors expect to achieve the optimal outcomes for the evaluation of robot safety. The research approach offers the possibility to combine the view of robot design evaluation as it is done in [Yamada97] where Yamada et al. take pain tolerance limits to improve the safety behaviour by padding the robot with viscoelastic material (also see [Heiligensetzer03]), with the investigation of safety control strategies, such as collision avoidance algorithms and compliance control [Zinn04], [Kulic04], which will hereby be achieved by FE analyses and by the simulation with ADAMS.

3.1. FE crash simulation with LS-DYNA

3.1.1. Introduction to FE crash simulation

The time dependant deformation of the body $\Omega \in \Re^n$, $n = 2, 3$, is to be computed (see Fig. 4). Thereby a point $\overline{P}=(X_i)$, $i=1,..,n$, initially on the undeformed body Ω_0 is displaced at a time $t \in [0,T]$ to a point $P=(x_i)$, with the displacement $u(t)$, $i=1,..,n$. This yields with the Lagrangian formulation to:

$$u = u(X,t) \qquad \text{in } \Omega \times [0,\mathrm{T}]$$

The initial conditions at $t = 0$ hereby are set to:

$$\begin{array}{ll} u(X,0) = X, & \text{in } \Omega \\ \dot{u}(X,0) = v_0(X), & \text{in } \Omega \end{array}$$

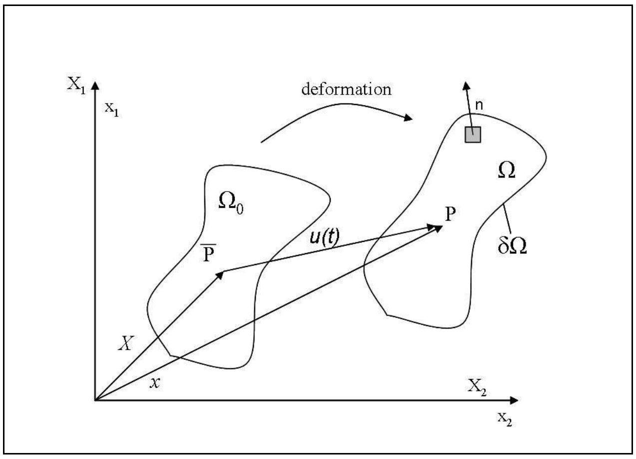

Fig. 4 Time dependant deformation of a 2-dim. body

The crash problem can in general be described as the momentum equation, with boundary conditions of the form:

$$\begin{array}{rcll} div\ \sigma + f & = & \ddot{u}, & \text{in } \Omega \times [0,T] \\ u(X,t) & = & g(t), & \text{on } \partial_d \Omega \times [0,T] \\ \sigma \cdot n & = & h(t), & \text{on } \partial_n \Omega \times [0,T] \\ (\sigma^+ - \sigma^-) \cdot n & = & 0, & \text{on } \partial_c \Omega \times [0,T] \end{array}$$

whose weak form will then be solved by finite element approximation. Thereby $\ddot{u}$ is the acceleration, σ the Cauchy stress, $f = \rho \cdot g$, with gravitation g and density ρ describe the internal forces. For the boundary conditions n describes the exterior normal vector and g and h are linear functionals. And the body's boundary is $\partial\Omega = \partial_d \Omega + \partial_n \Omega + \partial_c \Omega$ [Hughes00].

For the Finite Element Method the geometry of the body $\Omega \in \Re^n$, at a time $t \in [0,T]$ is represented with polygonal finite elements $\Omega_e,\ e=1,\ldots,E$, which fulfil $\bigcup_{e=1}^{E} \Omega_e = \overline{\Omega}$. For the deformed configuration $u(t) \in V \times [0,T]$, where V is the space of permissible displacement functions, finite element approximations $u_h(t) \in V^h \times [0,T]$, are constructed where $V^h \subset V$ is a subspace of finite dimension of V. Corresponding approximation procedures are to be done for the velocity and the acceleration of the body, depending on the applied finite element formulation.
Starting from a reference element $\hat{\Omega}$ whose local coordinate system corresponds to the global coordinate system, a map $\varphi_e \in C^\infty$, $\varphi_e : (\xi,t) \in \hat{\Omega} \times [0,T] \rightarrow (x_e,t) \in \Omega_e \times [0,T]$ is defined, which maps the coordinates $(\xi,t) = (\xi_1,\ldots,\xi_n,t)^T$ from the reference element to the local coordinates $(x_e,t) = (x_1,\ldots,x_n,t)^T$ to each individual element Ω_e. The sub- or superscript likewise define the affiliation of a coordinate or the constraint of a function to the corresponding element Ω_e.

The bodies' behaviour and its characteristics are then approximated by polynomial functions of low order to compute a finite set of solutions. This yields for the geometry to an interpolation of a form:

$$\left(x_h^e, t\right) = \sum_{a=1}^{m} \overline{N}_a(\xi)\overline{x}_a(t),$$

where *m* is the number of element nodes (e.g. $m=3$ in case of the discretisation of a 2-dim surface by triangular elements and $m=8$ in case of a discretisation of a 3-dim body by quadrilateral elements), $\overline{x}_a$ represents the coordinates of the corner nodes of the element Ω_e and $\overline{N}_a$ are the so called shape functions where $\overline{N}_a(\xi_a)=1$ for the node ξ_a of the reference element and $\overline{N}_a(\xi_b)=0$ for the other $m-1$ nodes ξ_b of $\hat{\Omega}$.

Each displacement on the reference element $\hat{\Omega}$ can then be described as $\hat{u}(\xi,t) = u(\varphi_e(\xi,t)) = u(x_e,t)$ and the approximated displacement for an arbitrary element Ω_e, $u_h^e(t) \in P^k(\Omega_e)^n \times [0,T]$, with $P^k(\Omega_e)^n$ representing some space of polynoms of order $\leq k$ depending on the corresponding FE formulation, can be interpolated analogous to the geometry interpolation above as:

$$\left(u_h^e, t\right) = \sum_{a=1}^{m} N_a(\xi)\overline{u}_a(t),$$

where $\overline{u}_a$ are the displacements of the nodes of the arbitrary element, and N_a polygons of order $\leq k$.

Different element formulations are available for a variety of element types to compute the time dependant displacements, velocities and accelerations with corresponding strains and stresses to describe the behaviour of impacted bodies.

LS-DYNA is a finite element code for the analysis of large deformation dynamics response of structures. Based on explicit time integration an impact-contact algorithm is provided to allow the evaluation of crash tests. The time integration will not be further described here. Fur reference refer to [Hallquist98].

3.1.2. Crash and Injury Index Evaluation for Robot Systems

LS-DYNA is one of the main simulation tools used for crashworthiness studies and together with the FAT[9] different FE models of the crash test dummies that are requested for the procedures proposed by the EuroNCAP have been developed within this code. For the robot-human impact FE simulation in this paper, the robot CAD data is implemented within the FE code. To reduce the computational effort, only the data of the robot axes that are directly involved in the crash need to be carried throughout the whole simulation. They are implemented as rigid bodies with the corresponding material parameters and the inertia data of the whole robot to simulate the movement properly. The information on the movement of the manipulator is not computed during the simulation, but is implemented directly as the time-velocity dependant path.

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[9] German Association for Automotive Research

The first FE simulations are conducted with a model of the KUKA KR150. The CAD data is meshed with quadrilateral elements with the mesh generator of the LSPRPOST with a maximum mesh size of 50mm for the first 2 axes and the maximum mesh size of 10mm for the upper part (see Fig. 5). The FE dummy model that is used for the injury index evaluation is the ES-2 model which is developed with and distributed by the DYNAmore GmbH.

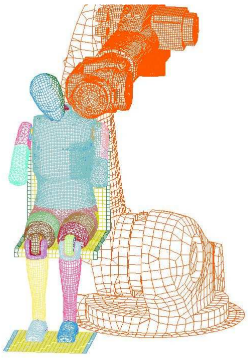

Fig. 5 Implemented dummy and robot in LS-DYNA

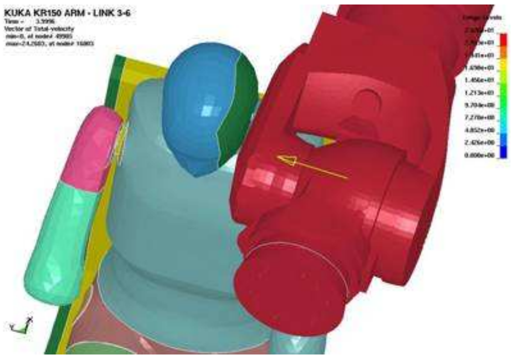

Fig. 6 Contact position between dummy and robot arm

The ES-2 is positioned on a chair which resembles a scenario where the worker is sitting in front of a workplace at the right side of the robot. The scenario has been chosen as the dummy models that are developed for car crash scenarios are always built for seated positions and the side impact dummy is always instrumented specifically for one side. This does not result in a limitation of evaluation scenarios as the focus of this research is the evaluation of injury indices arising right during the crash and they are affected at a stiff impact in the first period of the crash, therefore the kinematical behaviour of lower parts of the impacted dummy can be disregarded for the moment.

Fig. 6 presents the impact position between the robot arm and the dummy head, with the robot moving at a constant speed on the first axes in the direction of the dummy. The robot arm that is reduced to its upper part to save computational power is modelled as a rigid body with the material parameters specified as:

Poisson's ratio $\mu = 0.33$, mass density $\rho = 2\,680 \frac{kg}{m^3}$ and Young's modulus $E = 72\,400 \frac{N}{mm^2}$.

The contact definition between the robot arm and the dummy part that is impacted is implemented with the AUTOMATIC_SURFACE_TO_SURFACE contact within the LS-DYNA code. This card allows to check for penetrations of each node from a "slave" (dummy) through a segment of a "master" (robot) [Hallquist98], [LSDYNA05].

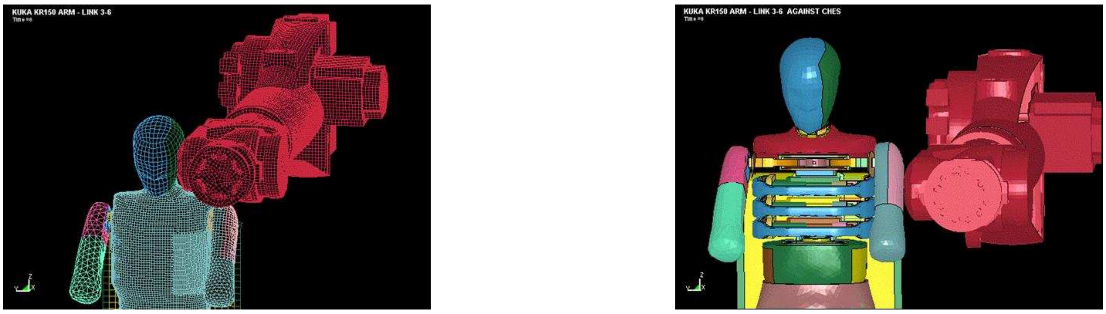

Fig. 7 LS-DYNA impact simulation on head and chest

For the simulation of the impact a pre-described path with constant velocities from $v = 10.5$ °/s to $v = 105.0$ °/s was applied as the robot motion, where the robot moves with full speed on the dummy. The dummy was impacted at different body parts with a specific focus taken on the study of the head impact.

In the centre of mass of the dummy head the aluminium skull is merged to a rigid accelerometer to report the acceleration of the head in the three directions x, y, z. The resultant acceleration of the dummy head together with the corresponding HIC values are shown in Fig. 8 for different velocities, up to the maximum velocity of $v = 105.0$ °/s which produces a HIC=873.9.

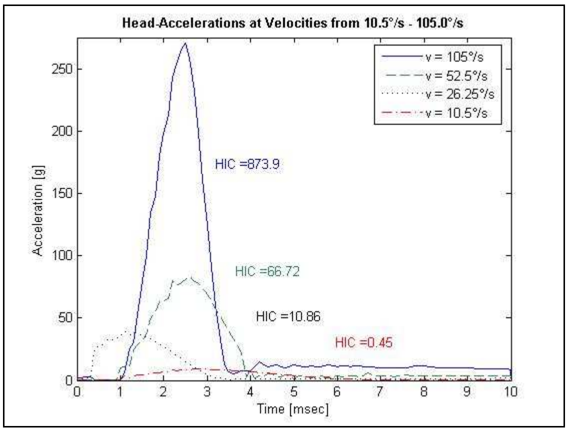

Fig. 8 Arising head acceleration with corresponding HIC values

For the automotive society the HIC is provided with a limit of 700 or 1000 (depending on the maximum impact time interval). In case the limit is exceeded, there is a high possibility of a non-reversible injury to the head [Crash05]. Maximum velocities of industrial robots of the underlying size will therefore surely not be adequate for the robot-human cooperation. Small velocities, as in this case 10% of the maximum velocity, do not necessarily result in a non-reversible head injury according to an evaluation of the HIC, as its values stay below 1. Still the knowledge of size and mass of the robot manipulator reveal a high impact force also at small velocities.

Here it must be mentioned again, that the HIC evaluation refers only to the acceleration of the head. This had been identified at the most hazardous potential in car crash scenarios, but might not resemble the situation in the short stiff impacts at hand. In a car crash the head directly contacts an airbag or the car interior or, in case of a pedestrian accident, the bonnet of a car. This results in softer contacts with higher acceleration as in the robot-human impact case. Hereby forces that are applied to head should not be disregarded to assess the injury severity.

3.1.3. Crash and Injury Index Evaluation for Robot with Small Payload

As a second example, a COMAU Smart NS16 is integrated in the LS-DYNA crash setup. First simulation results revealed that for crashes against the head with low velocities, the acceleration behaviour of the dummy head is independent from the rest of its body. Taking the head model out of the dummy safes a significant amount of computational power as the number of elements is highly reduced. Therefore the simulation for the HIC evaluation of the Smart NS16 is carried out with the reduced dummy model, as shown in Fig. 9.

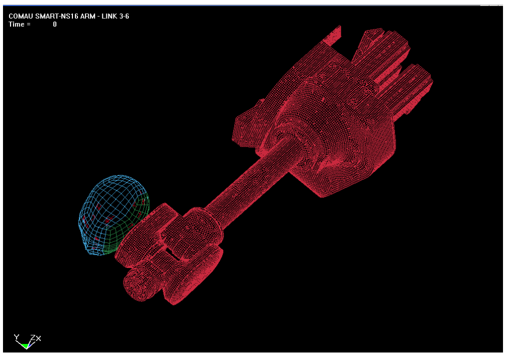

Fig. 9 Head impact with Smart NS16

The constant velocities evaluated hereby range from $v = 5.0$ °/s in time steps of 2.5 °/s to $v = 50.0$ °/s. The aluminium casting corresponds to the material parameters:

$$\text{Poisson's ratio } \mu = 0.34\text{, mass density } \rho = 2\,800\frac{kg}{m^3} \text{ and Young's modulus } E = 72\,600\frac{N}{mm^2}\text{ .}$$

The resulting HIC values are presented in Fig. 10.

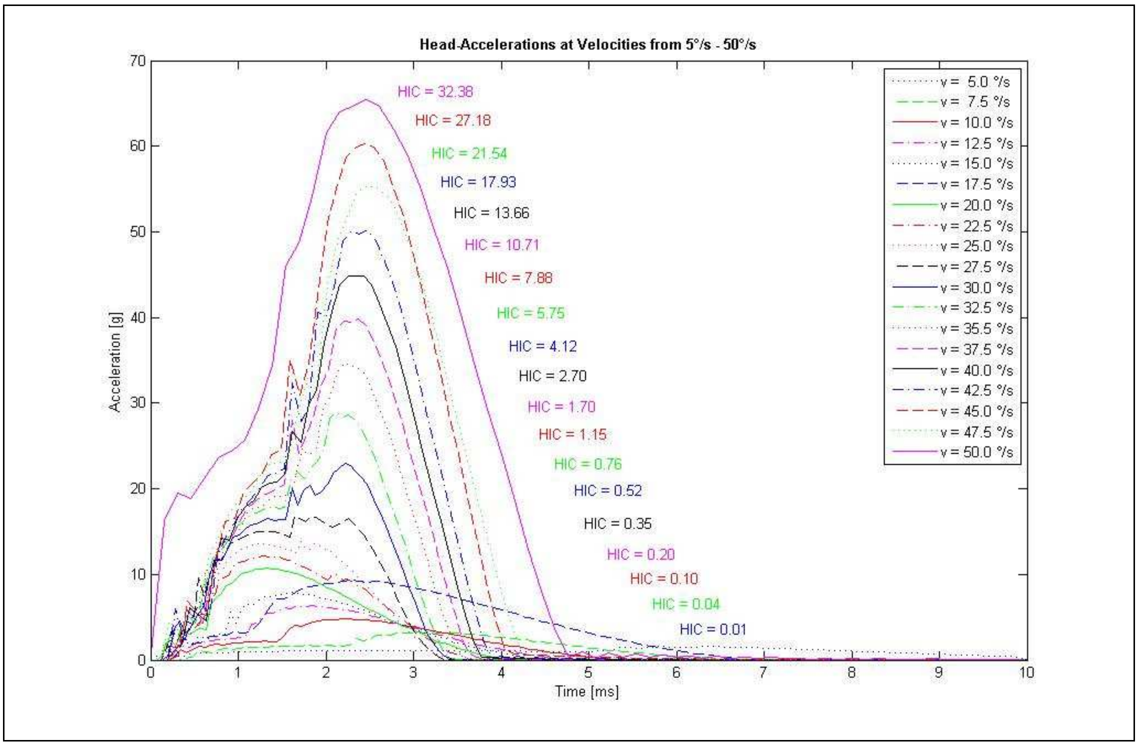

Fig. 10 Head accelerations with corresponding HIC values

Also this HIC evaluation reveals very low values, compared to experienced values. The comparison of the head accelerations from the different simulated velocities proof the stability of the FE head model also for the underlying short stiff impacts. The trend of the HIC value also resembles a stable simulation. As pointed out before, the limits that have been derived for the car crash scenarios take into account a maximum impact interval of either 15 or 36 milliseconds. As can be seen in the graph in Fig. 10 the impact interval for the impact between robot an head only covers up to 7ms even for the slow velocity of $v = 5.0$ °/s. To assess the severity from the acceleration of the head for these kind of impacts, limits for a HIC5 using a maximum interval of 5ms should be considered.

3.2. MBD crash simulation with ADAMS and LifeMOD

A substantial difference exists between car crash-tests and simulations of a human-robot collision. In a vehicle impact it is necessary to simulate as accurately as possible the deformation of the car chassis: the deformation energy absorbed by the structural part of the car during the deformation determines the energy saved to the occupant and, then the resulting consequences for the occupant. Therefore FE techniques are essential to execute large-deformation analysis.

A different situation is given, if on the one hand a certain minimum stiffness has to be guaranteed for the TCP during normal operating of the robot and on the other hand intrinsic (hardware) compliance of the mechanical structure and of mechanical transmissions must be considered. An important part of the energy absorbable by a robot as a result of an impact (avoiding its transfer to the operator) can be mainly due to the imposed dynamics to actuated joints by the control system: determined motion laws applied to joints can limit the amount of energy applied to the point of impact. The integration of control algorithms in impact simulations can represent an important factor to simulate the impact dynamics.

3.2.1. Aim

The aim of the scheme proposed here, is the simulation of robot-human impacts with the integration of robot-control reactions. The integration of the dynamical model and of the control scheme of the robot permits to simulate realistically what effectively happens during the impact and how the robot reacts. The Simulink environment permits to connect control schemes with dynamical models created in ADAMS/View and exported by ADAMS/Controls. The human dummy, modelled on the base of the Hybrid III dummy, is realised for the use in the LifeModeler tool, integrated inside ADAMS/View. For a correct description of the dynamic interaction between the human and the robot it is necessary to determine how forces are exchanged between two bodies during a contact [Forbes05].

3.2.2. Description

A cosimulation platform for Simulink and ADAMS simulation is set up. In Fig. 11 the main blocks which constitute the simulation environment are reported.

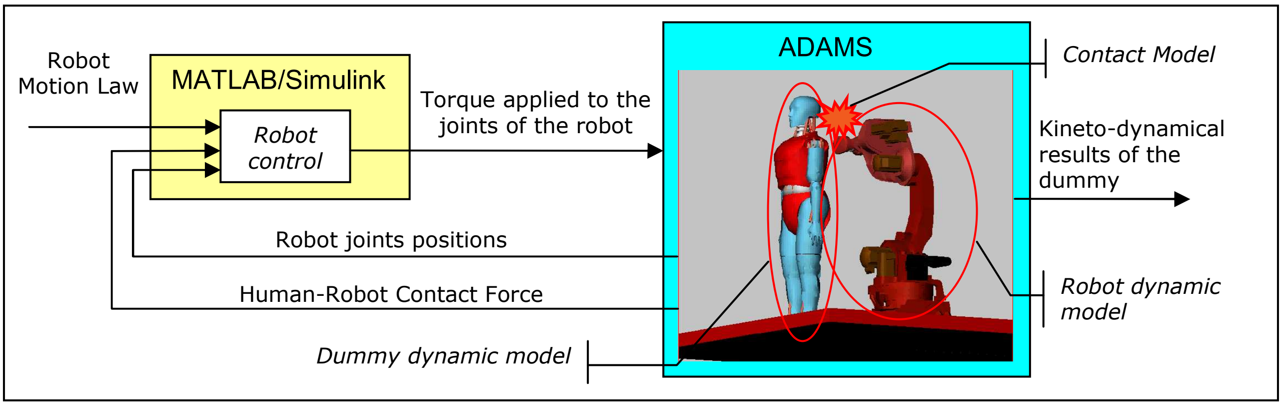

Fig. 11 ADAMS simulation scheme for human-robot interactions

During the simulation, kineto-dynamical measures are computed and automotive indices are evaluated on the basis of this data. In the following the different features of the cosimulation platform are describe. First a dynamic model of the robot is imported into the ADAMS/View environment. Then the dynamical model of the dummy is created by LifeMOD™. This plug-in tool to ADAMS/View is dedicated to the modelling, sensoring and analysing of a multibody model of the human. The joints of the created model for this type of analysis are characterised by a kinetodynamic behaviour in order to simulate the articulation of a real human body.

Through the use of ADAMS/Controls the dynamic model of the robot in ADAMS/View is driven by force/torque signals through appropriate control algorithms. The contact thereby has to be modelled to assure that the impact force between the robot and human during the impact is described in detail. The contact forces mathematical description takes into account the characteristic of the material at the impact zone. In ADAMS it is possible to specify the contact force as specified by the IMPACT function, which approximates the Hertzian formulation. However the Hertzian Contact Theory only considers the local deformation of the colliding bodies and does not consider their global deformation. In general terms the Hertzian formulation produces a good approximation for rigid bodies, but when bodies with lower stiffness are included, it does not sufficiently consider the deformations. This is the case for human body parts with their soft tissue material, that provide different mechanical responses than a robot arm. Thus, FE models provide better approximated reaction forces than can be achieved directly from the analytical IMPACT formulation. The contact force thereby is described with a generic non-linear viscoelastic response. For this reason, impact tests for different velocities that have been conducted in LS-DYNA with the FE dummy model are evaluated to adapt the contact of the ADAMS model.

In Fig. 12 a scheme of two colliding bodies is reported. The grey one represents the non-deformable robot, while the white stands for a generic body which constitutes the dummy. The reaction force can be expressed as a function of the deformation and the velocity of the deformation of the body. The deformation d of the body can be expressed, for the purpose at hand, as $d = \overline{P_{B0}P_{A0}} - \overline{P_B P_A}$. This is directly computed by the LS-DYNA measuring of the relative displacement of two nodes on the mesh of FE dummy's head (see red continous line in Fig. 12) and is equivalent to the penetration of two rigid models (see grey dotted line in Fig. 12).

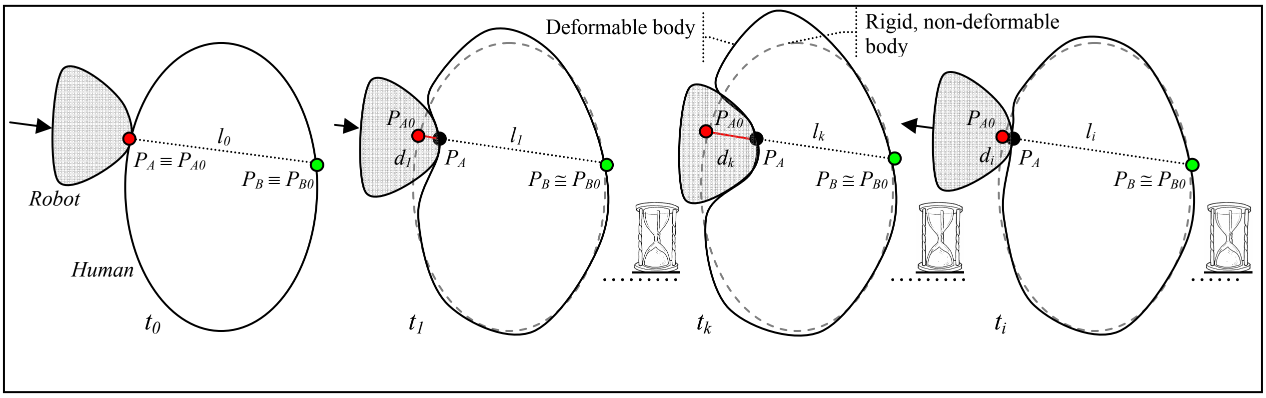

Fig. 12 Representation of two colliding bodies

In Fig. 13 a set of data collected by the LS-DYNA simulation is presented, which forms the basis for the modelling of the reaction of the human head that is impacted by the end-effector of a robot. The robot is driven by rotational velocity imposed on joint 1. The velocity ranges from 5 to 50°/s, as already for the simulation in the robot-head impact in paragraph 3.2.3.

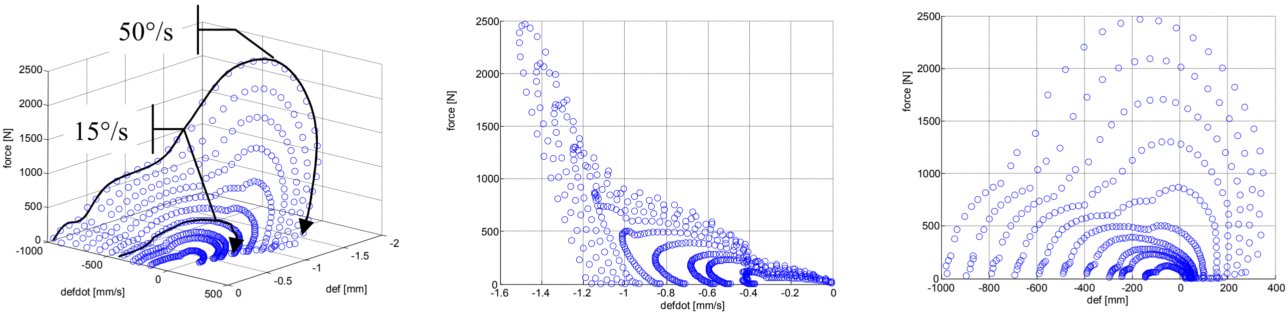

Fig. 13 Contact characterisation for ADAMS with LS-DYNA simulation data

During the ADAMS simulation the value of the contact force is estimated by the interpolation values obtained from the FE simulation. To estimate the deformation of the dummy, which is not measurable in a rigid model, the penetration of the bodies is evaluated, while the mechanical structure of the robot is considered non-deformable.

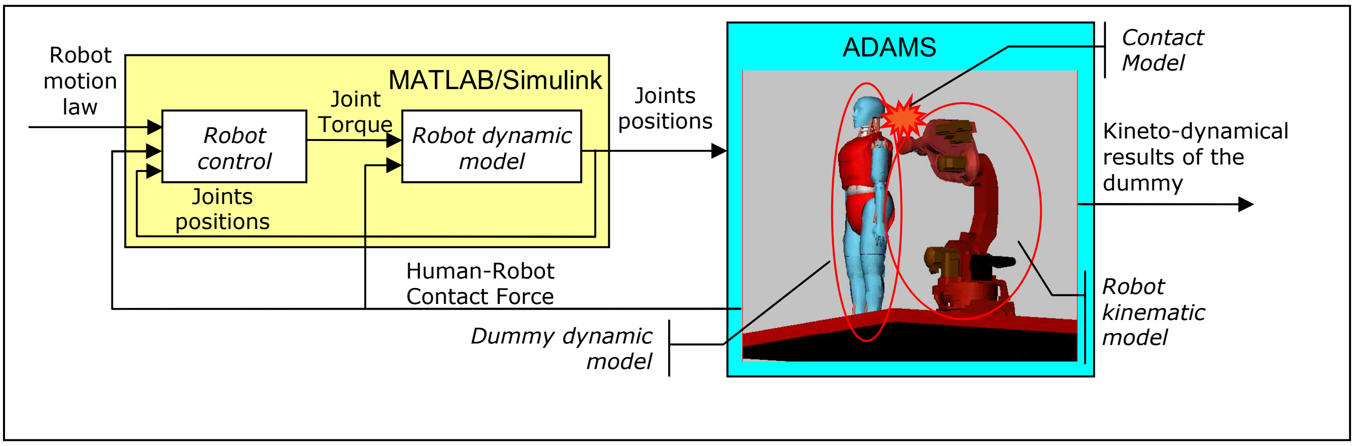

Fig. 14 Alternative ADAMS simulation scheme for human-robot interactions

An alternative version for the cosimulation is reported in *Fig. 14*: It is possible to substitute the dynamic model of the robot in ADAMS with a Simulink scheme, often used to model phenomena such as clearances, non-linearities, hysteresis phenomena. In this case it is not necessary to have a dynamic model of the robot in ADAMS, but a geometric model suffices, that is controlled by positions on the base of the dynamic Simulink simulation. The geometry of the robot in ADAMS is then only needed to execute internally the contact algorithms with the dynamic model of the dummy.

3.2.3. Simulations in the MBD environment

Data obtained from various velocities (from 5°/s to 50°/s) of the collision of the COMAU Smart NS16 robot have been used to characterise the contact. The representation of this data is reported in *Fig. 13*. The contact routines of ADAMS have been personalised according to the collected data.

In the following figure Fig. 15 some clips of the setup simulation are reported.

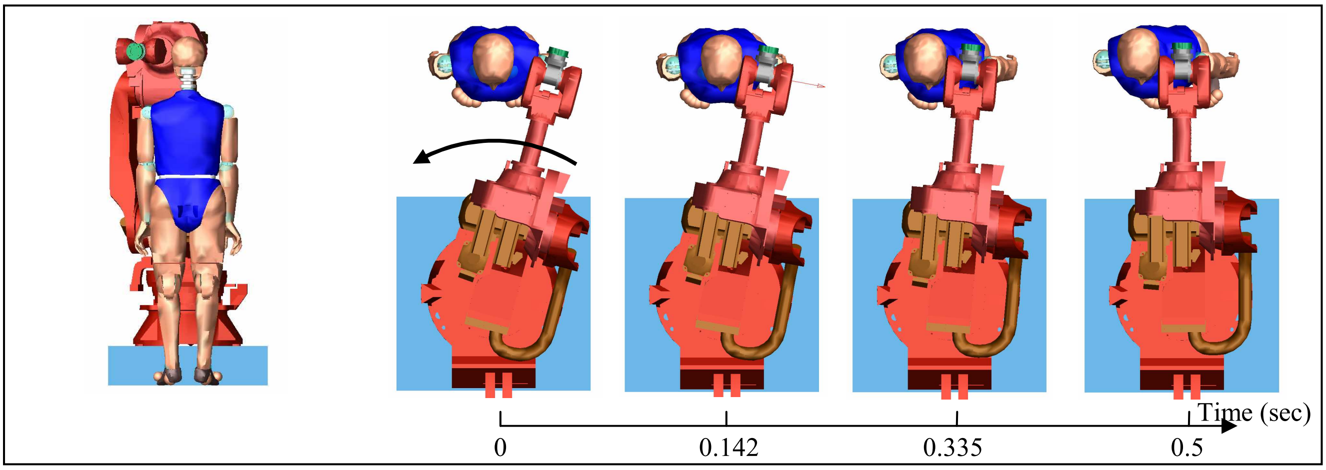

Fig. 15 Frames of the collision experiment in case of constant rotational velocity (30°/s)

The impact data corresponding to the described setup simulation is reported in Fig. 16. In the first simulation the joint 1of the robot is controlled in position, with 30° for the full movement (see red curve), and in the second simulation an idle joint 1 which absorbs the energy produced during the impact slowing down its rotational velocity is simulated (see green curve).

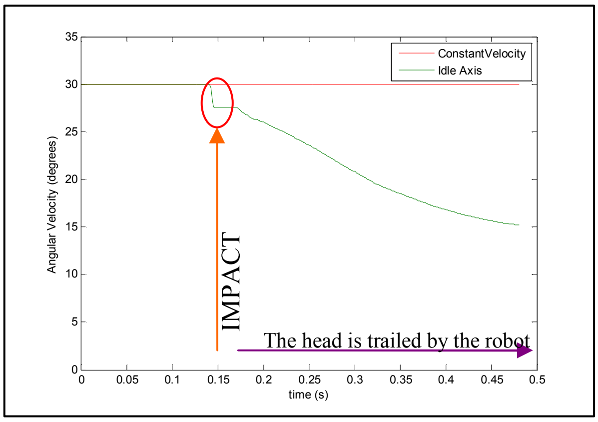

Fig. 16 Rotational velocity of the robot due to impact, considering J1 position-controlled (red) or idle (green). Modification of the velocity can be noticed due to the impact.

As a validation of the proposed platform the coherency for the results obtained by FE simulations (see Fig. 9) with the results obtained with the MBD simulation for a rotational velocity of 30°/s can be seen in Fig. 18. The same curves are obtained through FE and through MBD simulation and the computed HIC indices are comparable. This is considered as a confirmation of the modelled contact.

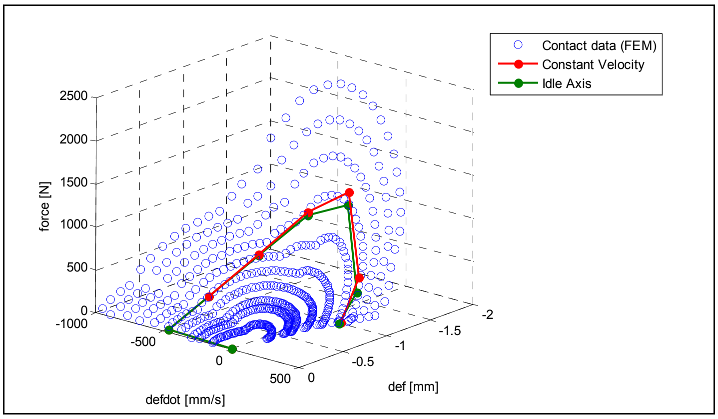

Fig. 17 Forces during the impact in two different rotational velocities of the robot due to the impact, considering joint 1 position-controlled (red) or idle (green). Modification of the velocity can be noticed due to the impact.

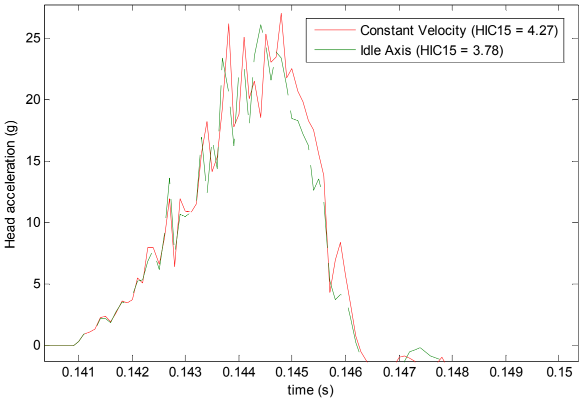

Fig. 18 Unfiltered head accelerations considering joint 1 position-controlled (red) or idle (green).

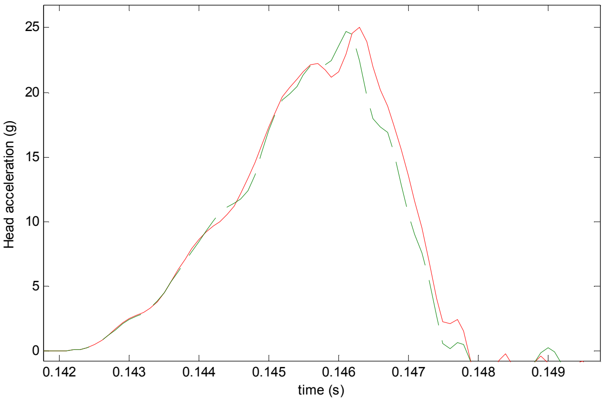

Fig. 19 Filtered head accelerations considering joint 1 position-controlled (red) or idle (green).

The oscillations of the head acceleration in the unfiltered measures depend mainly on rounding errors during the force interpolation (Fig. 17). This inconsistency can be easily overcome by denser force samplings of the FE data, or by implementing interpolations of higher order. It is important to mention that both the HIC index and the head acceleration, filtered through a lowpass filter to eliminate noise in Fig. 19 , result in lower values in the idle case, than in the constant velocity case, as expected due to the energy transfer to the human body.

4. Conclusion and future work

The studies proposed here present a first simulation and analysis setup to describe injury indices for accidents due to robot-human impacts. The studies hereby have been restricted to the head, further body regions will be investigated in the next step, taking into account the chest and the pelvis. Attention should also be taken to evaluate backlash consequences due to an impact of the robot with the back of the human body.

The examples presented to introduce the MBD environment with the integration of the control and the FE simulation are first examples to illustrate the effectiveness of the proposed platforms. The used simulation tools provide a high potential for the evaluation of additional safety features based on hardware equipment or control strategies. Even though significantly high differences between the masses and inertia of the standard industrial robot and the deformable head model exist, the implementation into both tools resembled analogous behaviour.

Further discussion with experts from biomechanics will be conducted to strengthen the applicability of the recent injury indices, as well as to further specify limits according to the situation of the stiff robot impact. As the HIC only takes into account the acceleration of the head, further hazardous impact potential like forces and torques the head is exposed during the crash need to be discussed in detail. Because of this short period of time in which a collision takes place it is important to introduce light and flexible robots with reactive controls, able to detect contacts and to change rapidly the control strategy modifying torques applied to motors.

5. Acknowledgement

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