Safety Map: A Tool for Global Robot Safety Evaluation and Safe Robot Design

Nico Mansfeld, Mazin Hamad, Marvin Becker, Antonio Gonzales Marin and Sami Haddadin

***Abstract*— Safety is a key requirement in physical human-robot interaction. In particular, the influence of robot dynamic properties on human injury probability has to be understood well. Then, potential harm can be minimized already at an early stage of the robot design process. In this work, we propose the *safety map* concept, a map that captures the robot inherent safety properties and human injury occurrence in a unified way from both a global, and a task-dependent perspective. This makes it a novel, powerful, and convenient tool to quantitatively analyze the safety performance of a certain robot design. We elaborate the concept, describe how to process human and robot data towards the *safety map* representation and show how it can be integrated into the safety assessment and (automatic) robot design workflow.**

I. Introduction

Physical contact is part of the process in physical human-robot interaction (pHRI) and unforeseen, potentially dangerous collisions can generally not be avoided. It is therefore a primary concern to ensure safety. Many efforts have been taken to develop safe mechanical designs and control strategies and analyze human injury mechanisms.

Lightweight manipulator design is generally regarded essential for ensuring collision safety in terms of kinematics and mechanics. Furthermore, intrinsic joint elasticity and soft covering were employed to improve safety [1]–[3]. Typically, the selection of inertial and elastic properties is driven by certain design decisions for most robots. In contrast, in [4], [5] it was proposed to integrate quantitative safety (and performance) criteria already in the mechanical design phase.

In terms of safe control, many metrics- and model-based approaches were proposed over the years [5]–[9]. A major drawback of model- and metrics-based ratings of a robot's safety characteristics, however, is that the consistency with medically observed injury is often insufficient. In our previous work [10], we therefore proposed to directly associate the instantaneous robot collision input parameters reflected mass, velocity, and contact geometry to observed human injury for a model-independent safety analysis. With this approach, no intermediate physical quantities such as force or pressure have to be associated with injury.

Based on systematic impact experiments, so-called safety curves were then derived that provide the maximum biomechanically safe velocity as a function of the instantaneous robot reflected mass. These safety curves were then employed in the safe velocity controller *Safe Motion Unit* that limits the current robot speed according to the safety curves, thus ensuring safety even in case of entirely unforeseen collisions.

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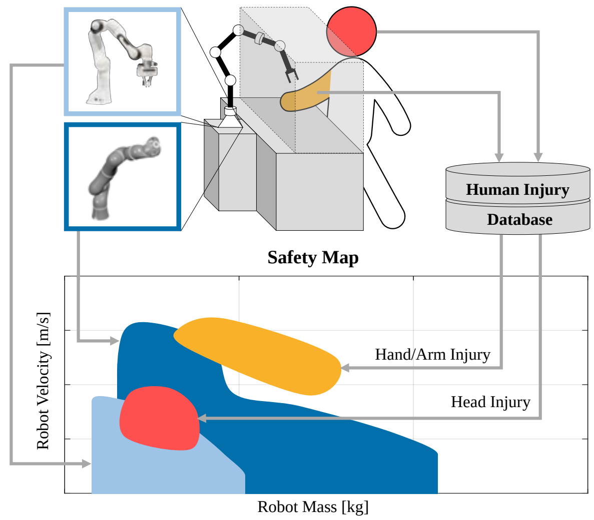

Fig. 1. *Safety map* concept. The global or task-specific (gray interaction area) mass/velocity ranges of different robots (here: DLR Lightweight Robot and Franka Emika Panda) and injury occurrence of human body parts are represented in a unified manner in the *safety map*. The injury data associated with the considered body parts is obtained from an injury database.

In this work, we follow this line of research and deduce a global perspective of a robot's safety characteristics. More specifically, we propose the concept of a *safety map*, which captures both the robot global dynamic properties and human injury occurrence in a unified manner. The *safety map* enables the user to address following (among other) questions:

- Is the considered robot capable of producing a certain type of injury during unforeseen collisions in my application?
- Where are the most dangerous areas in the reachable robot workspace?
- How do the robot safety characteristics compare with other performance indices? For example, how dangerous is the robot in its most dexterous workspace?
- How does the robot compare to other robots in terms of safety characteristics?

For relating entire robot designs to available biomechanics safety data in the *safety map*, we analyze the reflected mass and maximum velocity in task-dependent workspace sets. This is done for two exemplary robots, namely the *PUMA 560* and the *KUKA Lightweight Robot IV+ (LWR)*. In terms of human injury data, we classify, validate, and process a significant amount of relevant data from 50 years of biomechanics injury research into the mass/velocity representation and link it to the proposed *safety map*.

To sum up, the *safety map* concept may serve as a global safety assessment framework for entire robot designs without the need of simplifications. This makes it a valuable tool for safer robot design and safety-oriented planning.

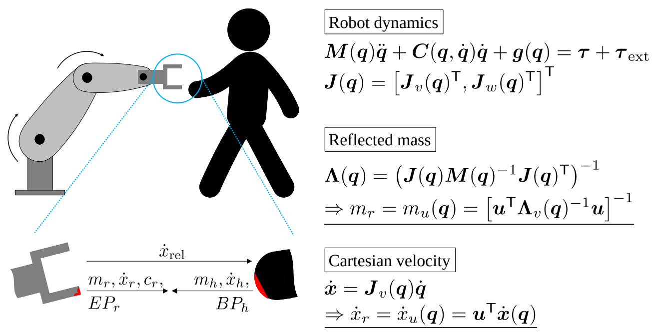

Fig. 2. Collision model for representing the instantaneous dynamic properties of the impactor/robot and subject/human. In the robot dynamic equations, $q \in \mathbb{R}^n$ denotes the generalized coordinates, $M(q) \in \mathbb{R}^{n\times n}$ the symmetric, positive definite mass matrix, $C(q,\dot{q}) \in \mathbb{R}^{n\times n}$ the Coriolis and centrifugal matrix, and $g(q) \in \mathbb{R}^n$ the gravity torque vector. The motor joint torque is denoted $\tau \in \mathbb{R}^n$ and the external joint torques $\tau_{\text{ext}} \in \mathbb{R}^n$. The Jacobian matrix associated with the impact location is $J(q) \in \mathbb{R}^{6\times 6}$ and the Cartesian mass matrix is $\Lambda(q) \in \mathbb{R}^{6\times 6}$. The scalar mass and velocity in normalized Cartesian direction $u \in \mathbb{R}^3$ are denoted $m_u(q) \in \mathbb{R}$ and $\dot{x}_u(q) \in \mathbb{R}$.

II. Definition Safety Map

In nowadays robot safety assessment, trajectories or so-called "representative" configurations are related to human injury probability or safety metrics in order to locally avoid unwanted injury via control or planning. In this work, we propose to

- **relate entire robot designs**, i. e., the mass/velocity pairs for the reachable workspace, respectively a task-dependent subset, **to**
- **human injury data**, which may
  - originate from different types of experiments and disciplines (robotics, forensics, biomechanics, simulations etc.),
  - consider different body parts,
  - impactor curvatures (blunt, edgy, sharp), and
  - collision cases (constrained, unconstrained),
- **in the same "coordinate system"**, namely the plane spanned by the robot reflected mass and velocity.

This global representation is denoted *safety map*, the concept is illustrated in Fig. 1. In the *safety map*, human injury data and dynamic robot properties can be aggregated, which enables a robot/task designer to assess the considered robot(s) in combination with the task specification in terms of safety already at a very early stage in the design process. In Fig. 1, e. g., the mass/velocity ranges of the two robots intersect with the head injury data, which means that both robots may harm the human head during collisions. Hand/arm injury, however, may only be produced by the second robot[1].

III. Collision Model & Synopsis of Human Head and Chest Data

For deriving the *safety map* representation of injury data and robot instantaneous dynamic properties, we use the collision model which is illustrated in Fig. 2. The model follows our approach taken in [10] and is based on the idea that any mechanical system can be represented by an instantaneous scalar mass, velocity, and surface properties in a certain Cartesian direction of motion. The impactor/robot

[1]Please note that these are no general conclusions as for illustrative reasons the data in Fig. 1 is fictitious.

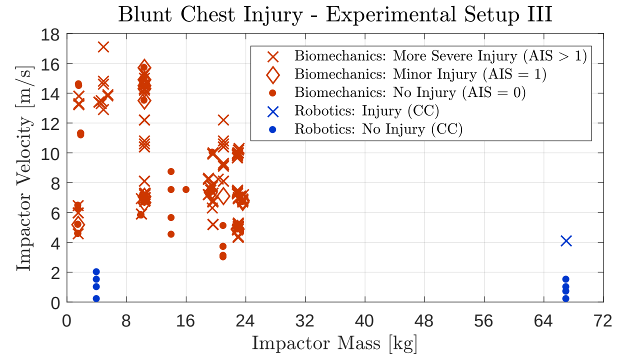

Fig. 3. Summary of relation between mass, velocity, and injury for selected data on the chest [11]–[13].

is represented by the so-called reflected mass m_r, velocity $\dot{x}_r$, curvature c_r, and elastic surface properties EP_r. The subject is represented in terms of the impact location BP_h, instantaneous mass m_h, and velocity $\dot{x}_h$.

Using this collision model, we classified and summarized relevant literature from biomechanics research on the most crucial human body parts, the head and the chest. We use a database to store the injury data in a systematic fashion. From the database, we can derive the *safety map* representation of human injury occurrence. An example is depicted in Fig. 3, where we provide the mass/velocity representation of blunt chest injury.

IV. Deriving Global Robot Dynamic Properties

Having collected, classified, and processed human injury data, we now describe how the kinematic and dynamic properties of a robot can be mapped to a mass/velocity range to represent the robot properties on a global or local, task-dependent, scale in the *safety map*. We seek to determine the reflected mass and maximum velocity for all reachable poses, i. e., Cartesian positions and orientations, and in every Cartesian direction u. A key idea of the concept is to derive the global dynamic properties of a certain robot only once. Afterwards, the data associated with task-dependent subsets of the robot workspace can be extracted, and also certain trajectories or single static configurations can be analyzed by interpolating the data. This allows for different degrees of granularity in the safety analysis.

The procedure for determining the global robot dynamic properties consists of four steps, namely

1) discretize the workspace and determine all reachable poses of a robot, in other words, its reachability map,
2) for each reachable pose, determine the set of reachable null space configurations if the robot is redundant,
3) generate a grid of Cartesian directions, and
4) calculate the Cartesian reflected mass and maximum velocity for each feasible pose, null space position, and Cartesian direction.

In Fig. 4, we provide the map representation of two exemplary robots, namely the *PUMA 560* and the *LWR IV+*. For both robots, we select a 5 cm uniform distance for generating the Cartesian position grid. We only consider one end-effector orientation for sake of clarity. In addition to the global mass/velocity range, we analyze a typical workspace area of $60 \times 20 \times 40$ cm size, which is the same for both robots.

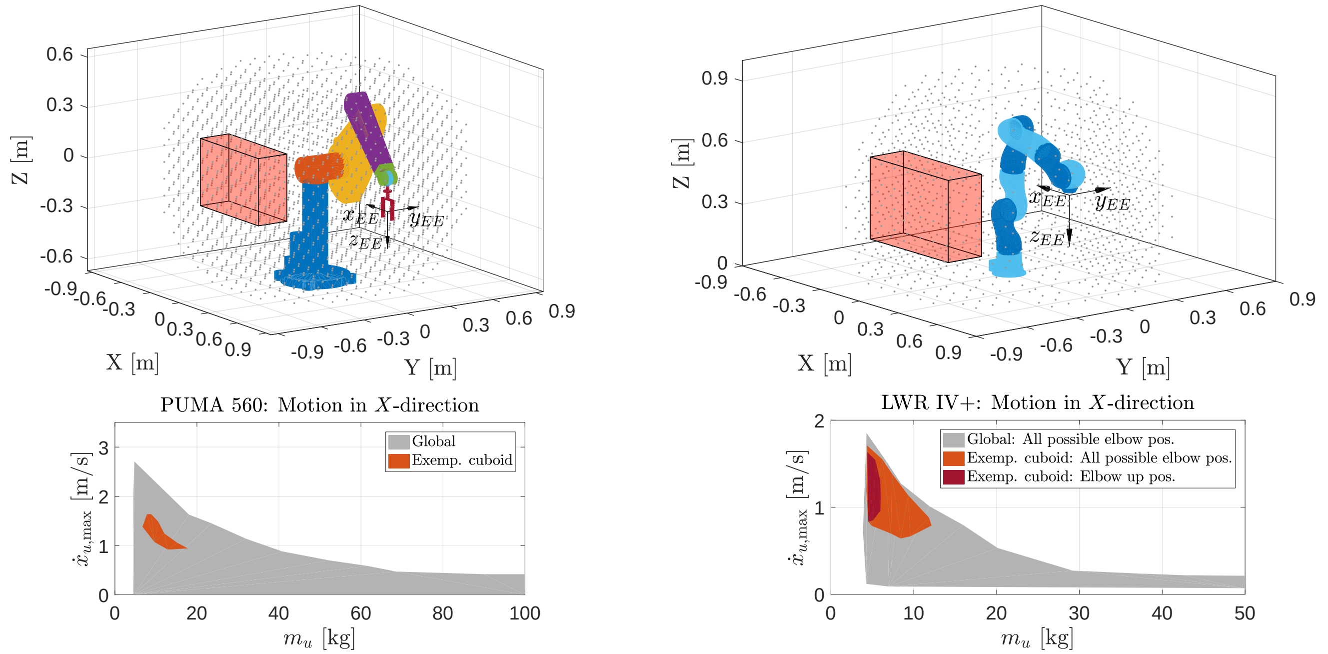

Fig. 4. Map representation of the *PUMA 560* and the *LWR IV+* for motions in Cartesian X-direction. In the upper row, the feasible Cartesian positions for the considered end-effector orientation are illustrated as dots, an exemplary subset of the workspace, a cuboid with $60 \times 20 \times 40$ cm, is colored red. In the lower row, the mass/velocity representations of the *PUMA 560* and *LWR IV+* are depicted.

V. Application of Safety Map to Safety Assessment and Robot/Task Design

The *safety map* is a tool for safety evaluation that can be integrated into the robot and task design workflow. For the global analysis of the robot intrinsic safety properties, the *safety map* can be utilized to determine, e. g., whether a) the robot is capable of producing a certain type of injury, b) where the most dangerous areas in the reachable workspace are located, or c) how safety properties compare with other performance indices such as manipulability/dexterity in certain workspace areas.

For assessing certain applications in terms of safety, following steps are to be carried out to derive the associated *safety map* representation:

1) Extract task-dependent mass/velocity data (workspace area or trajectory) from global robot dynamic properties,
2) Assign contact primitives with their parameters to points of interest on the robot structure (usually the end-effector),
3) Identify collision scenarios (constrained/unconstrained) and human body parts that may be hit during collisions by analyzing the shared workspace, and
4) Select corresponding injury data and relevant thresholds from the current standards.

If the robot and injury data intersect in the *safety map*, then collisions of this dynamic properties will likely result in an injury when the robot always travels at maximum velocity. Based on this information it can then be systematically analyzed which countermeasures in either control/planning or mechanical/task design are necessary in order to ensure safety. For example, critical geometries can be identified and then modified such that robot and human data no longer intersect in the *safety map*, or safe velocity control may be used in order to meet both safety and performance requirements at the same time.

Please note that this work primarily elaborates the *safety map* concept and describes how human injury data and robot dynamic properties can be processed towards the mass/velocity representation. The integration into automatic robot design is ongoing research.

VI. Conclusion

In this work, we proposed the concept of a *safety map*, a map that represents injury biomechanics data and robot collision behavior in a unified way. It is a novel tool for robot developers that can be utilized for safer robot design already at an early concept phase of the development process. The robot dynamic properties can be quantitatively compared to any available injury data for different contact primitives, collision cases, and human body parts. This gives the designer clear information which kind of injury is most likely to occur during operation. This guides not only the hardware design process, but also gives valuable information to the development of safe motion planning and interaction control. To the best of the authors' knowledge, the framework is the first global dynamic and exact safety analysis tool for robot manipulators, which may lead to significant changes in the way human-friendly robots are designed in the future.

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