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# Design of elastomeric foam-covered robotic manipulators to enhance human safety

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ABSTRACT

Unintentional physical human–robot contact is becoming more common as robotic manipulators operate in closer proximity to people. In this paper, we investigate the use of compliant foam covering to reduce impact severity and enhance human safety. An improved analytical impact dynamic model is introduced. The impact model conservatively approximates the impact force and resulting head acceleration; and incorporates the configuration-dependent manipulator dynamics and the coupling between the human head and moving torso. It is applicable to head impacts with impact velocities that do not exceed 1.25 m/s. Based on this model, the most important manipulator parameter for reducing the impact severity is the effective mass. Furthermore, the foam stiffness has a greater reduction effect than any of the manipulator parameters. A procedure to properly design the foam in accordance with a force-based or acceleration-based safety criterion and a foam thickness constraint is proposed. The impact model and model-based design procedure are tested experimentally. Impact experiments are performed with an apparatus simulating the human head–neck–torso. The maximum error between the predicted and experimental maximum head acceleration results is less than 7%.


## 1. Introduction

Whether in industrial applications such as teach programming, or service applications such as rescue robots, robotic manipulators are operating closer to humans than ever before. The close proximity of humans and robots makes unintentional contact likely. This contact could generate a large impact force and/or large head acceleration causing serious injury. Therefore the ability to reduce the human–robot impact force and/or head acceleration to enhance human safety is a fundamental requirement for these robots. Conventional impact reduction methods can be classified into four categories: active control methods, actuation methods, passive mechanisms and compliant coverings. Impact dynamic models are sometimes used to make these methods more effective. The relevant literature on these topics will be reviewed in the following sections.

### *1.1. Impact force/head acceleration reduction methods*

Previous researchers have utilized active control methods to reduce the impact force and/or head acceleration. Heinzmann and Zelinsky [1] developed an impact potential control scheme that limited the impact force of the robot by restricting the torque commands. De Luca et al. [2] developed a collision detection method that uses the manipulator dynamic model, and the position and velocity errors based on the built-in proprioceptive sensors. According to their experiments, the delay of the contact detection is about 0.004 s. After the collision is detected, a reflex strategy is used to move the manipulator backwards to reduce the impact force. De Luca and Ferrajoli [3] utilized a modified Newton–Euler method to improve the accuracy of the collision detection. Jeong and Takahashi [4] presented a control algorithm for stopping the manipulator with maximum deceleration to

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