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Physical Safety in Collisions Between Robots and Pedestrians

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***Abstract*— The widespread deployment of mobile service robots in public environments and the growing use of autonomy as control modality will increase the exposure to hazards for people simply sharing the robot floor. The need to ensure safety becomes an ethical and legal obligation for designers. However, current safety requirements are mostly focused on the end-users of robot services, while pedestrians are often not addressed in safety standard requirements. In this paper, we propose a preliminary method for assessing robot safety with respect to collisions with bystanders. Consisting of three main phases: (1) identification of collision contacts points; (2) estimation of collision injuries; (3) design and control recommendations. We evaluate the robot Qolo - a person carrier robot as example by simulating collisions with walking pedestrian models, using motion capture and body shape data of a male human adult, and a child. We present results of simulation comparing multiple post-collision reaction and discuss further work needed for creating a framework on robot safety requirements that address all vulnerable populations.**

***Index Terms*— Robot Safety, Mobile Service Robots, Human-Robot Interaction, Pedestrian's Collision Injury**

I. INTRODUCTION

Currently, the field of service robots is a growing sector of robotic applications with telepresence, mobile guidance and information, and delivery robots as some examples. Recent data show 10'400 units sold in 2017, 56% more than in 2016, and it is expected that robot tour guides and hostess in public events will increase to reach 93'350 units in 2021. Equally, the market of autonomous and semi-autonomous wheelchair is expected to grow [1]. As a consequence of the widespread of these robots in public spaces, collisions with pedestrians will become more frequent. Therefore, validation methods for assessing the risk during collisions and estimate probability of injuries are necessary. Moreover, inclusion of all possible bystanders must be considered in such analysis, such as, children, older adults, and pregnant women. Mitigating risks and ensuring that the robot is safe to use is an ethical and legal imperative that should be implemented in all stages of the process, from the design phase to recommendations of usage. What is missing in the current discourse on safety of mobile service robots operating in public environments are studies on collisions with bystanders during navigation, analogous to what has been done with manipulators and operators in industrial settings [2], [3] and automobiles.

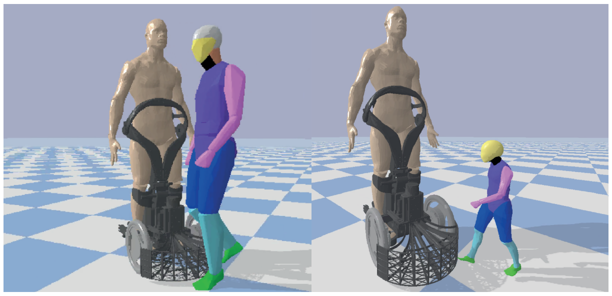

Fig. 1. Collision simulation between a manned service robot and an adult model (left) and a child model (right).

The general difficulty to model the human reaction and motor control to recover from collisions is a problem in both simulation and physical experiments. While some relevant experimental data is found in motion capture databases (e.g. for push recovery [4]), and some work in reinforcement learning has focused on controlling such dynamic behaviour in simulation [5], human behaviour modeling is yet an open field. Therefore, in our approach we focus on the short-term effects of a collision with a human body part. Proposing the assessment of safety by means of simulation in the worst case: direct collisions with pedestrians. We exemplified the method on the semi-autonomous standing mobility wheelchair Qolo [6] shown in Fig. 1. A type of personal mobility device similar to power scooter, hoverboards, and unicylcles, currently in widespread.

II. METHODOLOGY

In our simulation of collisions, neither human nor robot make any effort to avoid the imminent impact, herewith assuming the worst case scenario.

Phase 1: Identification of Collisions Contact Points This phase provides designers with information to identify: contact points on robot's structure, contact points on human body, and probability of collision and relative frequency of such contacts. Herewith, it is possible to evaluate whether any delicate robot part is hit (e.g. a sensor), compromising its operation and hence its safety.

Analysis with two type of bystanders have been included: an adult and a child, height of 1.75 m and 1 m, respectively. The simulation applies various initial states and trajectories from motion capture data available in the KIT Database [4]; so that, the collision occurs with the 3D robot model as in Fig. 1.

Phase 2: Estimation of Collision Injuries The contact points on human body computed in phase 1 are used to estimate of the severity level of the impacts based on the dynamics of contact. It can serve to identify combinations of robot properties (mass, shape) and operating conditions

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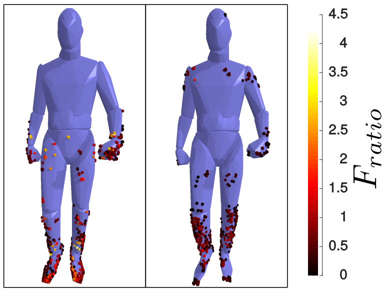

Fig. 2. Contact points detected in phase 1 on the pedestrian's body for the adult model (left) and the child model (right), showing results of phase 2 with the contact force peak to the corresponding pain threshold with F_{ratio}.

(driving speed, control reaction to collisions) that result in danger for humans. The impact simulation computes the contact forces of a collision found in the previous step via a spring-like contact model in a 2 DOF representation (further details are available on the online simulator).

This phase aims at providing designers with information concerning: probability of injury during collisions. From the impact estimation we extract the peak contact force, F_{peak}, and compare it to the thresholds beyond which the collision should be considered unsafe $F_{ratio} = F_{peak}/F_{threshold}$, thus, simplifying injury to any $F_{ratio} > 1$, which is summarised for the 2 models in Fig. 2 Currently, the best knowledge regarding body injuries at this level of collision forces could be obtained only from minimum force that could generate pain at each body part from ISO-15066 [2]). Although, this values are limited to healthy adults, and the application to children models would not hold valid.

Phase 3: Design and Control Strategy Recommendations This phase provides designers with recommendations on: sensor placement (navigation vs safety sensors); sensing quality; control strategy (e.g., mechanically compliant, or actively compliant control strategies); external cover design and materials (e.g. the use of soft material, padding, flat contours, etc. to prevent or mitigate possible injuries to humans in case of impact). Based on the previous results, the simulation further estimate probability of injury based on the control strategy, and the selected stiffness and damping of collision surfaces on the robot side.

As an example of design parameters for service robots that could be evaluated through this method, we assess the the risk change for three types of post-collision reaction, evaluated by simulating a braking force F_{brake} applied to the robot model. Comparing three cases: first, no reaction as baseline. Second, "Emergency stop", referring to a standard full power removal and activation of mechanical baking as defined in ISO-13482 [7]. Third, "Protective stop", a controlled stop activated by control logic and simulated by a passive impedance for zero-contact force [8]. The source code implemented in python bullet is available: *here*.

Results could be presented as in Fig. 3 through a histogram of normalized peak collision forces, where values overcoming the unit are considered unsafe under the measurement of pain sensitivity. Herewith, providing a clear measure of the probability of injury for multiple scenarios, in this case, we compared different control strategies for post-collision.

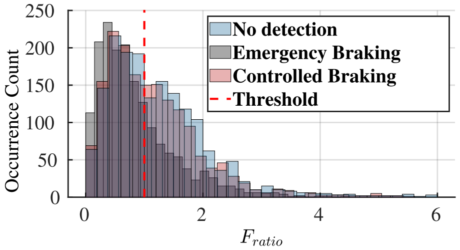

Fig. 3. Normalized peak collision forces to pain thresholds on [2] comparing post-collision handling: No detection, emergency braking, and zero-contact-force.

III. DISCUSSION

The proposed approach extends beyond to any mobile robot expected to operate among pedestrians, estimating injury probability, severity, and allowing designers to find solutions through interactive simulation and assessment of robot parameters. For instance, Fig. 3 shows less probable injury for emergency braking compared to a impedance-based controller, however, it comes with the risk of abrupt reaction from other agents if the robot comes to full hold. Therefore, analysis of this type of decision must come from the expected application of each robot. Equally, changes on the covers' shape, surfaces stiffness, robot mass, operational velocity, load, and sensing range could be evaluated.

Although this methodology is valid for any mobile robot, human injuries are an open ended question. Currently known pain thresholds were used as main measurement of injury which gives no real guarantees on safety, specially for vulnerable populations such as children or pregnant women. Therefore, careful analysis and further research should make clear safety definitions for creating an ethical and legal framework that considers the potential risk of a specific service robot and elaborate on the recommendations for its usage.

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