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A computationally efficient safety assessment for collaborative robotics applications

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ABSTRACT

Safety during interaction with unstructured and dynamic environments is now a well established requirement for complex robotic systems. A wide variety of approaches focus on the introduction of safety evaluation methods in order to shape a consequent safety-oriented control strategy, able to reactively prevent collisions between the robot and potential obstacles, including a human being. This paper presents a new safety assessment, named *kinetostatic safety field*, that captures the risk in the vicinity of an arbitrary rigid body "source of danger" (e.g. an obstacle, a human body part or a robot link) moving in $\mathbb{R}^3$. The safety field depends on the position and velocity of the body but it is also influenced by its real shape and size, exploiting its triangular mesh. The introduction of a body-fixed reference frame in the definition of the field provides closed form computability and an effective computation time reduction, that allows for real-time applications. In particular, intensive computations, connected to the specific body geometry, can be performed only once and off-line, ensuring a fast and constant on-line computation time, independently of the number of mesh elements. Furthermore, we combine the safety field concept with a safety-oriented reactive control strategy for redundant manipulators. Our approach allows to enhance safety in several real-time collision avoidance scenarios, including collision avoidance with potential obstacles, self-collision avoidance and safe human–robot coexistence. The proposed control strategy is validated through experiments performed on an ABB FRIDA dual arm robot.

1. Introduction

Safety in Human–Robot Interaction (HRI) has gained growing relevance in industrial environments, where, in the near future, humans and robots are expected to safely coexist and cooperate, while sharing the same workspace. Clearly, this safety aspect is strictly connected to the crucial task of collision avoidance. Possible collisions, in fact, can occur between a robot and a human being (human–robot coexistence), between a robot and potential obstacles, but also with the own robot structure, e.g. in a dual arm manipulator (self-collision avoidance).

Several methods focus on the assessment of the level of danger or safety, in order to reshape the robot behavior accordingly. In this respect, using repulsive potential fields introduced by Khatib [1] is now a well-established approach to achieve collision avoidance. An application of potential fields with demonstration on the Ranger Dexterous Manipulator can be found in [2]. Herein, repulsive potentials are designed with respect to obstacles, joint limits and singularities in the configuration space. One drawback of such approach is that the potential field does not consider the relative motion between the robot and the obstacles, unlike in [3]. Also for torque controlled manipulators, like the upper body of DLR's humanoid Justin, collision avoidance applications have been developed. Dietrich et al. [4,5] proposed an algorithm for reactive self-collision avoidance based on artificial repulsion potential fields, which extends the work in [6], with the inclusion of a damping design integrating the configuration dependence of the robot. Moreover, they merged the algorithm with a method to incorporate these unilateral constraints into a dynamic task hierarchy.

In [7,8], a novel method for safety assessment, called *danger field*, is proposed. It is essentially based on the potential field method [1], but it considers the robot and not the obstacles as source of danger, taking into account their relative position, velocity, and direction of motion. A control strategy that increases human safety is then built upon the concept of danger field. Such concept has been exploited in [9–11] to shape a danger field-based control strategy that ensures human safety.

Recent state-of-the-art methods aim at achieving real-time safety with formal guarantees by means of set invariance theory and reach-

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ability analysis. In [12,13] the robot motion planning and control problem in a human involved environment is posed as a constrained optimal control problem. A safety index is evaluated using the ellipsoid coordinates (EC) attached to the robot links that represents the distance between the robot arm and the worker. Furthermore, the linear momentum of the center of the robot links towards the direction to the agents is an additional considered factor. The safety index is used as a constraint in the optimization problem so that a collision-free trajectory within a finite time horizon is generated on-line iteratively for the robot to move towards the desired position. To reduce the computational load for real- time implementation, the formulated optimization problem is further approximated by a quadratic problem.

Pereira et al. [14] instead, present a fail-safe control strategy for on-line safety certification of robot movements in a collaborative workspace with humans. This approach plans, predicts and uses formal guarantees on reachable sets of a robot arm and a human obstacle to verify the safety and feasibility of a trajectory in real time.

Alternative approaches include on-line re-planning [15] and real-time collision avoidance methods based on collision models. In [16,17], Täubig et al. present a collision prediction approach that exploits the GJK-algorithm [18] to compute the distance between robot swept volumes. Corrales et al. [19] developed a safety strategy in a real human–robot interaction task, relying on a geometric representation for human operators and robotic manipulators made of a set of bounding volumes based on swept-sphere line primitives. Finally, in [20] real-time collision avoidance is performed through control in the velocity domain, based on introduced cost functions, with experimental validation on the HRP-2 humanoid robot.

In the framework of physical Human–Robot Interaction (pHRI), methodologies and experimental tests are presented for the problem of detecting and reacting to collisions between a robot manipulator and a human being.

In the work by Haddadin et al. [21–23], a human-friendly control architecture has been developed in order to achieve human-friendly behaviors in cooperation tasks. The robot task is defined distinguishing between four major functional modes (autonomous, human-friendly, collaborative, fault-reaction) of the robot potentially working in human vicinity and the information concerning the physical state currently occupied by the human is used to switch between the different functional modes. Though the proposed control architecture does not explicitly use any danger assessment, it turns out to be an effective approach for safe-oriented applications.

More recently, to guarantee interaction even in the absence of direct contact, the use of pointing gestures has been proposed, as well as the integration of vision with force. In this respect, Cherubini et al. [24] propose a framework to develop a human–robot manufacturing cell, requiring direct physical contact between robot and human, that includes trajectory optimization, admittance control and image processing.

Flacco et al. [25,26] propose an approach that evaluates point-to-object distances working in the depth space of a depth camera, recently extended to multiple depth sensors [27]. The distances are used to generate repulsive vectors that are used to control the robot while executing a generic motion task. The real-time performance of the proposed approach is shown by means of collision avoidance experiments.

In this paper, a new safety assessment, the *kinetostatic safety field*, is presented. Our goal is to introduce a safety measure, easily computable for any moving rigid bodies, using its triangular mesh, able to further ensure real-time applicability, independently of the number of mesh elements. The safety field concept is based on the cumulative danger field [7,8] and on the repulsive potential field approach [1] and is meant to overcome most of the limitations connected to these methods, such as the simplified line representation of the source of danger inherent in the danger field definition and the computationally expensive geometric modeling required by potential field-based approaches. In addition, the safety field concept accounts for the relative velocity between the source of danger and the point where the field is computed, which is instead missing in both danger field and potential field concepts. A detailed analysis on the novelty of the contribution with respect to the state-of-the-art approaches is reported in Section 5. Moreover, our approach, combined with a reactive safety-oriented control strategy, presented in Section 3, can provide safety enhancement in various real-time collision avoidance scenarios.

The present paper extends the preliminary work [28] by providing a detailed discussion of the safety field and the related properties, as well as a more complete experimental validation, enhancing the effect of relative velocity in the definition of the field. Furthermore, an accurate description on how to compute the closed form solution of the safety field is provided in Appendix A.

The paper is organized as follows. First, we derive the concepts of elementary and cumulative kinetostatic safety field in Section 2. Section 3 focuses on the integration of the safety field concept in a reactive control strategy. Experiments of real-time collision avoidance on an ABB FRIDA dual arm robot are performed and analyzed in Section 4. Section 5 compares our approach with state-of-the-art techniques and hints at limitations. Finally, concluding remarks and future work directions can be found in Section 6.

2. Kinetostatic safety field

The concept of safety field, recently proposed by the authors in [28], is addressed in this section.

The aim is to define a safety assessment that fulfills the following requirements:

1. it depends on the magnitude and the direction of relative position and relative velocity between a moving rigid body “source of danger” and a generic moving point in space;
2. it depends on the real shape and size of the rigid body “source of danger”, exploiting its triangular mesh;
3. it can be efficiently computed in closed form, allowing for real-time applications.

At first, some basic definitions are given for the case of a point mass. An extension to a basic geometric shape (triangle) and rigid bodies is given afterwards.

2.1. Basic definitions

Consider as “source of danger” a generic rigid body moving in $\mathbb{R}^3$ and a local reference frame l (see Fig. 1) such that the position of one of its points T is given by $\mathbf{r}_t = (x_t\ y_t\ z_t)^T$ while its velocity is zero in the introduced frame. We further denote with $\mathbf{r} = (x\ y\ z)^T$, and $\mathbf{v} = (v_x\ v_y\ v_z)^T$ the position and the velocity of a generic moving point in space P, respectively, expressed in local coordinates.

We additionally define:

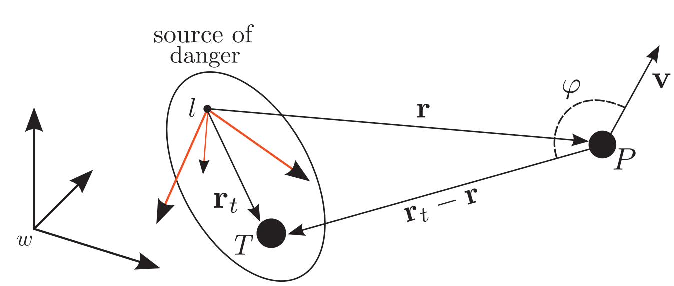

Fig. 1. Elements that play a role in the computation of elementary safety field, expressed in the reference frame l local to the moving rigid body “source of danger”.