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Robot Workspace Exploration Using Collision Detection and Isolation

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Abstract

Robots increasingly operate in collaborative environments with humans, where detecting and responding to physical contact is essential for ensuring safety. In such contexts, internal joint torque sensors o er an alternative to external sensing for detecting and localizing physical collisions. This work addresses the problem of enabling a robot to autonomously explore and map its workspace by detecting and localizing collisions through measurements of external torques acting on a robot. We demonstrate that a 7-DOF KUKA LBR iiwa robot can detect and localize obstacles in its workspace using a cylindrical approximation and collision-driven approach based solely on proprioceptive sensing. Implementing two types of search strategies, the main ndings show that a robot can localize contact points with reasonable accuracy. However, the accuracy decreases in near-singular con gurations and leads to larger localization errors.

Keywords: Collaborative Robotics, Collision Detection and Isolation, Proprioceptive Sensing, Robot Workspace Exploration, Cylindrical approximation

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Abstrakt

Roboti stále £ast¥ji pracují v prost°edí, kde dochází ke spolupráci s lidmi. V takových p°ípadech je pro zaji²t¥ní bezpe£nosti nezbytné spolehliv¥ detekovat fyzický kontakt a adekvátn¥ na n¥j reagovat. Senzory momentu v kloubech robota p°edstavují alternativu k vn¥j²ím senzor·m pro detekci a lokalizaci kolizí. Tato práce se zabývá problémem, jak umoºnit robotovi autonomn¥ prozkoumávat a mapovat sv·j pracovní prostor na základ¥ detekce a lokalizace kolizí, a to prost°ednictvím m¥°ení externích moment· p·sobících na jeho konstrukci. Ukazujeme, ºe robot KUKA LBR iiwa se sedmi stupni volnosti (7-DOF) je schopen detekovat a lokalizovat p°ekáºky ve svém pracovním prostoru pomocí válcové aproximace a kolizn¥ zaloºeného p°ístupu, který spoléhá výhradn¥ na proprioceptivní snímání. Pomocí implementace dvou typ· prohledávacích strategií tato práce demonstruje, ºe robot je schopen lokalizovat kontaktní body s p°im¥°enou p°esností. P°esnost lokalizace v²ak klesá v kon guracích blíºících se k singulárním pozicím, coº vede k v¥t²ím chybám v odhadu místa kontaktu.

Klí£ová slova: Kolaborativní robotika, Detekce a izolace kolizí, Proprioceptivní snímání, Pr·zkum pracovního prostoru robota. Válcová aproximace

P°eklad názvu: Pr·zkum pracovního prostoru robota pomocí detekce a izolace kolizí

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Chapter 1

Introduction

The integration of collaborative robots (cobots) into work environments has grown significantly in recent years. In 2023, they accounted for 10.5% of all robot installations, reflecting their rapid adoption and emphasizing the need to address safety in Physical Human-Robot Interaction (pHRI) [1]. A crucial aspect of ensuring safe interaction is the ability to detect collisions and accurately determine a point of contact on the robot. This capability ensures an appropriate response to incidents and avoids harm to humans or damage to the surrounding environment.

To achieve accurate collision detection and localization, there are various sensing strategies that rely on external and internal sources of information. External sensors may be attached directly to the robot, like tactile skin, or placed in its surroundings, such as cameras for visual perception. Internal sensors, such as joint position encoders and joint torque sensors, are embedded within the robot, providing essential data for contact estimation. By analyzing these internal sensor data through techniques such as inverse dynamics, joint velocity observers, or momentum observers, it is possible to estimate external torques. These external torque estimates are vital for detecting and locating collisions without the need for additional external sensors [2, 3].

Certain robots, including the KUKA LBR series and FRANKA ROBOTICS models, even offer external torque estimates directly from the robot controller. This eliminates the need for additional estimation algorithms and simplifies implementation.

1.1 Motivation and goals

In collaborative robotics, safe interaction with dynamic and unstructured environments presents a significant challenge. Unlike traditional industrial robots, which operate under constrained and predictable conditions, collaborative robots (cobots) must be equipped with responsive sensing and control strategies to deal with uncertain physical interactions, including unexpected contact with humans or objects [4]. Ensuring safety in these interactions goes beyond collision detection. It requires a structured understanding of the entire collision event pipeline, which can be divided into seven key phases: precollision, detection, isolation, identification, classification, reaction and postcollision as in Figure 1.1 [2].

Figure 1.1: Overview of the collision event pipeline from [2]. The pipeline is divided into seven phases: precollision, detection, isolation, identification, classification, reaction, and postcollision. In this work, we primarily focus on the Detection, Isolation, and Identification phases.

Conventional methods for collision detection and isolation often depend on additional hardware, such as vision systems or tactile sensor arrays. While effective, these solutions require additional equipment, increasing system complexity and cost. An alternative approach involves taking advantage of the internal sensing capabilities of the robots. Specifically, using the external torques acting on a robot to determine the point of contact and the external force. The key advantage of this method is that it relies solely on the robot's proprioceptive sensors, eliminating the need for external sensing [2,5–8].

The core idea behind this approach is to treat the robot itself as a sensor. By comparing the estimated external joint torques either from physical torque sensors or estimated via observers with the torques predicted by the robot's dynamic model, this allows for an approximate estimation of both the location and direction of the applied force.

In this work, we focus on the first four phases of the collision event pipeline, particularly on collision isolation and collision identification. An analytical approach will be implemented to estimate the location of the contact point on the robot structure based on the external torques. Due to the non-linear nature of this problem, a numerical optimization approach is used to solve for the computation of external torques that most closely align with those provided by the robot's controller.

Isolation and localization enables the robot to safely explore its environment through whole-body contact, without relying on vision systems or tactile sensors. Each detected collision is used as spatial information, which is then logged to create a map of the robot's workspace. The spatial information will be utilized to log each detected collision into a map of the robot's workspace. Through autonomous exploration and continuous collision detection, the robot incrementally builds a representation of its surroundings. This evolving map allows the robot to dynamically adapt its motion planning, improving safety and e ciency.

1.2 Thesis contribution

This thesis contributes to the eld of autonomous robot exploration by presenting a method that enables workspace mapping using only proprioceptive sensing, without reliance on external vision systems or tactile sensors. The core algorithm for contact localization and isolation was adapted from prior work [5], while not originally developed as part of this thesis, it was modi ed and re-implemented in Python to function on a our robotic platform.

The implemented method allows the robot to detect collisions through physical interactions trough whole-body and analytically estimate the corresponding contact points. This enables incremental mapping of the robot's surroundings, where both the contact locations on the robot's structure and the estimated positions of obstacles are recorded. This map supports better informed motion planning by allowing the robot to avoid previously encountered obstacles.

Experimental validation was performed on a KUKA LBR iiwa 7 R800 robot. The Python implementation demonstrated performance comparable to previous MATLAB-based studies.

Chapter 2

Related Work

In contrast to systems that utilize exteroceptive sensors, such as tactile skins or vision systems, to determine contact points, an alternative strategy in robotics is to estimate collisions using only the proprioceptive data of the robot. These proprioceptive approaches eliminate the need for additional hardware and instead rely on joint torque sensors and angle encoders to detect, localize and characterize contact events. Several strategies have been proposed for this purpose, including non-linear optimization methods, probabilistic filtering techniques such as particle filters, and learning-based approaches using neural networks. Each method varies in complexity, computational requirements, and accuracy. In this work, we adopt a method based on non-linear optimization for contact point estimation due to its relative simplicity and the advantage of not requiring large training datasets, as would be necessary in neural network-based approaches. Although this method can be computationally intensive due to the optimization process, real-time collision localization is not a strict requirement for our application, as the primary safety concern is to detect a collision and stop the robot as quickly as possible to ensure that any contact remains soft and minimally harmful. Since we assume only a single contact occurs at a time, the complexity of particle filtering designed for multi-contact scenarios is not needed. All the above-mentioned methods are further discussed in the following sections.

2.1 Non-linear optimization methods

Contact interactions generate external forces that induce external joint torques that are used to estimate the contact point and the force. The contact point estimation is a complex non-linear problem with multiple possible solutions. To simplify this, the method incorporates approximations that reduce the dimensionality of this problem while preserving essential contact information, as proposed in [5].

One key approximation assumes that the contact occurs at a single point rather than over a distributed surface, simplifying force modeling. Additionally, only one external force is considered at a time, ignoring multi-contact scenarios. The force is also assumed to act perpendicular to the cylindrical segments of the robot, eliminating torque components and reducing the number of unknowns. To further simplify the problem, the contact location is parameterized by a single scalar variable along the robot structure, effectively transforming the search space into a lower-dimensional optimization problem.

The estimation process is formulated as a constrained optimization problem, where the objective function minimizes the discrepancy between measured and estimated joint torques. Given the non-convex nature of the optimization landscape, which may contain multiple local minima, a two-stage optimization approach is employed. First, a global optimization method is used to obtain an approximate solution, which is then re ned using a local optimization method for improved accuracy.

2.2 Particle ltering

Particle ltering is a technique used to estimate unknown values based on a set of possible guesses, called particles. For pHRI it was described in [9] where it is called Contact Particle Filter (CPF). The method formulates contact localization as an optimization problem, aiming to nd the contact point and force that correspond to the observed changes in joint torque. Since solving this problem directly is complex, CPF approximates the solution using a particle lter, where each particle represents a possible contact location.

At rst, the location of the particles is randomly distributed on the surface of the robot to cover all possible contact points. As new sensor data are received, the algorithm updates the probability of each particle representing the true contact location. Particles that better explain the observed forces are given higher weights, while less likely ones are discarded. Through resampling, new particle locations are generated based on this updated probability distribution, ensuring that the lter gradually converges to the most accurate contact estimate.

One of the bene ts of using CPF is the ability to detect multiple simultaneous contacts. To achieve this, the algorithm extends its particle representation, allowing multiple sets of particles to track di erent contact points independently. Each contact is estimated by maintaining separate probability distributions and updating them based on sensor data.

Improved by Bimbo et al. [3], this technique integrates new measurements as the robot performs small exploratory movements. Therefore, it gets more updates and particle resampling that improve accuracy. This approach proves e ective in situations where previous methods encounter di culties in detecting contact points close to the robot's base.

2.3 Neural network based approaches

Popov's work [10] presents two neural network-based methods to address this problem, which will be the focus of this discussion. The rst method uses a simpli ed model to estimate the contact point of interaction. Instead of computing the full force vector and exact coordinates, this approach focuses on two parameters: the distance from the base to the contact point and the angle of applied force. A feedforward neural network processes joint angles and external torque values to predict these parameters. The network is trained on both simulated and real-world data, allowing it to approximate the contact location based on sensor input.

The second method, the xed node model, takes a di erent approach by de ning xed contact points on the robot's surface. Instead of estimating a continuous position, the neural network classifies interactions into one of these predefined points. A multilayer perceptron receives joint angles, torque values, and Jacobian matrices as input to determine the most likely contact location. By structuring the problem as a classification task, this method simplifies the estimation process and provides a structured way to map sensor data to predefined contact points.