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Research paper

Real-time trajectory planning based on joint-decoupled optimization in human-robot interaction

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ABSTRACT

In order to perform safe and natural interactions with humans, robots are required to adjust their motions quickly according to human behaviors. Performing the complex calculation and updating the trajectories in real-time is a particular challenge. In this paper, we present a real-time optimization-based trajectory planning method for serial robots. We encode the trajectory planning problem into a series of optimization problems. To solve the high-dimensional complex non-linear optimization problems in real-time, we provide a joint-decoupling method that transforms the original joint-coupled optimization problem into multiple joint-independent optimization problems, with much lower computational complexity. We implement and validate our method in a specific human-robot interaction case. Experimental results show that the computational feasibility and efficiency of optimization solution were greatly improved by the joint-decoupling transformation. Smooth, safe, and rapid motion of the robot was generated in real-time, establishing a basis for safe and reactive human-robot interactions.

1. Introduction

Robots are increasingly commonplace in human life and now interact with humans in many circumstances, including collaborative manufacturing [1–4], rehabilitation [5–8], and entertainment [9–11]. In applications with human-robot interaction (HRI), robots must react promptly to unexpected human behavior to avoid hurting users. Thus, generating safe and efficient trajectories in real-time is an essential matter [12].

Trajectory planning using non-linear optimization is an effective way to generate trajectories compromising among specific indices, encoding the combined requirements of safety and speed of motion into an objective function and constraints. However, as the objective functions and constraints are always complex in practical cases, the solution process is computationally demanding. Moreover, the motion of all of the robotic joints must be coordinated, meaning that the joint-related components in the optimization parameters are coupled with each other. As the number of degrees of freedom (DOFs) of the robot increases, the number of dimensions in the optimization problem increases as well. This leads to even greater computational complexity and makes it difficult to guarantee real-time performance. Additionally, higher numbers of DOFs lead to less flexibility in the solution from the additional constraints. The optimization solver may fail to output feasible solutions.

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In this paper, we address this complex problem. First, we encode the HRI trajectory planning problem into a series of non-linear optimization problems considering HRI safety and motion rapidity. To improve the computational efficiency and flexibility of solving the high-dimensional optimization problems, especially for cases with many DOFs, we decouple the joint-coupled optimization problem and transform it into multiple joint-independent optimization problems, each of which has fewer dimensions and faster solutions. We then study and implement our approach for a specific HRI case and experimentally verify its performance.

We organize the remainder of this paper as follows (Fig. 1). We first discuss state of the art approaches to optimization-based trajectory planning in Section 2. Then we describe the main problem discussed in this paper, real-time serial trajectory planning for HRI applications, in Section 3. We present the general optimization model for this problem and the joint-decoupling model transformation method in Section 4. We detail our implementation of our method in a specific case in Section 5. In Section 6, we evaluate the feasibility and efficiency of the presented method using numerical experiments and validate the real-time performance. Finally, we discuss our conclusions and future work in Section 7.

2. Related work

In HRI applications, robots must react to changing environments and human behaviors smoothly, quickly, safely, and efficiently. Thus, real-time trajectory planning is an essential procedure.

Optimization-based trajectory planning methods, in which the indices are encoded in a constrained optimization problem [13–19], are widely used to ensure safety and improve the motion efficiency. As the objective function and constraints are complex in practical applications, the optimization problems are generally non-linear, making them very time-consuming to solve.

Some researchers adopt parallel computing to reduce the calculation time. Bäuml et al. [20] perform computations in parallel with distributed computing resources and 32 CPU cores to cope with the high computational demands. Liu and Tomizuka [21] design a parallel controller combined with a baseline controller to compute the basic optimization problem offline with an online safety controller dealing with the non-linear, non-convex, and temporal safety constraints. Real-time performance can be achieved by these methods. However, they require significant hardware resources. Moreover, when it comes to more complex situations, such as ones with higher dimensions or more sophisticated models, the requirements of hardware resources will be even higher, which are not always be satisfied. Thus, it is hardly to generalize to more complicated problems.

Other researchers resort to machine learning methods to select an approximate initial value for the iterative solver to speed up the calculation [22–25]. Lampariello et al. [26] learn an approximate initialization by generating optimal database and constructing the regression model. Jetchev and Toussaint [27] proposed a high-dimensional feature selection method and a task space transfer, which can improve the efficiency of adapting the samples to new situations. Hauser [28] discussed theoretically the requirements of the database and the algorithm for the data-driven method to guarantee the performance of the solution. However, the initial solutions obtained by learning are not guaranteed to be feasible. Thus, the iterative solving process is still necessary. Although the calculations could be speed up in most of situations, real-time performance and feasibility could not be ensured.

Another method approximates the original problem using another form that can be solved efficiently. Kröger and Wahl [29] calculate the time-optimal trajectory with decision trees and non-linear equations that can be solved analytically. Tsai et al. [30] approximate the non-convex optimization problem to a convex optimization problem with a quadratic objective function and linear constraints to significantly reduce the calculation time. Liu et al. [31] transform the non-convex optimization problem into a sequence of convex subproblems and then iteratively solve the subproblems until convergence, improving the computational efficiency for reaching the local optima.

In this paper, we present a new optimization problem approximation method from a joint decoupling perspective. We decompose the original integrated problem into several parallel subproblems, achieving better computational efficiency and flexibility than the integrated form and the sequential subproblems, especially when scaling to higher-dimensional problems. Additionally, it can be combined with machine learning methods, in which the learned initial solutions can be refined in an analytical way rather than numerical iteration and thus the calculation time restriction and the feasibility can be ensured. Moreover, owing to the very low computational complexity, it can be implemented in hardware with relatively low performance.

3. Real-time trajectory planning for HRI

3.1. Human-robot interaction applications

In this paper, we consider a specific class of HRI applications: those in which the robot and human share a workspace and interact with each other to perform tasks such as hand-over [32], collaborative assembly [33,34], and haptic feedback [25].

We consider a reaching process in which the robot moves from a current state to a target state. The target state is determined according to the human motion. To adapt to variable tasks, rather than programming the trajectory in a fixed