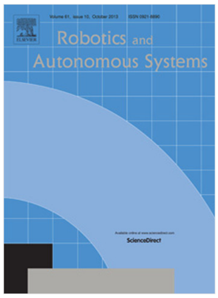

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Abstract

In highly dynamic tasks that involve moving targets, planning is necessary to figure out when, where and how to intercept the target. In robotic table tennis in particular, motion planning can be very challenging due to time constraints, dimension of the search space and joint limits. Conventional planning algorithms often rely on a fixed virtual hitting plane to construct robot striking trajectories. These algorithms, however, generate restrictive strokes and can result in unnatural strategies when compared with human playing. In this paper, we introduce a new trajectory generation framework for robotic table tennis that does not involve a fixed hitting plane. A free-time optimal control approach is used to derive two different trajectory optimizers. The resulting two algorithms, Focused Player and Defensive Player, encode two different play-styles. We evaluate their performance in simulation and in our robot table tennis platform with a high speed cable-driven seven DOF robot arm. The algorithms return the balls with a higher probability to the opponent's court when compared with a virtual hitting plane based method. Moreover, both can be run online and the trajectories can be corrected with new ball observations.

Keywords: Optimal Control, Motion Planning, Optimization, Robot Table Tennis

1. Introduction

Table tennis is a challenging game for humans to master. For robots, it also serves as a testbed to study and validate the effectiveness of different movement generation algorithms. Combining different estimation, movement generation and execution schemes and studying how close they come to imitating expert human behaviour will yield important insights for robotics research.

Optimality plays an important role in the search for efficient and feasible striking trajectories. However, so far most of the research in robotic table tennis were based on specialized systems, such as Cartesian coordinate robots (Matsushima et al., 2005; Huang et al., 2013), that eliminate great part of the difficulties in trajectory generation. Furthermore, most algorithms for robotic table tennis focused on simplifications of the game that reduced the dimensions of the search space (Mülling et al., 2011) in order to quickly come up with a movement plan. In this paper, we show the advantages of incorporating optimality in trajectory generation to create more flexible movement.

Our robotic setup with an anthropomorphic seven degree of freedom Barrett WAM arm is shown in Figure 1. The redundant arm can achieve high speeds and accelerations. It is a good platform to study different movement generation schemes. Optimal control based approaches have the potential to make use of all degrees of freedom in planning, contributing to more natural and efficient generation of strikes. The contributions of this paper are as follows: we introduce an optimal control framework in robot table tennis where the generation of striking trajectories is the result of an optimization problem. As opposed to previous works, inverse kinematics or a fixed plane to compute joint trajectories are not needed. Two different optimization approaches are presented that encode defensive and goal-oriented styles of playing. We show extensive experiments in simulation and on our table tennis platform, where we evaluate and compare the performance of the algorithms. We do not rely on pure physical modeling to compute desired ball and racket parameters. Instead, the parameters of the prediction models are estimated based on offline human ball-racket demonstrations and the angular velocity (spin) of the ball is estimated online from actual ball data.

In the remainder of this paper, the framework is described in detail. A brief survey of robot table tennis research is given and related work on trajectory generation is introduced in Section 2. Robot trajectory generation for table tennis is formalized as an optimal control problem in Section 3. Two efficient solvers are presented in Sections 4 and 5 for optimizing the cost functional under additional constraints. The performance of the two resulting players are evaluated in Section 6 and it is shown that they compare favorably with an inverse kinematics based

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