Motion Planning of a Dual Manipulator System for Table Tennis

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Abstract. This paper describes the design and development of a novel dual manipulator system for table tennis as an application of Human-Robot Interaction (HRI). To hit table tennis quickly, a method to obtain time-constrained trajectory joining two way-points is developed and implemented. Because the quintic polynomial trajectory is a smooth curve and can reduce jerk, it appears to be excellent choice for hitting task. Five phase quintic polynomials are adopted to fit the smooth trajectory in joint space under the constraint of robotic kinematics parameters. The boundary conditions of five phase quintic polynomials used to compute the trajectories are discussed under different initial kinematics conditions. Experimental results of actual robotic system with dual manipulators and vision system show that the proposed method works well.

1 Introduction

As one of the major effectors of a robot, HRI research is a multidisciplinary field with contributions from human-computer interaction, artificial intelligence, robotics, natural language understanding and social sciences. A robotic ping pong player system is a classic case of HRI, which involves the coordinated vision and arm movement to execute a task. In this paper, a new dual manipulator system is developed to hit ping pong ball, in which the vision system can predict the exact future trajectory of the ball through four-dimensional space-time, and provide the position, velocity of the ball and further direct the movement of the dual manipulator towards targets.

Andersson designed the first robot ping-pong player [1], which can play ping-pong against humans and machine, and meet the robot ping-pong rules proposed by Billingsley. The mechanical part of the robot is composed of a six degree of freedom (DOF) PUMA 260 manipulator with a paddle at the end of a 0.45m long stick. The 3D vision system consisted of four video cameras is charged with the task of predicting the exact future trajectory of the ball through four-dimensional space-time. Toshiba in Japan built a seven axis direct-drive (DD) articulated robot for the purpose of playing Ping-Pong [5]. The vision system consisted of two charged coupled device (CCD) cameras senses
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An important problem in this field is motion planning, which deals with the robotic interception of moving objects with necessary velocity at a specific instant in time. Kober et al. studied the hitting and batting tasks using the seven DOF Barrett WAM robot [7]. Hujic et al. presented a novel active prediction planning and execution system for the robotic interception of moving objects with the ability to intercept the object anywhere along its predicted trajectory [6]. Buttazzo et al. described a real time control methodology for catching a fast moving object adapting the prediction technique to compensate the time delays introduced by visual processing and by the robot controller [3].

This paper is organized as follows. First, Section II describes the dual manipulator system for table tennis, mainly focusing on the humanoid manipulator design, table tennis serving equipment design. Section III illustrates the real time trajectory planning for hitting task with continuous movement. In Section IV, an experiment is presented to prove the motion planning method. Finally, in Section V the conclusion of this paper is given.

2 Dual Manipulator System

So far, the developed robotic ping pong players including single robotic arm, dual robotic arm or humanoid robot only take hitting and batting tasks, and can’t serve table tennis ball using two arms, just as a human does. In this paper, a robotic ping pong player with two arms is developed. The left arm (named serving arm) is used for serving ball and right arm (named hitting arm) is used for hitting the ball. Fig. 1 illustrates the robotic ping pong player system developed by us.
2.1 Humanoid Arm Design

For the purpose of playing table tennis, we need control the position of the paddle center and the normal vector of the paddle plane. Although Andersson stated that only five DOF are required for the paddle to execute the table tennis task. A six DOF manipulator was adopted to play table tennis [1]. Redundant manipulators with seven DOF were used in [9, 11, 12].

A novel humanoid arm (hitting arm) with six DOF is built as shown in Fig. 2. The three DOF in shoulder and one DOF in elbow control the position of the paddle, and two DOF in wrist adjust the normal of paddle plane. Because rotating the paddle about its normal vector can’t change the flying trajectory of the ball after hitting. In this sense, we can see that the arm configuration is redundant. Moreover we can get the ideal joint velocity through varying the pose of the paddle in the condition of keeping the normal vector of the paddle unchanged. The serving arm has four DOF, which can adjust position and pose of serving equipment. In addition, the configuration of shoulder and elbow is same as the hitting arm.

![Vision system](image1.png)

**Fig. 1** Robotic ping pong player system

![Humanoid arm system](image2.png)

**Fig. 2** Robotic ping pong player system
2.2 Table Tennis Serving Equipment

Fig. 3 illustrates the table tennis serving equipment, which can serve five balls continuously. The cam is mounted on surface of the cam drive mechanism which is driven by a motor. When the cam turns, the cam follower moves down along the axis of the ejection mechanism. Then the ball in the delivering tube runs into the ejection guiding tube because of gravity. As the cam follower moves beyond the top point of the cam, the follower quickly moves up along ejection mechanism, and fires the ball. Then the ball flies out along the ejection guiding tube.

2.3 Control System

A multi-level distributed control architecture is put forward in the hardware design of the control system and a modular controller based on CANbus is designed to realize real-time control among multiple joints [4]. The real-time operation system VxWorks is adopted as the software platform of the control system.

2.4 Vision system

To track the ball, a vision system consisted of two CCD cameras (Point Grey) is built by Zhejiang University. The system can find the position of the ball at the end of each camera frame. After several frames, the observed trajectory fitted by the above data, is used to predict the future trajectory of the ball after it bounces on the table.

In this paper, the vision system predicts the ideal hitting position $p_f$, velocity $v_f$ of the incoming ball and hitting time $t_f$ to guide the hitting arm to hit the ball at a specified location in time.

![Fig. 3 Robotic ping pong player system](image-url)
3 Motion Planning

3.1 Table Tennis Task Description

In the human game play, the player serving the ball tosses the ball directly upward and strikes the ball with the racket on the ball’s descent, then a play is commenced. Simulating the game like the human being, the table tennis task consists of two tasks including serving task and target-hitting task.

In the serving task, the left arm adjusts the position and pose of the table tennis serving equipment to keep the ball flying out of the ejection guiding tube in different direction. When the cam follower fires the ball, the ball is tossed upward without spin, and the right arm hits the ball against the opponent at an ideal point which can be estimated as a known parameter according to the position and pose of the serving equipment. Then the game begins.

The target-hitting task can be seen as a sense-plan-act cycle, in which the vision system data trigger the controller to plan the motion trajectory and drive the motors. The target-hitting task can be divided into three subtasks including waiting task, hitting task and returning task [9]. In the waiting task, the data provided by vision system are employed to estimate the normal vector \( \mathbf{a} \) of the paddle and hitting velocity \( v_p \) associated with the trajectory to return the ball to the opponent, at the same time, smooth jerk-bounded trajectories in joint space are planned through the four way-points including initial position \( \mathbf{p}_0 \), hitting position \( \mathbf{p}_p \), final position \( \mathbf{p}_m \), and position \( \mathbf{p}_0 \). The hitting task is to return the incoming ball back at hitting position \( \mathbf{p}_p \) at the time \( t_f \), in which time the velocity of the paddle gets hitting velocity \( v_p \). The returning task is to return the paddle to the initial position \( \mathbf{p}_0 \) to prepare for the next hitting.

3.2 Motion Planning Algorithm

Several relevant trajectories were reviewed and compared in [1, 2, 10], such as trapezoidal velocity, quintic polynomials, cosine, and sinusoid on ramp. The advantage of the quintic polynomial is that the acceleration doesn’t change to or from a finite value instantaneously. To eliminate the jerk partly caused by acceleration, it is clearly that the quintic polynomial approach appears to be an excellent choice for hitting task. However, when the initial and/or final speeds are non-zero, the resulting trajectory will be slower and may have a number of undesirable oscillations in position, velocity and acceleration among the way-points. For obtaining smooth jerk-bounded trajectories, a concatenation of the quintic polynomial is used to provide a smooth trajectory between two points [8].

Unlike Macfarlane’s algorithm, we aim to solve the time-constrained motion planning problem. The desired motion trajectory of each joint is given as a quintic polynomial of time, and the basic equation is
\[ p(t) = a_5t^5 + a_4t^4 + a_3t^3 + a_2t^2 + a_1t + a_0, \] (1)

Where \(a_0-a_5\) are real coefficients. The boundary conditions are

\[ p(0) = p_i, v(0) = v_i, a(0) = a_i \]
\[ p(t_f) = p_f, v(t_f) = v_f, a(t_f) = a_f \] (2)

Where, variable \(p_i\) denotes the initial position; \(v_i\) denotes the initial velocity; \(a_i\) denote the initial acceleration. Similarly, variable \(p_f, v_f, a_f\) light up as the final position, velocity and acceleration respectively. \(t_f\) denotes the duration time.

In this paper, five phase quintic polynomials are adopted to fit a smooth trajectory joining two way-points for each joint, as shown in Fig. 4. The general boundary conditions corresponding to the five phase quintic polynomials are shown in Table 1. The acceleration ramp up and ramp down are symmetrical, and the speed ramp is also symmetrical about a straight line down from the start of the ramp to the end of the ramp [8]. The first phase is a acceleration trajectory and at the time \(t_1\) the acceleration reaches the max value \(a_{\text{max}}\). The second phase is also a acceleration trajectory, but the acceleration decreases from \(a_{\text{max}}\) to 0. After the acceleration trajectory, a constant speed trajectory follows. It is similar to the acceleration trajectory, the deceleration trajectory is divided into two phases: in the forth phase the acceleration decreases form 0 to \(-a_{\text{max}}\) and the duration time is \(t_2\); in the fifth phase the acceleration increases form \(-a_{\text{max}}\) to 0. In Table 1, the positions of the way-points are

\[ p_2 = p_i + a_{\text{max}}t_1^2 \left( \frac{1}{4} - \frac{1}{\pi^2} \right) \]
\[ p_3 = p_i + a_{\text{max}}t_1^2 \]
\[ p_4 = p_i + a_{\text{max}}t_1^2 + a_{\text{max}}t_1(t_f - 2t_1 - 2t_2) \]
\[ p_5 = p_i + a_{\text{max}}t_1^2 + a_{\text{max}}t_1(t_f - 2t_1 - 2t_2) - a_{\text{max}}t_2^2 \left( \frac{1}{4} - \frac{1}{\pi^2} \right) + a_{\text{max}}t_1t_2 \]
\[ p_f = p_i + a_{\text{max}}t_1^2 + a_{\text{max}}t_1(t_f - 2t_1 - 2t_2) + a_{\text{max}}t_2^2 \] (3)

| Node | Time   | Position | Velocity | Acceleration |
|------|--------|----------|----------|--------------|
| 1    | 0      | \(p_i\)  | 0        | 0            |
| 2    | \(t_1\) | \(p_2\)  | 0.5\(a_{\text{max}}\)\(t_1\) | \(a_{\text{max}}\) |
| 3    | 2\(t_2\) | \(p_3\)  | \(a_{\text{max}}\)\(t_1\) | 0            |
| 4    | \(t_f - 2t_2\) | \(p_4\)  | \(a_{\text{max}}\)\(t_1\) | 0            |
| 5    | \(t_f - t_2\) | \(p_5\)  | \(a_{\text{max}}\)\(t_1\) - 0.5\(a_{\text{max}}\)\(t_2\) | \(-a_{\text{max}}\) |
| 6    | \(t_f\)  | \(p_f\)  | \(v_f\)  | 0            |

In the hitting task, the initial kinematics conditions of each joint are
and the kinematics constraints are as following

\[-v_{\text{lim}} \leq v_{\text{lim}} \leq v_{\text{max}}, -a_{\text{lim}} \leq a_{\text{lim}} \leq a_{\text{max}},\]  

(5)

Where $v_{\text{max}}$ is the joint’s max velocity; $v_{\text{lim}}$ denotes the extreme value of the joint’s velocity; $a_{\text{lim}}$ denotes the extreme value of the joint’s acceleration.

When the initial parameters of each joint are

\[p_i \neq p_f, v_i = v_f = 0, a_i = a_f = 0,\]  

(6)

One quintic polynomial can ideally draw the motion trajectory. But if the max velocity or acceleration is beyond its own limit under time constraint, the motion trajectory becomes unfeasible. Five phase quintic polynomials are used to represent the smooth trajectory and the acceleration time $t_1$ is equal to the deceleration time $t_2$. By applying the condition (6), we rewrite the equation (3) and obtain

\[p_f - p_i = 2a_{\text{max}}t_1^2 + a_{\text{max}}t_1(t_f - 4t_1)\]
\[a_{\text{max}} \geq 8(p_f - p_i)/t_f^2\]
\[v_{\text{max}} \geq a_{\text{max}}t_1\]  

(7)

When the initial parameters of each joint are

\[p_i \neq p_f, v_i = 0, v_f \neq 0, a_i = a_f = 0,\]  

(8)
If the max velocity or acceleration is beyond its own limit, and \( v_f/a_{\text{max}} \leq t_f - (p_f - p_i)/v_f \), the smooth trajectory is fitted by three phase quintic polynomials, and is constrained by the following conditions

\[
p_f - p_i = a t_1^2 + a t_1 (t_f - 2t_1)
\]
\[
v_f = a t_1
\]
\[
a \leq a_{\text{max}}
\]

If the max velocity or acceleration is beyond its own limit, and \( v_f/a_{\text{max}} > t_f - (p_f - p_i)/v_f \), the smooth trajectory is fitted by five phase quintic polynomials, and is constrained by the following conditions

\[
p_f - p_i = a_{\text{max}} t_1^2 + a_{\text{max}} t_1 (t_f - 2t_1) - a_{\text{max}} t_2^2 + 2v_f t_2
\]
\[
v_f = a_{\text{max}} (t_1 - t_2)
\]
\[
v_{\text{max}} \geq a_{\text{max}} t_1
\]

We can easily compute the time variable \( t_1 \) and \( t_2 \) and get the boundary conditions in Table 1 according to initial parameters. In our application, we can compute the joint positions \( j_0 \) and \( j_p \) corresponding to \( p_0 \) and \( p_p \). Similarly, we can calculate the velocity \( v \) based on \( v_p \). The final position \( p_m \) is unknown, but it can be computed by \( j_m \) in joint space. For any joint \( i \), the boundary conditions are

\[
p(t_f) = j_p, v(t_f) = v_p, a(t_f) = 0
\]
\[
v(t_s) = 0, a(t_s) = 0
\]

A straightforward attempt to compute the maximum acceleration as a function of an arbitrary \( j_{mi} \), and then to minimize this maximum over \( j_{mi} \) turns out to be feasible. Applying the boundary conditions, we can obtain the final joint position

\[
j_{mi} = j_{pi} + v_{ji}^2/a_{\text{max}}
\]

4 Experimental Result

To examine the method presented in Section III, a series of smooth trajectory for all joints are planned. A set of data provided by vision system is

\[
p_p = [55.990, 1545, 291.134]^T \text{ mm}
\]
\[
v_i = [0.0475, 2.5412, -0.8327]^T \text{ m/s}
\]

In addition, the hitting motion’s duration is 0.36s.

Fig. 5 shows the smooth trajectories of each joint for one table tennis task cycle. Fig. 6 shows the continuous velocity curves of each joint. As shown in Fig. 7, the acceleration curves of each joint is continuous and at all interval points the acceleration doesn’t change to or from a finite value instantaneously.
Fig. 5 Smooth trajectories of multiple joints

Fig. 6 Velocity curves of multiple joints

Fig. 7 Acceleration curves of multiple joints

5 Conclusion

The paper addresses the design and build of a dual manipulator system for table tennis. For hitting task, we have described a method to plan a smooth trajectory with jerk limit. Five phase quintic polynomials are used to fit the joint trajectory according to initial kinematics conditions. Comparing with Macfarlane’s work, we
emphatically solve the time-constrained trajectory problem. Experimental results have shown that at all interval points the acceleration doesn’t change to or from a finite value instantaneously, and doesn’t excite vibrations in the dual manipulator system.

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