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主 論 文 の 要 旨

論文題目 Racket Control and Spinning Ball Measurement for Table Tennis Robot
(卓球ロボットのためのラケット制御とスピンボール計測に関する研究)

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論 文 内 容 の 要 旨

In recent decades, with the rapid developments of computer vision and robot hardware, the robots can play active parts not only in the factory but also in the human community, and hence it is very important for the robots to work in the dynamic environments as well as the unstructured environments. In such an environment, the robot has to online acquire and perceive the information of the surrounding environment by using external sensors e.g. force sensor, tactile sensor, vision sensor. Moreover, it has to predict the future development trend of the object and then quickly makes a decision for planning the motion of the robot's mechanical body.

"Table tennis robot" is a representative of them, which means a robot can play table tennis with humans. In order to be smart enough to overcome the variety of coming balls, the robot has to sense a coming ball's trajectory; make a reasonable judgment about how to return the ball and realize a flexible striking, which is a typical *real-time* and *intelligent* process.

The research about "table tennis robot"already has nearly thirty years' history since Prof. John Billingsley from Portsmouth University in England initiated the table tennis robot competition in 1983. During these years, the table tennis robot research has gradually become a research hotpot by reason of its difficulty and challenge in both real-time and intelligent design. There have been many robot systems developed for playing table tennis in the countries of USA, Japan, Spain, China and so on. Although the shapes of them are different, all these systems consist of three basic subsystems: vision system, control system and mechanical system. It shows that the presented robots have already been able to perform a rally of the table tennis during continuously long time with a human opponent. However, "Robot beats humans" in a table tennis competition is still a long way to go for the research of table tennis robot.

As you know, table tennis is a "high technique" sport since the ball is so "small" and "light" that it can have high rotational speed and various kinds of spins, e.g. top spin, back spin, side spin. By controlling the spin of the ball, the expert could serve balls with different kinds of tactics such as chop, drive, loop, push and so on. Therefore, in order to compete with a human player who has high skills in a table tennis game, the robot must be able to master how to detect the incoming ball's rotational velocity and how to control the returning ball's rotational velocity.

However, until now, almost all the presented table tennis robots cannot control the rotational velocity of a table tennis ball. The first main reason is that the developed vision systems can only detect the incoming ball's position and translational velocity. The ball's rotational velocity is ignored, mainly because there is neither suitable vision sensor nor algorithm of measuring the ball's rotational velocity in the high real-time demand situation of table tennis. When a human being plays a table tennis, the translational velocity of the ball is in the range of 4-30 m/s, nevertheless, in the robot case, the ball's translational velocity generally is smaller than 7 m/s since if it is too fast, the response time left for the robot is too short to be used for striking the ball. Actually, if the translational velocity is 5-7 m/s, the ball's flying duration from the position being detected to the striking position is about 400-600 ms and the robot usually needs about 300-500 ms for moving the manipulator from the waiting position to the striking position. Therefore, the vision system must complete the detection task in just a few milliseconds (the time from sensing the image to obtaining the measuring results should be smaller than 80 ms), which is a great challenge for both the hardware of the vision sensor and the detection algorithm.

The second main reason is that there is not a racket striking method for controlling the returning ball's rotational velocity precisely. The previous researches have not considered exact physical models of aerodynamics, table rebound and racket rebound. In order to play table tennis, the robot has to predict a striking position and a striking time, and also the robot has to determine a racket's striking state. There have been many aerodynamics models and rebound models presented by the previous table tennis researches. However, those models were data based models, i.e., they have been constructed mostly from experimental data and so they only considered the translational velocity of the ball. The rotational velocity of the ball was not considered as one deciding factor of the ball's motion. Therefore, those models are not suitable for a spinning ball. Furthermore, the returning ball's rotational velocity has not been treated as one of control variables. The object of controlling the returning ball was to return the ball to a desired position on the opponent's court without requiring the rotational velocity.

In this research project of realizing a new table tennis robot, the following three subgoals have been set

(A) Detecting a ball's state (position, translational and rotational velocities) by using vision sensors immediately after the opponent player hit the ball,

(B) Predicting the ball's trajectory by using the ball's state detected in (A), aerodynamic model and collision models with the table as well as the racket, and

(C) Determining the racket's posture and velocity at the striking time such that the returned ball would reach a given destination on the opponent table with a desired landing state and planning a reference trajectory of the robot manipulator with the racket by the ball's trajectory predicted in (B).

In this thesis, a racket control method based on physical models, where the returning ball can be controlled to be returned to a desired position on the opponent's court with a desired spin, and a spinning ball measurement method with high speed cameras, which can detect both translational and rotational velocities of the coming ball in a real-time situation, are developed for table tennis robots. The thesis consists of five chapters.

Chapter 1 is an introduction, where the research state of the table tennis robot is discussed in detail and the problems of the presented robots are also analyzed.

In Chapter 2, an on-line method is proposed for measuring both translational and rotational velocities of a table tennis ball by using only a few consecutive frames of image data which are sensed by two high speed cameras. In order to estimate the translational velocity, three-dimensional (3D) position of the ball's center at each instant of camera frame is obtained, where the on-line method of reconstructing the 3D position from the two-dimensional (2D) image data of two cameras is proposed without the pattern matching process. The proposed method of estimating the rotational velocity belongs to the image registration methods, where in order to avoid the pattern matching process too, a rotation model of the ball is used to make an estimated image data from an image data sensed at the previous instant of camera frame and then the estimated image data are compared with the image data sensed at the next instant of camera frame to obtain the most plausible rotational velocity by using the least square and the conjugate gradient method. The effectiveness of the proposed method is shown by some experimental results in the case of a ball rotated by a rotation machine as well as in the case of a flying ball shot from a catapult machine.

In Chapter 3, three physical models are demonstrated in detail, which include the aerodynamics model (ADM), table rebound model (TRM) and racket rebound model (RRM). Comparing with the previous research of the table tennis robots, these three models have a significant improvement that the ball's rotational velocity is considered as one of the deciding factors of the ball motion. As for ADM, the ball's gravity and drag force as well as the Magnus force caused by the ball's rotational velocity are considered influencing the ball's trajectory. The rebound models (TRM and RRM) characterize the variation of the ball's translational and rotational velocities just before and after the rebounding. Some experimental data are shown to verify the effectiveness of these models, which include top spin balls, back spin balls and side spin balls. These three models are the basis of controlling a spinning table tennis ball.

Chapter 4 proposes a racket control method for returning the ball to a desired position with a desired rotational velocity at a desired landing time. The determined racket's state includes the translational velocity and the posture of the yaw and the pitch angles. The proposed racket control method is based on the racket rebound model (RRM) and the aerodynamics model (ADM). The racket control problem is divided into two subproblems; (a) the problem of solving a set of nonlinear equations which comes from RRM and (b) the two-point boundary value problem of the nonlinear differential equation which comes from ADM. Then fundamental properties of those subproblems are clarified: for the first subproblem about RRM, an existence condition for real solutions of the set of nonlinear equations is derived and the solutions are expressed in the closed form; as for the second subproblem associated with ADM, it shows that the two-point boundary value problem of ADM needs too much computing time to be treated in real-time manner. Therefore, an on-line algorithm is proposed by using an approximate aerodynamic model. Some numerical simulations and experimental results have been demonstrated to verify the effectiveness of the proposed method.

In Chapter 5, the conclusions are summarized and some suggestions about the hardware of the table tennis system and the presented physical models are shown for the further research.