Visual Servo Control for Balancing a Ball-Plate System

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***Abstract*—This paper presents a skillful robotic wrist system using a visual servo control technique to demonstrate dexterity of the mechanical wrist from the viewpoint of the table tennis. A ball and plate system is chosen as the first stage of this long-term project. A two degrees-of-freedom robotic wrist with an acrylic plate attached as the end effector is developed. A visual feedback control system is implemented with a video camera and a personal computer to acquire the ball's position. In order to implement decision making for changing orientation of the plate, a Linear Quadratic Regulator (LQR) control algorithm is designed. As a result, the ball can be balanced at specific positions. Experimental results exhibit preliminary and promising achievement. Based on this progress, further improvement and deeper exploration can be carried on in the future.**

***Index Terms*—intelligent control, Linear Quadratic Regulator (LQR), robotics, the ball-plate system, visual servo**

I. Introduction

Traditional robots have been widely applied to repetitive processes in assembly lines such as soldering and welding, paint spraying, grabbing and placement, *et al*. Although they are able to accomplish assigned tasks with satisfactory efficiency and performance, lacking operational dexterity has been a major obstacle to deal with varying working environment. As a result, intelligent robots, robots with sensory feedback and skillful dexterity, have gained great attention because of their competence to cope with uncertain and indeterminate situations.

The multi-fingered robotic hand has been commonly used in peg-in-hole assembly tasks. Since contact between peg and hole cannot be completely avoided, by incorporating visual servo and force feedback into the control loop, dexterity with compliance was successfully implemented [1]. A billiard robot that can provide suitable pushing force to sink a target ball into a pocket or make a position play was also developed [2]. In order to build a ping-pong robot player, a well-designed robotic wrist plays an important role [3]. A Toshiba research group created a volley ball robot, which not only could play an one-on-one game, but owned capability of interacting with humans by shaking hand and recognition via voice and facial image [4].

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The ball-plate system, an extension from the ball-beam structure, has become a popular target device for controller implementation because of its simple configuration and easy implementation. An approximate input-output linearization method based on an imprecise model was introduced for the purpose of tracking control [5]. Actual experiments were presented by applying a touch panel as a position sensor with a conventional PID controller [6]. Furthermore, a ball-plate system for teaching was also developed [7]. A number of researchers established an online-learning fuzzy control algorithm based on this teaching device [8]. A fuzzy control scheme was also raised by acquiring the ball’s position using a CCD camera instead of the touch panel device [9]. A Samsung Fara-AS1 commercial robotic arm was applied to drive a ball-plate system for balancing tasks [10]. A big mechanical ball-plate system was built to perform a control loop by acquiring the ball’s position using a video camera [11].

In order to implement such an intelligent dexterity onto a robotic system, the balancing problem with a ball-plate system driven a two-degree-of-freedom mechanical wrist, as shown in Fig. 1 is studied in this paper. A video camera will be employed to simulate human eye to visualize location of the ball on the plate. Intelligent control algorithm using a Linear Quadratic Regulator (LQR) approach will be developed to adjust the plate’s attitude to guide the ball to a specific position to achieve given balancing tasks.

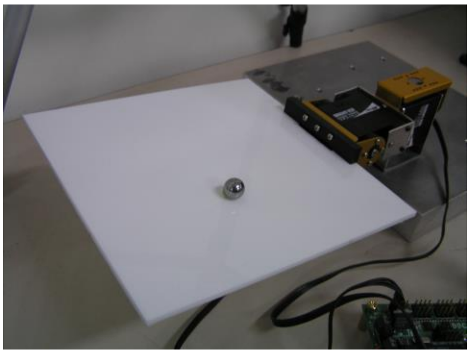

Figure 1. The ball-plate system studied in this paper.

II. Dynamic Modeling of a Ball-Plate System

The complete dynamic equations of a ball-plate system demonstrate highly nonlinear and coupling characteristics.

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For the purpose of simplicity and clarity, a reasonable assumption of small angle movement needs to be made. Fig. 2 depicts the coordinate systems applied to the ball-plate system, which is driven by two motor actuators. The origins of the global reference system (*O*; *X*, *Y*, *Z*) and the moving reference system (*p*; *x*, *y*, *z*) attached on the plate coincides at the intersection of rotation axes of those two actuators. θ_x and θ_y represent rotational angles along x and y axes, respectively. Let the ball with mass m and moment of inertia I be located at (x, y) on the plate. The position of the ball (X, Y, Z) can therefore be written in the following form:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\theta_y & \sin\theta_x \sin\theta_y & -\cos\theta_x \sin\theta_y \\ 0 & \cos\theta_x & \sin\theta_x \\ \sin\theta_y & \sin\theta_x \cos\theta_y & \cos\theta_x \cos\theta_y \end{bmatrix} \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} \quad (1)$$

In order to obtain dynamic equations of the ball-plate system, the Euler-Lagrangian method will be employed. Assume the ball is in pure rolling condition and there is no rotation with respect to the normal of the plate for the ball. The kinetic energy and the potential energy of the ball can be expressed by

$$K = \frac{1}{2} m \left|\dot{B}\right|^2 + \frac{1}{2} I \left(\left|\dot{\Theta}\right|^2 + \left|\Omega\right|^2 \right) \quad (2)$$

$$V = mg\left(x \sin\theta_y + y \sin\theta_x \cos\theta_y \right) \quad (3)$$

where B is the linear velocity of the ball, which can be solved by taking time derivative of (1). $\dot{\Theta}$ and Ω denote the angular velocity of the ball provided by the plate and its self-spin velocity, respectively, and can be derived as

$$\dot{\Theta} = \left[\dot{\theta}_x \quad \dot{\theta}_y \cos\theta_x \quad -\dot{\theta}_y \sin\theta_x \right]^T \quad (4)$$

$$\Omega = \left[\frac{-\dot{y}}{r} \quad \frac{\dot{x}}{r} \quad 0 \right]^T \quad (5)$$

where r is the ball's radius. Incorporating (2), (3), (4) and (5) into the Euler-Lagrangian approach leads to the dynamic equations as follows:

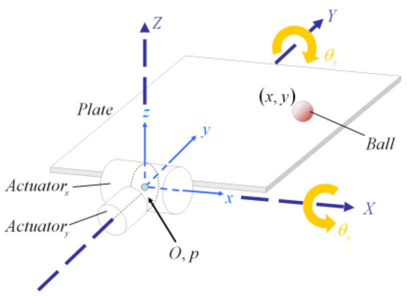

Figure 2. Coordinate systems for the ball-plate system.

$$\left(1 + \frac{I}{mr^2}\right)\ddot{x} - g\sin\theta_y + (2\dot{y}\dot{\theta}_y + y\ddot{\theta}_y)\sin\theta_x - x\dot{\theta}_y^2 + 2y\dot{\theta}_x\cos\theta_x = 0 \quad (6)$$

$$\left(1 + \frac{I}{mr^2}\right)\ddot{y} + \sin\theta_x(g\cos\theta_y - 2\dot{x}\dot{\theta}_y - x\ddot{\theta}_y) - y\left(\dot{\theta}_x^2 + \dot{\theta}_y^2 \sin^2\theta_x\right) = 0 . \quad (7)$$

Simplified dynamic equations for the purpose of controller design can be obtained by assuming negligible angular displacements, velocities, and accelerations.

$$\left(m + \frac{I}{r^2}\right)\ddot{x} - mg\theta_y = 0 \quad (8)$$

$$\left(m + \frac{I}{r^2}\right)\ddot{y} + mg\theta_x = 0 \quad (9)$$

Apparently, the simplified dynamic equations listed above show two single-input-single-output linear equations. Manipulation controller can therefore be designed based on the prescribed dynamic behavior.

III. Visual Servo Control

The developed visual servo control algorithms have to be fast enough to catch up with the framing rate of the camera without down-grading performance of the whole system. Therefore, efficiency and simplicity are two major concerns for the development.

A. Locating the Ball on the Plate

The ball used in this research can be differentiated with the plate easily using the threshold approach according to difference of their color appearance. The main challenge is to quickly locate the ball on the plate within limited time.

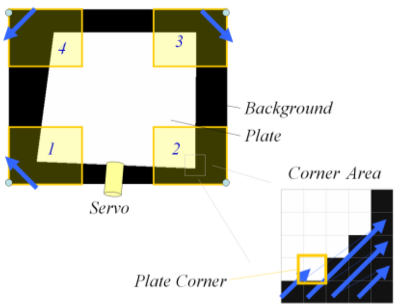

Figure 3. Illustrative searching strategy for four corners of the plate.

Before determining the ball on the plate, the position of the plate needs to be detected at the beginning. Although the global searching method is able to locate the plate's corners accurately, it is discarded due to its expensive time efficiency. Since only small movement of the plate is allowed, four corners of the plate can be always found near the corner areas of the image as illustrated in Fig. 3. Therefore, four corner areas occupying only one third of the whole image need to be explored. The searching direction with 45 degrees was chosen to decide the coordinates of the plate's corners. Then the center coordinates of the ball can be obtained by inner search based on those four corner positions.

However, image distortion is usually caused because of different viewing angle. As a result, true position cannot be determined just by simply proportional distance relationship. Location of the ball on the plate will be determined by incorporating the projective mapping transformation technique [12]. A full projective transformation includes translation, rotation, scaling, and shearing, can be expressed by

$$I_i = \frac{a_{11}P_x + a_{12}P_y + a_{13}}{a_{31}P_x + a_{32}P_y + a_{33}} \quad (10)$$

$$I_j = \frac{a_{21}P_x + a_{22}P_y + a_{23}}{a_{31}P_x + a_{32}P_y + a_{33}} \quad (11)$$

where (I_i, I_j) and (P_x, P_y) respectively represent the coordinates on the image plane and its position on the same plane in three dimensional space, and a_{mn} are transformation coefficients. Without losing generality, a_{33} can be set to 1. Therefore, only eight unknown parameters need to be solved in (10) and (11) and can be fully determined by applying equations at four corners. As a result, the actual position of the ball on the plate can be located.

B. Controller Design

For the purpose of satisfactory manipulation performance, the LQR (Linear Quadratic Regulator) approach was selected for controller implementation. The LQR controller was developed based on the optimal control framework with least control effort for designated control objective [13]. Consider a linear and controllable system described by

$$\dot{\mathbf{x}}(t) = \mathbf{F}\mathbf{x}(t) + \mathbf{G}\mathbf{u}(t) \quad (12)$$

where $\mathbf{x}$ and $\mathbf{u}$ stand for the system state vector and the control input vector, respectively. Given two weighting matrices $\mathbf{Q}$ and $\mathbf{R}$, minimization of the following performance index

$$J = \int_0^\infty \left[\mathbf{x}^T(t)\mathbf{Q}\mathbf{x}(t) + \mathbf{u}^T(t)\mathbf{R}\mathbf{u}(t)\right] \quad (13)$$

leads to an optimal controller

$$\mathbf{u}(t) = -\mathbf{K}\mathbf{x}(t) \quad (14)$$

to make the whole system become asymptotically stable, where $\mathbf{K}$ is the feedback gain matrix and can be expressed by

$$\mathbf{K} = \mathbf{R}^{-1}\mathbf{G}^T\mathbf{P} \quad (15)$$

$\mathbf{P}$ is the solution of the following algebraic Riccati equation:

$$\mathbf{PF} + \mathbf{F}^T\mathbf{P} - \mathbf{PGR}^{-1}\mathbf{G}^T\mathbf{P} = -\mathbf{Q} \quad (16)$$

Since both (8) and (9) have the same form as (12), following standard design process for LQR brings about an optimal controller for the balancing problem of the ball-plate system

IV. Balancing Experiments

An experimental setup for balancing experiments as shown in Fig. 4 was built up to demonstrate balancing performance using the proposed control strategies. The plate is operated by a two degrees-of-freedom mechanical wrist driven by two servo motors. A web camera Philips SPC300NC, with 30 fps capability, is attached at the tip of a tripod to provide visual image of the ball and the plate. The control objectives are to maintain the ball always at the center of the plate or follow a specified circular trajectory.

The plate is a square acrylic board with 15 cm edge length and 3 mm thickness. The ball is made of steel with a diameter of 1 cm and is commonly applied to ball bearing.

Two balancing experiments, including positioning the ball at central point of the plate and allowing the ball to follow a circular path, were conducted. The former one is to justify the balancing performance of the proposed control scheme. The latter one considers tracking capability given a specified trajectory.

Assume those two weighting matrices $\mathbf{Q}$ and $\mathbf{R}$ have the following expressions:

$$\mathbf{Q} = \begin{bmatrix} 120 & 0 & 0 & 0 \\ 0 & 100 & 0 & 0 \\ 0 & 0 & 120 & 0 \\ 0 & 0 & 0 & 100 \end{bmatrix} \quad (17)$$

$$\mathbf{R} = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix} \quad (18)$$

By choosing system poles at -1.1809, -1.1809, -2.9335, and -2.9335, it can be concluded that

$$\mathbf{P} = \begin{bmatrix} 142.5266 & 34.6410 & 0 & 0 \\ 34.6410 & 41.1439 & 0 & 0 \\ 0 & 0 & 142.5266 & 34.6410 \\ 0 & 0 & 34.6410 & 41.1439 \end{bmatrix} \quad (19)$$

$$\mathbf{K} = \begin{bmatrix} 0 & 0 & 3.4641 & 4.1144 \\ 3.4641 & 4.1144 & 0 & 0 \end{bmatrix} \quad (20)$$

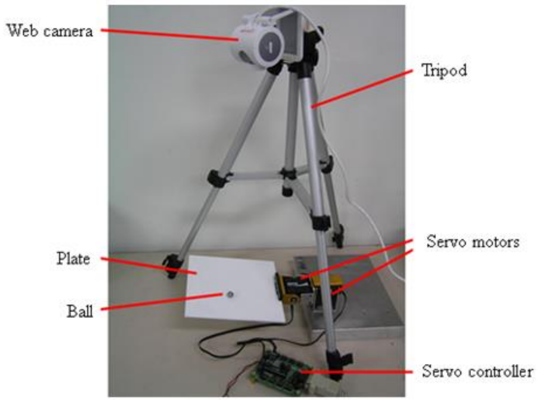

Figure 4. The experimental setup for balancing the ball-plate system.

At the beginning of the balancing experiments, the ball was positioned at (-49 mm, 135 mm) on the plate. The control objective is to manipulate the plate using a two degrees-of-freedom robotic wrist to bring the ball back to the center of the plate at (0, 95 mm). In order to examine whether the proposed control algorithm was capable of overcoming possible unknown disturbance, the ball would be interfered by unexpectedly impulsive force at 11.5 sec and 15.5 sec. Fig. 5 depicts the trajectories of ball along x and y directions and planar trajectory of the ball during the balancing process. Simulation results using Simulink® were also presented in the same figure for the purpose of comparison. It appears that both simulation and experimental results demonstrate similar responses. Furthermore, those impulsive disturbances would bring the ball off the track temporarily without surprise. But after the unknown disturbance disappeared, the presented control framework was able to restore the control task by guiding the ball to the central region of the plate. It should be noticed that control effort becomes small when the ball is near the central region and position error may be caused when the friction dominates the ball's motion.

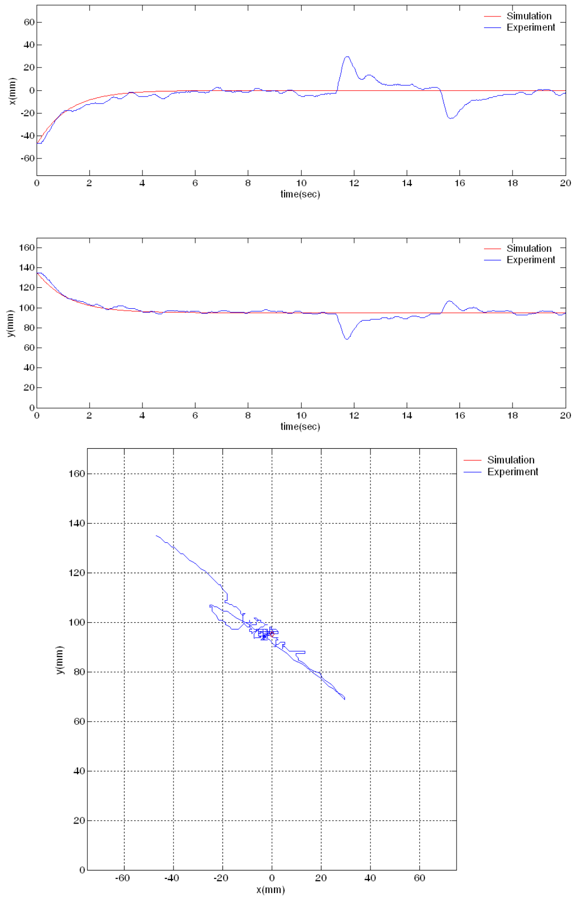

Figure 5. Position responses and planar trajectory of the balancing experiment.

Another balancing experiment allowing the ball to follow a circular path with a diameter of 80 mm was also conducted to demonstrate effectiveness of the proposed control method. The position command was formulated as $x_d = 40\sin(0.5t)$ and $y_d = 40\cos(0.5t)$. Fig. 6 illustrate tracking performance in terms of planar trajectory and individual response along *x* and *y* directions, respectively. Because the tracking experiment covers positioning at wider region compared to previous balancing experiment, levelness and local friction distribution of the plate, existing centrifugal force, and limited sampling frequency for imaging, inevitably degrade tracking performance. Although tracking error was caused along the tracking process, satisfactory tracking performance for a circular path was still successfully exhibited.

V. Conclusions

Operational dexterity with intelligence has been a major objective for recent development of robotics. This paper aims at creating human-like intelligent operational skill for a ball-plate system to accomplish balancing tasks. A CCD camera was applied to simulate human eye to locate the ball's position on the plate. An LQR control algorithm was implemented to manipulate a two degrees-of-freedom robotic wrist for guiding the movement of the ball. Two balancing experiments, including positioning the ball at central point of the plate and allowing the ball to follow a circular path, were conducted to demonstrate satisfactory and promising control performance.

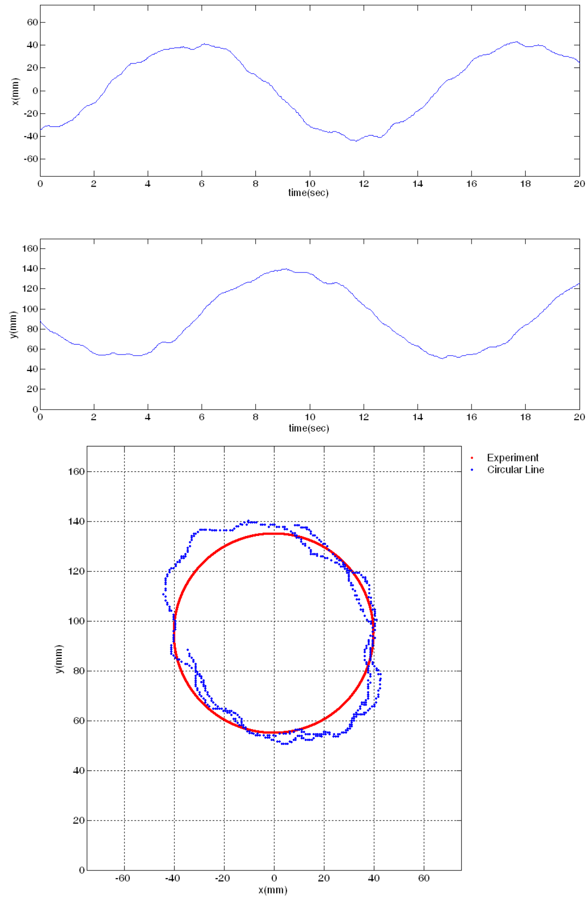

Figure 6. Position performance along *x* and *y* directions and planar trajectory for tracking a circular path.

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