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Basketball Robot: Ball-on-Plate with Pure Haptic Information

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***Abstract*— Building a basketball robot is a recently launched project at the Institute of Automatic Control Engineering (LSR) for investigating fast manipulation with non-negligible dynamics and changing contact situation. This study presents one of the main preliminary results of the project which is balancing a basketball on a plate using a six degrees of freedom serial industrial robot based on pure haptic information. The Ball-On-Plate system has been one of the classical applications of control theory and many studies have been conducted on this issue. However, most of these studies employed vision systems to update the current state of the ball on the plate. In this paper, the concept of balancing a ball on a plate purely based on haptic information is discussed. The velocity of the basketball which rolls on a plate is estimated based on the force data measured by a force-torque (F/T) sensor mounted on the end-effector and the proposed control scheme brings the basketball back to a still standing on the plate. Experimental results are presented to validate the efficiency of the proposed control scheme.**

I. INTRODUCTION

Many studies on skillful human motion and animal movement have enriched robot functionalities as well as their performance. Inversely, struggles to transfer dextrous skills of human being to robots may also deepen the understanding and insight into human physiology itself. In order to imitate highly evolved creatures robotics researchers are facing many challenges from sensing to decision making, from design to actuation as well as control. Sports may be one of the most challenging tasks for robots as it requires fast, highly dextrous manipulation including non-negligible dynamics, although most human beings can easily learn and enjoy it. Nakawaki *et al* [1] modeled the kip motion of gymnasts and compared the performance to human experts. In [2] Hasekawa *et al* introduced a skiing robot that has various primary skiing skills. The prototype of a robot ping-pong player was introduced by Acosta *et al* in [3], and ball juggling experiments have been conducted by Riley *et al* in [4].

For the investigation of fast, dextrous manipulation with non-negligible dynamics, basketball may offer many interesting challenges. It requires highly dynamical and precise motion and dexterity in handling a basketball. Moreover, the basketball is normally oversized compared to conventional robot hands so that ball catching by grasping will fail, unless the robot is equipped with overly dimensioned grippers. From this context, a new project, *basketball robotics*, was launched recently at the Institute of Automatics Control Engineering, Technische Universität München. Basketball robotics covers a wide range of interesting problems in robotics research, such as motion planning and coordination, visual servoing, sensor data fusion, and skill transfer as well as various physical phenomena such as friction, impact, momentum conservation, bouncing ball, etc.

Many research groups have previously investigated about ball catching with multi-fingered hands, see e.g. [5]–[8]. However, little attention has been given to catching an oversized ball by dynamically balancing it. As a first nontrivial challenge dynamical catching of a basketball was chosen. For the catching an oversized ball such as a basketball, a dynamical balancing and stabilizing strategy should be used instead of grasping with a multi-fingered hand. In order to realize this, ball balancing, which is often called ball-on-plate system, is one of the crucial features which should be done in the first place. Some research has been conducted on these issues, see [9]–[12], in most of which ball balancing is achieved either for a one dimensional problem (balancing beam) or using stereo vision to update the state of the ball on the plate. In this paper, the ball balancing on a plate is achieved based on pure haptic information by employing four Degrees of Freedom (DoF) which are two tilting angles and two translational motions of a robot end-effector. The balancing ball-on-plate problem is challenging even for humans when the available sensor data is limited to pure haptic information.

This paper is structured as follows: In Section II, the physical model of the ball-on-plate system is derived. A control scheme for ball balancing is introduced in Section III. The experimental setup and results are shown in Section IV to demonstrate the efficiency of the proposed scheme. Finally, Section V describes the conclusions drawn from this study.

II. PHYSICAL MODELING OF A BALL-ON-PLATE SYSTEM

In order to realize ball balancing on a plate, it is necessary to estimate the current state of the ball on the plate, which consists of the velocity and position of the ball. In conventional studies on this issues a touching pad or a vision system was employed to measure the state. Since we limited the available sensor data to only haptic information, an alternative way is devised based on F/T sensor. We assume that the robot manipulator as a balancing system is equipped with a six DoF F/T sensor between the plate and the end-effector.

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A. Physical background

In this section, we consider a balancing problem of a basketball on a plate which can only be controlled by two tilting angles. Fig. 1 shows a schematic view of the ball on an inclined plate mounted on end-effector of a serial industrial robot. The following simplifications are made in order to avoid unnecessary complexity:

- *No slippage condition*: translational motion of the ball can be mapped one-to-one into its roll motion.
- *No rotational motion of the ball with respect to its vertical axis*: kinetic energy of any rotational motion of the ball about its vertical axis is neglected.
- *Symmetry of plate*: the end-effector plate is homogeneous and symmetric with respect to the end-effector axes x_e and y_e, respectively. Further the origin of end-effector frame $x_e - y_e - z_e$ is placed at the center of gravity of the plate.
- *No friction force and torque*: all friction forces and torques are neglected.

Considering the above assumptions, the kinetic energy of the ball can be expressed as a sum of rotational energy with respect to its center and translational energy:

$$T_b = \frac{1}{2} m_b \left(\dot{x}_b^2 + \dot{y}_b^2\right) + \frac{1}{2} \Theta_b \left(\omega_x^2 + \omega_y^2\right) \tag{1}$$

where T_b is the kinetic energy of the ball; m_b is the mass and Θ_b the moment of inertia of the ball; $\dot{x}_b$, $\dot{y}_b$, ω_x, and ω_y are translational and angular velocities of the ball along x_e and y_e direction, respectively. Due to the no slippage condition between the ball and the plate, the following relations between translational and rotational velocities hold:

$$\dot{x}_b = r_b \omega_y, \quad \dot{y}_b = r_b \omega_x. \tag{2}$$

where r_b denotes the radius of the ball. Substituting (2) into (1) yields

$$T_b = \frac{1}{2}\left(m_b + \frac{\Theta_b}{r_b^2}\right)\left(\dot{x}_b^2 + \dot{y}_b^2\right). \tag{3}$$

Similarly, representing the ball placed in the position(x_b, y_b) as a point mass, the kinetic energy of the plate including rotational energy of the ball with respect to the center of the plate can be calculated by

$$T_p = \frac{1}{2}\left(\Theta_p + \Theta_b\right)\left(\dot{x}_b^2 + \dot{y}_b^2\right) + \frac{1}{2} m_b \left(x_b \dot{\alpha} + y_b \dot{\beta}\right)^2. \tag{4}$$

Thereby $\dot{\alpha}$ and $\dot{\beta}$ denote the rate of tilting angles around the axes y_e and x_e, respectively.

On the other hand, potential energy of the ball due to the gravity by

$$V_b = m_b g \left(x_b \sin\alpha + y_b \sin\beta\right). \tag{5}$$

Using (3-5), Lagrangian of the given system is given by

$$L = T_b + T_p - V_b. \tag{6}$$

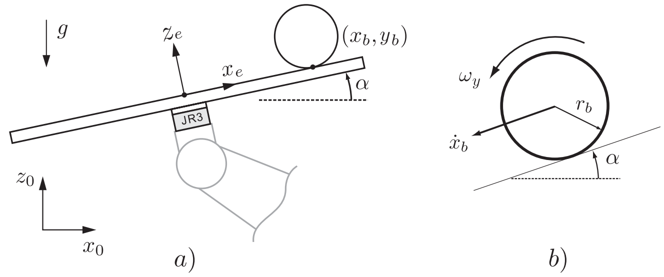

Fig. 1. Schematic side-view of a ball-on-plate system a) and a rolling ball on an inclined surface b)

Thus, the motion of the ball on the plate can be described by the following nonlinear differential equations using the well known Euler-Lagrange equation:

$$\left(m_b + \frac{\Theta_b}{r_b^2}\right)\ddot{x}_b - m_b\left(x_b\dot{\alpha}^2 + y_b\dot{\alpha}\dot{\beta}\right) + m_b g \sin\alpha = 0, \tag{7}$$

$$\left(m_b + \frac{\Theta_b}{r_b^2}\right)\ddot{y}_b - m_b\left(y_b\dot{\beta}^2 + x_b\dot{\alpha}\dot{\beta}\right) + m_b g \sin\beta = 0. \tag{8}$$

Considering the moment of inertia of the ball Θ_b can be represented as a spherical shell

$$\Theta_b = \frac{2}{3} m_b r_b^2, \tag{9}$$

the motion of equation (7) and (8) can be rewritten as

$$m_b\left\{\frac{5}{3}\ddot{x}_b - \left(x_b\dot{\alpha}^2 + y_b\dot{\alpha}\dot{\beta}\right) + g\sin\alpha\right\} = 0, \tag{10}$$

$$m_b\left\{\frac{5}{3}\ddot{y}_b - \left(y_b\dot{\beta}^2 + x_b\dot{\alpha}\dot{\beta}\right) + g\sin\beta\right\} = 0. \tag{11}$$

Assumed that only small angles and slow change rates of the tilting angles are used to control the balancing system, the second terms in (10) and (11) representing nonlinear centrifugal and Coriolis forces can be neglected and they can be further linearized as

$$\frac{5}{3}\ddot{x} + g\alpha = 0, \tag{12}$$

$$\frac{5}{3}\ddot{y} + g\beta = 0. \tag{13}$$

Finally, (12) and (13) can be used to estimate the current states of the ball: x_b, y_b, $\dot{x}_b$, and $\dot{y}_b$

B. Balancing problem including lateral motion

In practice, more interesting features arise when it comes to stabilizing the basketball on the plate against disturbance forces. When the ball is disturbed by external forces, it can have non-zero velocities even though the plate stays horizontal. Moreover, when the lateral motion of the plate is allowed which is more efficient to keep the ball on the limited size the plate than using only tilting angles, the physical model may not provide meaningful states of the ball, and the lateral motion of the plate may introduce additional inertial force to the basketball through the inclined surface. In this case, the position and the velocity of the basketball can be estimated by using F/T sensor data. Consider a basketball is in the position (x_b, y_b) on a moving plate. The torque due to the gravity of the ball and the inertial force can be determined as

$$M_y = m_b x_b \left(g \cos\alpha - \ddot{x}_e \sin\alpha\right), \quad (14)$$
$$M_x = m_b y_b \left(g \cos\beta - \ddot{y}_e \sin\beta\right). \quad (15)$$

where $\ddot{x}_e$ and $\ddot{y}_e$ denote the translational accelerations of the end-effector. Hence, the position of the basketball can be obtained from the measured torque M_y and M_x as

$$x_b = \frac{M_y}{m_b(g\cos\alpha - \ddot{x}_e \sin\alpha)}, \quad (16)$$
$$y_b = \frac{M_x}{m_b(g\cos\beta - \ddot{y}_e \sin\beta)}. \quad (17)$$

Furthermore, the velocity of the ball on the plate can be evaluated either by direct derivative of the ball position or by observing the change rates of the measured torques and tilting angles. In practice, however, derivatives of F/T sensor signals cannot be employed in controllers due to its noisy data.

III. CONTROL SCHEME FOR BALL BALANCING

Basketball playing requires robots to cope with impact forces. One promising control scheme for handling impact force is position-based impedance control [13]. Hence, an overall balancing control is also implemented based on impedance control. The overall control scheme for ball balancing is illustrated in Fig. 2. The proposed control scheme consists of three parts including balancing control, impedance control, and inner position control. When the ball looses its equilibrium on the plate and starts moving, the velocity and position are estimated and the corresponding desired trajectory for stabilizing the ball is generated in the balancing control. The impedance control is supposed to take out the kinetic energy from the ball and modifies the desired trajectory to avoid unendurable contact forces. The inner position control loop generates motor torque commands for the robot to track the desired trajectory. Generally, impedance control modifies the desired trajectory according to the measured contact force and may thus deteriorate the balancing actions generated by the balancing control. In order to prohibit such problems, selection matrices

$$S = \mathrm{diag}([0\ 0\ 0\ 1\ 1\ 0]) \quad (18)$$
$$S' = I - S = \mathrm{diag}([1\ 1\ 1\ 0\ 0\ 1]) \quad (19)$$

are introduced to decompose the impedance controller from the balancing controller. Since the balancing control needs only the measured moments M_x and M_y, corresponding

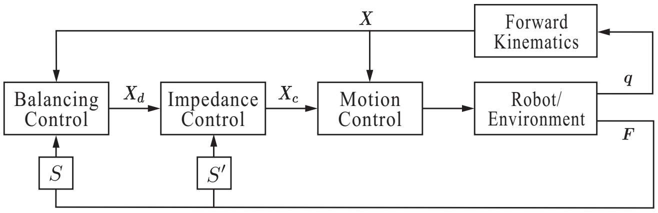

Fig. 2. Overall control scheme

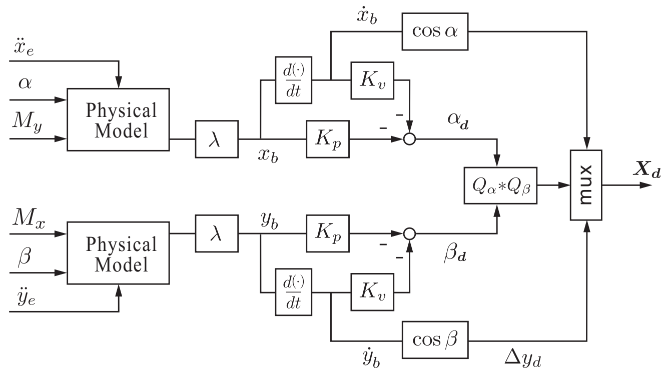

Fig. 3. Block diagram of balancing control

entries in the selection matrix S have 1 otherwise 0. The selection matrix S' for the impedance control is defined as a complement matrix of S. Balancing is achieved not only through rotating the plate but also through translational motion of the plate. Thus, the inner impedance control may disturb the outer balancing control. However, possible modification of the translational desired trajectory which can be caused by friction force is negligible. Since the states of the basketball (x_b, y_b, $\dot{x}_b$, $\dot{y}_b$) are estimated by noisy F/T sensor data using (16) and (17), the noise of the F/T sensor is to be reduced by a low-pass filter (LPF) . However, LP filtering the F/T sensor signal introduces system delay and deteriorates the estimation performance such that the whole system is getting slower. As a remedy to this problem, a lead compensator can be combined with a low-pass filter.

The resulting structure of the balancing control is illustrated in Fig. 3. Thereby, K_p and K_v denote the control gains for the position and the velocity, and λ scaling factor which can be experimentally determined such that the estimated arc length of the ball trajectory corresponds to the real one. Since the aim of the balancing control is rather to keep the ball on the plate and to let it settle down than to control its position relative to the plate, the desired position and velocity of the ball are simply set to zero. Furthermore, the position gain K_p can be released, in case the equilibrium position where the ball settles down does not matter. Once both tilting angles α and β are determined, then they are converted to desired orientations using a quaternion product.

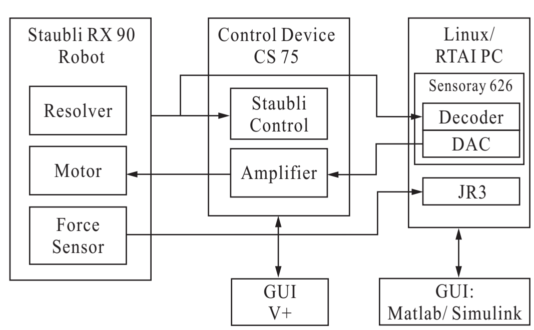

Fig. 4. Hardware configuration with an additional PC

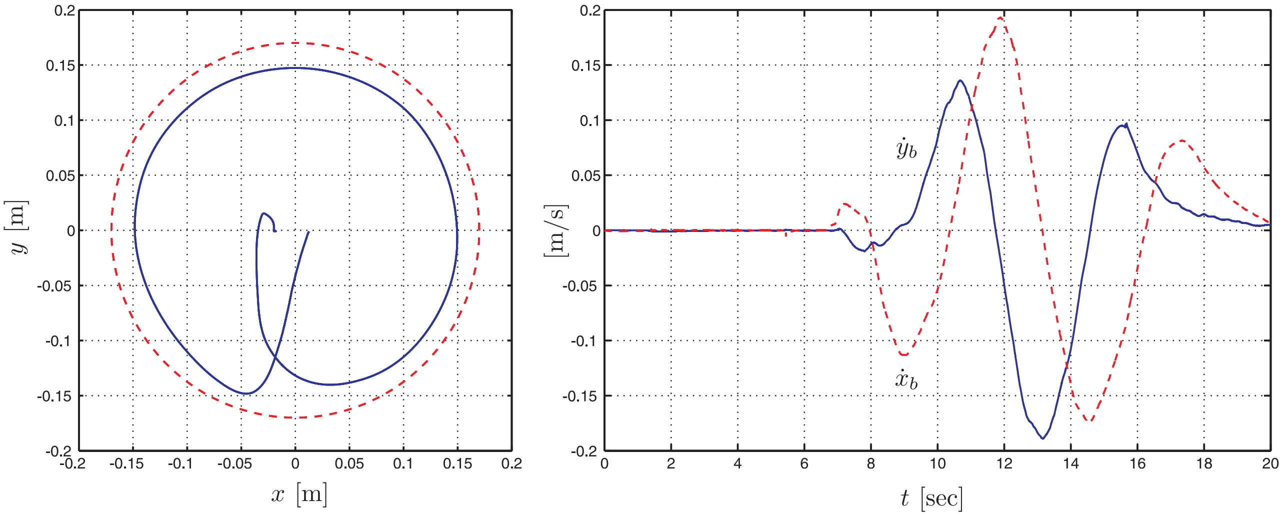

Fig. 5. Estimated basketball trajectory on a circular plate of which edge is denoted by a dashed line (Left) and velocity (Right) while the ball completes a counter-clockwise circle

IV. Experimental Results

A. Experimental setup

The proposed basketball balancing control scheme is experimentally validated using the industrial robot Stäubli RX90 that has six DoF revolute joints equipped with a JR3 F/T sensor at the end-effector. Two different types of aluminum plates are used in the experiment: a rectangular plate (25 $\times$ 40 cm) and a circular plate (radius 17 cm). Standard control of industrial robots is inappropriate for testing complex control algorithms. A possible solution to create a rapid prototyping test environment [14] is to run the system with Matlab/Simulink. Fig. 4 describes the hardware configuration used in this experiment with an additional PC, on which Matlab/Simulink is executed under a realtime Linux (RTAI) environment. It is integrated with sensoray cards and F/T sensor receivers. Advantages of using this hardware configuration are that new control algorithms can be designed easily in Matlab/Simulink and executed in the realtime Linux environment while keeping significant safety measures such as motor brakes, supervising joint limits and speeds as well as emergency brake from the original system.

B. Experimental Studies

The experimental studies are three-fold: trajectory estimation of a basketball on the plate, balancing a basketball on a plate which follows a desired trajectory, and stabilizing a basketball on a plate against external disturbance forces.

Trajectory estimation

In this experiment, the ball rolls from the center of the circular plate to the front edge, and completes a circle in counterclockwise direction. The estimated trajectory of the basketball and corresponding velocity are illustrated in Fig. 5. The F/T sensor signal is filtered by a low-pass filter with cutoff frequency 0.1 Hz combined with a lead compensator (LC) of the form $\frac{1.6s+1}{0.1s+1}$ for better system responsiveness. It is noted that the smooth estimated ball trajectory could be achieved by the strong low-pass filtering and the higher cutoff frequency will provide noisier trajectory. The same LPF and LC are further applied throughout the experimental studies.

Balancing on a moving plate

In this experiment, the end-effector is required to follow a sinusoidal trajectory along the axis x_e with the amplitude of 0.25 m while keeping the plate horizontal. The basketball is placed on the plate at $t = 13$ s and the control scheme is supposed to keep the basketball within the plate. Along the axis x_e, the control action is taken only by the tilting

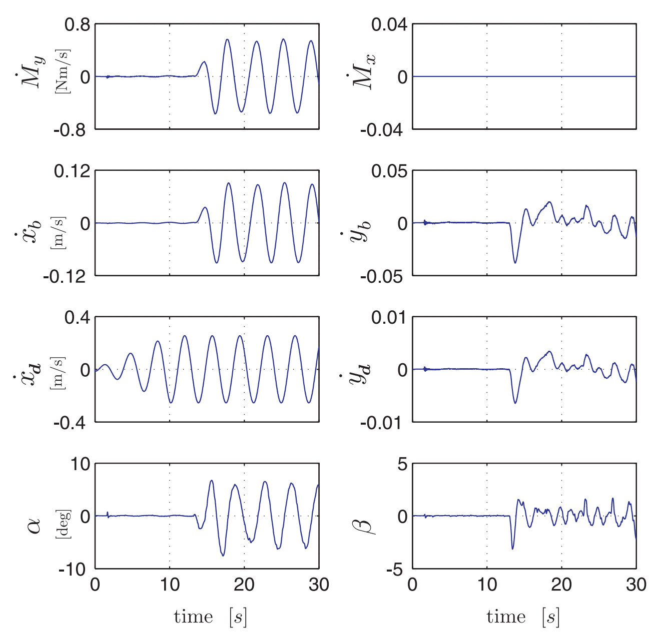

Fig. 6. Balancing a basketball on a moving plate.

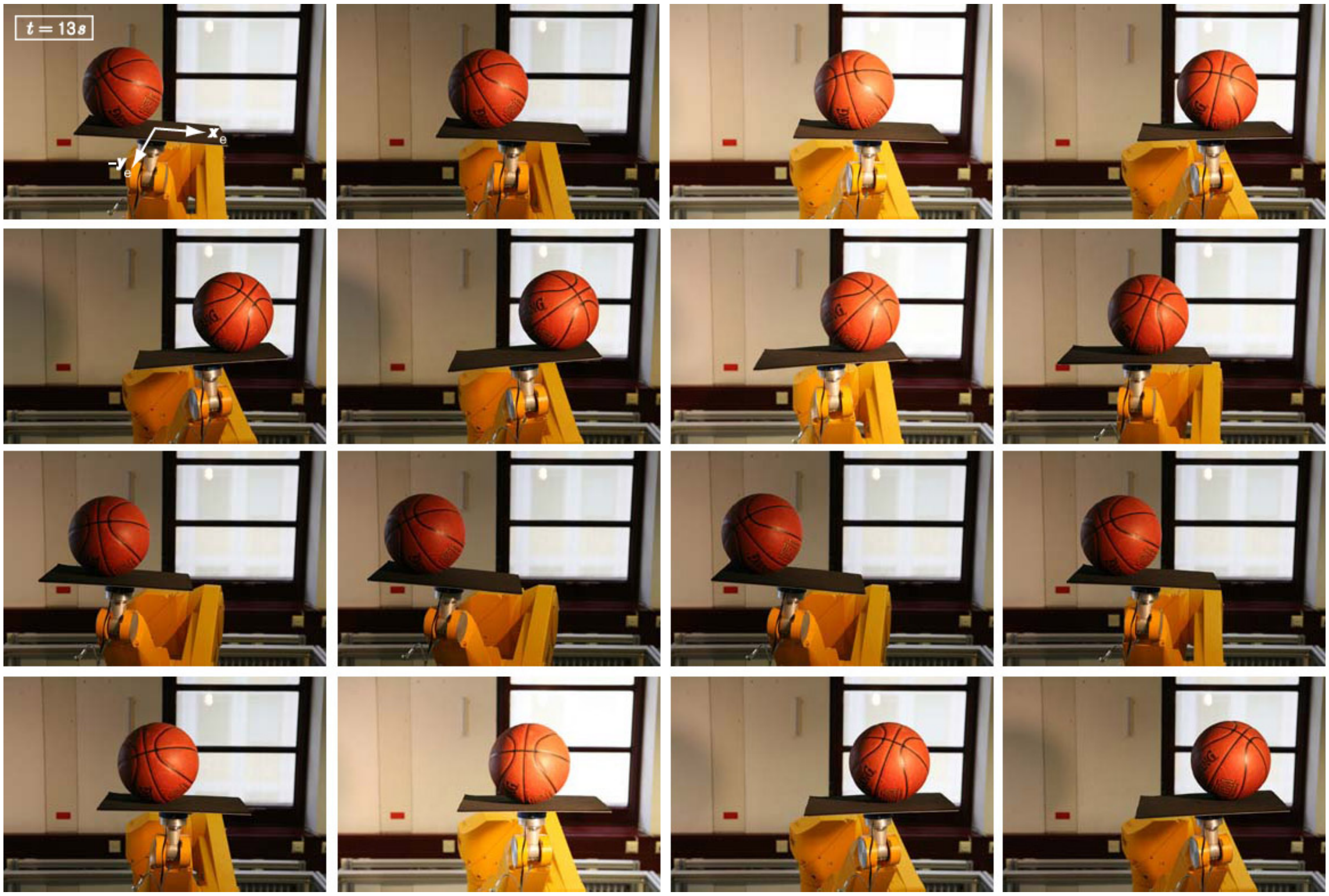

Fig. 7. Sequential view of a basketball balancing on a moving plate.

angle α to guarantee tracing of the desired trajectory, and both translational and rotational balancing actions are taken for the y_e direction. Fig. 6 shows the change of measured torque ($\dot{M}_y$, $\dot{M}_x$), the estimation of the basketball velocity ($\dot{x}_b$ and $\dot{y}_b$), desired trajectory ($\dot{x}_d$), and balancing actions (α, $\dot{y}_d$, β). No control action can be observed before the basketball is placed on the plate at $t = 13$ s and the plate follows the desired trajectory keeping the plate horizontal. Once the basketball is placed, due to the relative motion of the basketball on the plate, the measured torque changes continuously and the control scheme starts to balance the ball by using the two tilting angles α and β, and one lateral motion $\dot{y}_d$. A series of sequential snapshots of this experiment are shown in Fig. 7. It is also challenging for humans to do the same task without visual information, and even with using vision, it requires still high concentration.

Balancing against external disturbance forces

In this experiment, the basketball is initially in an equilibrium position at the center of the plate. At $t = 4$ s, it starts moving to the negative x_e direction due to an external disturbance force from the positive x_e direction. The evolution of torque change $\dot{M}$ measured by the F/T sensor and the estimated basketball velocities $\dot{x}_b$ and $\dot{y}_b$ relative to the center of the plate are illustrated in Fig. 8. Thereby, $\dot{x}_d$ and α, and $\dot{y}_d$ and β denote translational and rotational

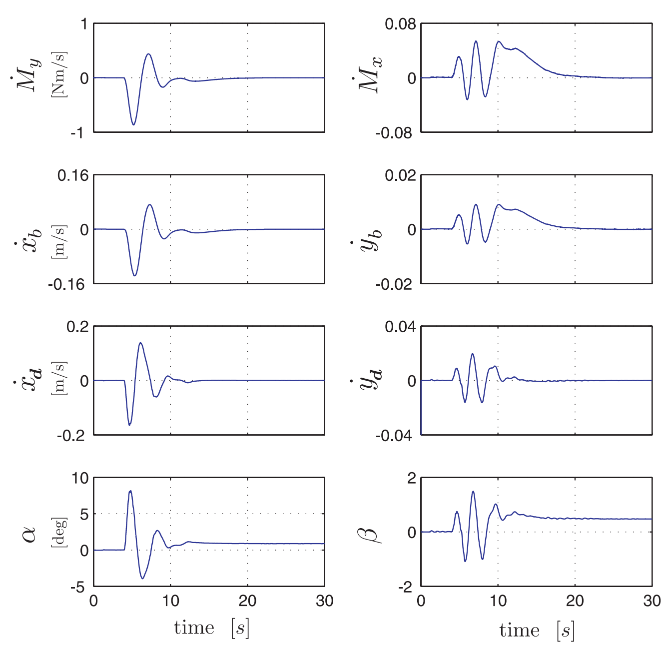

Fig. 8. Stabilizing basketball against external impact force at $t = 4$ s: x-direction (left) and y-direction (right)

Fig. 9. Sequential snapshots of stabilizing a basketball against an external impact force at $t = 4$ s.

stabilizing actions for the x_e and y_e direction, respectively. A sequence of snapshots of such a stabilizing process are shown in Fig. 9. The axes x_e and y_e are denoted in the first snapshot. Considering that the stabilizing is done purely based on haptic information and without any vision system, the performance is excellent compared to that of a human for the same task.

V. CONCLUSION

In this paper we presented a basketball balancing control scheme based on pure haptic information without using any vision systems. Velocity and position of a basketball are estimated from F/T sensor data. Although the measured signals provided by the F/T sensor are quite noisy, the estimated velocity and position of the basketball were accurate enough so that stabilizing the basketball against external disturbances and balancing the basketball on a moving plate could be achieved.

The presented method has been implemented on the industrial robot Stäubi RX90B and tested using Matlab/Simulink under realtime RTAI Linux. The performance of the method is validated with experiments and recorded as a video which is submitted with this paper as well as some other preliminary achievements of basketball robotics. Although the slow responsiveness of the system introduced by LPF could be improved by adding a LC, it is not enough fast for dynamic basketball catching and balancing without multi-fingered robot hands. Moreover, the time delay induced by the LPF imposes an upper limit on the control gains to guarantee the system stability so that the responsiveness of the system with LPF combined with LC is limited. To tackle this problem, advanced filtering approaches such as Kalman filter are to be employed in the near future.

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