

Paper:

Development of a Robot Balanced on a Ball – First Report, Implementation of the Robot and Basic Control –

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This paper proposes the implementation and control scheme of a robot balanced on a ball. Unlike a two-wheeled inverted pendulum, such as the Segway Human Transporter, an inverted pendulum using a ball moves in any direction without changing orientation, enabling isotropic movement and stabilization. The robot on the ball can be used in place of the two-wheeled robots. Our robot has three omnidirectional wheels with stepping motors that drive the ball and two sets of rate gyroscopes and accelerometers as attitude sensors. It can keep station, traverse in any direction, and turn around its vertical axis. Inverted pendulum control is applied to two axes to maintain attitude. Ball acceleration is used as control input of the system, unlike most of inverted pendulums which use torque or force as input. This acceleration input makes the robot robust against change of inertia parameters, as confirmed by Nyquist diagrams. The mechanism of the robot, the control method, and the experimental results are described in this paper.

Keywords: inverted pendulum, ball balance, stepping motor, omnidirectional wheel, ballbot

1. Introduction

The ball-riding robot we developed to ride and balance on a ball was inspired by acrobatic human and animal feats such as those commonly seen at the circus. *BallIP*, as we call it, was realized using the inverted pendulum control and an omnidirectional driving mechanism for the ball.¹

We have developed several types of pendulums, including a wheel-driven pendulum that could ride on a pipe as shown in **Fig. 1(a)**. It was a prototype robot, whose concept has been applied to the proposed robot. In addition, many of omnidirectional mobile robots were informative in ball drives.

There were previous efforts on such robots. Many inverted pendulums have been developed for mobility or as platforms to verify control algorithms. Practical ap-

plications such as the *Segway Human Transporter* [5] and Hitachi's *EMIEW* [6] are increasing, although they use wheels and have directional limitations in movement. However, an isotropic motion and thus isotropic stabilization or avoidance can be realized using a ball as a wheel.

Controlling a robot on a single ball using an inverted pendulum control had already been mentioned in the 1970s [7]. However, we know only a few successful robots.

The *ballbot* [8] of Lauwers et al. used an inverse mouse-ball drive for movement and a LQR control to feed back sensory information. The objective was a dynamically stable mobile robot tall enough to interact with human users. Although their first attempt did not rotate around the yaw axis due to drive limitations, they eventually added a yaw-drive to rotate the body [9].

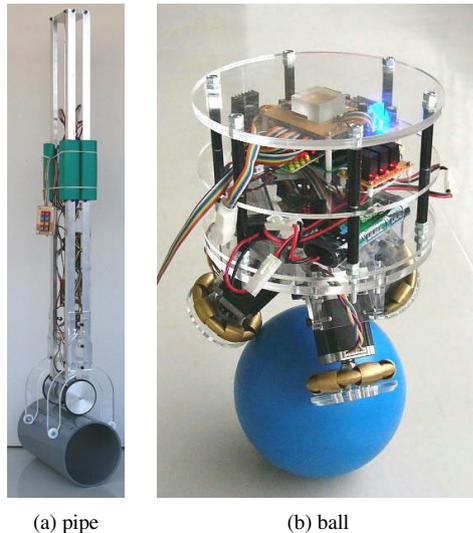
B. B. Rider [10], a wheelchair proposed by Endo et al. used four omnidirectional drives for balancing on a ball and turning on a vertical axis. Unfortunately, to the best of our knowledge, practical results could not be found. Our concept using an omnidirectional ball drive and assuming the robot as an inverted pendulum is same to their work though we designed ours independently of their work. Our work differed from theirs mainly in realization, e.g., their torque control using a drive with four pairs of spherical wheels versus our acceleration control using a drive with three single-column omnidirectional wheels.

After developing a prototype pipe-riding robot, we focused on mobile robots using omnidirectional wheels such as that developed by Asama et al. [11, 12], which we selected because it remains in contact at a single point during wheel rotation rather than using two or more partially continuous trajectories.

2. Robot Mechanism

Following our first 1,300 mm tall prototype [3], we developed and built the 500 mm tall robot in **Fig. 1(b)**, which weighed 8.7 kg. We built four same robots for multi-robot experiments. The intended purpose of this robot was the transportation of loads, and it was designed to be shorter than the first prototype. This robot used bowling ball approximately 220 mm in diameter, weighing 3.8 kg, and coated in liquid rubber spray (Plasti Dip).

1. Parts of this paper have been presented at Robomec 08,09 [1, 2], ICCAS 08 [3], and ICRA 09 [4].



(a) pipe (b) ball

Fig. 1. Robots balancing on pipe and ball.

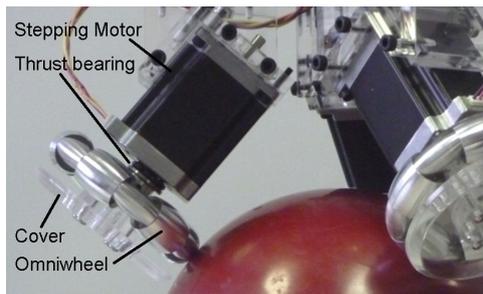


Fig. 2. Ball drive.

The mechanical properties of the ball were not measured, but it was not dented by the contact pressure of the wheels. It had enough friction between the wheels and the ball, and between the ball and a floor. A slip was observed when we tried to balance it on a slope of more than 8° inclination, where the motor also reaches the torque limit and begins to lose steps. The ball also slipped around the vertical axis when a large external torque was applied while the robot did not intend to turn.

The robot body consisted of an electronic circuit including sensors and a ball drive with three stepping motors and the omnidirectional wheels in **Fig. 2**. The wheel was directly attached to the shaft of the motor with no reduction gear, which reduced the mechanism backlash. The use of the stepping motors reduced the cost of the mechanism, the driving circuits, and the control software because of the stepping motor's open loop characteristics and its larger torque than that of a DC servomotor. This direct-drive mechanism provided a smooth and low oscillatory motion to the robot. Using stepping motors with an inverted pendulum is rare but not unheard of as shown by Hiraoka et al.'s focus on the advantages of stepping motors [13, 14].

As shown in **Fig. 3(b)**, the three wheels were fixed symmetrically at 120° intervals through the motor shaft to make them perpendicular to the tangent plane of the ball, as shown in **Fig. 3(c)**. Zenith angle ϕ was 50° . The omnidirectional wheel proposed by Asama et al. [11, 12]

used for this robot has only one contact line, making it easy to drive the robot on a spherical surface. The wheel was 100 mm in diameter.

We used the unipolar motor KH56QM2-913 (Nidec Servo Co.) as a bipolar motor to obtain larger torque of approximately 2 Nm. Each motor had a microstep controller TA8435 (Toshiba semiconductor) to divide individual motor steps of $1.8^\circ/\text{step}$ into $0.225^\circ/\text{step}$ to smooth wheel rotation. Motors ran on three 7.2 V Ni-MH batteries, also used for the controller.

The control system used MEMS attitude sensors and a 16-bit micro-controller H8/3052 (Renesas). The output of two sets of an angular velocity rate gyro sensor ADXRS401 (Analog Devices) and an accelerometer ADXL203 (Analog Devices) are converted to inclination signals and combined into one inclination in frequency domain [15]. The rate gyro sensor signal is used for the higher response and that from the accelerometer for absolute inclination angle stability.

3. Robot Control

The robot was realized using an inverted pendulum control in two directions (back and forth and right and left) and an omnidirectional ball drive as mentioned above.

3.1. Robot Attitude and Station Control

Robot attitude and position (movement) are controlled separately in two orthogonal directions, simplified and modeled two-dimensionally as the wheeled inverted pendulum shown in **Fig. 4** having parameters listed in **Table 1**. The ball is assumed to be a *virtual* wheel controlled to maintain robot inclination θ at zero (vertical) and position x .

Figure 5 shows typical PD feedback control for our robot using the robot's inclination obtained by the sensors and the wheel's travel as follows:

$$\begin{aligned} a_x &= K_A \theta_x + K_{AV} \dot{\theta}_x + K_T(x - x_0) + K_V v_x \\ a_y &= K_A \theta_y + K_{AV} \dot{\theta}_y + K_T(y - y_0) + K_V v_y, \quad \dots \quad (1) \end{aligned}$$

a is control input commanding *virtual* wheel acceleration, θ inclination toward each axis, x and y travel and v *virtual* wheel velocity. Subscripts x and y are related state variable axes and K the constant gains tuned experimentally. v and $x(y)$ were obtained by numerically integrating acceleration a . $x, y, v_x,$ and v_y are measured on the ball rather than using world coordinates, i.e., $x = r\psi$. Although these values almost coincide with floor movement, a discrepancy is anticipated, especially if the robot's path is complex.

Kumagai applied the acceleration-input equation from the paper by T. Emura [7] to over 10 pendulums, including wheeled and reaction wheeled types. T. Emura mentioned in the paper the case that the control input to the system is the torque/force of the actuator as many of inverted pendulums do, while we had used the acceleration