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ALGORITHM FOR INVERSE KINEMATIC ANALYSIS OF ROBOTIC MANIPULATOR

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ABSTRACT

The ballbot is a dynamically stable mobile robot designed to balance on a single ball, whose dynamic stability enables improved navigability in narrow, crowded, and dynamic environments. Through its single contact point with the ground, ballbot is omnidirectional and exceptionally agile, maneuverable, and organic in motion compared to other ground vehicles. For dealing with the challenging and imperative issues about ballbot, such as balancing, yaw, position control algorithms as well as the mathematical kinematic model, a novel model employing the Lagrange Equation is derived and control algorithm based on the similar principle as the second-order inverted pendulum is proposed, which is used for tackling the balancing, yaw, and position control. A cascade fuzzy proportional derivative (PD) controller and another controller with proportional integral (PI) control and PD feedback are designed for position and speed, respectively. Yaw control is presented, including head-hold mode and head-free mode. Some experiments are carried out to validate the effectiveness of the mathematical model and control algorithm.

INTRODUCTION

With the rapid development of robotics, all kinds of robots are gradually entering people's lives, especially dynamic balancing robot [1]. One of the most popular dynamic balancing robots is the two-wheeled Segway Balancing robot [2]. As a Vehicle, one-wheeled Balancing robot also won a huge market. However, these balancing robots have turn limits, only move forward and backward, human can't move in accordance with owns wishes, in other words, these robots can only do one dimensional motion [3], [4]. The ballbot improves the mobile efficiency result of moving in any direction without a radius of rotation.

It is supported by a ball that move in all directions, which means that it is not necessary to turn around like a wheeled or multi-legged robot to change the way forward. Moving omnidirectionality and the characteristics of single contact point with the ground makes it more suitable for navigating in the limited space [5]–[8]. In 2005, the first ballbot was invented at Carnegie Mellon University, which used the inverse mouse-ball drive mechanism to drive the ball to achieve a dynamic balance, but this structure is more cumbersome, and cannot rotate along the vertical axis. It used linear quadratic regulator (LQR) controller for full state feedback [9]. 'BallIP' was developed in 2008, the first ballbot used the structure of three Omnidirectional wheels. It achieves rotation around the vertical axis, which is a breakthrough in the ballbot. However, the paper does not describe the modeling method in detail. In terms of control algorithms, 'BallIP' used classical PD controller [10].

Ballbot with a manipulator has been proposed by Asgari et al in 2013. It has been proved that the dynamics equations of the assumed mobile robot. At the same time, a control algorithm is proposed to realize the stable motion control of the system. Finally, the execution of the simulation program is to verify the advantages of the algorithm [11]. Aiming at the ballbot is an underactuated, nonholonomically constrained system (there are more degrees of freedom than independent control inputs), Aykut et al presented the linearized equations of motion and the controllability analysis is carried out. They consider that ballbot was a linear system except for rotating about the vertical axis of the ballbot. They provided a PD controller and presented simulation results. Unfortunately, they did not implement the algorithm on a real robot [12]. There is some recent work on the application of the ball robot in a specific environment, for example, paper focuses on the control methods of the ball robot climbing and proposes ballbot with an annular support leg, which can keep statically stable when powered off [13]. Paper presents the equations of motion for the ballbot system on a sloped surface with a center-of-mass offset [14]. In this paper, we propose the control method and analyze the kinetics of the ballbot. Firstly, we derive the Lagrange equation of the plane model of ballbot and the mathematical relationship between the speed of the omnidirectional wheel and the speed of the plane model.

The only contact point between the ballbot and the ground is the ball, thus it only relies on the inertial force of the body to maintain the dynamic stability. Cascade fuzzy PD control used for dynamic balancing in high angle non-linear areas. Head-free model and head-hold model are presented for yaw controller with little attention in previous work. Outer-loop position controller and inner-loop speed controller outputs desired attitude angle, which couples balancing and position control. The key is to achieve position and yaw control while maintaining its own balance. Finally, the ballbot is implemented shown in Fig. 1 and the experiments are carried out, including self-balancing, station-keeping, antiinterference and position-moving.

SYSTEM DESCRIPTION AND MODELING

System Description

Fig. 1 shows the structure of the system. The ballbot is divided into two parts: ball and body. The ballbot body included processor, sensor, driver, motor, omnidirectional wheel. The processor adopts Freescale Kinetis K60 series MCU, whose hardware interfaces is wealthy and operating speed can be overclocked up to 150MHz. Robot measures the triaxial angle velocity and acceleration of the ballbot body through the Inertial measurement unit (IMU) MPU-6050. The measurement range can be controlled by a program write register. In order to adapt to the fast-dynamic movement of the ballbot, we set the measurable range of the gyroscope to be 2000◦ /s, and the measurable range of acceleration to be 8g. Triaxial magnetic field intensity is gauged by three axis magnetometer HMC5883L measurement. Event-triggered sampling method is used to save the power energy [15]. The measurement ranges from milli Gauss to 8Gauss, then the Euler angle of the robot is calculated by quaternion algorithm. To get a more accurate Euler angle, we used a sliding average filter for angle velocity. Roll and pitch are input of the balancing controller, because the ballbot body balances on the ball dynamically. the yaw angle used to achieve the ballbot body rotate around a vertical axis.

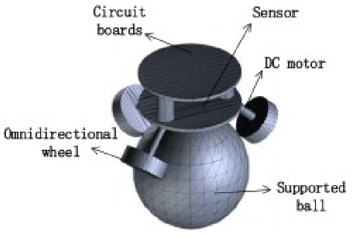

Fig. 1. Ballbot

At the same time, ZigBee is used for wireless data transmission between ballbot and computer, including real-time sensor data, system configuration parameters. We select the direct current gear motor to provide enough torque and the Motor reduction ratio is 1: 16. Robomasters RM35 motor is a dedicated 5 ~ 20kg robot customized power motor. The encoder feedback the motor speed integrated in the back end of motor. The three motors are 120◦ on the xoy plane, and the angle between the ball and plane of omnidirectional wheel α is 45◦ , if α is too large, the ballbot body is easy to fall; on the contrary, the mobile robot will be subject to certain restrictions. The omnidirectional wheel is used on this robot. Two alternating driven wheels ensure that the omnidirectional wheel has no sliding friction when moving parallel to the center axis, and there is no twitching phenomenon of the ballbot body. The diameter of the omnidirectional wheel is 100mm and the weight are 290g [16]. B. DYNAMIC MODELING The dynamic analysis of the system used the Lagrange equation which is an important method for dynamic modeling. It simplifies the modeling process obviously when the degree of freedom of the system is less, because it only needs to analyze the system kinetic energy, potential energy and generalized force, rather than the complicated force analysis [17], [18]. To facilitate the analysis, the ballbot can be regarded as a uniform rigid body and a uniform rigid ball, and we decompose the three-dimensional dynamic system into three planes. It is worth noting that modeling is based on the following two assumptions:

(i)The mechanical structure is completely symmetric, and the motion of the xoz plane and the yoz plane is uncoupled.

(ii)There is rolling, no sliding and spin between the supporting ball and the ground.

BALLBOT CONTROL

This section describes the various controllers used on the ballbot. The complete control block diagram of the ballbot is shown as Fig. 5, including position control of x, y axes and yaw control. The ballbot feedback roll, pitch, roll rate, pitch rate, speed and position to position control and yaw, yaw rate to yaw control. The speed of the three wheels is determined by the superposition of the outputs of the yaw control and position control.

BALANCING CONTROL

It was proposed to use the control methods of inverted pendulum to control the robot. For the balance of ballbot, it holds the balance around the unstable point by controlling the rotation of three omnidirectional wheels. The ballbot drive balls to roll forward by controlling three motors and the roll speed of the ball is faster than the dumping speed of the body. It is possible to use the similar principle of the inverted pendulum to simulate the ballbot. Balancing control can be equivalent to two inverted pendulum of x, y direction, which is a typical nonlinear, multivariate, strong coupling and unstable system. We use the cascade PD controller, and use fuzzy control in the outer-loop angle control. The inner loop of the cascade control system is a follow-up control system whose set value varies with the output of the outer loop controller.

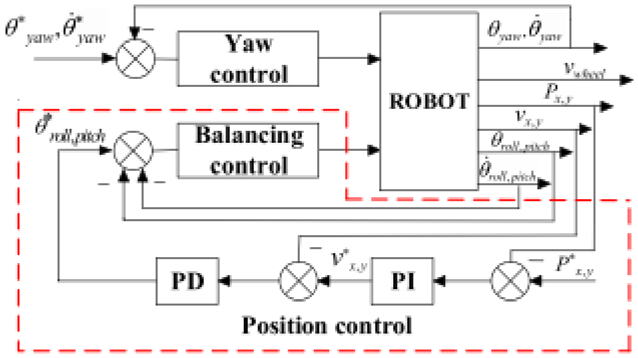

Fig. 2. Control block diagram of ballbot

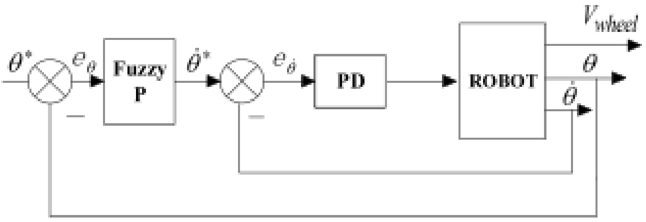

Fig. 3. Block Diagram

The outer loop controller can continuously adjust the set value of the inner loop controller according to the operating conditions and load changes, to ensure that the control system still has better control effects under the condition that the operating conditions and load change. The fuzzy PD control automatically adjusts the PD value according to the preset parameter table according to the input error. Different PD values act on nonlinear systems to accelerate the response speed of nonlinear systems.
The block diagram of balancing control is shown as Fig. 3, Equation (19) shows the error between the desired angle and the Euler angle, which is considered as the input of the outer-loop angle controller. While there is only the balancing controller, the desired angle is 0deg. Desired angle velocity is output of the outer-loop angle controller. The angle velocity interference is more likely to cause instability of the ballbot than the angle, cascade controller plays the role of anticipatory control and effectively suppresses the inner loop interference. The inner-loop angle velocity is controlled by PD. As shown in Equation (20), the output of the inner-loop is the acceleration in the direction of x and y. The perform frequency of the inner-loop is usually 2 ~ 5 times of the outer-loop frequency in cascade control. We choose 2 times according to the experience of the experiment.

The controller in xoz plane is the same as yoz plane, the parameters setting is the same. The fuzzy control rule table is shown in Table 1, While the angle and angle velocity are in the same direction, the system becomes more and more unstable, and the error should be eliminated quickly, Kp should be the largest one. On the contrary, if the system has a trend of gradual stabilization, and Kp will be set to be small to avoid overshoot. In addition to this, the adjustment of Kp is also related to the magnitude of the angle and angle velocity. The speed is obtained by integrating acceleration in sampling time, as show in Equation (21). The speed in the direction

θ / $\dot{\theta}$	PB	PM	PS	NS	NM	NB
PB	PB	PB	PB	PB	PM	PS
PM	PB	PM	PM	PM	PS	PS
PS	PM	PS	PS	0	0	0
NS	0	0	0	PS	PS	PM
NM	PS	PS	PM	PM	PM	PB
NB	PS	PM	PB	PB	PB	PB

$$\dot{\theta}^* = kp_{Angle}(\theta^* - \theta)$$

$$F = kp_{Angle\_rate}(\dot{\theta}^* - \dot{\theta}) + kd_{Angle\_rate}\ddot{\theta}$$

$$v = v + \frac{F}{m}t$$

CONCLUSION

Cascade fuzzy control method is designed to solve the balance of the ballbot which moves in any direction flexibly and turn more efficiently than traditional wheel-supported robot. Position control uses cascade PI and PD controller and yaw control divided into head-hold and head-free modes are proposed. The ballbot is completed according to the mathematical model and the designed controller. Using the cascade fuzzy control, the ballbot achieves a dynamic balance of −0.4 ◦ ~ 0.4 ◦ and completes anti-interference experiments with amazing performance. The ballbot walking along the preset trajectory with an error of 7.2% under the joint operation of position control and yaw control. Due to the excellent omnidirectional movement of the ballbot, it moves freely in a narrow environment.

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