Design and Analysis of a Spherical Robot with Two Degrees of Freedom Swing

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Abstract: Aiming at the problem that the mechanical structure of the ordinary pendulum spherical robot is improperly designed to cause a certain degree of freedom to swing the range, this paper proposes a two-degree-of-freedom spherical robot XK-I with a swing around the X and Y axes. The design concept, mechanical principle and rolling and rotating motion characteristics of the XK-I robot are introduced. According to the characteristics of XK-I robot motion, the dynamic model of linear motion is established by Lagrangian equation and simulated. According to the kinetic model, the XK-I robot steering is implemented by controlling the number of steps of the stepping motor by the pulse signal, so that the XK-I robot can move in any direction. The linear and steering tests of the XK-I robot were carried out through real experiments to verify the feasibility of the design.

Key Words: Spherical robot, Two degrees, Lagrangian mechanics, Kinetic model.

1 INTRODUCTION

Compared with land mobile robots, the spherical robots are characterized by exquisite structure, strong environmental adaptability, good concealing performance, they are able to carry a variety of mission loads [1] and are widely used in agricultural field vegetation monitoring, snow and water inspections, as well as special environment detection (Chemical, nuclear, etc.). However, spherical robots have the characteristics of non-holonomic constraints, under-actuation, non-chain, strong coupling, etc. So the structural design and motion control of spherical robots have attracted extensive attention all over the world.

Currently, pendulum and wheel-driven spherical robots are the two most common types of spherical robots [2]. The wheel-driven spherical robot has the advantages of simple structure and control system, but the internal slippage and poor contact are difficult to control. For example, Halme.et al. [3] have developed the first spherical motion mechanism Rollo with driving wheel and balance wheel, and established a dynamic model for the forward rolling of the spherical robot. However, the structure is driven by an internal unicycle, and there is a problem that it is difficult to precisely control the position of the spherical robot.

The structural design and control of the pendulum drive are currently the most difficult problem. Mukherjee et al. [4] proposed a spherical robot driving scheme that changes the centroid driving motion. The scheme realizes the omnidirectional motion of the robot by changing the four high-quality positions to generate the eccentric moment. However, the structure requires higher symmetry of the installation position of the four masses. Sweden's Rotundus Co. [5] developed a commercial spherical robot called GroundBot using a two-degree-of-freedom single pendulum drive. It solves the turning problem of the spherical robot by moving the position of the pendulum left and right, but the ability to overcome obstacles is weak, and the turning function is not flexible. Zhao Bo et al. [6] designed a double eccentric mass-driven spherical robot, which uses two symmetrical drive units to drive an eccentric mass, compared with a two-degree-of-freedom single-swing-driven spherical robot. The structure provides more eccentric torque and has made great progress in turning flexibility. Mahboubi et al. [7] developed a double pendulum-driven spherical robot that can realize linear motion, circular motion, in-situ steering, and jitter. The structure uses the Boltzmann-Hamel equation to establish the dynamic model, and the dynamic analysis of linear motion, circular motion and jitter is carried out respectively, and the open loop control of the robot is realized. However, the two spherical robot structures designed in [6-7] have the problem that the spherical pendulum rotates along the arc when the two sides of the pendulum are asymmetrically placed and the rotational speeds of the motors on both sides are inconsistent. Zhang Dongquan et al. [8] designed a spherical robot that relies on the long-axis motor and the short-axis motor to realize the turning. However, the single pendulum motion range of the structure is limited, causing some turning problems.

Considered the above turning problems of spherical robot, this paper proposes a pendulum spherical robot structure with two degrees of freedom to realize more flexible movement. The spherical robot can realize the unrestricted turn or straight movement depending on the centroid change. At the same time, the kinematics and dynamics analysis of the robot is carried out, and the kinematics and dynamic equations of the linear motion are obtained. Finally, simulation experiments and real experiments were carried out. The experimental results show that the

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proposed method is correct and reliable, which provides a reference for the expansion of spherical robots.

In this paper, a new structure of a pendulum spherical robot with two degrees of freedom was designed but only a sub-system dynamics of the spherical robot was modeled. Furthermore, some experiments were conducted to show the feasibility of the sub-system.

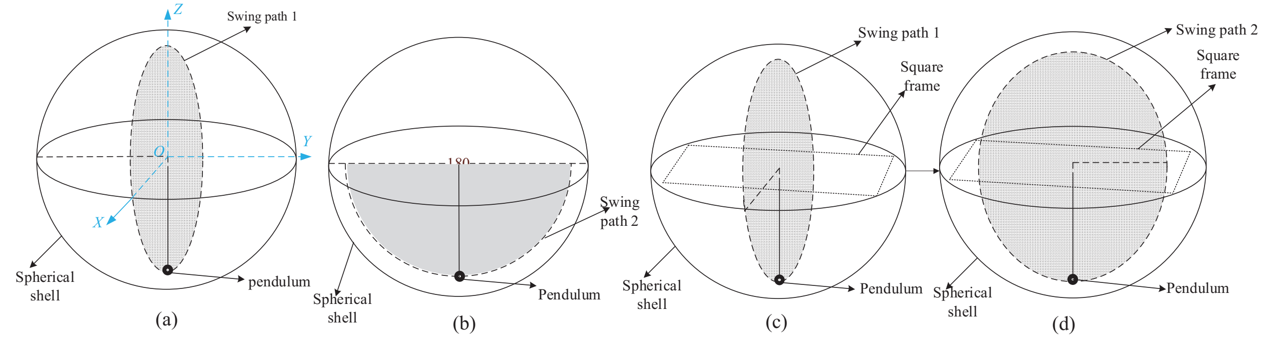

Fig 1. Spherical robot design concept

2 MECHANICAL DESIGN

The pendulum of ordinary pendulum spherical robot is located at the center of the ball. the Cartesian coordinate system O-XYZ with the center of the sphere is set as the origin O, as shown in Fig. 1. It can be seen from Fig. 1 that the pendulum has two swing paths [9]: When the pendulum motion moves as swing path 1, the pendulum swings around the OY axis, and the swing range is 0-2π as shown in Fig. 1(a). When the pendulum motion moves as swing path 2, the pendulum swings around the OX axis, and the range of motion in the direction is limited due to problems such as motor mounting, as shown in Fig. 1(b).Therefore, the general pendulum spherical robot has a limited driving direction capability. Aiming at the problem of motion defects in ordinary pendulum spherical robots, this paper designs the XOY plane into a square frame according to the design concept of ordinary pendulum spherical robot (as shown in Fig. 1(c) and (d)). The motor can be installed in the square. The outside of the frame (as shown in Fig. 2) effectively solves the problem of the motion limitation of the pendulum movement direction and the horizontal axis on the same level.

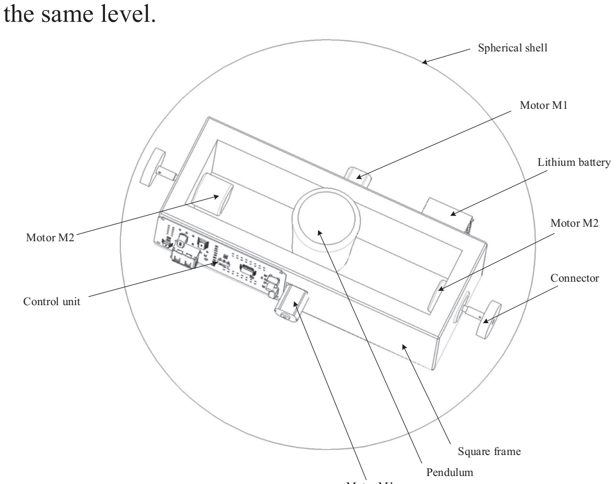

Fig 2. Schematic diagram of XK-I pendulum spherical robot

The structure of the spherical robot is shown in Fig. 2. It consists of a spherical shell, a square frame, a control module, a drive unit, and a pendulum. The pendulum and the square frame are driven by motors M1 and M2, respectively. The motor M1 generates a driving torque in the direction of the OX axis, for driving the rotation of the pendulum so that the sphere moves linearly; the motor M2 produces a tilting torque of the OY axis for driving the rotation of the square frame to make the sphere steer. The output shaft of the motor M1 is connected to the upper portions of the left and right sides of the pendulum device. The square frame is connected to the M2 motor, the M2 shaft is mounted on the flange shaft, and the flange shaft is connected to the spherical shell. The schematic diagrams of the pendulum rotation and the square frame rotation are shown in Fig. 3 and Fig. 4. When M1 or M2 rotates, the rotation of the pendulum or square frame changes the center of gravity of the pendulum, creating a moment of gravity that causes the robot to move forward or backward. When M1 and M2 rotate simultaneously, the pendulum and the square frame will tilt and generate a moment of gravity, thereby changing the direction of motion of the robot. Therefore, the spherical robot can be moved and rotated as expected under the driving of the motors M1 and M2. Thus, the motion of the spherical robot can be controlled by controlling the motors M1 and M2.

Therefore, the spherical robot structure proposed in this paper has four driving directions of forward, backward, rightward and leftward when moving from a stationary state, while the ordinary spherical robot has only two driving directions of forward and backward. When changing the driving direction, the ordinary pendulum spherical robot can manipulate the moving direction at a certain speed. The radius of the curvature path is shown in Fig. 5(a), and the spherical robot proposed in this paper can control the moving direction like a normal spherical robot. Besides, the direction of motion can be changed orthogonally while moving, as shown in Fig. 5(b). Thus, the XK-I spherical robot has a wider range of motion due to its structure compared with conventional spherical robot.

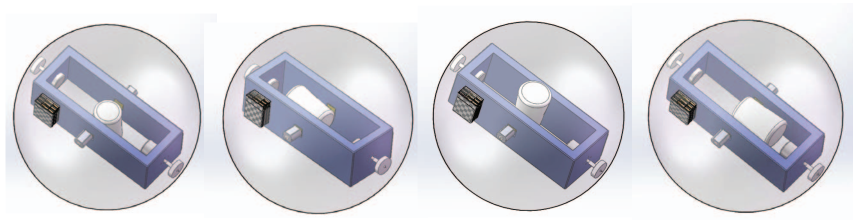

Fig 3.Schematic diagram of pendulum rotation

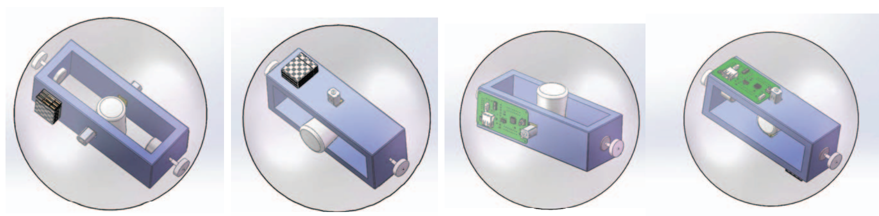

Fig 4.Schematic diagram of square frame rotation

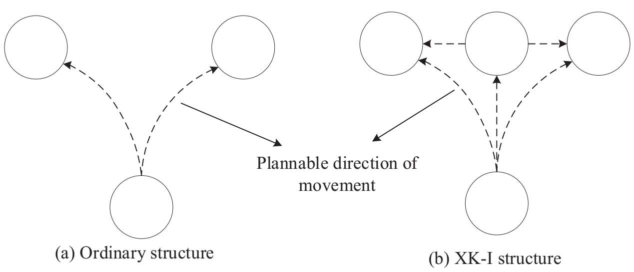

Fig 5.The difference of motion direction between XK-I spherical robot and ordinary spherical robot

3 DYNAMIC MODELING OF SPHERICAL ROBOT

In order to analyze the structure and performance of the spherical robot reasonably and effectively, this paper simplifies the overall structure into a massless pendulum, a thin spherical shell with rigid rods and rigid rods (as shown in Fig. 6).In Fig. 6 ,m_1, m_2, m_3 refer to the mass of the shell, the mass of the drive, the control and the battery, as well as the mass of the pendulum, respectively, Kg .R refers to the inner radius of the spherical shell, m;g refers to gravity acceleration,m/s^2 ;l refers to the length of rigid connecting rod, m;α, φ are respectively the swinging angle of the pendulum and the spinning of the spherical shell, rad; τ is the output torque of M1,$kg \cdot m$; Further, motion analysis on two-dimensional coordinate system for the simplified spherical robot model were derived under the following assumptions: the rolling and rotational behavior of the spherical robot are driven by motor group M1and motor group M2, respectively , and there is no slippage when moving; The geometric center of the shell and the center of gravity of the driving unit are concentric; The density and thickness of the shell are uniformly distributed and the shell has no thickness. The friction loss at the rotating shaft can be ignored.

The rolling and rotational driving force of XK-I spherical robot are generated by motor group M1 motor group M2. The system of spherical robot is a nonholonomic, nonlinear, underactuated and strong coupling system, which makes the controlling design much difficult. Referring to the situation that the car 's steering during linear motion is realized by giving the car a steering control signal, in this paper, the rolling and steering motions of XK-I spherical robot are separated from each other. That is, the driving force generated by motor group M1, causing the spherical robot's linear motion. When the robot needs to turn in a linear motion, only a pulse signal is input to motor group M2 to control the steering of the spherical robot. Through this decoupling method, the incomplete system becomes two decoupled complete subsystems, which greatly simplifies the dynamic equation of the spherical robot and improves the maneuverability of the system. Therefore, the rolling motion model of the spherical robot on the XOY plane can be simplified as a mechanical model composed of two generalized coordinates (the swing angle of the pendulum and the rolling angle of the spherical shell) and generalized forces (the output torque of motor group M1)in the plane.

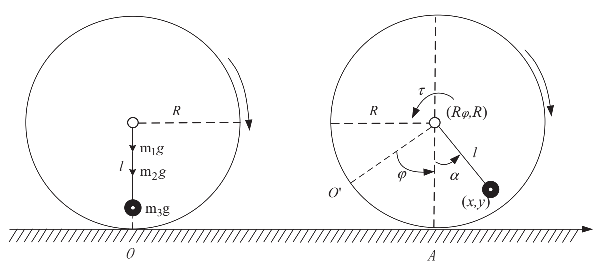

Fig 6. Simplified model

It is assumed that the initial moment of the sphere is located at point O in Fig. 6, and reaches point A after time t. In order to facilitate the establishment of the kinematics equation, the coordinates of the spherical center are set to. $(R\varphi, R)$, in the two-dimensional coordinate system, and the coordinates of the pendulum are(x, y), then:

$$\begin{cases} x = l sin\alpha + R\varphi \\ y = R - l cos\alpha \end{cases} \tag{1}$$

Differentiate Eq. (1) to get the speed of the pendulum:

$$\begin{cases} \dot{x} = l\dot{\alpha}cos\alpha + R\dot{\varphi} \\ \dot{y} = l\dot{\alpha}sin\alpha \end{cases} \tag{2}$$

According to Eq. (2), the acceleration of the pendulum can be deduced as follows:

$$\begin{cases} \ddot{x} = l\ddot{\alpha}cos\alpha - l\dot{\alpha}^2 sin\alpha + R\ddot{\varphi} \\ \ddot{y} = l\ddot{\alpha}cos\alpha + l\ddot{\alpha}sin\alpha \end{cases} \tag{3}$$

Thus, the kinetic equation of the spherical robot is obtained. However, for the complete motion control of a spherical robot, it is not enough to rely solely on kinematics analysis. Spherical robot is a non-holonomic system, so the first type of Lagrangian equation is used to analyze the spherical robot dynamics model.

Assuming that the motion velocity of the spherical robot isV_{cm}, the displacement of the spherical robot from *O* to *A* can be calculated as follows:

$$R\varphi = V_{cm}t \tag{4}$$

Perform time derivation on both sides of Equation 4 to obtain:

$$R\dot{\varphi} = V_{cm} \tag{5}$$

The spherical shell motion can be decomposed into the rotation of the spherical shell around the center of the spherical shell and the linear movement of the spherical shell.Then it can be concluded that the kinetic energy of the spherical shell is [10]:

$$E_1 = \frac{1}{2}m_1 V_{cm}^2 + \frac{1}{2}J_s\dot{\varphi}^2 \tag{6}$$

Since the spherical shell is equivalent to a thin spherical shell, the rotational inertia is

$$J_s = \frac{2}{3}m_1 R^2 \tag{7}$$

In addition, the kinetic energy generated by the pendulum is

$$E_2 = \frac{1}{2}J_i\dot{\alpha}^2 + \frac{1}{2}m_3[(V_{cm} - l\dot{\alpha}\cos\alpha)^2 + (l\dot{\alpha}sin\alpha)^2] \tag{8}$$

Where, $J_i$is the moment of inertia output from motor M1 group. As the driver, controller and battery are mounted on a square frame and driven by motor unit M2, the rotation movement is not affected by motor unit M1, and the system has been decoupled into two subsystems. Therefore, the kinetic energy of this part during linear motion is

$$E_3 = \frac{1}{2}m_2 {V_{cm}}^2 \tag{9}$$

According to Koenig's theorem, the pure rolling process of a sphere can be viewed as a translation process and a rotation process around the center of mass. Therefore, the overall kinetic energy of the system is the sum of the kinetic energy of the spherical shell, the square frame and the pendulum, that is:

$$E = E_1 + E_2 + E_3 \tag{10}$$

And the potential energy of the whole system is

$$P = m_3 glcos\alpha \tag{11}$$

According to the total kinetic energy and potential energy of the system, the Lagrangian function is deduced as follows : L=E-P (12); According to Lagrangian method, the swinging Angle of the pendulum and the rolling angle of the spherical shell are regarded as the two generalized coordinates respectively, namely:$q_1 = \varphi, q_2 = \alpha$.The linear motion of the spherical robot is mainly driven by the output torque τ of the motor group M1, and the rolling direction of the ball is opposite to the swinging direction of the pendulum. The Euler-Lagrangian motion equation [11] of the simplified system model can be derived as:

$$\begin{cases} \frac{d}{dt}(\frac{\partial L}{\partial \dot{q}_1}) - \frac{\partial L}{\partial q_1} = -\tau \\ \frac{d}{dt}(\frac{\partial L}{\partial \dot{q}_2}) - \frac{\partial L}{\partial q_2} = \tau \end{cases} \tag{13}$$

Under the pure rolling condition, we have

$$\dot{x} = -R\dot{\varphi} \tag{14}$$

Revising the generalized coordinate $q_1 = \varphi$ to $q_1 = x$,i.e.$\dot{x} = \dot{q}_1$and since $\dot{\varphi} = \dot{q}_1$.By sorting and simplifying equations (5)-(14), we can get:

$$\begin{cases} m_3 l\cos q_2 \ddot{q}_1 + (J_i + m_3 l^2)\ddot{q}_2 + m_3 gl\sin q_2 = \tau \\ \left(\frac{5}{3}m_1 + m_2 + m_3\right)\ddot{q}_1 + m_3 l\cos q_2 \ddot{q}_2 - m_3 l\sin q_2 \dot{q}_2^2 = (\frac{1}{R})\tau \end{cases} \tag{15}$$

According to the dynamic equation of the spherical robot in formula (15), it can be expressed as a matrix

$$M(q)\ddot{q} + C(q,\dot{q}) = B\tau \tag{16}$$

Where

$$M = \begin{pmatrix} \frac{5}{3}m_1 + m_2 + m_3 & m_3 l\cos q_2 \\ m_3 l\cos q_2 & J_i + m_3 l^2 \end{pmatrix}$$

$$C = \begin{pmatrix} -m_3 l\sin q_2 \dot{q}_2^2 \\ m_3 gl\sin q_2 \end{pmatrix}$$

$$B = \begin{pmatrix} \frac{1}{R} \\ 1 \end{pmatrix}.$$

Thus, the dynamic equation of spherical robot is obtained under the driving of motor group M1, while motor group M2 is designed to use stepping motor to drive the square frame to achieve the steering, and its control model is similar to that of automobile driving on a straight road by inputting one or more pulse signals to control the steering.

4 EXPERIMENTAL RESEARCH

4.1 simulation experiment research

The simulation parameters are set according to the physical object of the spherical robot (XK-I type). The weights of the spherical shell, the drive and the pendulum are respectively 0.262 Kg, 0.39 Kg, 0.21 Kg, the radius of the ball is 0.1 m, and the pendulum length is 0.07 m. According to the spherical robot dynamics equation (15), the state variable $x = [x_1, x_2, x_3, x_4]^T = [q_2, \dot{q}_2, q_1, \dot{q}_1]^T$, and the initial value $x_0 = [0,0,0,0]$. In the simulation, the fourth-order runge-kutta method (ode45 function) was used to solve the differential equation, so that the swing angle, the swing angular velocity, the spherical rolling angle and the rolling angular velocity of the spherical robot pendulum change with time under constant torque are obtained. The results are shown in Fig. 7. It can be seen from Fig. 7 that under the action of the constant torque of the motor, the open loop roll motion of the robot is oscillatory with a period of about 0.7 seconds. The displacement and velocity curves show an overall upward trend.

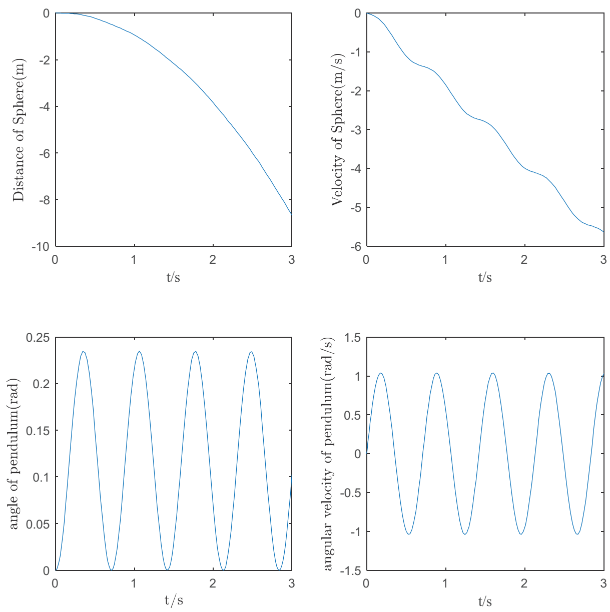

Fig 7. Simulation results of pendulum swing and spherical shell rotation

4.2 real experimental research

A spherical mobile robot XK-I with convenient control and simple structure is designed. The physical object is shown in Fig. 8.

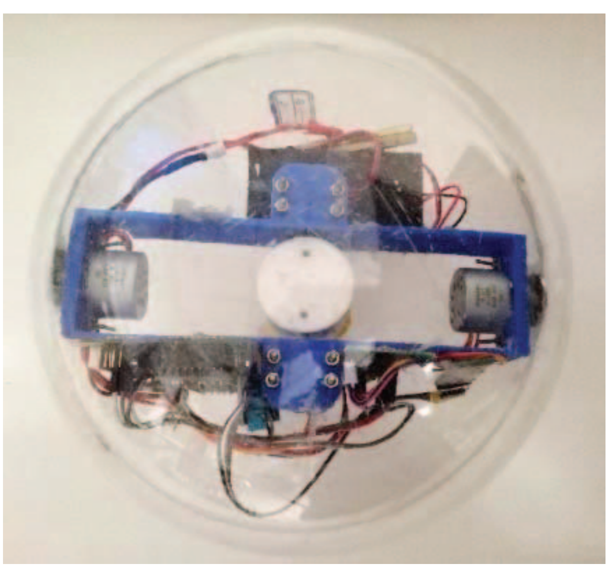

Fig 8. XK-I spherical robot

The XK-I spherical robot uses the STM32F103C8T6 as the underlying drive controller, utilizing the ULN2003 driver to drive two stepper motor rotations, and the TB6612 driver to drive the N20 motor with the encoder disk. The encoder can output the pendulum rotation information. In order to make the whole hardware circuit more concentrated, the MPU6050 module, HC05 Bluetooth module, voltage acquisition module, temperature and humidity sensor module DHT11, and the underlying controller are designed on the same PCB. During the experiment, the host sends the control command and receives the posture, swing speed and other data returned by the XK- I spherical robot through the Bluetooth module. By changing the position of the counterweight, the XK- I spherical robot can move in four directions: forward, backward, left and right. Since the motion of the spherical robot is achieved by changing its centroid position, any factors that affect the position of the centroid will affect the control of the spherical robot. According to the dynamics model, the straight motion and straight-turning motion of XK- I spherical robot was tested, and the results were shown in Fig. 9. The electronic resource of the experimental results video can be found in [12]. It can be seen that there were some deviation in straight motion and straight-turning motion, as shown in Table.1. This is because the center of mass of the XK-I spherical robot is affected by the internal square frame, the drive unit, the battery, etc., and is not on the same horizontal line as the pendulum, so that the movement direction is deviated due to the influence of this heavy moment during the movement.

5 CONCULUSION

In this paper, a two-degree-of-freedom spherical robot with an unrestricted pendulum swing around the X and Y axes is studied. The mechanical structure of the spherical robot is analyzed from the design concept, and the dynamics and kinematics equations of the linear motion are obtained. Finally, the rotation and oscillation of the spherical shell and the pendulum are simulated under the action of constant torque, and the real experiment is verified. In the future, we will focus on solving the problem of large deviation of motion control caused by the imbalance of the internal weight of the spherical robot.

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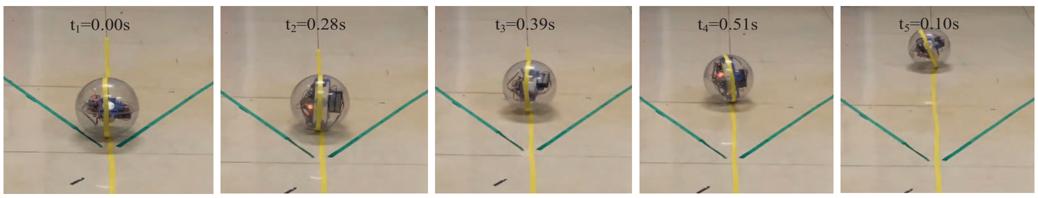
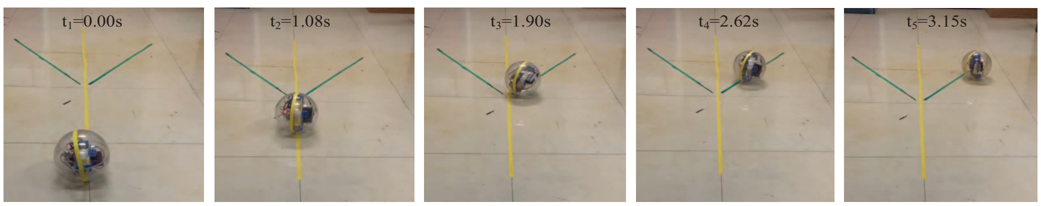
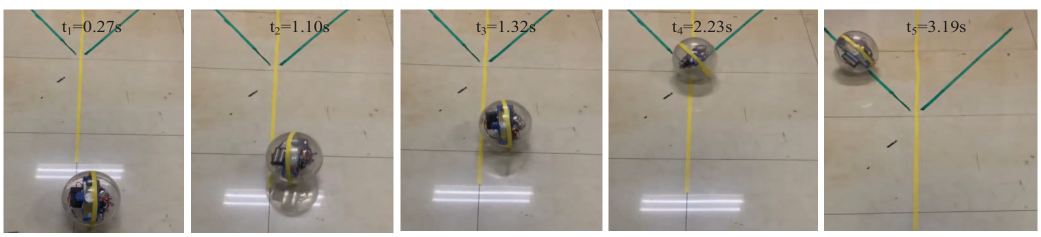


(a) Linear motion test



(b) Straight right turn motion test



(c) Straight line left motion test

Fig 9. Experimental results

Table 1. Real experimental test data

NO.	Motion state	Movement distance(cm)	Motion timeme(s)	Offset distance(cm)	Offset direction	Offset angle(°)
1	Liner Motion	120	3	7.7	Right	3°40'17”
2		120	3	5.6	Left	2°40'19"
3		180	6	10.3	Left	3°16'30"
4		180	6	7.5	Left	2°23'09"
5		240	8	11.5	Left	3°44'36"
6		240	8	10.1	Right	2°24'35"
7	Steer	20	18	1.0	Left	2°51'45"
8		20	18	1.4	Left	4°00'15"
9		30	35	2.0	Left	3°48'51"
10		30	35	3.4	Left	6°27'57"
11		40	40	5.5	Left	7°49'45"
12		40	40	4.5	Right	6°25'08"