Kinetic Model for a Spherical Rolling Robot with Soft Shell in a Beeline Motion

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Abstract—A simplified kinetic model called Spring Pendulum is developed for a spherical rolling robot with soft shell in order to meet the needs of attitude stabilization and controlling for the robot. The elasticity and plasticity of soft shell is represented by some uniform springs connected to the bracket in this model. The expression of the kinetic model is deduced from Newtonian mechanics principles. Testing data of the driving angle acquired from a prototype built by authors indicate that testing data curve accords to the theoretic kinetic characteristic curve, so the kinetic model is validated.

Index Terms—Soft Shell; Spherical Rolling Robot; Kinetic Model

I. INTRODUCTION

Spherical robot is a kind of robots which can roll by themselves. More and more researchers are focusing on spherical robot due to their many advantages on moving and their hermetrical structure. More than 10 species spherical robots and their accessories are advanced as well [1-4]. These robots are preliminarily applied in many domains. All these robots are mainly constructed by hard shell. Soft-shell spherical robot has many advantages like good cross ability, changeable bulk and good impact resistance comparing to the hard-shell robots. Li Tuanjie and his group researched the light soft-shell spherical robot driven by wind power and founded the equation to describe the ability of the robot to cross the obstacle without deeply research about how much would the soft-shell influence the spherical robot [5]. Sugiyama Y, Irai S and other people researched the transformation-driven spherical robot. It uses several shape memory alloys to support and control the reduction by change the amount of the voltage to make the robot roll like crawling. It moves slowly and now still stands at the stage of checking the principle [6]. Fang Xiang and Zhou Shouqiang have gained the patent of automatically aerating and discharging soft-shell spherical robot [7].

On the modeling of spherical robot, Ref. [8, 9] began with the principle of kinematics, found the dynamic model of the hard-shell spherical robot walking along a straight line driven by pendulum. Since they ignored the quadratic items, there would be some errors in the dynamic model when the robot moves in high speed. In order to make the robot start and stop steady and speed controllable, Ref. [10] researched the kinematic model of a kind of spherical robot driven by two masses deflected from the centre of the sphere moving straight in order to control the robot starting and stopping smoothly. According to the description of Euler angles, Ref. [11] found a kinematic model of the spherical robot. Ref. [12, 13] found the dynamic model of a hard-shell spherical robot from the angle of Newton mechanics. They simplified the model of a straight moving spherical robot to a single pendulum hung on the centre of the ball connected to the shell through the drive motor. They all had a simulation experiment on the dynamic model of their spherical robot respectively, but didn’t check the data from the experiment to prove the correctness of the model. So this paper will deeply analyze the characteristics of the soft-shell spherical robot on kinematics and dynamics to establish its mechanic model and use the experimental sample to check the correctness of the model.

In this paper we consider a class of spherical rolling robots actuated by internal rotors. Under a proper placement of the rotors the center of mass of the composite system is at the geometric center of the sphere and, as a result, the gravity does not enter the motion equations. This facilitates the dynamic analysis and the design of the control system.

The idea of such a rolling robot and its design was first proposed in [14], and later on studied in [15]. Also relevant to our research is the study [16] in which the controllability and motion planning of the rolling robots with the rotor actuation were analyzed.

A spherical robot is a new type of mobile robot that has a ball-shaped outer shell to include all its mechanisms, control devices and energy sources inside it. This structural characteristic of a spherical robot helps protect the internal mechanisms and the control system from damage. At the same time, the appearance of a spherical robot brings a couple of challenging problems in modeling, stabilization and position tracking (path following). Two difficulties hinder the progress of the control of a spherical robot. One is the highly coupled dynamics between the shell and inner mechanism, and another is that although different spherical robots have different inner mechanism including rotor type, car type, slider type, etc (Joshi, Banavar and Hippalgaonka, 2010), most of them have the underactuation property, which means they can control more degrees of freedom (DOFs) than drive inputs. There are still no proven general useful control methodologies for spherical robots, although
researchers attempted to develop such methodologies. Li and Canny (Li and Canny, 1990) proposed a three-step algorithm to solve the motion planning problems of a sphere, the position coordinates of the sphere can converge to the desired values in three steps. That method is complete in theory, but it can only be applied to spherical robots capable of turning a zero radius as the configurations are constrained. Mukherjee and Das et al. (Das and Mukherjee, 2004), (Das and Mukherjee, 2006) proposed a feedback stabilization algorithm for four-dimensional reconfiguration of a sphere. By considering a spherical robot as a chained system Javadi et al. (Javadi and Mojabi, 2002) established its dynamic model with the Newton method and discussed its motion planning with experimental validations. As compared to other existing motion planners, this method requires no intensive numerical computation, whereas it is only applicable for their specific spherical robot. Bhattacharyya and Agrawal (Bhattacharyya and Agrawal, 2000) deduced the first-order mathematical model of a spherical robot from the non-slip constraint and angular momentum conservation and discussed the trajectory planning with minimum energy and minimum time. Halme and Suomela et al. (Halme, Schonberg and Wang, 1996) analyzed the rolling ahead motion of a spherical robot with dynamic equation, but they did not consider the steering motion. Micchi, et al. (Antonio B. et al., 1997), (Antonio and Alessia, 2002) established a simplified dynamic model for a spherical robot and discussed its motion planning on a plane with obstacles. Joshi and Banavar et al. (Joshi, Banavar and Hippalgaonka, 2009) proposed a path planning algorithm for a spherical mobile robot. Liu and Sun et al. (Liu, Sun and Jia, 2008) deduced a simplified dynamic model for the driving ahead motion of a spherical robot through input-state linearization and derived the angular velocity controller and angle controller respectively with full feedback linearized form [17].

It should be noted the even though the gravitational term is not considered: the motion planning for the system under consideration is still a very difficult research problem.

In fact, no exact motion planning algorithm has yet been reported for the case of the actuation by two rotors. In [18], the motion planning problem was posed in the optimal control settings using an approximation by the Phillip Hall system [19]. However, since the robot dynamics are not nilpotent, this is not an exact representation of the system and it results to inaccuracies. An approximate solution to the motion planning problem using Bullo’s series expansion was constructed in [19], but that has been done for the case of three rotors. An exact motion planning algorithm is reported only in [6], but as we will see it later it is not dynamically realizable. Thus, the motion planning in dynamic formulation for the robot under consideration is still an open problem and a detailed analysis of the underlying difficulties is necessary.

This constitute the main goal of our paper. The paper is organized as follows. First, in Section II we provide a geometric description and a kinematic model of the system under consideration and then, in Sections III derive its dynamic models. A reduced dynamic model is then furnished in Section IV, and conditions of dynamic realizability of kinematically feasible trajectories of the rolling sphere are established in Section V. A case study, dealing with the dynamic realizability of tracing circles on the surface of the sphere, is undertaken in Section VI. Finally, conclusions are drawn in Section VII.

II. DYNAMICS MODEL OF SOFT-SHELLED SPHERICAL ROBOT

A. Constitution

The soft-shelled spherical robot developed by PLA Uni. of Sci & Tech is shown in Fig. 1. There are 3 electromotors inside the spherical shell to provide moment of force input. One steering motor is connected to a bevel gear rolling in a gear circle. The battery and load are connected to the bevel gear as well in order to control the rotation direction. The other two drive motors in-phase and their shells are fixed on the bracket, while the armatures of them are on the shell of the spherical robot to provide drive moment of force.

Fig. 1 illustrates the overview of the internal driving mechanism. The internal driving mechanism is composed of two rotors with their axes perpendicular to each other. Each axis is called Yaw axis and Pitch axis, respectively. An actuator is put at the bottom of each axis and a rotor is put at the both ends of Pitch axis. The spherical shell is driven by the reaction torque generated by actuators. The internal driving device is fixed to the spherical shell at a point P. The point P is at the geometric center of the sphere. The gravity point of the internal driving device does not lie at the center of the sphere. Due to this asymmetry, the robot tends to be stable when the weights are beneath the center, while it tends to be unstable when they are above the center. This is important to realize both the stand-still stability and quick dynamic behavior by a single mechanism.

Figure 1. Planform for inner machines of the spherical soft shell robot

Figure 2. Appearance & planform for inner machines of the spherical soft shell robot

B. Exterior Structure

Fig. 2 illustrates the overview of the exterior structure. The exterior part is composed of two hemispheres and
circular board that divides the sphere in half. All electronic components such as sensors, motor drivers, and a microcomputer are put on the circular board. Weight of electronic components are large enough that we can not neglect them when we construct the dynamic model. Moreover, distribution of weight on the circular board is invariable. Therefore, the gravity point of exterior structure does not lie at the center of sphere. By considering this asymmetry property in the dynamic model, we can construct more accurate model and simulate the effects of distribution of weight on motions of the robot.

C. System Models in a Beeline Motion

Without considering the viscous friction on robot produced by air resistance, the robot can be decomposed into two subsystems: one is the bracket and spherical shell, another is the single pendulum, then we make the following assumptions:

a. The spherical shell is equivalent to a rigid and thin spherical shell which quality is \( m_0 \) and radius is \( R \). There is no deformation of the spherical shell when it is contact with the ground, the soft and elastic properties of the spherical shell is reflected by the relative displacement of different directions between spherical shell and bracket.

b. The component inside the ball equivalent to a solid ball which quality is \( M \) and radius is \( r \) beside the storage battery and load; They are equivalent to the connection through the radial light spring, known as the model called spring pendulum (Fig. 3). In Figure 3, the distance offset centre affected by the spring force is \( \Delta R \) which becomes \( \Delta X \) and \( \Delta Y \) when it decomposed into horizontal and vertical displacement. (Fig. 4).

![Figure 3. The model called spring pendulum](image)

Establishing the inertial coordinate system \( XOY \) on the ground and decomposing the spherical shell robot into two subsystems: spherical shell and “frame + pendulum”. The two subsystems connected by the bearing force and the bearing countermoment associated with each other. The positive direction of every parameter shows in Fig. 4.

When the system is pure rolling in the horizontal plane in a straight line, the displacement of spherical and pendulum on the direction of \( X \) and \( Y \) is \( X_p, Y_p, X_{p0}, Y_{p0} \) respectively according to kinematic law:

\[
\begin{align*}
X_p &= \phi R \\
Y_p &= 0 \\
X' &= X_{p0} + L \sin \theta - \Delta X \\
Y' &= L - L \cos \theta + \Delta Y
\end{align*}
\]

(1)

Taking the above equation second derivative with time, then we can get the acceleration of spherical and pendulum on the direction of \( X \) and \( Y \) is \( a_{x0}, a_{y0}, a_{px}, a_{py} \) :

\[
\begin{align*}
a_{x0} &= \ddot{\phi} R \\
a_{y0} &= 0 \\
a_{px} &= \phi R + \theta L \cos \theta - \theta^2 L \sin \theta - \Delta X \\
a_{py} &= \theta L \sin \theta - \theta^2 L \cos \theta + \Delta Y
\end{align*}
\]

(2)

The force and moment balance of vector mechanics and moment of momentum theorem for spherical shell and pendulum can be presented as two equations: (3) and (4)

\[
\begin{align*}
F_x - F_x (m_0 + M) a_{x0} &= 0 \\
F_x' + (m_0 + M) x - F_x &= 0 \\
T - F_x R + F_y \Delta Y - F_y \Delta X &= \frac{\gamma}{2} m_0 R^2 \ddot{\phi} + \frac{\gamma}{2} Mr^2 \ddot{\phi} \\
F_y &= \mu_a F_x
\end{align*}
\]

(3)

\[
\begin{align*}
F_x' &= ma_{px} \\
F_y' &= ma_{py} \\
T' - m\ddot{R} L \cos \theta - mgL \sin \theta &= mL \ddot{\phi}
\end{align*}
\]

(4)

where the static friction is \( F_y \) caused by the ground. The orthogonal component force is \( F_x, F_x' \) when the bracket forces on shell in the plane; The supportive force is \( F_y \), the angle that rotated relative to the ground by the shell is \( \phi \) and the angle that relative to the vertical direction by the pendulum is \( \theta \); The friction of static coefficient is \( \mu_a \). When considering about the constraint when the ball is pure rolling and assuming that the motor is rotating in constant angular velocity as \( \omega_f \), we can get the equation (5):

\[
\omega_f t = \phi - \theta
\]

(5)

Dates of manuscript submission, revision and acceptance should be included in the first page footnote. Remove the first page footnote if you don’t have any information there. Taking equations (1), (2) and (5) into equations (3) and (4) and sorting, then omitting the quadratic term of \( \Delta X \) and \( \Delta Y \) as small high-end quantity, where \( \sin \theta=\theta, \cos \theta=1 \).
III. Calculation and Analysis of Dynamic Model of Soft Shell Spherical Robot

Equation (4) is composed of two order nonlinear differential equation. Generally it is hard to get the analytical solution. So this paper used the method of difference approximation for the numerical solution. The values of $\Delta \bar{X}$ and $\Delta \bar{Y}$ are relevant to $\theta$. First of all, omitting the related items of $\Delta \bar{X}$ and $\Delta \bar{Y}$, it can get the dynamic equation of hard spherical robot. Substituting relative parameters: the mass of spherical $m_b=0.62$kg, radius $R=0.39$m, the mass of internal mechanism and support $M=3.12$ kg, equivalent radius $r=0.07$m; the mass of battery and load $m_e=6.29$kg, $L=0.28$m, $\mu_0 =0.5$. Defining the initial conditions: the 0 time, $\theta(0)=\dot{\theta}(0)=0$. Substituting relative parameters, difference discretization of the two differential equations, taking 0.05 as steps, it can get the numerical solutions of hard shell spherical robot driving angle $\theta$, which was shown by solid line in figure 4. By determination, the values of $\Delta \bar{X}$ and $\Delta \bar{Y}$ were less than $10^{-2}$, it may be assumed as constants, $\Delta \bar{X} = \Delta \bar{Y} = 0.02$m/s$^2$. Substituting equation (6), it can get dynamic equation on soft spherical robot; the numerical solution of the equations was shown in dotted line in figure 4.

$$\begin{align*}
mLR\ddot{\theta} + (ml^2 - \frac{2}{5}m_bR^2 + \frac{1}{5}Mr^2 - mR^2)\ddot{\theta} + mgL\dot{\theta} + mR\Delta \bar{X} & = 0 \\
m\mu_0 LR\ddot{\theta} + (ml^2 + mLR - \frac{2}{5}m_bR^2 + \frac{1}{5}Mr^2)\ddot{\theta} - m\mu_0 LR\ddot{\theta} + mgL\dot{\theta} - (m_e + M)g\mu_0 R + m\mu_0 R\Delta \bar{Y} & = 0
\end{align*}$$

(6)

As can be seen from Fig. 5, in the case of a constant speed of drive motor, The change of horizontal line pure rolling soft shell spherical robot driven angle has consistent trend with hard shell spherical robot of the same parameters: firstly, the maximum swing angle appeared in a relatively short time, and then decreased rapidly, finally, kept in a certain angle oscillation. Soft shell spherical robot driven angular oscillation amplitude was bigger than the hard shell spherical robot, but the maximum swing angle was smaller, the impact was relatively small.

IV. Prototype Test

A. Test Conditions

To demonstrate the feasibility of the new driving mechanism shown in Sec. II, we make the spherical rolling robot move with a desired translational velocity by a simple feedback controller. Based on the observed state shown in the above subsection, the driving torque $r$ in (5) is given by a state feedback law. It should be noted that the counter torque $-r$ is applied to the inner subsystem composed of the gyro case and the gyro as shown in (3). Since the gyro has a large angular momentum, nutation of the subsystem may be caused by the angular momentum. However, the nutation was not seen in the results of preliminary experiments. It seems that the nutation is quickly damped by the frictional torque between the outer shell and the gyro case.

In this paper, we adopt Strategy A and use the feedback law (6) in the experiments. In Strategy A, the rotational motion of the outer shell around the vertical axis would not be controlled by (6). However, the rotation around horizontal axes would approach the desired horizontal rotation, and the experimental results in the next section will show that the spherical rolling robot can achieve a translational motion by the feedback law (6).

The experimental prototype quality, size and other parameters are the same to the last chapter, the filled pressure of spherical shell is $1.8\times10^5$Pa and the battery voltage is 12V. Using photoelectric encoder to control the speed of driving motor should be maintained in the $\pi$ rad/s and the robot starts from rest. PID is used to control the steering angle of steering motor so that to keep the robot lateral stability and the robot can keep a horizontal linear to move. What’s more, it also makes use of the three axis accelerometer and a three axis gyro sensors to measure the three axis acceleration and angular velocity at the same time. The sampling frequency is 20Hz. Through data processing, we can get the change trend of driven angle $\theta$, which is shown in dotted line in Fig. 6.

V. Case Study

Spherical rolling robots have a unique place within the pantheon of mobile robots in that they blend the efficiency over smooth and level substrates of a traditional wheeled vehicle with the maneuverability in the holonomic sense of a legged one. This combination of normally exclusive abilities is the greatest potential
benefit of this kind of robot propulsion. An arbitrary path that contains discontinuities can be followed (unlike in the case of most wheeled vehicles) without the need for the complex balancing methods required of legged robots. However, spherical rolling robots have their own set of challenges, not the least of which is the fact that all of the propulsive force must somehow be generated by components all of whom are confined within a spherical shape.

This general class of robots has of late earned some notoriety as a promising platform for exploratory missions and as an exoskeleton. However, the history of this type of device reveals that they are most common as a toy or novelty. Indeed, the first documented device of this class appears to be a mechanical toy dating to 1909 with many other toy applications following in later years.

Many efforts have been made to design and construct spherical rolling robots and have produced many methods of actuation to induce self-locomotion. With a few exceptions, most of these efforts can be categorized into two classes.

The first class consists of robots that encapsulate some other wheeled robot or vehicle within a spherical shell. The shell is then rolled by causing the inner device to exert force on the shell. Friction between the shell and its substrate propels the assembly in the same direction in which the inner device is driven. Early examples of this class of spherical robot had a captured assembly whose length was equal to the inner diameter of the spherical shell, such as Halme et al. and Martin, while later iterations included what amounts to a small car that dwells at the bottom of the shell, such as Bicchi et al.

The second major class of spherical robots includes those in which the motion of the sphere is an effect of the motion of an inner pendulum. The center of mass of the sphere is separated from its centroid by rotating the arm of the pendulum. This eccentricity of the center of mass induces a gravitational moment on the sphere, resulting in rolling locomotion. Examples of these efforts are those of Michaud and Caron, Jia et al. Javadi and Mobajbi [16] as well as Mukherjee et al. have devised systems that work using an eccentric center of mass, but each moves four masses on fixed slides within the spherical shell to achieve mass eccentricity instead of tilting an inner mass. Little work has been done outside these two classes. Jeevaraisilawong and Laksanacharoen and Phipps and Minor each devised a rendition of a spherical robot.

These robots can achieve some rolling motions when spherical but are capable of opening to become a wheeled robot and a legged walking robot respectively. Sugiyama et al. created a deformable spherical rolling robot using SMA actuators that achieves an eccentric center of mass by altering the shape of the shell. Finally, Bart and Wilkinson and Bhattacharya and Agrawal each developed spherical robots where the outer shell is split into two hemispheres, each of which may rotate relative to each other in order to effect locomotion.

The condition of dynamic realizability (4) imposes a constraint on the components of the vector of the angular velocity $\omega_0$, and this constraint needs to be embedded into the motion planning algorithms. If the motion planning is based on the direct specification of curves on the sphere or on the plane, as is the case in many conventional algorithms [10], [12], the embedding can be done as follows.

Assume that the path of the rolling carrier is specified by spherical curves, and the structure of the functions $u_i(t)$ and $v_i(t)$ up to some certain constant parameters is known. The kinematic equations (3) can now be casted as

\[
\dot{v}_u = R \dot{u}_0 \sin \theta \cos \phi + R \dot{v}_0 \cos \phi \\
\dot{u}_u = -R \dot{u}_0 \cos \psi \cos \theta + R \dot{v}_0 \sin \psi
\]

In [6] the rotors are mounted on the axes $n_1$ and $n_2$, so the condition of dynamic realizability becomes $n_2 \cdot k \omega_0 = 0$. However, the motion planning algorithm in [6] is designed under the setting $n_2 \cdot \omega_0 = 0$, which is not equivalent to the condition of dynamic realizability.

To guarantee the dynamic realizability, express $\omega_z$ in the last formula through $\omega_x$ and $\omega_y$. In doing so, we first need to express $\omega_x$, $\omega_y$ as well as $n_{x_0}$, $n_{y_0}$, $n_{z_0}$ in terms of the contact coordinates. From the definition of the angular velocity $\omega_0 = R \dot{R}^T$, one obtains

\[
\omega_x = -\dot{u}_0 \cos v_0 \sin \phi - \dot{v}_0 \cos \phi \\
\omega_y = -\dot{a}_0 \cos v_0 \cos \phi + \dot{v}_0 \sin \phi
\]

while $n_z$ is simply the last column of the orientation matrix $R$. Therefore,

\[
n_{x_0} = -\sin u_0 \cos v_0 + \cos u_0 \sin v_0 \sin \phi \\
n_{y_0} = \sin u_0 \sin \phi + \cos u_0 \sin v_0 \cos \phi \\
n_{z_0} = \cos u_0 \cos v_0
\]

Having expressed everything in terms of the contact coordinates, one can finally replace $\phi$ in (13) by

\[
\phi = (1-k) \dot{u}_0 \sin v_0 + k \dot{v}_0 \tan \frac{u_0}{\cos v_0}
\]

If we, formally, set here $k = 0$ the variable $\phi$ will be defined as in the pure rolling model. However, in our case $k > 1$.

Consider a maneuver when one traces a circle of radius $a$ on the spherical surface. This maneuver is a component part of many conventional algorithms (see, for instance [6], [10], [13], [14]). Tracing the circle results to the non-holonomic shift $\Delta h(a)$ of the contact point on the plane and to the change of the holonomy (also called as the geometric phase). $\Delta \psi(a)$. By concatenating two circles of radius $a$ and $b$, one defines a spherical figure eight. By using the motion planning strategy [13], based on tracing an asymmetric figure eight n times, one can, in principle, fabricate an exact and dynamically realizable motion planning algorithm.

A detailed description of the circle-based motion planning algorithm is not presented in this paper due to
the page limitation. However, in the remaining part of his section we illustrate under simulation an important feature of this algorithm—the dependance of the nonholonomic shift on the inertia distribution specified by the parameters $k$.

B. Results Analysis

The most apparent behavior that the spherical robot prototype displayed was a tendency to wobble or rock back and forth with little damping. For example, when the sphere was at rest with the pendulum fixed inside, bumping the sphere would cause it to oscillate back and forth about a spot on the ground. The sphere also wobbled if a constant pendulum drive torque was suddenly applied to the sphere starting from rest. In this case, it would accelerate forward while the angle between the pendulum and the ground would oscillate. Since the pendulum was oscillating, the forward linear velocity of the sphere also appeared to oscillate as it accelerated. When traveling forward and then tilting the pendulum a fixed angle to the side to steer, the radius of the turn would oscillate as well.

Another behavior that was observed but not found to be discussed in the literature was the tendency of the primary drive axis to nutate when the sphere was traveling at a reasonable forward velocity. Specifically, the primary drive axis (the axis of the main drive shaft attached to the spherical shell) would incur some angular misalignment from the axis about which the sphere was actually rolling. When traveling slowly (estimated to be less than 0.5 m/s) this nutating shaft behavior, which could be initiated by a bump on the ground, would damp out quickly. When traveling at a moderate speed, the nutation would persist causing the direction of the sphere to oscillate back and forth.

When attempting to travel at high speed (estimated to be above 3 m/s) the angular misalignment between the axes would grow unstable until the primary drive axis was flipping end over end. Even during a carefully controlled test on a level, smooth surface

The angle of inclination of the gyro increased rapidly from 0 [deg] to about 10 [deg] by $t = 0.25 [s]$, and kept increasing slowly to about 20 [deg] for $0.25 \leq t \leq 3 [s]$. It seems that the increase after $t = 0.25 [s]$ was caused by the rolling friction at the contact point between the outer shell and the floor surface that was covered with carpet tiles. The rolling friction may change the total angular momentum of the robot.

The friction torque about the vertical may also decrease the total angular momentum, when $\omega(0) 10z$ is not zero. We will examine the behavior of the inclination angle for other types of floor surfaces and for Strategy B in future works.

Moreover, due to the limited power of the DC motors, the maximum angular speed of the outer shell that was achieved in the experiments was about 1.5 rad/s.

Comparing with the driven angle measured curve (dashed line) and the results of theoretical calculations (solid line) of the soft shell spherical robot in Fig. 5, we can see that the measured curve is basically agree with the theoretical calculation results, which can prove the correctness of the dynamics model of “spring pendulum” of soft shell spherical robot in this paper. The theoretical and experimental curves calculated difference: (1) the final angular oscillation amplitude is smaller than the theoretical analysis, probably because the theoretical model does not consider the energy loss of internal movement; (2) the measured maximum pendulum angle is bigger than the theoretical results, which is probably caused by the modeling error. For example, the parameters of support quality equivalent radius $r$ is difficult to be precise enough, and the other reason to result in modeling errors is that the support eccentric displacement acceleration $Δ\ddot{X}$ and $Δ\ddot{Y}$ are approximately regarded as constant.

VI. CONCLUSIONS

A dynamic model named spring pendulum of the soft-shell spherical robot is advanced in this paper. The theoretic curve of drive angle for time is educed in the condition of invariable drive motor rev from this dynamic model. The test result on a soft-shell prototype is identical to the theoretic result which proves the validity of the spring pendulum model. The rules of drive angle fluctuation and the influence characteristics will be proposed by means of numerical research on the spring pendulum model in order to stabilize and control the attitude of soft-shell spherical robot.

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