UDC 519.87, DOI: 10.2298/CSIS1001051S

Modeling and Simulation of a Spherical Mobile Robot

SANG Shengju[1,2], ZHAO Jichao[2], WU Hao[1], CHEN Shoujun[1], and AN Qi[1]

[1] School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, P.R. China, 200237;
sang1108@163.com, wh@mail.ecust.edu.cn, csj19850112@yahoo.com.cn, anqi@ecust.edu.cn
[2] School of Information Science and Technology, Taishan College, Shandong Taian, P.R. China, 271021
{sang1108, zjc}@163.com

Abstract. Spherical mobile robot (SMR) has been studied analytically and experimentally in this paper, a novel design with an internal propulsion mechanism and mathematical models of the robot's dynamics and kinematics are introduced. A 3D model of robot is built by SOLIDWORKS and then exported to ADAMS2007 for simulation. The results of simulation by combining MATLAB / SIMULINK with ADAMS are presented. It is shown experimentally that the behavior of actual model consist well with the prediction of simulation.

Keywords: spherical mobile robot (SMR), simulation, ADAMS, virtual prototype, kinematics and dynamic, mathematical model.

1. Introduction

Spherical mobile robot (SMR) is a new type of robot [1]-[4], which has a ball-shaped outer shell to accommodate all its mechanism, control devices and energy sources in it. Spherical robot is characterized as simple, compact, well-sealed structure and agile motion and it has attracted the interest of many researchers. The spherical structure offers extraordinary motion properties in cases where turning over or falling down will bring risks during motion. A spherical mobile robot which has full capability to recover from collisions with obstacles can be used to survey unstructured hostile industrial environment or explore other planets [9]. In addition, a spherical mobile robot can quickly move as a wheeled robot and also can easily detour obstacles as a legged robot.

This paper presents a novel robot that can achieve many kinds of unique motion, such as all-direction driving on rough ground, without great loss of stability. The structure of the robot presented in this paper is one of spherical mobile robots, which can be seen in Fig. 1.

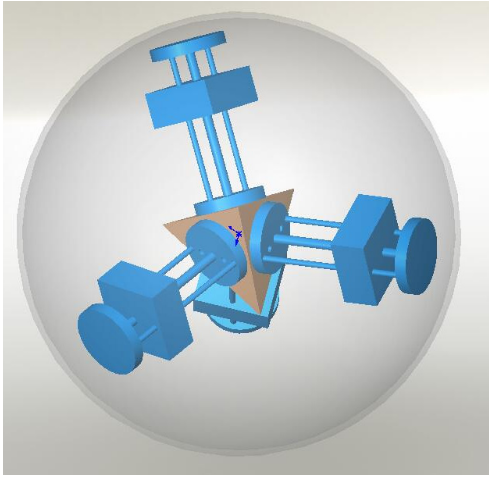


Fig. 1. Prototype of the spherical robot

2. Related Works

The spherical mobile robots have been studied by using a variety of mechanisms [1-8]. In other words, several omnidirectional platforms have been known to be realized by developing a specialized wheel or mobile mechanism. Mobile robots of spherical shape have been described by only a few authors. The first spherical robot was developed by Halme et al. [1]. They proposed a spherical robot with a single wheel resting on the bottom of a sphere. Bicchi et al. [3] developed a spherical vehicle consisting of a hollow sphere with a small car resting on the bottom. Bhattacharya et al. [10] proposed a driving mechanism that is a set of two mutually perpendicular rotors attached to the inside of the sphere. Ferriere et al. [7] developed a universal wheel to actuate a spherical ball to move the system, and in their mechanism, the actuation system is out of the sphere. It is, however, obvious that the autonomous spherical rolling robot, described in this paper, glory, differs from the previous designs. The driving mechanism is a set of four spokes distributing weights radially along them inside the sphere, in contrast to a wheel resting at the bottom of the sphere or, two mutually perpendicular rotors attached to the inside of the sphere, in previous works. Mukherjee et al. [11] studied the feasibility of moving a spherical robot to an arbitrary point and orientation. They had presented two strategies for reconfiguration. Glory is the only implemented spherical robot which can traverse omni-directionally [4]. The review papers discussing constructional details of available spherical mobile robots are [10, 11] and a concise review on the existing path planning algorithms and feedback algorithms for the system can be obtained from [12, 13]. In this paper, we present a systematic study of a spherical mobile robot, designed, fabricated and analyzed in our laboratory.

The organization of this paper is as follows. Related work is reviewed in section 2. Section 3 describes the construction and design in detail. Section 4 describes the mathematical modeling of the system using quaternion. In Section 5, the trajectory of the robot is discussed in the quaternion space. The simulation and experimental setup along with the discussion on the experimental results is reported in section 6. Section 7 provides concluding remarks.

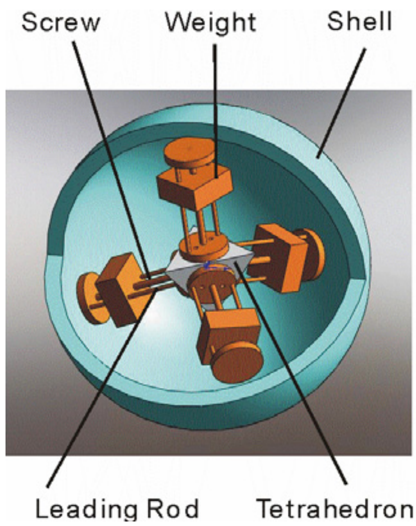


Fig. 2. Structure of the spherical mobile robot

3. Design

The spherical mobile robot presented in this paper has an external spherical shape. It is composed of a spherical shell, a Propulsion Mechanism and a stable tetrahedron. Fig.1 shows its 3D model and Fig.2 shows the structure of the spherical mobile robot.

The spherical shell is made up of acrylic material having 4 mm thickness. The inner radius of the robot is 360mm. The transparent acrylic spherical shell enables researchers to monitor the state of internal mechanism while in motion. The spherical robots work on the principle of change in the center of gravity. A crucial aspect of the design is to place the internal components to make the center of mass of the robot exactly at the geometric center of the sphere. This is very important so that the robot will not tip over on its own. The easiest way to achieve this is to place all the internal components symmetrically [18, 19]. It is absolutely vital that there be no relative motion between the two hemispheres in motion. This can be achieved screwing a connecting rod along the axis of the sphere.

The propulsion mechanism consists of four power screwed spokes, connected in 109.47° inside a tetrahedral shape [4], There are four heavy objects (heavy shortly or weight), placed through spokes, which are elevated upward and downward using four stepper motors, with 200 steps per revolution, connected directly to the spokes. The motor that is driving the heavy is also fixed on the hollow shaft and tied to the heavy by a link.

4. Mathematical Modeling

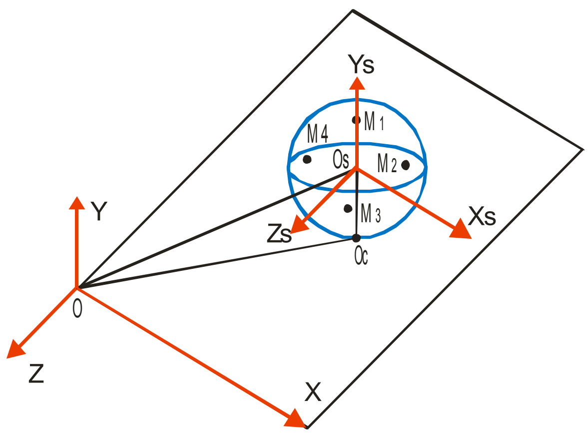


Fig. 3. Coordinates setup of the spherical mobile robot

This section describes the development of an analytical model of the spherical rolling robot using quaternion. Considering a spherical robot, rolls on a horizontal plane as shown in Fig.3, an inertial coordinate frame is attached to the ground and denoted as XYZ with its origin at the point O. The body coordinate axes XsYsZs, parallel to XYZ, are attached to the sphere and have their origin at the center of the sphere Os. The set of generalized coordinates describing the sphere consists of 1) Coordinates of the contact point Oc on the plane, and 2) any set of variables describing the orientation of the sphere [14]-[17].

We use Euler parameters (instead of Euler angles) which is a set of 4 parameters to describe the orientation of the sphere. Euler parameters have the advantage of being a nonsingular two to one mapping with the rotation. In addition, Euler parameters form a unit quaternion and can be manipulated using quaternion algebra [20, 21].

Because the spherical robot cannot move in Y direction, five variables $(X, Z, \alpha, \beta, \gamma)$ are enough to describe its space state. x and z are the coordinates of the contact point Oc between the sphere and the plane and (α,β,γ) are the generalized Euler angles used to describe the sphere orientation. We have adopted a Newton formulation for propulsion mechanism since the acceleration of the sphere appears explicitly in the equation. These equations have the form:

$$\sum \vec{M} = (\sum [I]) \bullet \vec{\omega} + \sum \vec{\rho} \times m \vec{\rho}^{\cdot} \tag{1}$$

Where $(\sum [I])$ is the moment due to the weights of the individual unbalanced masses, I is the moment of inertia of the robot and $\vec{\omega}$ is the angular acceleration of the sphere. The vector $\vec{\rho}$ represents the position vector of ith weight with respect to the relative spoke. The vectors represented by $\vec{\rho}^{\cdot}$ are equivalent to the absolute accelerations of individual weights.

In our implementation, due to discrete nature of stepper motors, we can suppose, for each step of simulation, each heavy is temporarily fixed in its position related to the geometry. Thus we can neglect the second term on the right hand of the equation in a good rate of approximation. It helps calculating angular acceleration. A static analysis only considers the moments due to the weights of the unbalanced masses and has the following form:

$$\sum \vec{M} = (\sum [I]) \bullet \vec{\omega} \tag{2}$$

Let i, j, k be the unit vectors of the body frame and ω_s be the angular velocity of the sphere given by

$$\omega_s = (\dot{\alpha}\,\mathrm{c}\beta\,\mathrm{c}\gamma + \dot{\beta}\,\mathrm{s}\gamma) i + (-\dot{\alpha}\,\mathrm{c}\beta\,\mathrm{s}\gamma + \dot{\beta}\,\mathrm{c}\gamma) j + (\dot{\alpha}\,\mathrm{s}\beta + \dot{\gamma}) k \tag{3}$$

Where $\mathrm{c}\beta$ and $s\beta$ are short for $\cos\beta$ and $\sin\beta$ respectively.

Let ξ, η, ζ be the unit vectors of inertial coordinate frame, and the projection of the angular velocity vector on the body axes can be derived and expressed in the following form.

$$\begin{aligned} \omega_s &= \omega_\xi + \omega_\eta + \omega_\zeta \\ &= (\dot{\alpha} + \dot{\gamma}\,\mathrm{s}\beta)\xi + (\dot{\beta}\,\mathrm{c}\alpha - \dot{\gamma}\,\mathrm{s}\alpha\,\mathrm{c}\beta)\eta + (\dot{\beta}\,\mathrm{s}\alpha + \dot{\gamma}\,\mathrm{c}\alpha\,\mathrm{c}\beta)\zeta \end{aligned} \tag{4}$$

We assume that the robot rolls without slipping. Hence, the velocity of the contact point Oc, with respect to the inertial coordinates is zero, i.e. $\upsilon_{Oc} = 0$. The constraint equations reduce to

$$\upsilon_{\iota}^{\xi} = \dot{x} + \omega_\zeta r = \dot{x} + (\dot{\beta}\,\mathrm{s}\alpha + \dot{\gamma}\,\mathrm{c}\alpha\,\mathrm{c}\beta) r \tag{5}$$

$$\upsilon_{\iota}^{\zeta} = \dot{z} - \omega_\xi r = \dot{z} - (\dot{\alpha} + \dot{\gamma}\sin\beta) r \tag{6}$$

Where r is distance vector.

Due to the symmetric design of the ball, the gravity force acts vertically trough the center of the spherical robot and the contact point Oc. Both the ground reaction force and frictional force act through the contact point. Hence, the sum of the external moment at the contact point Oc is zero. And the angular moment of the robot at Oc is a conservative quantity. Hence, weights are the only bodies that cause moment and define the movement direction with their inter-relation. Therefore, the resultant moment vector is as following.

$$\overline{M} = mg \begin{bmatrix} z1 + z2 + z3 + z4 \\ 0 \\ -x1 - x2 - x3 - x4 \end{bmatrix} \tag{7}$$

Where xj and zj are the position of the j^{th} weight (1<j<4).

5. Trajectory Planning

Because of omnidirectional property of the robot, direct path is proposed and the traveling path is very close to the shortest path to the target. For calculating the moment of inertia we use three 3X3 matrixes as below:

$$I_j^w = \begin{bmatrix} I_{jxx}^w & I_{jxy}^w & I_{jxz}^w \\ I_{jyx}^w & I_{jyy}^w & I_{jyz}^w \\ I_{jzx}^w & I_{jzy}^w & I_{jzz}^w \end{bmatrix}, I_j^c = \begin{bmatrix} I_{jxx}^c & I_{jxy}^c & I_{jxz}^c \\ I_{jyx}^c & I_{jyy}^c & I_{jyz}^c \\ I_{jzx}^c & I_{jzy}^c & I_{jzz}^c \end{bmatrix}, I^s = \begin{bmatrix} I_x^s & 0 & 0 \\ 0 & I_y^s & I_{jyz}^w \\ 0 & 0 & I_z^s \end{bmatrix} \tag{8}$$

Where I_j^w, I_j^c and I^s are the moment vector caused by the weight, the propulsion mechanism and the spherical shell respectively, and I_j^c, I^s are both constant. In Eq. (8), I_{jxx}^c and I_{jxy}^c are as follows:

$$\begin{aligned} I_{jxx}^w &= \overline{I}_{jxx}^w + mdx^2, \\ I_{jxy}^w &= \overline{I}_{jxy}^w + mdy^2, \\ I_{jxz}^w &= \overline{I}_{jxz}^w + mdz^2 \end{aligned} \tag{9}$$

Equation (9) is transfer-of-axis relations for transferring $\overline{I}$ from the center of mass to Os. Also, in Eq. (9), due to symmetrical design of the robot $I_{xy} = I_{yx}$, and the other parameters are calculated likewise.

Let X, Y and Z be the projection of the weight on the body coordinate axes be the angular velocity of the sphere, the relational equation can be expressed by

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \left(\prod_{k=n-1}^{0} A_K \right) \begin{bmatrix} 0 \\ -mg \\ 0 \end{bmatrix} \tag{10}$$

In the above equation, the elements of the ration matrix A_K is given by

$$A_K = \begin{bmatrix} \mathrm{c}\,\beta_k\,\mathrm{c}\,\gamma_k & \mathrm{c}\,\alpha_k\,\mathrm{s}\,\gamma_k + \mathrm{s}\,\alpha_k\,\mathrm{s}\,\beta_k\,\mathrm{c}\,\gamma_k & \mathrm{s}\,\alpha_k\,\mathrm{s}\,\gamma_k - \mathrm{c}\,\alpha_k\,\mathrm{s}\,\beta_k\,\mathrm{c}\,\gamma_k \\ -\mathrm{c}\,\beta_k s\gamma_k & \mathrm{c}\,\alpha_k\,\mathrm{c}\,\gamma_k - \mathrm{s}\,\alpha_k\,\mathrm{s}\,\beta_k s\gamma_k & \mathrm{s}\,\alpha_k c\gamma_k + \mathrm{c}\,\alpha_k\,\mathrm{s}\,\beta_k s\gamma_k \\ \mathrm{s}\,\beta_k & -\mathrm{s}\,\alpha_k c\beta_k & c\alpha_k c\beta_k \end{bmatrix} \tag{11}$$

We assume that $\varepsilon_x^n, \varepsilon_y^n$ and ε_z^n are the projection of the angular velocity of the sphere in the $(n-1)^{th}$ step, given by

$$\begin{aligned} \begin{bmatrix} \varepsilon_x^n \\ \varepsilon_y^n \\ \varepsilon_z^n \end{bmatrix} = \begin{bmatrix} \dot{\omega}_\xi^n \\ \dot{\omega}_\eta^n \\ \dot{\omega}_\zeta^n \end{bmatrix} &= \begin{bmatrix} 1 & 0 & \mathrm{s}\,\beta_n \\ 0 & \mathrm{c}\,\alpha_n & -\mathrm{s}\,\alpha_n c\beta_n \\ 0 & \mathrm{s}\,\alpha_n & c\alpha_n c\beta_n \end{bmatrix} \begin{bmatrix} \ddot{\alpha}_n \\ \ddot{\beta}_n \\ \ddot{\gamma}_n \end{bmatrix} \\ &+ \begin{bmatrix} 0 & 0 & \dot{\beta}_n c\beta_n \\ 0 & -\dot{\alpha}_n s\alpha_n & -\dot{\alpha}_n c\alpha_n c\beta_n + \dot{\beta}_n s\alpha_n s\beta_n \\ 0 & \dot{\alpha}_n c\alpha_n & -\dot{\alpha}_n s\alpha_n c\beta_n - \dot{\beta}_n c\alpha_n s\beta_n \end{bmatrix} \begin{bmatrix} \dot{\alpha}_n \\ \dot{\beta}_n \\ \dot{\gamma}_n \end{bmatrix} \end{aligned} \tag{12}$$

From Eq. (8), Eq. (10) and Eq. (12) the resultant moment Equation in the n^{th} step is as following

$$\begin{bmatrix} Z\sum_{K=1}^{4} y_{k-n} - Y\sum_{K=1}^{4} z_{k-n} \\ X\sum_{K=1}^{4} z_{k-n} - Z\sum_{K=1}^{4} x_{k-n} \\ Y\sum_{K=1}^{4} x_{k-n} - X\sum_{K=1}^{4} y_{k-n} \end{bmatrix} = \left[\sum_{K=1}^{4} (I_k^w + I_k^c) + I^s \right] \begin{bmatrix} \varepsilon_x^n \\ \varepsilon_y^n \\ \varepsilon_z^n \end{bmatrix} \tag{13}$$

Therefore, by Eq. (5), Eq. (6) and Eq. (13), the next position of weights can be calculated as below:

$$\begin{aligned} &\begin{bmatrix} Z\sum_{K=1}^{4} y_{k-n} - Y\sum_{K=1}^{4} z_{k-n} \\ X\sum_{K=1}^{4} z_{k-n} - Z\sum_{K=1}^{4} x_{k-n} \\ Y\sum_{K=1}^{4} x_{k-n} - X\sum_{K=1}^{4} y_{k-n} \end{bmatrix} = \left[\sum_{K=1}^{4} (I_k^w + I_k^c) + I^s \right] \begin{bmatrix} \varepsilon_x^n \\ \varepsilon_y^n \\ \varepsilon_z^n \end{bmatrix} \\ &\dot{x}_n + \left(\dot{\beta}_n\,\mathrm{s}\,\alpha_n + \dot{\gamma}_n\,\mathrm{c}\,\alpha_n\,\mathrm{c}\,\beta_n \right) r = 0 \\ &\dot{z}_n - \left(\dot{\alpha}_n + \mathrm{s}\,\alpha_n + \dot{\gamma}_n s\beta_n \right) r = 0 \end{aligned} \tag{14}$$

With the Eq. (14), we can calculate all possible positions of weights.

6. Simulation and Experiments

ADAMS is the most widely used multi-body dynamics and motion analysis software in the world. Traditional "build and test" design methods are now too expensive, too time consuming, and sometimes even impossible to do. ADAMS multi-body dynamics software enables engineers to easily create and test virtual prototypes of mechanical systems in a fraction of the time and cost required for physical build and test. Unlike most CAD embedded tools, ADAMS incorporates real physics by simultaneously solving equations for kinematics, static, quasi-static, and dynamics.

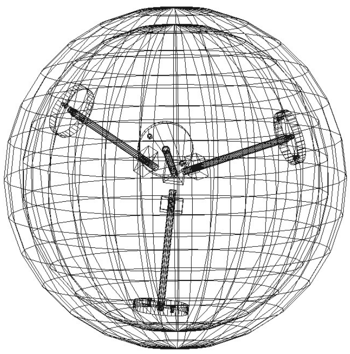
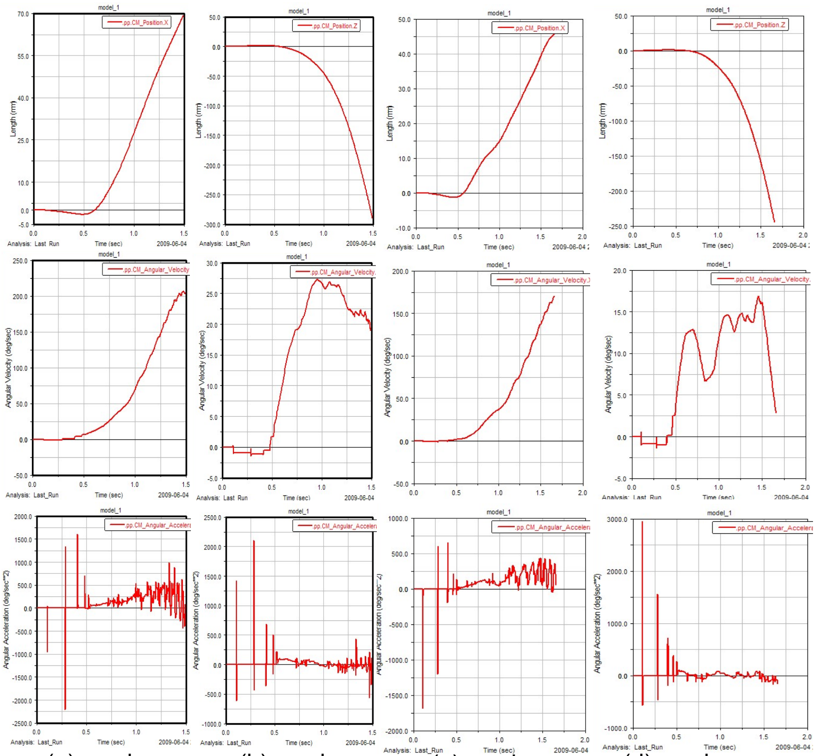


Fig. 4. 3D model of SMR in ADAMS

Due of 3D solid modeling ability of ADAMS is not very strong, we employed the SOLIDWORKS2007 software to set up the 3D model, and then export to ADAMS2007 for simulation, the model is shown in Figure 4. Also, because the ADAMS' controllers are not ones for professional modeling tool, so its control capabilities are limited, however, interfaces between ADAMS and other soft wares such as MATLAB, EASY and so on allow ADAMS complete fine system simulation.

In this section, simulation results on the spherical robot by ADAMS using a time step 0.01s are presented to demonstrate the effectiveness of the design and verify the path following performance. The system parameters are given in Table 1, and the experiment results shown in Fig. 5 and Fig. 6.

The evolutions of the variables for tracking the desired curve are shown in Fig.5 (a, b). The reference linear velocity of the weight v_s is 100mm/s. Fig. 5 (a, b) indicate that the robot starts roll in the x-z plane at t=0.75s, in contrast with Fig.5 (c, d) where the robot starts at t=0.5s. This corresponds to a pure rolling motion. Simulation indicates that the angular velocities generated oscillatory and chattering behavior with these assumptions.



(a) x-axis (b) z-axis (c) x-axis (d) x-axis

v_s =100mm/s v_s =200mm/s

Fig. 5. The performance of SMR at v_s =100mm/s

Table 1. The experimental setup configuration of SMR

Variable	Quantity	Unit
Holding torque of motors	3.250	kg/m
Weight of motor (each)	0.550	m
Radius of spokes	0.040	m
Pitch of power screw	0.060	m
Weight of power screw (each)	0.206	kg
Weight of unbalanced masses (each)	1.125	kg
Radius of spherical shell	0.300	m
Weight of spherical shell	3.779	kg

Fig.6 shows the results of the robot in tracking a straight line in x-z plane, in contrast with reference line (red). As expected, simulations reveal that the spherical robot converges globally uniformly to the desired point with acceptable dynamic performances.

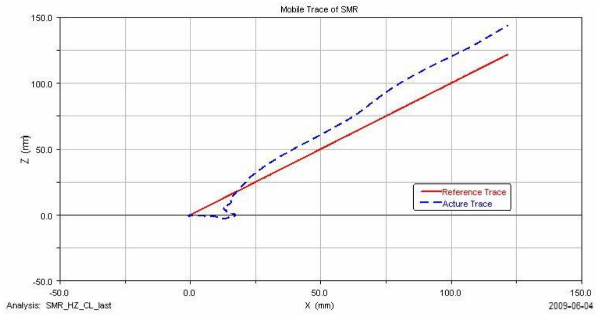


Fig. 6. The trajectories of SMR on the x-z plane

For several missions, the experimental results agree well with those of the simulations. In each case, the experimental trajectory follows the predicted one with a reasonable accuracy. Some factors contribute to these inaccuracies are:

1) the center of mass of the robot is not exactly at the geometric center of the robot;

2) imperfections on the surface of the sphere;

3) open-loop nature of the robot control.

The following are several issues of experimental results. The figures are in three parts; figure in the top-left shows the distance between the robot's center and origin, where the robot has began its travel, figure in bottom-left shows the absolute velocity of robot and figure on the right shows the movement of robot in x-z plane, predicted by dynamic model.

7. Conclusions

A mathematical model of omnidirectional spherical mobile robot motion was established using the no-slip rolling constraint and conservation of angular momentum, and an algorithmic motion planning was developed. The model was validated through a set of simulations. Results of simulations and experimental trajectories of the robot on the plane were found consistent with a reasonable accuracy and the methods are effective. Trajectories are quite accurate despite lack of on-board feedback control. Comparing with existing motion plans, most of which require intensive numerical calculations, strategies in this paper involve simple algorithmic iteration and provide the scope for easy implementation. However, experiments also show that the spherical robot has a strong tendency to oscillate and the uneven ground could make the robot oscillate for a long time. So the control problem of spherical robot couldn't be solved by open-loop control strategy and a robust closed-loop controller and suitable stabilization method are necessary. Study in this paper demonstrates the feasibility of the approaches and a better controlled robot is expected to be improved in the future.

8. Acknowledgments

The work was partially supported by the Natural Science Foundation of Shandong, China (2009ZRA01105), the science and technology development fund of Tai'an (20083002) and the Foundation provided by Taishan College (Y06-2-15).

9. References

1. A. Halme, T. Schonberg, Y. Wang, Motion control of a spherical mobile robot, in 4th IEEE International Workshop on Advanced Motion Control AMC'96, Mie University, Japan, 1996, pp. 100-106.
2. F. Michaud, S. Caron, Roball: the rolling robot, Autonomous Robots, vol. 12, no. 2, 2002, pp. 211-222.
3. A. Bicchi, A. Balluch, Introducing the 'SPHERICLE': an experimental testbed for research and teaching in nonholonomy, in Proceedings of the 1997 IEEE Int. Conf. Robotics and Automation, Albuquerque, New Mexico, April 1995, pp. 2620-2625.
4. A. Javadi, P. Mojabi., Introducing august: a novel strategy for an omnidirectional spherical Rolling Robot, in Proc. IEEE Int. Conf. Robotics and Automation, 2002.
5. Qiang Zhan, Tingzhi Zhou, Ming Chen, Sanlong Cai. Dynamic Trajectory Planning of a Spherical Mobile Robot. in Proc. IEEE Int. Conference. Robotics Robotics, Automation and Mechatronics, 2006, pp. 1-6
6. Masayoshi, W., and Shunji, M., ''Modeling and Control of a New Type of Omnidirectional Holonomic Vehicle,'' in AMC896, 1996, pp. 265–270.
7. Wheels,'' in Proceedings of IEEE International Conference on Robotics and Automation, 1996, pp. 3664–3670.
8. Tang, J., Watanabe, K., and Shiraishi, Y., ''Design and Traveling Experiment of an Omnidirectional Holonomic Mobile Robot,'' in Proc. IEEE Int. Conf. Intelligent Robots and Sys., 1996, pp. 66–73.
9. Agrachev, A. A., ''An Intrinsic Approach to the Control of Rolling Bodies,'' in Proceedings of the Conference on Decision and Control, 1999, pp. 431–435.
10. Bhattacharya, S., and Agrawal, S. K., ''Spherical Rolling Robot: A Design and Motion Planning Studies,'' in Proceedings of IEEE International Conference on Robotics and Automation. 2000,
11. Mukherjee, R., Minor, M. A., and Pukrushpan, J. T., ''Simple Motion Planning Strategies for Spherobot: A Spherical Mobile Robot,'' in Proceedings IEEE International Conference on Decision and Control, 1999, pp. 2132–2137.
12. T. Ylikorpi, J. Suomela, Ball shaped robots: An historical overview and recent development at TKK, Field and Service Robotics, vol. 25, no. 6, 2006, pp. 343–354.

13. R.H. Armour, J.F.V. Vincent, Rolling in nature and robotics: A review, Journal of Bionic Engineering 3, 2006, 195–208.
14. T. Das, R. Mukherjee, Exponential stabilization of the rolling sphere, Automatica, 2004, 1877–1889.
15. T. Das, R. Mukherjee, Reconfiguration of a rolling sphere: A problem in evolute–involute geometry, ASME Journal of Applied Mechanics, 2006, 590–597.
16. Fredrik C. Bruhna, Henrik Kratza, JohanWarellb, etc. Apreliminary design for a spherical inflatable microrover for planetary exploration. Acta Astronautica, vol. 63, 2008, pp.618 – 631.
17. A. Gilyén and P. Szvoboda. Development of the Hungaroshere: the Husar-11 Rover within a Transparent Sperial Space Probe Model with Special Planetrary Surface Activities. 40th Lunar and Planetary Science Conference, 2009
18. Stefan Staicu. Recursive Modelling in Dynamics of Agile Wrist Spherical Parallel Robot. Robotics and Computer-Integrated Manufacturing, vol. 25, 2009, pp. 409-416.
19. Zhan Qiang, Liu Zengbo and Cai Yao. A Back-stepping Based Trajectory Tracking Controller for a Non-chained Nonholonomic Spherical Robot. Chinese Journal of Aeronautics, vol. 21, 2008, pp. 472-480.
20. V. Joshi, R. Banavar, Motion analysis of a spherical mobile robot, Robotica, 2009, 343-353, doi: 10.1017/ S0263574708004748.
21. V.A. Joshi et al., Design and analysis of a spherical mobile robot, Mech. Mach. Theory, 2009, doi: 10.1016/ j.mechmachtheory.2009.04.003

Sang Shengju was born in Taian, P.R.China in 1965. He received his M.Sc degree in Measurement-Control Tech from Harbin University of Science and Technology, Harbin,P.R.China in 1991. He is currently a Ph.D Candidate in the East China University of Science and Technology, Shanghai, P.R.China. and working as a senior Engineer of computer science at theTaishan College, Taian, P.R.China. His research interests include image processing, embedded system and spherical robot.

Zhao Jichao is a professor of Computer Science at the Taishan College, Taian, P.R.China. His current research focuses on image processing, embedded system and spherical robot.

Chen Shoujun and **Wu Hao** are Ph.D students in the School of Mechanical and Power Engineering, East China University of Science and Technology. The areas of interest and research are galling mechanism and preventive methods with anti-sulfur oil tubing in high steel grade.

An Qi received his PhD degrees from the Department of Mechanical Engineering, Zhejiang University, Hangzhou, P.R.China in 2001.He is currently a full professor, Ph.D tutor in the School of Mechanical and Power Engineering at the East China University of Science and Technology, Shanghai, P.R.China. His research interests include Image Processing and CAD/CAPP/CAM.

Received: May 06, 2009; Accepted: October 15, 2009.