Design and Motion Control of a Spherical Robot With Control Moment Gyroscope

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Abstract —**Despite much work has been done to study and develop different types of spherical robots in the recent years, there are few practical applications. Limited by the totally enclosed spherical shell and the special walking style of rolling, existing spherical robots usually lack exteroceptive sensors, such as laser, vision camera and sonar. So they have weak capability of environmental perception and low precision of motion control. This paper presents a spherical robot carrying a Control Moment Gyroscope (CMG) group. The robot aims to have greater ability to cross obstacles and climb up slopes, and it will have a more stable platform for sensors to enhance the environmental perception. The mechanical structure of the spherical robot is introduced. Under reasonable assumptions, simplified dynamic model is developed as well. The motion control of the robot with CMG group is studied by simulations. Simulation results validate the feasibility of the structure design. The work presented here is a step towards the overall goal of an autonomous spherical robot.**

Keywords—spherical robot;control moment gyroscope; motion control

I. INTRODUCTION

Spherical robot refers to one kind of mobile robot that has a ball-shaped case including all its mechanisms, control devices inside it. The ball-shaped case works as walking device of the robot. Compared with traditional wheeled and tracked mobile robots, the spherical robot can provide efficient protection for the driving mechanisms, sensory devices and control devices because all of them are placed inside the shell. On the other hand, because of the spherical shape of the robot, the robot can restore stability after brief irregular motions if it collides with obstacles. Even if it occurs that the robot falls from a height or meets with other dangerous situations, it can still continue to work because there are no overturning problems. Thirdly, the spherical robot can move flexibly and it can pass through the passage whose diameter is slightly larger than the robot's diameter. That holds the spherical robot is superior to traditional wheeled or tracked mobile robots for navigation in unknown or varying territories, such as lunar explorations, social service establishments, disaster areas such as earth quakes, etc.

In the recent years, there has been much attention of researchers to study and develop different types of spherical robots [1]-[6]. And they have carried lots of research work on the spherical robot's mechanical design, modeling and control. However, limited by the totally enclosed spherical shell and the special walking style of rolling, existing spherical robots usually lack exteroceptive sensors, such as laser, vision camera and sonar. Motion control of spherical robots mainly uses remote control or feedback control based on proprioceptive sensors, such as encoder and inertial sensor, which cause the robot to suffer low control accuracy, unbounded cumulative error and weak capability of anti-interference [8]-[12]. On the other hand, some spherical robots may be equipped with an external platform with measuring sensors, but these platforms result in that it is difficult for the robots to achieve quick start, and they may also not be able to move flexibly, etc. So it is difficult for the existing spherical robots equipped with external measuring sensors to have quick start, but for one robot, both of the steady and flexible walking performance and sensitive perception of the outside environment are indispensable. Based on the above conclusion, this paper proposes a new spherical robot with Control Moment Gyroscope (CMG). The high-speed flywheel rotor generates additional torque by its gyroscopic precession effect, so the robot can get greater acceleration and ability to cross obstacles and climb up slopes [13]-[15]. At the same time, using the new mechanical structure designed with new steering mechanism makes the robot be able to move more flexibly. On the other hand, the spherical robot has built-in driving wheel, the frame with wheel will have very small amplitude while rolling, and the platform for sensors could be built on the frame so that the robot might be able to get steady information from the outside environment. The robot can control its own movements precisely using the information.

This paper proposes the new spherical robot with a CMG group, new walking and steering mechanism and verifies the feasibility of the robot design by motion simulation experiments. It also presents a motion control algorithm; we can control the spherical robot to complete some path work with the algorithm.

This work is supported in part by the National Natural Science Foundation of China under grant No. 61305126.

II. MECHANICAL STRUCTURES AND DYNAMIC MODEL OF THE ROBOT

The spherical robot with CMG group consists of the 300mm-diameter outer spherical shell and driving system placed in the case. The driving system consists of mechanical structures and control systems. The overall design of the robot's assembly is illustrated in Figure 1. The details are shown in Figure 2 and Figure 3. It includes homogeneous spherical shell, straight driving mechanism, steering mechanism and the CMG group. The straight driving mechanism includes driving motor and wheel and they are placed at the bottom of the frame. The wheel has the same arc as the shell so that it could contact with the robot's internal surface completely, and this will reduce the negative factors which is not conducive to the robot's movement such as too small area in contact with the shell.

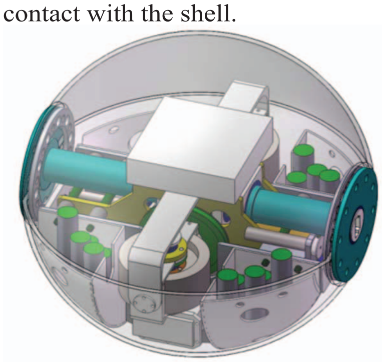


Figure 1 Spherical robot with CMG

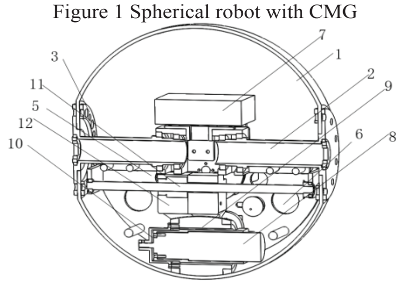


Figure 2 Mechanical structure of the spherical robot (2)

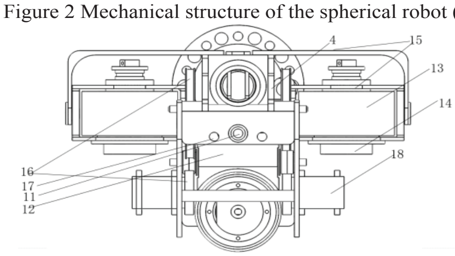


Figure 3 Mechanical structure of the spherical robot (3)

TABLE 1 ROBOT'S MECHANICAL STRUCTURE

1	Homogeneous spherical shell
2	Hollow axle
3	Flange
4	Frame structures
5	Frame connector
6	Battery
7	Control electro circuit
8	Straight-driving motor
9	Straight-driving wheel
10	Wheel coupling
11	Steering lead screw
12	Steering weight
13	Momentum flywheel
14	Flywheel motor
15	CMG frame
16	Pulley group
17	Support member bar
18	CMG tilting motor

A. *Straight and steering structure of the spherical robot*

TABLE 2 VARIABLES DEFINITION

τ_{roll}	Output torque of the straight motor
τ_f	Obstructive torque
ω_{f1} ω_{f2}	Flywheel angular rotation velocity
ω_{t1} ω_{t2}	CMG frame tilting angular velocity
θ	Angle between frame and z_c
α, β, γ	Precession angle, lean angle and spin angle
φ	Angle between fictitious link and x_C
m_b m_c	Mass of the shell, frame plus CMG
I_F	Flywheel rotation moment of inertia
Σ_O Σ_B	Inertial, Spherical-shell coordinate systems
Σ_C Σ_G	Frame, CMG coordinate systems

The spherical robot's straight motor produces torques to drive the robot rolling forward/backward and robot can steer with the cooperation of the steering weight. As it is shown in Figure 4, the driving wheel contact with the internal shell drives the robot rolling forward/backward by friction between wheel and the shell. Moving steering weight changes the position of the center of gravity so that the robot could steer. The steering mechanism consists of steering motor, steering weight, lead screw and member bars. The homogeneous spherical shell is fixedly connected with the hollow axles which are connected with the frame by revolute joints.

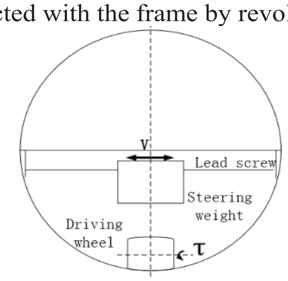


Figure 4 Layout of the driving and steering mechanism

B. *CMG group of the spherical robot*

For traditional spherical robots driven by changing the position of the center of gravity, the closer the center to the spherical shell, the better to control the robot flexibly. The driving system built-in can be seen as a pendulum as the Figure 5 shown. The motor's output torques make the mc be lift a certain angle and the driven torque would be generated to drive the spherical shell to roll forward. When the robot is rolling, the robot's control system controls the lifting angle by controlling the motor's output torque, so the robot's movement will be in control. Closer the center of gravity of mc to the shell, the larger ranges of the robot's forward driving torques would be. Then the robot will be more flexible.

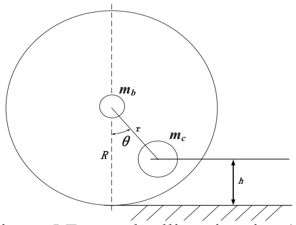


Figure 5 Forward rolling situation (1)

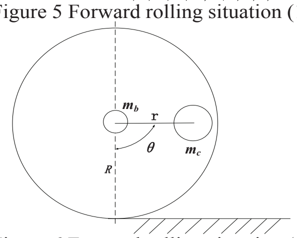


Figure 6 Forward rolling situation (2)

As Figure 6 shows, when the angle θ reaches 90°, the pendulum goes to the forward place, the driving torque becomes the largest. If the motor outputs larger torque, the angle will exceed 90° but the robot's acceleration will be reduced. This case reduces the movement performance of spherical robots making them unable to achieve enough acceleration and deceleration. On the other hand the fluctuating angle makes the robots cannot provide a steady platform for the sensors such as camera, laser, etc.

This paper proposes a robot designed with CMG group to overcome these limitations. The CMG group can provide increased torque to control the pendulum, and the straight's output torque could drive the shell roll immediately without lifting an extra angle. This mechanism can make robot overcome large obstacles and achieve steadier motion.

For one single flywheel as the Figure 7 shows, L is the angular momentum of the flywheel, τ_{tilt} is the applied tilting torque on the flywheel, and τ_{px} is the precession torque produced in the direction necessary for supplementing forward motion. This paper proposes a CMG group which two flywheels added together like Figure 8. The angular momentums L1 and L2 equal a net angular momentum of zero for the two flywheels. The tilting torques τ_{tilt1} and τ_{tilt2} are applied to the flywheels in opposite directions resulting in no net torque on the whole assembly. The precession torques τ_{px1} and τ_{px2} are produced, however, added together in the same direction necessary for supplementing forward motion.

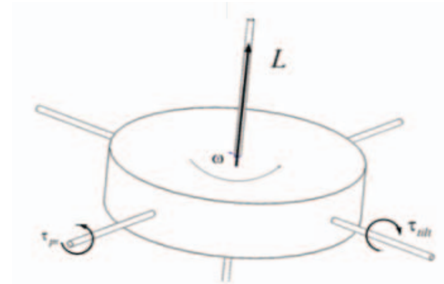


Figure 7 One single CMG

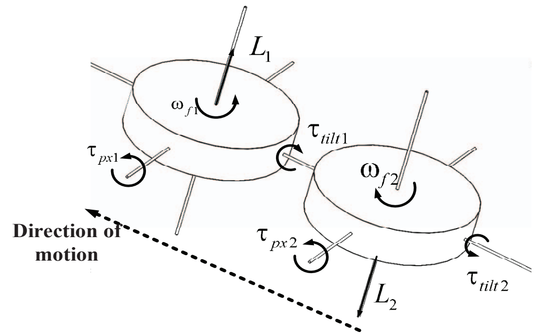


Figure 8 CMG group

For CMG group, the flywheel's spinning velocity is ω_{f1}, ω_{f2} ,and $\omega_{f1} = -\omega_{f2}$. The tilting velocity ω_{t1}, ω_{t2}. $\omega_{t1} = -\omega_{t2}$, so that the τ_{px} and τ_{tilt} are shown in Figure 7.

$$\tau_{px} = \tau_{tilt}\cos\theta_{tilt}$$

$$\tau_{tilt} = L_{total}\frac{d\theta_{tilt}}{dt} = L_{total}\omega_{t1}$$

$$L_{total} = I_F\ \omega$$

the resultant torques τ_p and τ_t are

$$\tau_p = \tau_{px_1} + \tau_{px_2} = 2\tau_{tilt}\cos\theta_{tilt} = 2I_F\ \omega_{f1}\omega_{t1}\cos\theta_{tilt}$$

$$\tau_t = \tau_{tilt1} + \tau_{tilt2} = 0$$

C. *Dynamic model of the spherical robot*

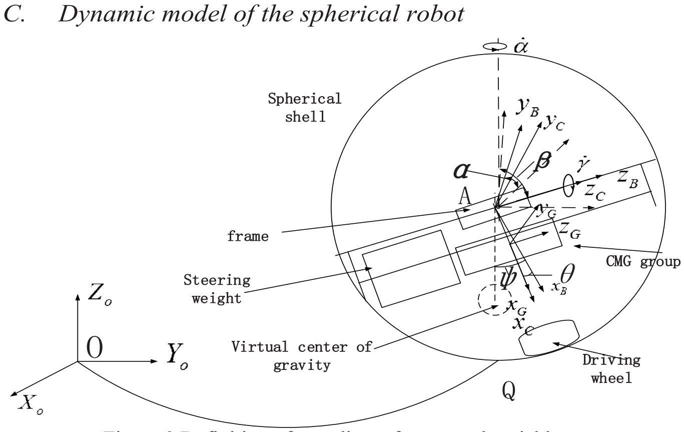


Figure 9 Definition of coordinate frames and variables

System model of the spherical robot consists of homogeneous spherical shell, frame, pendulum and CMG group. The homogeneous spherical shell is rolling on the horizontal ground. The frame is rigid body used to link the shell, driving wheel, steering weight and CMG group. The CMG group can be seen as the one part of the frame while not providing precession torques. We assign four coordinate frames as shown in Figure 9. $\Sigma_0\{X\ Y\ Z\}$ is the inertial coordinate frame, whose x-y plane is anchored to the horizontal plane; $Ax_By_Bz_B$ is the coordinate frame of the spherical shell, denoted by Σ_B, whose origin A is located at the center of the shell, and whose z axis represents the axis of rotation of the shell; $Ax_Cy_Cz_C$ is the coordinate frame of the central frame, denoted by Σ_C, whose origin also is located at the center of the shell, whose z axis coincides with z_B. $x_Gy_Gz_G$ is the coordinate frame of the CMG group, denoted by Σ_G. Let Q denote the contact point of the spherical shell with horizontal plane.

We define (i, j, k) to be the unit vectors of the inertial coordinate frame Σ_O. Let $S_\alpha := \sin\alpha$ and $C_\alpha := \cos\alpha$. The transformation between ΣO and ΣB is given by:

$$\boldsymbol{R}_B^O = Rot\left(z, \alpha + 90^\circ\right) Rot\left(y, \beta\right) = \begin{pmatrix} -S_\alpha C_\beta & -C_\alpha & -S_\alpha S_\beta \\ C_\alpha C_\beta & -S_\alpha & C_\alpha S_\beta \\ -S_\beta & 0 & C_\beta \end{pmatrix}$$

Let ω denote the angular velocity of the spherical robot with respect to the inertial frame. Then we have:

$$\boldsymbol{\omega} = \boldsymbol{R}_B^O \begin{pmatrix} 0 \\ \dot{\beta} \\ \dot{\gamma} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \dot{\alpha} \end{pmatrix} = \begin{pmatrix} -\dot{\beta}C_\alpha - \dot{\gamma}S_\alpha S_\beta \\ -\dot{\beta}S_\alpha + \dot{\gamma}C_\alpha S_\beta \\ \dot{\alpha} + \dot{\gamma}C_\beta \end{pmatrix} \tag{1}$$

For the Q point contact with the horizontal plane, we have $\boldsymbol{v}_Q = \boldsymbol{v} + \boldsymbol{\omega} \times \boldsymbol{r}_Q = 0$ (2) and $\boldsymbol{v} = \dot{X}i + \dot{Y}j$ (3) represents the linear velocity of the robot.

Substitute (1) to (2), then we have the velocity of the robot with respect to the inertial frame.

$$\begin{cases} \dot{X} = r\left(\dot{\gamma}C_\alpha S_\beta - \dot{\beta}S_\alpha\right) \\ \dot{Y} = r\left(\dot{\gamma}S_\alpha S_\beta + \dot{\beta}C_\alpha\right) \\ \dot{Z} = 0 \end{cases}$$

III. FORWARD MOTION-CONTROL STRATEGY OF THE ROBOT

Assume that there is no slipping between wheel and the internal surface of shell, the shell and the ground. The CMG group provides increased torque to control the frame so that it could achieve steadier motion and overcome some large obstacles. While the straight-driving motor is working, tilting torque τ_{tilt} is applied on the high-speed flywheel, and then the precession torque τ_{px} would be produced in the direction necessary for supplementing forward motion. The τ_{px} will be applied on the frame to overcome the lifting tendency, so most of the motor's output torques would be used to drive the robot roll instead of lifting the frame. Also it could be used to control the frame's rotating angle θ. Through this way, the utilization efficiency of driving torques would be maximized and the angle θ would be controlled effectively. These advantages will let the robot achieve higher acceleration, move more flexibly and have a steadier platform for sensors. When the driving motor applies backward torque on the shell, the τ_{px} can also be opposite to the above. The robot will decelerate as soon as possible.

Assume that the frame is seen as a fictitious pendulum and link to the A as Figure 9 shown. When the robot rolls, the CMG group cooperating with the motor controls the angle θ and the velocity. We can assume that the motion of the frame is sufficiently small to be ignored, thus $\theta \approx 0$ and $\beta + \varphi = 90°$. Substituting $\theta \approx 0$ and $\beta + \varphi = 90°$

for the spherical shell and the hollow axles,

$$\tau_{roll1} = \tau_{fb} + I_{byy}\ddot{\gamma}$$

for the frame and CMG group,

$$\tau_{roll2} + \tau_p = m_c g l \sin\theta + \tau_{fc} + m_c \ddot{\gamma} r$$

$$\tau_{roll1} + \tau_{roll2} = \tau_{roll}$$

τ_{roll} is the output torque of straight driving motor, Among the equations,

$$\tau_p = \tau_{px_1} + \tau_{px_2} = 2\tau_{tilt}\cos\theta_{tilt} = 2I_F\ \omega_{f1}\omega_{t1}\cos\theta_{tilt}$$

$$\tau_p = m_c g l \sin\theta$$

so we can have: $\ddot{\gamma} = \dfrac{\tau_{roll} - \tau_f}{I_{byy} + m_c r}$

After a period of accelerating process, we control angular velocity of the robot through PID control method $\dot{\gamma}_{ref}$

$$\tau_{roll} = K_P(\dot{\gamma}_{ref} - \dot{\gamma}) + K_I\int(\dot{\gamma}_{ref} - \dot{\gamma})dt + K_D\frac{d(\dot{\gamma}_{ref} - \dot{\gamma})}{dt}$$

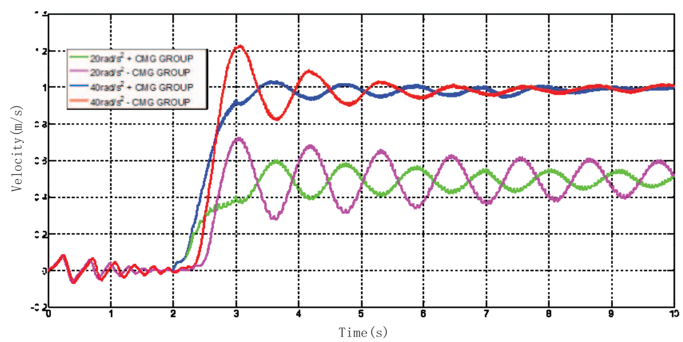


Figure 10 Speed comparison

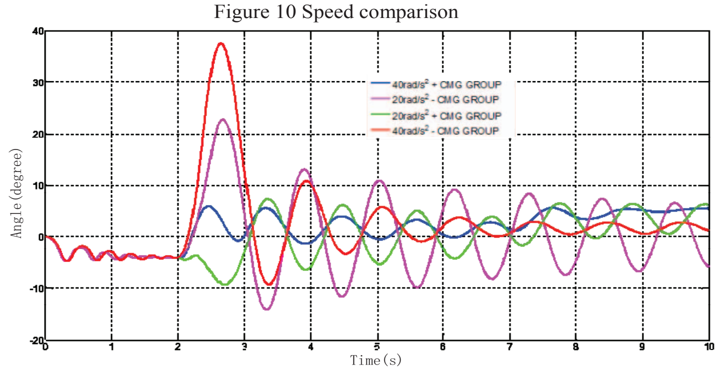


Figure 11 Lifting angle comparison

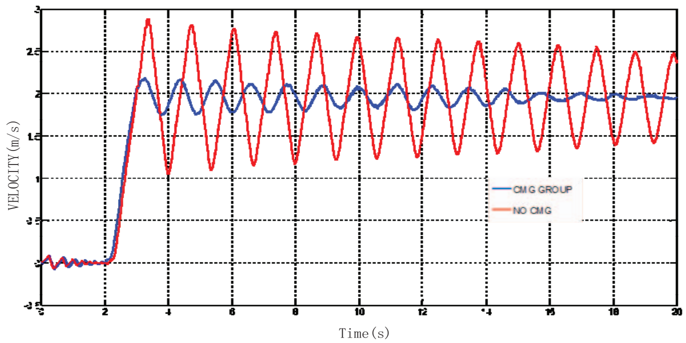


Figure 12 Speed comparison (large acceleration)

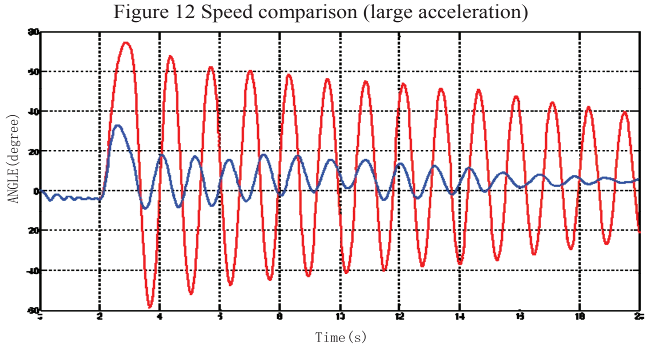


Figure 13 Lifting angle comparison comparison(large acceleration)

The Figure 10 and Figure 11 are comparison diagrams in common cases. Figure 10 is the linear velocity comparison chart of the spherical robot while the Figure 11 is the angle θ comparison chart. We can have that the robot is more sensitive and flexible with CMG group from Figure 10, and it also shows that the motor's output torque can be applied on the shell more directly. From Figure 11, it is clear that the pendulum can be held efficiently in use of CMG group and the range of the fluctuant angles θ must be much higher than the range without CMG in the accelerated rolling situation. Figure 12 and Figure 13 show that when the robot works in high accelerated situation and the angle θ goes to nearly 90° . If the motor's output torque is larger, the pendulum will be higher, then the robot's acceleration will be less and it will even lose control. From the blue line in both Figure 12 and Figure 13, we can have that the pendulum's fluctuant angles can be held by the CMG efficiently and the robot might roll smoother and steadier. On the other way, from control perspective, with help of the CMG group, we could apply larger torques on the spherical shell but not limited by the pendulum's mass and distance. If we want to get the same acceleration, the robot could be lighter. From practical perspective, when the pendulum's angle could be controlled in small range efficiently, the platform for sensors could be steadier, and some stability demanding sensors can be used, such as cameras which could enable the robot see the outside environment and it is important for one robot.

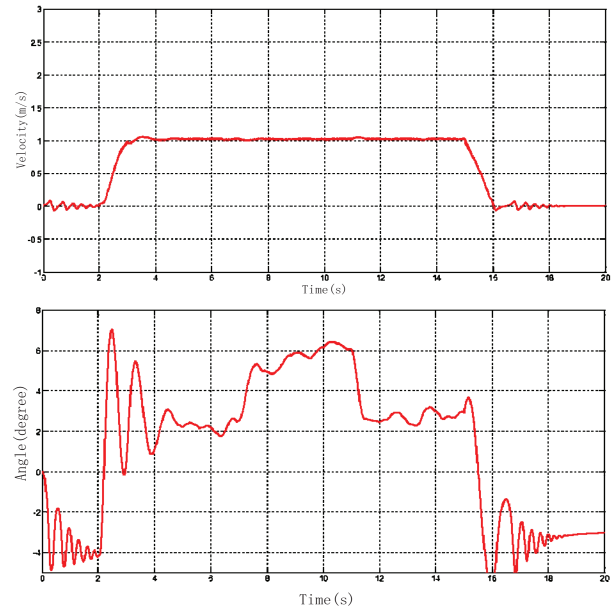
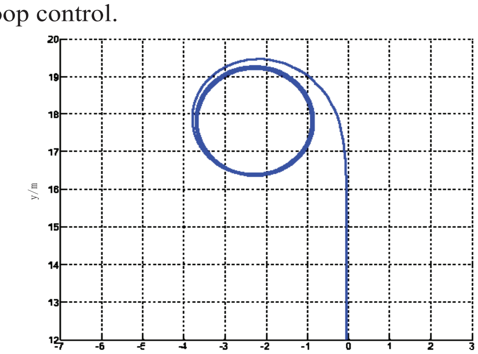


Figure 14 One stable situation of the robot

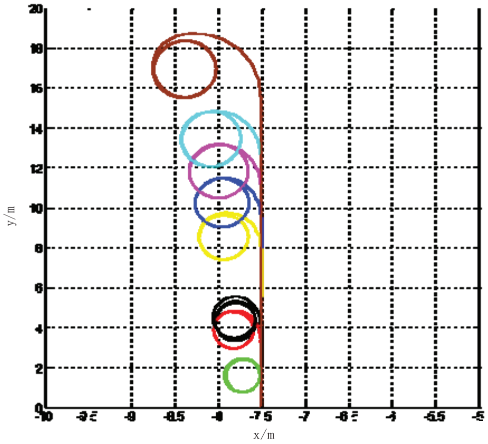
Robot's rolling speed is about 1m/s as Figure 14 shows. The pendulum's angular range is within the scope of the stable position $\pm 2^\circ$. This means the platform based on the frame is stable enough to carry sensors such as lasers and cameras. Thus the robot will be able to achieve outside information and control its movement to finish work by itself.

IV. STEERING CONTROL OF THE ROBOT

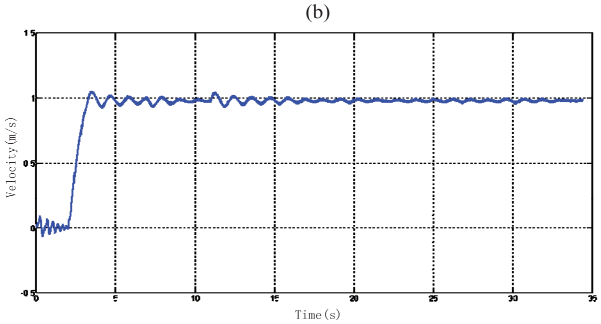
Assume that the robot is rolling at a uniform speed, the frame would remain upright during the movement, so we can have $\theta \approx 0$ and $\beta + \varphi = 90°$. The driving system can be simplified as two independent single-input control systems. One of them is the $\dot{\gamma}$-control system by controlling τ_{roll}, and it is used to control the angular rotating velocity. The other one is the steering control system. The robot changes the center of gravity of the frame by moving the steering weight and the angle φ and β would be changed as a result. The $\dot{\gamma}$ can be seen as a constant after control, therefore, the remaining system can be seen as a linear constant system. Moving the steering weight will push the robot to turn. This paper tests the robot's movement performance using single open-loop control.



(a)



(b)



(c)

Figure 15 Turning radius comparison

Figure 15 (a) shows a single test of the robot's steering performance. The spherical robot rolls at a 1m/s after acceleration in Figure 15(c). Then move steering weight to terminal of the lead screw and hold it. This will change the center of gravity and push robot to turn. As shown in Figure 15(a), the robot's turning radius decreases while the steering weight moving on the lead screw. The turning radius stabilizes at around 1.5m after some time and then the robot rolls in a smooth circular motion. The Figure 15(b) is testing the smallest turning radius. Control the robot's rolling linear speed from 0.1m/s to 1m/s. Then move steering weight to the terminal and hold it there. From Figure 15, we can have that the turning radius of the robot can reach 0.4m, and it is small enough for the robot to accomplish some simple movement route control experiments.

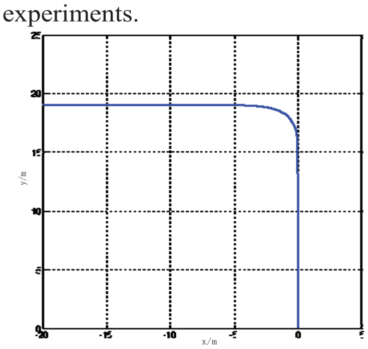


Figure 16 The right-angle route

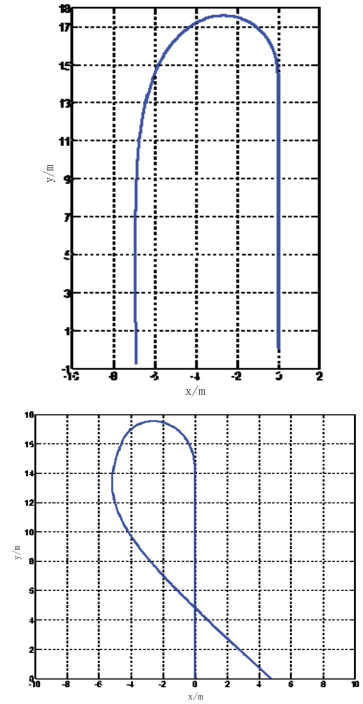


Figure 17 Common single route

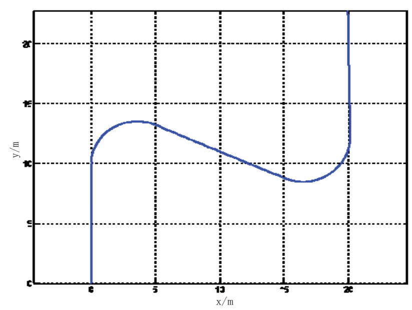


Figure 18 Two-turn route

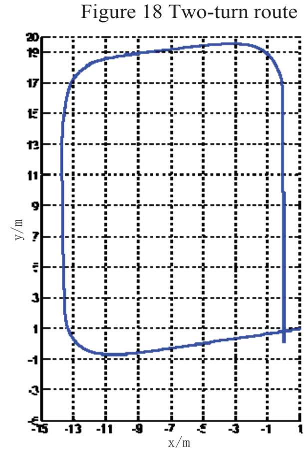


Figure 19 Parallelogram route

As shown in Figure 17, hold the speed around 1m/s. Then push the robot turn and get back to straight line motion then we can get the route in the Figureure. The Figureure means that the robot has basic ability to accomplish some complex routes. Then we conducted some extra experiments as Figure 18 and Figure 19 show. From the contents above, we can come to a conclusion that the spherical robot proposed by this paper has the ability to work in difficult situation and complete some complex motion paths.

V. Conclusion

In this paper, we presented a spherical robot equipped with CMG group. The cooperation enables the robot to get larger acceleration and overcome larger obstacles. This paper also proposes a velocity control system and the plan can make the robot hold the frame upright while accelerating or decelerating, so the robot rolls steadier and it could provide a stable platform for sensors. This might enable the robot finish work outside by itself.

VI. ACKNOWLEDGMENTS

This work is supported in part by the National Natural Science Foundation of China under grant No. 61305126.

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