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Research Article

A New Kind Spherical Mobile Robot

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Abstract: In this study, we design a new kind of spherical robot named BYQ-X. This robot has two moving statuses. When the robot moving on flat terrain, the spherical shell is folding, robot moves in traditional way by the pendulum. When the robot climbing a slope the climbing links stretch out and the spherical shell is unfolding. In this status the spherical is driven by electromotor directly. So the output torque of the electromotor is not limited by the pendulum, the robot can climbs slope of great gradient. Mechanical model of BYQ-X moving in traditional way on flat terrain and the mechanical model of robot climbing slope with climbing link are created. Mechanical model of BYQ-X turning in the status when climbing links stretch out is created. The mechanical structure and motion control system are introduced. Finally, the accuracy of these mechanical models is verified by simulation and experiment.

Keywords: Climbing link mechanism, mechanical model, mechanical structure, simulation and experiment, spherical robot

INTRODUCTION

Spherical mobile robot is completely sealed. The control system, electric motor and power source are all contained in the spherical shell which is used as movement mechanism (Ranjan and Mark, 1999). The spherical mobile robot' structure is simple. It can move with large agility on the ground. It can roll with zero turning radius and does not have the risk of falling over. It has high moving efficiency. It has its own superiority and it is focused by scholars in the world (Amir and Puyan, 2002; Ranjan *et al.*, 2007).

Traditional spherical mobile robot moves by changing the gravity center. The climbing ability of traditional robot depends on the percentage of pendulum, the higher percentage the pendulum occupy the stronger climbing ability the spherical robot has Xiao *et al.* (2004). But if the percentage of pendulum becomes higher the payload of the spherical robot will be lower. The percentage of the pendulum occupies the weight of traditional robot always less than 25%, the climbing ability is less than 15 degrees (Wang *et al.*, 2007).

For enhance the climbing ability of spherical robot a new kind of spherical robot with climbing link mechanism is designed. This new kind of spherical robot can move in traditional way by the pendulum or climb a slope of great gradient by the new climbing link mechanism. When the spherical robot moving in Flat terrain, the spherical robot moves in traditional way by the pendulum, now there are no passive friction wheel in the robot, the friction are all used for motive power, the energy utilization is high, the spherical robot can do the omnidirectional motion When the spherical robot climbs abrupt slope, it will use the climbing link mechanism (Zhao *et al.*, 2009).

In this study, we design a new kind of spherical robot named BYQ-X. This robot has two moving statuses. When the robot moving on flat terrain, the spherical shell is folding, robot moves in traditional way by the pendulum. When the robot climbing a slope the climbing links stretch out and the spherical shell is unfolding. In this status the spherical is driven by electromotor directly. So the output torque of the electromotor is not limited by the pendulum, the robot can climbs slope of great gradient. Mechanical model of BYQ-X moving in traditional way on flat terrain and the mechanical model of robot climbing slope with climbing link are created. Mechanical model of BYQ-X turning in the status when climbing links stretch out is created. The mechanical structure and motion control system are introduced. Finally, the accuracy of these mechanical models is verified by simulation and experiment.

THE MECHANISM STRUCTURE OF BYQ-X

Rolling motion driving portion*:* BYQ-X contains two subsystems: the rolling motion driving portion and the climbing link portion. The BYQ-X continues to use the spherical shell as the motion portion. The BYQ-X has two motion modes. In the first mode, the shell is in the fold status, as shown in the Fig. 1, components and control system are all contain in the spherical shell, the robot moves by the change of gravity center, driven by the pendulum the robot can move omnidirectionally, in this status the BYQ-X is similar to traditional spherical robot (Halme *et al.*, 1996; Bicchi *et al.*, 1997). As shown in the Fig. 2, the climbing links get out from

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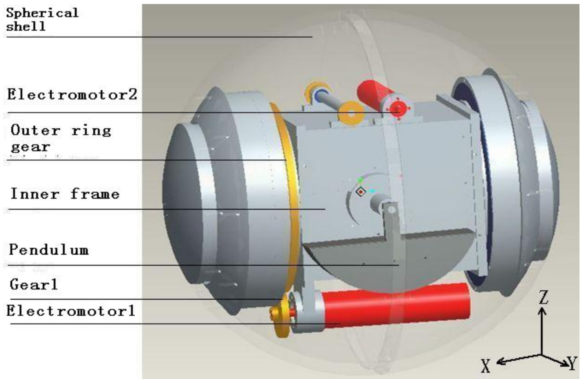

Fig. 1: Spherical robot in folding status

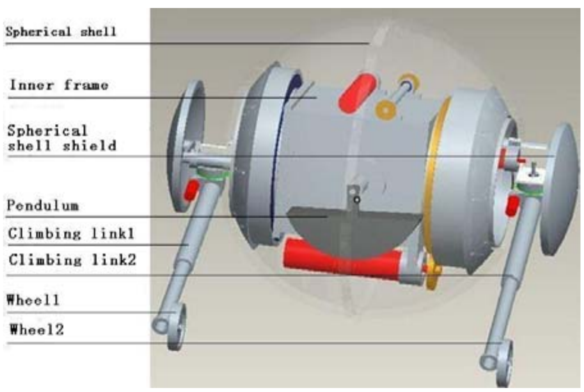

Fig. 2: Spherical robot in unfolding status

sphere shell. Wheels in the apex of links will contact the ground. The sphere is directly driven by the electromotor.

As shown in Fig. 1, when the sphere shell is folding, bearings in the sphere shell sustain the rotating inner frame. Electromotor 1 is fixed in the inner frame。Electromotor 1's gear meshes with the outer ring gear that is fixed in the spherical shell. So the inner frame could rolling around the axis X driven by electromotor 1. Electromotor 2 is fixed in the inner frame, it drives pendulum which could rolling around the axis Y. The BYQ-X can move omnidirectionally in the ground by electromotor1 and 2. In this status the structure and dynamics model of BYQ-X is similar to traditional spherical robot (Wang *et al*., 2007; Zhao *et al*., 2009). Figure 1 shows the spherical robot in folding status. Figure 2 shows the spherical robot in unfolding status.

As shown in Fig. 2, when the BYQ-X puts out links, Wheels in the apex of links will get to the ground. When the inner frame rolling relative to the spherical shell driven by electromotor 1, because climbing links are locked with the inner frame so the climbing links will rolling in the same direction, but the ground prevents the motion of climbing links., the spherical shell will rolling in the opposite direction, friction between the ground and spherical shell makes the sphere moving forward. In this status the electromotor 1 drives the robot directly. The driving moment does not depend on the pendulum but depends on the moment of electromotor.

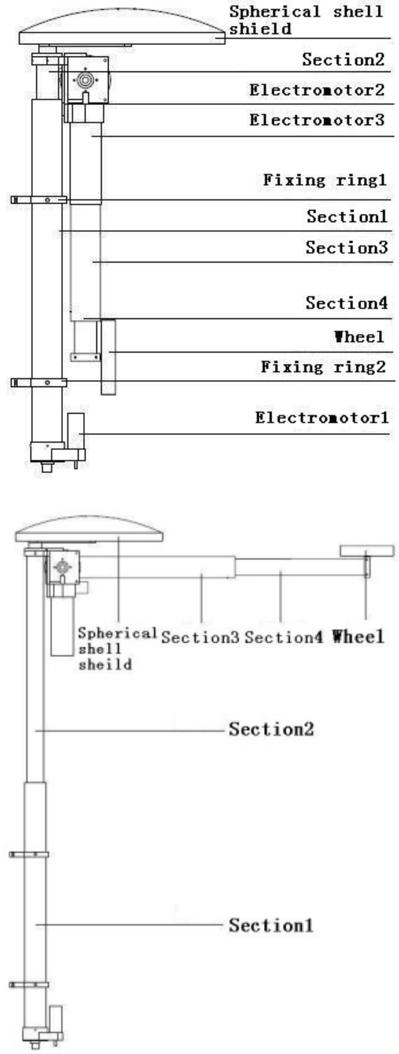

Fig. 3: Structure of climbing link

Structure of climbing link: BYQ-X has two climbing links, each climbing link has 4 sections. Each link has two sliding joints, one revolute joint and one wheel as shown in Fig. 3.

Fixing ring 1 and fixing ring 2 fix the section 1 on the inner frame. Section 2 inserts in section 1, it is driven by lead screw. Electromotor 1 which is fixed on section 1 drives the lead screw to make the section 2 stretch out and draw back. The top of section 2 connects with spherical shell shield. When climbing links shrink into the spherical shell, spherical shields will seal the spherical shell. Electromotor 2 fixed on section 2 drives the section 3 by angle bear. There is a brake between section 2 and section 3, the brake can lock the section 2 and section 3 to make them at any angle. Section 4 and section 3 connect by lead screw;

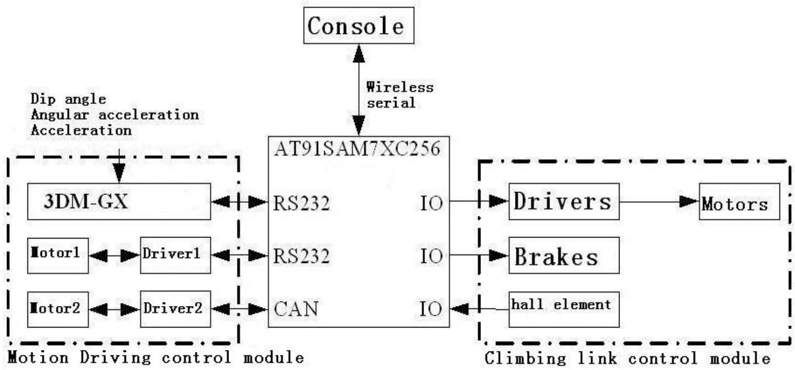

Fig. 4: Structure of the control system

the electromotor 3 fixed in the section 3 drives section 4 by lead screw.

The procedure of the spherical robot putting out climbing links is as follow: first the robot puts out section 2, second section 3 turns 90 degrees, last the robot puts out section4.

The control system:

BYQ-X could be divided into two parts: the motion driving part and climbing link part. These two parts are semi-open systems. So the control system has a main module and two Auxiliary Modules: the motion driving control module and the climbing link control module as shown in Fig. 4.

The main module is fixed on the inner frame, it uses the 32 bits ARM7 processor AT91SAM7XC256 as the main processor, uses the RF200 wireless transmission module receives the console's order and transfer feedback data to the console. It use the serial port transfer the angular velocity, angular acceleration and Eulerian angles parameters obtained by the gyroscope fixed in the inner frame. The motion drive control module communicate with electromotor2 by CAN bus, communicate with electromotor 1 by RS232 serial. The motion driving control module could drive the spherical robot do the line motion, curve motion and static balance by electromotor 1and 2. Electromotor 1 is MAXON RE50, its driver is EPOS 50/5, Electromotor 2 is MAXON EC40, its driver is Elmo Solo Whistler.

Climbing link control module controls electromotor on the link to make the link stretch out and draw back. This module also could gather the data from hall elements and limit switch fixed on the link. Each link has 3 MAXON electromotor 1 OGURA brake and 1 LMD18200T driver.

MECHANICS MODEL AND SIMULATION

Mechanics model of BYQ-X in the folding status: When the BYQ-X is in folding status, the mechanical model of BYQ-X is similar to traditional spherical robots. In this mechanical model the robot is simplified to a pendulum, a spherical shell and a frame which is

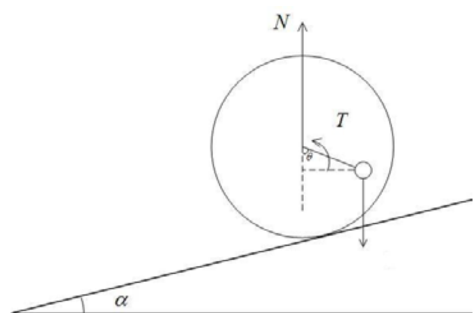

Fig. 5: Force analysis of traditional spherical robot

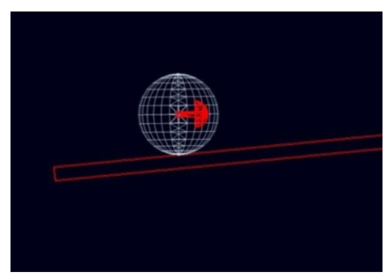

Fig. 6: Simulation of traditional spherical robot climbing slope by ADAMS

simplified to an axis cross the center of spherical. The driving torque is the eccentricity moment torque of the robot (Bhattacharya and Agrawal, 2000). The mechanical model is shown in Fig. 5. α is the gradient, R is the radius of the spherical shell. l is the equivalent length of the pendulum. G is the gravity of the whole robot. μ is the share of the gravity of pendulum in the G. T is the torque of electromotor. θ is the angle between the pendulum and the vertical direction.

In this time the expression of the electromotor torque is shown as Eq. (1):

$$T = \mu \times G \times l \times \sin\theta \tag{1}$$

In the ideal hypothesis, The equivalent length of the pendulum $l = R$, f is the maximum frictional force between the slope face and the spherical shell. The influence of parameter μ on the climbing ability is described as:

$$f \times R = \mu \times G \times l = \mu \times G \times R \tag{2}$$

$$f = G \times \sin\alpha \tag{3}$$

$$\alpha = \arcsin\mu \tag{4}$$

The weight of the BYQ-X is 74 kg, the diameter of the spherical is 630 mm, the length of the climbing link is 1.4 m and friction coefficient of the slope is 0.91. By equations in the front of this paper we can obtain that when the BYQ-X in the folding status the α is 15°.

Simulation of the climbing ability of BYQ-X in the folding status: The simulation software ADAMS is used to simulate the mechanical model. As shown in Fig. 6, a rolling plane is created in ADAMS, the gradient of the plane will increase with the rolling of the plane. The model of Spherical robot is created by PRO-E and sent into ADAMS. The model of spherical robot is moving on this plane, when the acceleration of the robot is 0, we consider that the robot reaches the upper limit of its climbing ability.

At last, the result of simulation indicates that the largest gradient that spherical robot can climb up is less than or equal to 15°. This result is similar with the result obtained by equations in front. This result verifies the validity of the mathematical model of BYQ-X climbing the slope in its folding status.

The mechanics model of BYQ-X in the unfolding status: When the two climbing links stretch out, the position of the pendulum will not change. Now the mechanical model of the BYQ-X climbing the slope is shown in the following Fig. 7. Two climbing links and wheels can be simplified into one link and one wheel. The whole model could be divide into three parts: the spherical, the climbing link and the wheel. In Fig. 7, α is the gradient of the slope, θ is the angle between the climbing link and the slope surface, $G_q$is the gravity of the spherical, G_h is the gravity of wheel, G_g is the gravity of climbing link, F_m is the friction between spherical and the slope. f is the friction between wheel and the slope. N_q is the supportiveness exerts by the slope surface on the spherical, N_h is the supportiveness exerts by the slope surface on the wheel.

First, we analyze the force situation of the climbing link. As shown in following Fig. 8, N is the vertical force acting on the tip. Correspondingly there is another equal and opposite in direction force on the other port of the link. These two force form a couple which is balance to the electromotor torque T. F_q and F_n are the

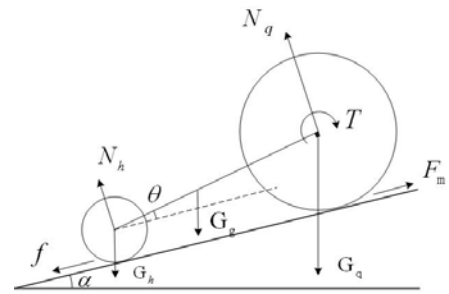

Fig. 7: Force analysis of robot climbing slope by climbing link mechanism

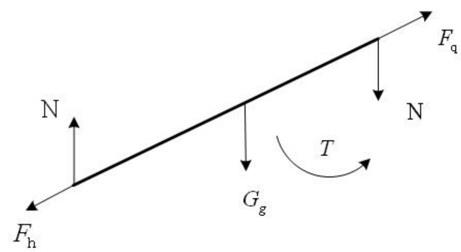

Fig. 8: Force analysis of climbing link

components of the forces exert by spherical and wheel on the climbing link along the link.

F_h is the component of Interaction force between wheel and link along the link. In this time the pressure on the slope surface exerts by the wheel is the sum of the gravity of the wheel and the pressure force exerts by link on the wheel.

We divide the forces in the ends of the link to component forces along the link and along the vertical direction, when the system in the force balance status, the forces along the link and along the vertical direction are 0, and the resultant force couple is 0, k_q is the friction coefficient of the spherical shell, δ_q is the rolling friction of the spherical shell, δ_h is the rolling friction of the wheel, R is the radius of the spherical, r is the radius of wheel. The largest traction F_m between the slope surface and the robot is shown in following equations:

$$F_m = \left(G_q + \frac{G_g}{2}\right)\sin\alpha + F_q\cos\theta \tag{5}$$

$$F_m = k_q\left[\left(G_q + \frac{G_g}{2}\right)\cos\alpha + F_q\sin\theta - N_d\right] \tag{6}$$

We can obtain the equations about α the largest gradient the robot can climb:

$$\frac{R-r}{\sin\theta} = l_e \tag{7}$$

$$F_m R + \delta_q\left[\left(m_q g + \frac{m_l g}{2}\right)\cos\alpha + F_q\sin\theta - N\right] - N l_e\cos\theta = 0 \tag{8}$$

$$\frac{\delta_h[(m_h+\frac{m_l}{2})g\cos\alpha+N_d-F_q\sin\theta]}{r}+(G_h+\frac{G_g}{2})\sin\alpha-F_q\cos\theta=0 \qquad (9)$$

We simultaneous Eq. (5-9) we can obtain the value of α.We can obtain that when the BYQ-X in the unfolding status the α is 25°.

Simulation and analysis of the BYQ-X in unfolding status: The simulation software ADAMS is used to simulate the movement of BYQ-X spherical robot climbing slope with climbing link. As shown in Fig. 9, a rolling plane is created in ADAMS, the gradient of the plane will increase with the rolling of the plane. The model of Spherical robot is created by PRO-E and sent into ADAMS. The model of BYQ-X is moving on this plane, when the acceleration of the robot is 0, we consider that the robot reaches the upper limit of its climbing ability.

At last, the result of simulation indicates that the largest gradient that spherical robot can climb up is less than or equal to 25°. This result is similar with the result obtained by equations in front. This result verifies the validity of the mathematical model of BYQ-X climbing the slope in its unfolding status.

The mechanics model of BYQ-X in the unfolding status: Turning flexibility is a basic ability of mobile robot. When the BYQ-X is turning in unfolding status, two wheels provide the driving forces. These two forces form a couple, when this couple is larger than the friction couple between the ground and the spherical, the spherical will turn. In this section we create the mechanical model of the BYQ-X turning in unfolding status. The side view of mechanical model of the BYQ-X turning is shown in the following Fig. 10.

N_h is the supportiveness exerts by the slope surface on a wheel. N_q is the supportiveness exerts by the slope surface on the spherical. θ is the angle between the climbing link and the slope surface, G_q is the gravity of the spherical, G_h is the gravity of wheel, G_g is the gravity of climbing link, T is the electromotor torque. f is the frictional force between ground and the wheel.

The supportiveness exerts by the slope surface on a wheel is shown as follow Eq.10:

$$N_h=\frac{1}{2}(\frac{T}{l*\cos\theta}+\frac{1}{2}G_g+G_h) \qquad (10)$$

The coefficient of friction between wheel and surface is k_2, the friction f is shown as follow Eq. (11):

$$f=\frac{1}{2}(\frac{T}{l*\cos\theta}+\frac{1}{2}G_g+G_h)*k_2 \qquad (11)$$

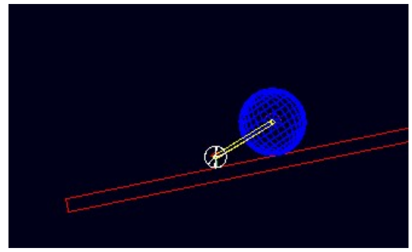

Fig. 9: Simulation of spherical robot climbing slope with climbing link by ADAMS

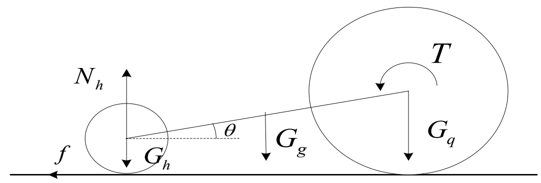

Fig. 10: The side view of mechanical model of the BYQ-X turning

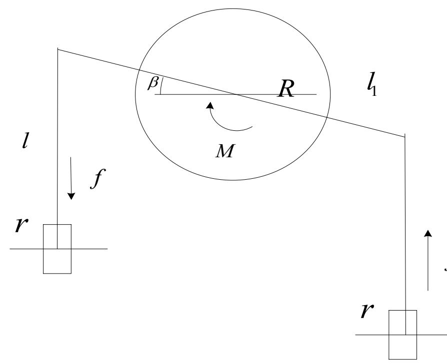

Fig. 11: The plan view of mechanical model of the BYQ-X turning

Turning flexibility is a basic ability of mobile robot. In this section we create the mechanical model of the BYQ-X turning in unfolding status. The plan view of mechanical model of the BYQ-X turning is shown in Fig. 11.

l is the length of the climbing link, l_1 is the length of the assistant climbing link, M is the friction couple exerts by the ground on the spherical. β is the angle the robot has turned. We can obtain these equations:

$$N_q=G_q+\frac{1}{2}G_g-\frac{T}{l*\cos\theta} \qquad (12)$$

$$M=\mu N_q=\mu(G_q+\frac{1}{2}G_g-\frac{T}{l*\cos\theta}) \qquad (13)$$

When the spherical turns the Eq. (14) was establish:

$$\begin{aligned}M&\le 2*f_2*(l_1+R)*\cos a\\&=2*\frac{1}{2}(\frac{T}{l*\cos\theta}+\frac{1}{2}G_g+G_h)*k_2*(l_1+R)*\cos a\end{aligned} \qquad (14)$$

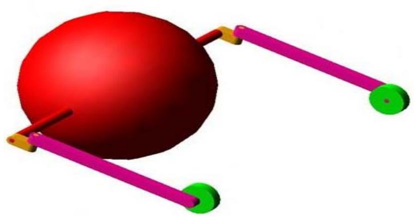

Fig. 12: Simulation of spherical robot turning in unfolding status by ADAMS

The angular acceleration $\ddot{\beta}$ is shown as follow:

$$\ddot{\beta}=(\frac{T}{l*\cos\theta}+\frac{1}{2}G_g+G_h)*k_2*(l_1+R)*\cos a \\ -\mu(G_q+\frac{1}{2}G_g-\frac{T}{l*\cos\theta}) \tag{15}$$

From these equations we can see that the $\ddot{\beta}$ increases with the T. Calculate with the parameters of BYQ-X , even the T = 0, the robot can turn until the climbing link contact the spherical, the β is more than 30°.

Simulation and analysis of the BYQ-X in unfolding status: The simulation software ADAMS is used to simulate the movement of BYQ-X spherical robot turning in unfolding status. As shown in Fig. 12. The model of Spherical robot is created by PRO-E and sent into ADAMS.

At last, the result of simulation indicates that the BYQ-X spherical robot can turn 32°.

EXPERIMENT

Transformation test: In the beginning of the test, the robot is in folding status, the PC console sent the orders: stretch out links, unfold links and so on to BYQ-X by wireless communicate modules. When the BYQ-X receives orders the robot begins the process of transformation. The robot puts out section 2, then section 3 turns 90°, at last the robot puts out section4. The process is shown in Fig. 13.

Turning experiment: In this test, the robot is in unfolding status, we set the $T=0$, the BYQ-X can turn 32°, until the climbing link contact the spherical, and then we set $T=2N\cdot m$, the BYQ-X can also turn 32°, until the climbing link contact the spherical, but the time of the turning process is shorter. The process is shown in Fig. 14:

Climbing experiment: As shown in Fig. 15, we make a slope by wood board. Then we cover the slope by rubber gasket to increase the friction coefficient to simulate the out-door road condition like soil pavement and concrete pavement with big friction coefficient. The friction coefficient of the slope is 0.91 (Antol, 2003). The weight of the BYQ-X is 74 kg, the diameter of the spherical is 630 mm and the length of the climbing link is 1.4 m. By equations in the front of this paper we can obtain that when the BYQ-X in the folding status the α is 15°, when the BYQ-X in the unfolding status the α is 25°.

Fig. 13: Process of BYQ-X transformation

Fig. 14: Process of BYQ-X turning

Fig. 15: Climbing experiment

As shown in the Fig. 15, we do the climbing experiment of BYQ-X in two statuses. First we do the climbing experiment of BYQ-X in the unfolding status. We set the gradient of the slope from 20° to 30°. Then we put the BYQ-X in unfolding status on the slope, and put barriers in back and front of the robot to make it stop in the slope. Then we start the robot and take away barriers to make the robot move in the slope without initial velocity. We record movement distances in 2 sec as shown in Table 1:

From Table 1 we can see that when gradient of the slope changes from 20° to 30° the value of movement distance changes from positive number to negative number. The robot move down along the slope on the heavy gradient slope and move up along the slope on the light gradient slope. Because the robot's initial velocity is 0, so the gradient of the slope that the robot stop on it is the climbing ability of the robot. From data in Table 2 we can know that the maximum climbing angle of robot in unfolding status is in the range 22° to 24°, we do the climbing experiment of BYQ-X in the unfolding status again; we set the gradient of the slope

Table 1: Experiment data of BYQ-X in unfolding status

Gradient (degree)	20	22	24	26	28	30
Movement distance in 2 seconds (m)	0.73	0.17	-0.10	-0.21	-0.57	-1.03

Table 2: Experiment data of BYQ-X in unfolding status

Gradient (degree)	22.5	23	23.5
Movement distance in 2 sec (m)	0.10	0.05	-0.07

Table 3: Experiment data of BYQ-X in folding status

Gradient (degree)	10	12	14	16	18	20
Movement distance in 2 sec (m)	0.72	0.31	-0.12	-0.31	-0.69	-1.31

Table 4: Experiment data of BYQ-X in unfolding status

Gradient (degree)	12.5	13	13.5
Movement distance in 2 sec (m)	0.15	0.07	-0.05

from 22° to 24°. Then we record the movement distance in 2 sec as shown in Table 2:

From data in Table 2 we can know that the maximum climbing angle of robot in unfolding status is in the range 23° to 25° this data is consistent with the value obtained by equations.

First we do the climbing experiment of BYQ-X in the folding status. We set the gradient of the slope from 10° to 20°. Then we put the BYQ-X in folding status on the slope, and put barriers in back and front of the robot to make it stop in the slope. Then we start the robot and take away barriers to make the robot move in the slope without initial velocity. We record the movement distance in 2 seconds as shown in Table 3:

From data in Table 3 we can know that the maximum climbing angle of robot in unfolding status is in the range 120° to 14°, we do the climbing experiment of BYQ-X in the folding status again; We set the gradient of the slope from 12° to 14°. Then we record the movement distance in 2 seconds as shown in Table 4:

From data in Table 4 we can know that the maximum climbing angle of robot in folding status is in the range 13° to 13.5°, this data is consistent with the value obtained by equations.

From the result of experiment we can see that the climbing ability of BYQ-X in unfold status is in the range 23° to 23.5° in fold status is in the range 13° to 13.5°.

Experiment result analyze: We can obtain these conclusions according the experiment result:

- The BYQ-X can finish the process of transform.
- The BYQ-X can turn in the unfolding status.
- The climbing link mechanism can enhance the climbing ability of BYQ-X.

The climbing ability of the BYQ-X is close to the theoretical values, the validity of the climbing link mechanism are verified. But these two actual values are all less than theoretical values. The primary reason is the friction between components inside the robot. The secondary reason is the form of pendulum is not regulation, so the torque obtained by the pendulum is not exact.

CONCLUSION

In this paper a new kind of spherical robot with climbing link mechanism is designed. This new kind of spherical robot can move by traditional way by the pendulum or move through a slope of great gradient by the new climbing link mechanism. When the spherical robot moving in Flat terrain, the spherical robot moving by traditional way by the pendulum, when the spherical robot cross abrupt slope, it will use the climbing link mechanism. so the BYQ-X can be used in outdoor environment, the applied range of the spherical robot is expanded.

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