Configuration design and motion performance analysis of a new wheeled rolling robot

Bian Hui

Yanshan University

Zhang Chun

Yanshan University

wang shi jie (✉ wangshij669988@163.com)

Yanshan University <https://orcid.org/0000-0002-2260-9461>

Research Article

Keywords: Rolling robot, wheeled robot, cardiological adjustment device, mechanism, variable diameter, eccentric torque drive

Posted Date: September 27th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1161950/v2>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Title page

Configuration design and motion performance analysis of a new wheeled rolling robot

Hui Bian, born in 1982, at present, he is the master supervisor and associate professor of *Yanshan University*. His research interests include the theory and application of parallel robot mechanism, rehabilitation robot and bionic robot.

Tel: 13784526496; E-mail: ysubh@ysu.edu.cn

Chun Zhang, born in 1995, she obtained the honor of master's degree from *Yanshan University* in June 2020. Her research interests include parallel robot mechanism theory and application, rolling robot.

E-mail: 1751565072@qq.com

Shi-Jie Wang, born in 1998, is currently a master in mechanical and electronic engineering of *Yanshan University*.

Tel: 15848632049; E-mail: wangshij669988@163.com

Jia-Chen Li, born in 1997, is currently a master in mechanical and electronic engineering of *Yanshan University*.

E-mail: jdxyljc@whut.edu.cn

Xue-Lei Xie, born in 1998, is currently a master in mechanical and electronic engineering of *Yanshan University*.

E-mail: junyan318@126.com

Wen-Bo Guan, born in 1997, is currently a master in mechanical and electronic engineering of *Yanshan University*.

E-mail: 1445653876@qq.com

Corresponding author: Shi-Jie Wang E-mail: wangshij669988@163.com

Configuration design and motion performance analysis of a new wheeled rolling robot

Hui Bian^{1,2} • Chun Zhang³ • Shi-Jie Wang^{1,2} • Jia-Chen Li^{1,2}

Abstract: A new wheeled rolling robot is designed based on planar 3-RRR parallel mechanism and spoke wheel with variable diameter, by adjusting the 3-DOF outputs of the planar 3-RRR parallel mechanism, the deformation and rolling motion of the rolling robot are realized, the rotation output of the parallel mechanism realizes the differential change of the diameter of the two supporting wheels of the rolling robot, and the moving output of the parallel mechanism changes the mass distribution of the system, so that the rolling robot can complete the forward, backward, turning and other motions. Based on the introduction of the performance parameters, driving system, variable diameter wheel configuration and motion mechanism of the rolling robot, the eccentric driving torque is analysis and the existing space of the eccentric torque is given, so as to further complete the selection of the driving motor of the robot. This article analysis three typical motions of robots and its performance parameters, such as straight movement, turn movement, climbing exercise, and builds a simple prototype under laboratory conditions to verify the feasibility of the three movements.

Keywords: Rolling robot; wheeled robot; cardiological adjustment device, mechanism; variable diameter; eccentric torque drive

1 Introduction

With the rise of the robot industry, the structural structure of various functions is constantly emerging ^[1]. The rolling robot exists as a special robot ^[2-5], and changes the torque of the support point in turn through the constant adjustment of the internal centroid of the structure to realize various movements ^[6-8]. Due to its characteristics of high flexibility,

strong stability, energy consumption, etc. ^[9,10], the road is uneven, the environmental rugged investigation and exploration is rapid, received by colleges, scientific research institutions and high-tech enterprises ^[11-13].

Most of the rolling robots are spherical structures, HALME et al. ^[14] uses the wheels of crawling in the cassette to develop Rollo, and the robot is rolled by controlling the movement of the car ^[15]. Similarly, BERNSTEIN et al ^[16] also used a trolley drive to design SPKR+ to improve stability. The robot was driven by two-wheeled car. KARAVAEV et al. ^[17] modified by Mecanum Wheel as the support of the bucket internal trolley and established a kinematics model, and controlling the movement of the robot. CHEN et al ^[18] drives the outer cassette scroll through the two orthogonal arrangements of the motor drive, and the outer casing is rolled, and the full-directional motion performance of the robot has also been confirmed. Such rolling robots often have low stability, can't be self-avoiding, anti-side slip, grip performance difference, etc. In order to improve the stability of the rolling robot, there have been a variety of different structural rolling robots.

Beijing Jiaotong University is a vehicle body with a plane 6R single-ring closed link, and has designed multi-mode two-wheel mobile robot ^[19]. By controlling the body deformed, the robot can perform a variety of deformation according to the different environments and the set tasks, and switch to the corresponding walking system ^[20]. Harbin Institute of Technology uses a continuous electric moisture-wet effect ^[21] as a micro mechanism, drives the robot movement, effectively narrowing its volume to expand the application range. Megascout robots designed by KRATOCHVI ^[22] can sense differences in real-time road conditions to switch different action wheels to adapt to changes in road environment. The spherobot ^[23] developed by the Ranjan Mukherjee team adjusts the centroid position along the movement of the metal spokes, so that the robot is moved under the gravity

✉ Shi-Jie Wang
wangshij669988@163.com

1 Parallel Robot and Mechatronic System Laboratory of Hebei Province, Yanshan University, Qinhuangdao 066004, China
2 Key Laboratory of Advanced Forging & Stamping Technology and Science (Yanshan University), Ministry of Education, Qinhuangdao 066004, China
3 Beijing Institute of mechanical equipment, Beijing 100080, China

moment. In order to further improve the flexibility of heavy moment drive, Vrunda Joshi ^[24] improved the spoke weight drive structure, but due to the limitation of the weight of the weight, the rapid speed of such driving mode movement is relatively slow.

Comprehensively consider the configuration, driving method of various robots, driving methods and parallel mechanism ^[25], the speed advantage of wheeled walking, a new wheel rolling robot based on parallel mechanism, small structure, light weight, flexible and fast, flexible, and through a number of physical experimental research on robot platform, comprehensive testing robots' mobile performance, motor performance, climbing performance, and balance performance, etc. to assess the role environment of the robot and analyze the dynamics model and the effectiveness of the control strategy to continue to improve the important components of the robot to improve the performance of robots. At the same time, the R & D of the robot will provide new technologies, new choices for innovative design, new robots, including exploration, military mine, cargo transportation, and mass entertainment.

2 Robot configuration design

2.1 conceptual design

The original intention of the scalable wheel-diameter rolling robot is to complete the reconnaissance, search and rescue tasks in a variety of terrains and road conditions. The conceptual model of the robot design is shown in Figure 1. It can be broadly divided into three parts: the frame part, the drive unit of the center of gravity adjustment device based on the parallel mechanism, and the spoke-type variable-diameter wheel.

Figure 1 Robot conceptual model

The robot moves under the torsional torque generated by the center of gravity adjustment device carried by the 3-RRR biplane parallel mechanism ^[26], the power take-off shafts, telescopic universal joint couplings and intermediate rotating shafts at both ends are output to the coupling driving wheel, which causes the change of spoke angle, and then affects the concentric scaling of the outer ring circular arc, so as to change the wheel diameter of the robot, and realize two kinds of movements: straight walking on the same wheel and turning with different wheel diameter.

2.2 Overall index parameter design

Combined with the overall design principles and functional requirements of wheeled rolling robot, referring to the structural parameters and design task requirements of various existing rolling robots, the index parameters of the robot prototype are preliminarily drawn up, as shown in Table 1 below.

Tab. 1 preliminary parameters of robot

Name	Symbol	Proposed parameters
Total weight of robot	M_t	$\leq 4\text{Kg}$
Center distance of left and right wheels	L	370mm
Coupling wheel radius	n	85mm
Spoke assembly length	m	135mm
Zoom angle	ρ	$[10^\circ, 60^\circ]$
Roll angle	α	$[0, 15^\circ]$
Walking speed	$V_{\max}$	$\geq 1\text{m/s}$
Climbing slope	γ	10°
Maximum wheel diameter	$D_{\max}$	420mm
Minimum wheel diameter	$D_{\min}$	340mm
General traveling	R_L^o	190mm

wheel diameter		
Obstacle crossing height	Y_z	$\geq 20\text{mm}$
Adaptable terrain	Grassland, highway and forest land	

2.3 Design of spoke variable diameter outer wheel

The rotary-sparked variable diameter outer wheel is composed of a coupling wheel, a joint frame, a ball head joint bearing, a T-column, a spoke, and a scalable outer wheel, and the configuration is shown in Figure 2. The arc pieces of the same specification front and rear stacks, the left side of the arc sheet opens the same specification, the slide of the adjacent arc sheet is connected through the chuck, and the other end of the chuck is connected to the spokes.

Figure 2 Component drawing of variable diameter adjustable spoke type outer wheel

The spoke bottom end and the coupling wheel bearing roller coaxial edge is solid, realizes the connection of the diameter outer wheel and the coupling wheel, then passes through the openings T-column through the spoke, the variable diameter outer wheel is connected to the rack wheel to obtain a rotary variable diameter outer wheel. In order to solve the balance problem of the scalable outer wheel of the robot in the non-rolling state and avoid the contraction of the spoke group under the action of gravity, three sets of support springs are arranged between the coupling driving wheel and the coupling fixed wheel.

Figure 3 Single branch partial enlarged view

Figure 3 shows a single branch schematic diameter outer wheel, which is known that the spoke and coupling wheel joints are known, and the T-column and the connecting wheel joints and the collet and the outer circular arc sheets are R pars; the connection between the spokes and the T-column and the joints of the chuck and the circular arc contain each contain one P sub. At the same time, the design of the outer chuck is tightly connected to the adjacent circular arc, so that the arc sheet remains compactly in the diameter of the contact wheel and keep the robot movement in a steady state, the body does not cause trembling and instability due to the mating of the transfers wheel components.

Figure 4 Single branch wheel diameter contraction diagram

The scaling of the radius of the robot is rotated by the drive shaft, and the angle θ of spokes is driven. The spokes are stretched in the direction of the T-column, and the outer circular arc sheet is subjected to the zoom movement. Taking its pulse diameter as an example, as shown in Figure 4, the drive shaft is rotated in the counterclockwise direction, and the coupling wheel drives the spokes, the spokes are contracted along the T-column, so that the outer collet is slidable in a clockwise direction of the arc slide, complete contraction. Figure 5 shows the overall wheel shrinkage variation of the robot, and the

wheel is magnified motion.

Figure 5 Change diagram of wheel diameter contraction

3 Construction of robot driving system

3.1 Design of workspace driven by eccentric torque

The driving principle of the cardiological adjustment device can be briefly summarized as destroying the internal balance state of the robot system through the cardiac of gravity offsets, so that the system moves to restore or find a new balance state. The structural schematic diagram of the cardiological adjustment device is shown in Figure 6, the workspace of the 3-RRR biplane parallel mechanism contains the movable range of the cardiac of gravity offset of the robot, and the analysis of the reachable motion space of the parallel mechanism is the basis of studying the existence space of eccentric torque of the robot.

When the diameters of the left and right wheels are consistent, the robot moves in a straight line driven by the center of gravity adjustment device. By adjusting the offset position of the center of gravity of the system, the robot can roll forward or backward. The workspace of 3-RRR parallel mechanism is analyzed and combined with its force, the effective workspace of the center of gravity adjustment device of rolling robot is obtained, which is defined as eccentric torque workspace.

Fig. 6 Structure schematic diagram of cardiological

adjustment device

In order to find out the optimal $L_1:L_2$ rod length ratio parameters and obtain the optimum eccentric torque driving space. According to the simulation operation test of the mechanism, take four groups of data with L_1 length of 50mm, 60mm, 70mm and 80mm respectively, the corresponding dimensions of L_2 are 110mm, 120mm, 90mm and 80mm, four groups of rod length ratio parameters are calculated $(5:11)1 \cdot (3:5)2 \cdot (7:9)3 \cdot (1:1)4$. By comparing the degree of spatial defects, the variation law of spatial defects of the driving force with the ratio coefficient of rod length is explored. By observing the movement space point set of the center of gravity adjustment device, it is found that within $\varphi \in [-30^\circ, 30^\circ]$, there are some irregular incomplete positions in the workspace, intercept the workspace plan of the working platform rotation angle φ under the five positions of $\varphi = 30^\circ, 15^\circ, 0^\circ, -15^\circ, -30^\circ$, as shown in Figure 7 below.

Fig. 7 change diagram of spatial defect state under each group of parameters

The results show that when: $L_1:L_2=1:1$, as shown in Figure d), the space section is completely connected, and the trend curve of the workspace is smooth. By calculating the driving force space under another rod length ratio, we could find that when $L_1:L_2 \geq 1$, the section of eccentric moment workspace basically has no incomplete position, at this time, the parallel mechanism of the center of gravity adjustment device moves

smoothly and stably.

On the premise of the determined frame size, the installation size of the servo actuator base of the center of gravity adjustment device is fixed, in the frame with a radius of $R_B=120\text{mm}$, the radius of the working platform is $r_d=35\text{mm}$, and $L_1+L_2=160\text{mm}$ (Fixed value). With the value change of L_1 and L_2 , the space of driving force changes accordingly.

Based on the above analysis, the rod group coefficient size of center of gravity adjustment device is determined: $L_1=80\text{mm}$ 、 $L_2=80\text{mm}$. Through the omni-directional space three-dimensional search method^[27], in MATLAB, it is obtained that the eccentric torque exists in the workspace, as shown in Figure 8 below.

Fig. 8 Existence space of eccentric moment

According to the results, the eccentric moment workspace obtained by the optimization calculation of the rod length parameters is regular and continuous. This shows that cardiological adjustment device of the rolling robot has decent motion fluency and good eccentric torque transmission performance under this set of rod length design parameters, which shows that the robot can obtain uninterrupted driving torque in the rolling process.

3.2 Analysis of gravity center adjustment device platform

The working platform of the center of gravity adjustment device is used to carry equipment components such as battery pack, controller, driving circuit and series of sensors. The mass and volume of the battery pack are the main considerations in the design of the robot working platform. It can be seen from the eccentric torque formula generated by the cardiological adjustment device when the robot walks in a straight line that the structural size

parameters of the robot are certain, the eccentric torque is positively correlated with the sinusoidal function of the swing angle of the parallel mechanism rod group. So, there is:

$$\beta \geq \arcsin \frac{\mu M_t}{m_1(R_L^0 - L_d)}$$

Let the weight ratio $K_m = \frac{m_1}{M_1}$ and bring in $(R_L^0 - L_d) = 90\text{mm}$. then the above formula can be expressed as:

$$\beta \geq \frac{180}{\pi} \arcsin \frac{\mu}{90k_m}$$

Under different rolling friction coefficients, the relationship between mass ratio and swing angle is shown in Figure 9 below.

Fig 9 diagram of relationship between swing angle and mass ratio

It can be seen that the larger K_m , the smaller the swing angle β of the rod group required for the movement of the wheeled rolling robot, and the better the maneuverability of the robot. It can be seen from the figure that improving the equivalent mass of the center of gravity adjustment device can make the system drive the robot when the swing angle is small.

3.3 Analysis of robot driving torque

The rolling of the robot is generated by the eccentric moment generated by the movement of the center of gravity adjustment device, which changes the position of the overall center of gravity of the system and overcomes the rolling friction couple moment^[28] between the variable diameter contact outer wheel and the ground. The

power of the variable diameter wheeled robot is supplied by three double servo actuators evenly distributed in the middle of the frame, T^* represents the driving torque.

Fig. 10 Comparison of dimension of scaled wheel diameter

Firstly, the rolling friction couple that hinders the rolling of the robot is analyzed. As shown in Fig. 10, when the small driving force F^* of the robot causes the robot to roll, the action wheel of the robot contacts and squeezes the ground to produce contact deformation, so that the constraint reaction force on the contact wheel is unevenly distributed.

As the driving force F^* increases, the rolling friction couple moment $\mu_1 F_N$ balances the rolling couple generated by the main driving force F^* and the ground distributed force system F . The maximum rolling friction couple moment is expressed in M_{max}^f . When μ_1 reaches the maximum value μ , the system rolling friction couple moment reaches the maximum value, which increases the driving force of the system, and the robot will roll, and have:

$$M_{max}^f = \mu F_N$$

Take $\mu = 0.2$, the plane motion mechanical model of wheeled rolling robot is shown in Figure 11 below.

Fig. 11 motion force diagram of robot

According to the motion force analysis and the motor parameters of the driving system, the maximum rolling friction couple moment of the robot:

$$M_{max}^f = \mu F_N = \mu M_t g = 0.069 N \cdot m$$

In addition, when the center of gravity adjustment device is located at the lowest position, the distance from the center to the ground is L_d , and there is the driving torque to drive the robot:

$$T^* \geq m_1 g (R_L^o - L_d) \sin \beta = M_{max}^f$$

The total driving torque of three annular uniformly distributed servo actuators is:

$$T \geq 0.023 N \cdot m$$

The output power of driving steering gear is:

$$P = \frac{T_n}{9549} \approx 3.2 w$$

In view of the power loss of the actuator in the actual situation of the robot, the DC servo actuator with an output power of 10W is selected.

4 Analysis on scaling relationship of robot wheel diameter

According to the connection principle of variable diameter gear train components, that is, the variable diameter gear train is connected with the gravity center adjustment driving unit based on the parallel mechanism through the symmetrical retractable universal joints arranged at both ends, and the coupling driving wheel and the frame wheel are connected through the spoke group to analyze the wheel diameter switching of the robot [29,30].

Taking the left turning movement as an example, the diagram of wheel diameter changing process is shown in Figure 12 below. The middle yellow block represents the moving platform of the center of gravity adjustment device, which is connected with the coupling driving wheel in the variable diameter gear train through the middle blue rotating shaft, and the black vertical line represents the outer scaling wheel. When the robot is stationary with R_1 as the radius of the rolling wheel, the center of gravity adjustment device rotates an angle θ , which is simultaneously transmitted to the coupling driving wheels on both sides through the universal shaft to drive the spokes to change. Due to the reverse arrangement of the spokes group of the variable diameter gear train on both sides, the spokes on one side are contracted and the outer wheel

diameter is reduced to R_2 driven by the coupling driving wheel; The spokes on the other side open and the outer wheel diameter expands to R_3 .

Fig 12 schematic diagram of robot variable wheel diameter

The wheel diameter adjustment process of rolling robot is shown in Fig 13 and Fig 14. The Yellow wheel disc represents the moving wheel disc, and the primary color wheel disc is the fixed wheel (frame wheel). It is defined that the center of the moving wheel is O_d , the fixed node between the bottom end of the spoke and the moving wheel is T_d , the implicated point between the middle part and the T -pillar of the frame wheel is T_s , and the connecting point between the top end and the circular arc piece of the moving wheel is T_p . At the same time, the radius of coupling driving wheel is defined as R_d , the radius of frame wheel is defined as R_s , and the radius of variable wheel diameter outer wheel is defined as R_L , $R_R \cdot |T_d T_s| = m_1$, total length of spokes: $|T_d T_p| = m$.

Fig 13 left variable wheel diameters pokes shrink state

When the robot rolls in a straight line $\angle T_d O_d T_s = \alpha$, Then in the triangle $\Delta T_d O_d T_s$ it is obtained from the cosine theorem:

$$m_1^2 = R_d^2 + R_s^2 - 2R_d R_s \cos \alpha$$

Let $\angle O_d T_d T_s = \beta$, then:

$$\cos \beta = \frac{R_d - R_s \cos \alpha}{\sqrt{R_d^2 + R_s^2 - 2R_d R_s \cos \alpha}}$$

In $\Delta T_d O_d T_p$:

$$\cos \beta = \frac{R_d^2 + m^2 - R_L^2}{2mR_d}$$

Gain:

$$\frac{R_d^2 + m^2 - R_L^2}{2mR_d} = \frac{R_d - R_s \cos \alpha}{\sqrt{R_d^2 + R_s^2}}$$

Sorted out:

$$R_L^2 = R_d^2 + m^2 - \frac{2mR_d^2 - 2mR_d R_s \cos \alpha}{\sqrt{R_d^2 + R_s^2 - 2R_d R_s \cos \alpha}}$$

Fig 14 right variable wheel diameters pokes shrink state

It can be seen that the outer wheel radius R_L of is only related to the input angle α of the moving wheel. Because the parameters of gear trains on both sides are the same when the robot rolls in a straight line, in the right wheel variable diameter gear train, we have:

$$R_R^2 = R_d^2 + m^2 - \frac{2mR_d^2 - 2mR_d R_s \cos \alpha}{\sqrt{R_d^2 + R_s^2 - 2R_d R_s \cos \alpha}}$$

After the rotation of the robot center of gravity adjustment device is completed, the right figure in Figure 12 shows the state of the system angle of the robot left reducer gear train under the action of the rotation angle θ of the moving wheel. The spoke rod group shrinks counterclockwise and is arranged compactly. Similarly:

$$R_L'^2 = R_d^2 + m^2 - \frac{2mR_d^2 - 2mR_d R_s \cos (\alpha + \theta)}{\sqrt{R_d^2 + R_s^2 - 2R_d R_s \cos (\alpha + \theta)}}$$

In the formula, all are fixed values except angle.

Let $R_L^2 + m^2 = A$, $2mR_d^2 = B$, $2mR_d R_s = C$, $R_s^2 + R_d^2 = D$, $2R_s R_d = E$,

Among them, A , B , C , D , E are all positive, the above formula can be simplified as:

$$R_L'^2 = A - \frac{B - C \cos (\alpha + \theta)}{\sqrt{D - E \cos (\alpha + \theta)}}$$

As shown in Figure 10, When the right variable diameter gear train of the rolling robot rotates along the

angle θ , the spoke group swings reversely to make it radial, and $\angle O_d T_d T_s$ increases. Thus :

$$R_R'^2 = R_d^2 + m^2 - \frac{2mR_d^2 - 2mR_dR_s \cos(\alpha - \theta)}{\sqrt{R_d^2 + R_s^2 - 2R_dR_s \cos(\alpha - \theta)}}$$

Bring A 、 B 、 C 、 D 、 E in:

$$R_R'^2 = A - \frac{B - C \cos(\alpha - \theta)}{\sqrt{D - E \cos(\alpha - \theta)}}$$

5 Three basic motions of robot

5.1 Linear motion analysis

The linear walking ability of wheeled rolling robot is determined by the eccentric torque provided by its center of gravity adjustment device and the scaling size of variable diameter wheel. Considering that the motion of the robot can be divided into two types from the relative dimensions of the left and right wheels, one is the straight motion with equal wheel diameter, and the other is the turning motion with different wheel diameter, the parameter design of the straight-line walking wheel diameter should not only maximize the output torque transmission efficiency^[31] during straight-line walking, but also provide the most reasonable size and position conditions for the variable diameter motion of the side wheel diameter turning motion^[32].

We define the ratio of the larger wheel diameter to the smaller wheel diameter of the robot scalable wheel in the turning state as the scaling ratio. The scaling ratio represents the wheel diameter changing ability and the angle adaptation ability of the wheeled robot. As shown in Figure 15, the zoom angle ρ of the variable diameter wheel, that is, the included angle between the holding spoke and the tangent of the coupling driving wheel, represents the deformation ability of the robot.

Fig. 15 Schematic diagram of variable diameter wheel

switching wheel diameter

The wheel diameter of the two mobile wheels of the robot is adjustable. The general walking radius is defined, that is, if the wheel diameter of linear walking is R_L^0 , the size range is: $R_{min} < R_L^0 < R_{max}$.

The radius dimension of the coupling driving wheel is n , the length of the holding spoke rod is m , and the tangent included angle at the connection between the spoke and the driving wheel is ρ . According to the cosine theorem, the radius dimension of variable diameter wheel is:

$$R_L^2 = (n^2 + m^2 - 2mnsin\rho)$$

Considering that the variable diameter wheeled rolling robot will not produce side slip during linear walking, but a pure rolling motion, the linear walking motion equation of the wheeled rolling robot is listed based on the nonholonomic system theory:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos\varphi & -a\sin\varphi \\ \sin\varphi & a\cos\varphi \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} v \\ \omega \end{bmatrix}$$

Let $K = \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$, then we have:

$$K = \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \cos\varphi & -a\sin\varphi \\ \sin\varphi & a\cos\varphi \end{bmatrix} \cdot \begin{bmatrix} v \\ \omega \end{bmatrix} = A \begin{bmatrix} v \\ \omega \end{bmatrix}$$

Where $A = \begin{bmatrix} \cos\varphi & -a\sin\varphi \\ \sin\varphi & a\cos\varphi \end{bmatrix}$.

and $A^{-1} = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\frac{1}{a}\sin\varphi & \frac{1}{a}\cos\varphi \end{bmatrix}$, the inverse

kinematics matrix equation of the wheeled rolling robot can be obtained as follows:

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\frac{1}{a}\sin\varphi & \frac{1}{a}\cos\varphi \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

When the torque of the servo actuator of the rolling robot is set to be constant in ADAMS simulation, the torque of the center of gravity adjustment device input by the robot is constant, and the linear motion speed curve and displacement trajectory of the wheeled rolling robot are obtained as shown in Figure 16 and Figure 17 below.

Fig. 16 speed curve of robot linear rolling

Fig. 17 Linear rolling displacement curve of robot

Due to the constant torque of the servo actuator and the continuous increase of the eccentric torque input by the robot center of gravity adjustment device, the angular acceleration of the rolling robot will continue to increase, and the body motion speed, rolling wheel linear speed and robot displacement will continue to increase.

5.2 Turning motion analysis

The robot walks in a straight line with the general walking radius R_L^0 , when it travels to the curve area (as shown in Figure 18), the left wheel of the robot immediately shrinks and the right wheel expands to complete the left turn. The roll angle of the robot turning state is defined as α . the larger the roll angle is, the smaller the turning radius R_H of the robot is; Smaller turning radius enable the robot greater motion flexibility, which is also an important index for the motion performance of the robot.

Fig. 18 Calculation of robot turning radius

The robot roll angle according to the geometric relationship is:

$$\alpha = \arccos \frac{R_r - R_l}{L}$$

The turning radius is:

$$R_H = \frac{L}{2} \cdot \frac{R_l + R_r}{(R_r - R_l)} = \frac{R_r + R_l}{2 \tan \alpha}$$

Considering the limit rotation size of the robot, we get:

$$\alpha_{max} = 6.2^\circ, R_{min}^H = 1.76m$$

If the overall turning linear speed of the robot is v and the angular speed is ω , the linear speeds of the left wheel and the right wheel are v_l and v_r respectively. According to the coaxial movement relationship of the left and right reverse installed power take-off shafts, the speeds of the two wheels are:

$$v_l = (1 - \lambda)\omega R_L^0; v_r = (1 + \lambda)\omega R_L^0$$

5.3 Uphill motion analysis

In the process of climbing, due to the influence of gravity and slope friction, the wheeled rolling robot is easy to be in an unstable state, which has a great impact on the robot to maintain the balance of uphill motion. Two preconditions are defined before analyzing the slope motion of the robot:

- 1) In the climbing process, the extrusion deformation between the outer circle circular arc and the slope is ignored, and the variable diameter wheel is a rigid body;
- 2) In the process of climbing, the action wheel rolls purely without slipping.

The overall weight of the system is divided into two parts. The mass of the center of gravity adjustment device is specified as m_1 and the mass of other parts is specified as m_2 .

Fig. 19 Analysis of robot climbing motion

$\sum_0\{X \ Y\}$ is the orthogonal coordinate system

consolidated on the slope, the starting position of the robot is set at point O , the displacement is on the slope with inclination γ is x , θ is the angle of the gravity center adjustment device relative to the vertical direction, and φ is the driving torque of the robot, as shown in Figure 19 above.

On the premise that the wheeled rolling robot can climb the slope, the eccentric driving torque τ generated by the robot center adjustment device moves clockwise, and the friction F_f between the slope and the robot contact wheel is greater than the slope component of the robot system, which is defined as F_o .

Therefore, the force conditions for the rolling robot to move uphill is:

$$\begin{cases} \gamma \leq \arcsin\left(\frac{m}{m+M}\frac{l}{R}\right) \\ \gamma \leq \arctan\mu \end{cases}$$

The constraint equation of robot slope motion is analyzed according to the generalized coordinate method. Assuming that the left and right wheels of the wheeled rolling robot do not slide or expand radially during the uphill process, the constraint equation of the robot on the slope is:

$$\dot{x} = R\dot{\theta}$$

According to the integration of the above formula, the shape and position equation of the whole system can be expressed by the angle θ of variable diameter rotation and the angle φ of the offset of the center of gravity adjustment device relative to the vertical direction. The generalized coordinates of the system are selected as:

$$q_1 = \theta, q_2 = \varphi$$

The Lagrange function [29] of the robot system is:

$$L = T - V$$

The Lagrange equation of the system can be expressed as:

$$\begin{cases} \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = \tau \\ \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\varphi}}\right) - \frac{\partial L}{\partial \varphi} = \tau \end{cases}$$

It can be seen from the above formula that there are two control variables θ and φ of the robot system, while there is only one input variable of the system. This input coupled underactuated system can establish its nonholonomic constraint equation through the dynamic model of the robot system.

Besides, $\theta = \frac{x}{R}$, $\ddot{\theta} = \frac{\ddot{x}}{R}$, the constraint relationship of slope motion of wheeled rolling robot is:

$$\lambda_1 \ddot{x} + \lambda_2 \ddot{\varphi} + \lambda_3 \dot{\varphi}^2 + \lambda_4 = 0$$

Where:

$$\lambda_1 = (m_1 + 4m_2)R - m_1 l \cos(\varphi - \gamma)$$

$$\lambda_2 = m_1(Rl - R^2 - l^2)$$

$$\lambda_3 = -m_1 R l \sin(\varphi - \gamma)$$

$$\lambda_4 = (m_1 + 2m_2)gR \sin\gamma - m_1 g l \sin\varphi$$

The equilibrium state in the process of slope motion can be divided into slope static state and slope uniform motion. Starting from the slope static state, the slope motion performance of the robot is studied, and the critical state of the robot on the slope is analyzed, so as to solve the critical value of the robot climbing angle γ .

When the robot is stationary on the slope, there are:

$$\dot{x} = 0, \quad \ddot{x} = 0, \quad \dot{\varphi} = 0, \quad \ddot{\varphi} = 0$$

Brought into the Lagrange equation of the system, we have:

$$\begin{cases} (m_1 + 2m_2)gR \sin\gamma = \tau_0 \\ m_1 g l \sin\varphi_0 = \tau_0 \end{cases}$$

Where, φ_0 is the critical deflection angle of the center of gravity adjustment device relative to the vertical plane, and τ_0 is the critical output torque.

Assuming that the power input of the robot is continuous and can provide strong output torque, the following requirements shall be met:

$$\tau \geq \tau_{0max} = m_1 gl$$

The climbing ability of rolling robot is limited. Whether the slope movement can be completed is directly related to the slope angle. It is assumed that the maximum slope angle that the robot can pass through, that is, the limit slope angle of the robot climbing, is γ_{max} .

From $(m_1 + 2m_2)gR\sin\gamma = m_1 gl\sin\varphi_0$:

$$\varphi_0 = \arcsin \left[\left(\frac{m_1 + 2m_2}{m_1 l} \right) R \sin\gamma \right]$$

According to the properties of arcsine function, the definition domain is $[-1, 1]$, therefore, the slope inclination angle γ must be bounded, thus:

$$M_t = m_1 + 2m_2$$

$$\gamma \leq \arcsin \left(\frac{m_1}{M_t} \cdot \frac{l}{R} \right)$$

It can be seen that when the rolling friction coefficient and the length of parallel mechanism are certain, the greater the mass ratio, the better the climbing performance. The second equilibrium state of the robot's slope motion, that is, the uniform linear motion of the slope, also meets the above relationship. Therefore, the maximum slope inclination of the wheeled robot when moving on the slope is:

$$\gamma_{max} = \arcsin \left(\frac{m_1}{M_t} \cdot \frac{l}{R} \right)$$

When the slope angle exceeds the maximum slope angle that the robot can move, the robot will be unstable. Therefore, in the actual operation process, reasonable path planning is particularly important for the robot movement. Experiments show that when the center of gravity adjustment device moves to the horizontal position, that is, the position parallel to the slope, the wheeled robot reaches the theoretical maximum climbing angle. Taking the structural parameters of the robot into account, the maximum climbing angle is $\gamma=10.2^\circ$. The relationship between the uphill ability of the robot during operation and the mass ratio and size ratio is shown in Figure 20.

Fig. 20 variation of uphill capacity

6 Basic walking performance test of prototype

According to the theoretical analysis of robot function positioning and schematic design, a conceptual prototype is processed and assembled, as shown in Figure 21. The splicing arc piece, collet, spoke, wheel frame and other parts are self-designed aluminum alloy processing products.

Three steering gears are evenly distributed in the middle of the frame. The motion program is input in the steering gear control board to give instructions to the robot for desired practical tasks. The preliminary experiments of equal wheel diameter straight-line walking and different wheel diameter around turning are carried out in the laboratory environment.

Fig. 21 physical picture of robot conceptual prototype

As shown in Fig. 22, the robot is placed in a simulated asphalt pavement environment with a friction coefficient of about 0.6, the robot rolls forward driven by the eccentric torque generated by the center of gravity adjustment device, and the motion speed is adjusted by controlling the offset of the center of gravity adjustment device of the robot based on the parallel mechanism relative to the axis center position of the system.

The experimental results show that the fastest running speed of the robot is 0.8m/s. If the robot walks on other roads with low friction resistance, such as ceramic tile ground or cement road, its walking speed will be greater than the experimental results, so the walking speed parameters of the robot basically meet the design requirements of 1m / s.

Fig. 22 Robot linear rolling experiment

Test the eccentric torque driving angle of the rolling robot under different motion environment and motion speed, according to the actual environment, the running speeds of the robot are 0.45m/s, 0.90m/s and 1.35m/s respectively, the movement environment is selected on ceramic tile pavement, cement pavement and asphalt pavement with low friction coefficient, and the change of driving angle of robot gravity center adjustment device is observed respectively. The experimental results are shown in Table 2 below.

Tab. 2 Planar motion parameters of robot

Robot running speed	Rolling pavement environment	Driving angle / °
0.45m/s	Tile pavement	24.50
	Smooth cement pavement	35.00
	asphalt pavement	45.50
0.90m/s	Tile pavement	30.00
	Smooth cement pavement	38.50
	asphalt pavement	50.80
1.35m/s	Tile pavement	40.50
	Smooth cement pavement	45.55
	asphalt pavement	61.50

Figure 23 shows the performance test experiment of different wheel diameter around turning. Figure (a) shows the path diagram of robot around motion silhouette synthesis. The robot zoom ratio is set to 10:9 and the theoretical surround radius R_H is 3.5m. The experimental results show that the actual R_H is 3.48m. Figure (b) shows the limit zoom ratio surround turning motion experiment carried out by the robot. According to the comprehensive experimental results, the surround motion of the robot basically meets the initial design parameters.

Fig. 23 experiment of different diameter encircling motion

7 Conclusions

- (1) By analyzing and comparing the motion modes and driving structures of various typical robot mechanisms at home and abroad, a new variable diameter wheel rolling robot driven by gravity center adjustment device is designed. The robot is driven by the center of gravity adjustment device and two scalable gear trains as the motion mechanism. The ground contact wheel composed of multiple groups of circular arc pieces is restrained by spokes to adjust the wheel diameter of the robot, achieve the linear walking of equal wheel diameter and the rotary movement of different wheel diameter, and can complete the walking tasks in different road environments.
- (2) Based on classical mechanics, the kinematics characteristics of linear rolling, turning and slope motion of rolling robot are analyzed. The energy method is used to establish a slope motion theory model, the relationship between the climbing angle and size ratio and mass ratio of the robot climbing

movement is plotted. On this basis, the uphill ability of the wheeled robot is evaluated, and the maximum climbing angle of the robot is obtained.

- (3) The structure of the robot prototype is introduced, and the robot linear walking experiment and plane steering experiment are carried out to verify the feasibility of the robot movement.

8 Declaration

Availability of data and materials

Not applicable

Competing interests

This paper does not involve competing economic interests.

Funding

This research was financially supported by Natural Science Foundation of China (Grant No. 51305380) and Natural Science Foundation of Hebei Province (Grant No. E2015203144).

Authors' contributions

The author's contributions are as follows: Hui Bian was in charge of the whole trial; Chun Zhang and Shijie Wang wrote the manuscript; Other students are responsible for assisting the prototype experiment and result analysis.

Acknowledgements

I sincerely thank my mentor, associate professor Hui Bian, for his careful guidance, for the teachers' critical discussion and reading in the preparation of my manuscript, and for the teachers' earnest instruction. At the same time, I would like to thank the younger brothers and sisters of the laboratory for their help and cooperation.

Author information

Hui Bian, born in 1982, at present, he is the master supervisor and associate professor of *Yanshan University*. His research interests include the theory and application of parallel robot mechanism, rehabilitation robot and bionic robot. Tel: 13784526496; E-mail: ysubh@ysu.edu.cn

Chun Zhang, born in 1995, she obtained the honor of master's degree from *Yanshan University* in June 2020. Her research interests include parallel robot mechanism theory and application, rolling robot. E-mail: 1751565072@qq.com

Shi-Jei Wang, born in 1998, is currently a master in mechanical and electronic engineering of *Yanshan University*.

E-mail: wangshij669988@163.com

References

- [1] Cai Zixing Robotics [M] Beijing: Tsinghua University Press, 2014: 25-190.
- [2] Yu Tao, Wang Yibo, sun Hanxu, Zhao Wei Research on control strategy of longitudinal motion of a spherical rolling robot [J] Machine tools and hydraulics, 2020, 48 (11): 1-6 + 20.
- [3] Guan Yonghan, Yao Yan'an, Liu Chao Single degree of freedom octahedral probabilistic rolling robot [J] Journal of mechanical engineering, 2020, 56 (07): 44-51.
- [4] G. Rigatos, K. Busawon, J. Pomares, M. Abbaszadeh. Nonlinear optimal control for a spherical rolling robot[J]. International Journal of Intelligent Robotics and Applications, 2019, 3(2): 9-19.
- [5] Xiangzhi Wei, Yaobin Tian, Shanshan Wen. Design and locomotion analysis of a novel modular rolling robot[J]. Mechanism and Machine Theory, 2019, 133: 4-23.
- [6] Liu Youzhi Research on self-driving rolling robot based on chemical reaction [D] Beijing University of chemical technology, 2020.
- [7] Zhang Yi Mobile robot technology and its application [M] Beijing: Electronic Industry Press, 2007: 68-240.
- [8] Qiu-Hong W U, Ming H U, Wen-Hua C, et al Design & Analysis for the Configuration of a Radially Foldable Wheel[J]. Machinery Design & Manufacture, 2011: 83-87.
- [9] Zhu Lei, Chen Jun Review of wheeled mobile robot research [J] Machine tools and hydraulics, 2009, 37 (8): 242-247.
- [10] Gao Feng, Guo Weizhong Strategic thinking on the development of robots in China [J] Journal of mechanical engineering, 2016, 52 (07): 1-5.
- [11] Tao Zhang, Qing Li, Chang-shui Zhang, Hua-wei Liang, Ping Li, Tian-miao Wang, Shuo Li, Yun-long Zhu, Cheng Wu. Current trends in the development of intelligent unmanned autonomous systems[J]. Frontiers of Information Technology & Electronic Engineering, 2017, 18(1): 68-84.
- [12] Duan Xingguang, Huang Qiang, Li Kejie Design and motion characteristics analysis of small wheel legged compound robot [J] Journal of mechanical engineering, 2005, 41 (8): 2-8
- [13] Chen Yanchao, Ren Chunhua, Liu Hao, Gu Chenyang. Research on slipping-pattern recognition and positioning error compensation of wheeled robot. [J]. The Review of scientific instruments, 2021, 92(8): 3-15.
- [14] HALME A, SCHONBERG T, WANG Y. Motion control of a spherical mobile robot[C]//4th IEEE International Workshop on Advanced Motion Control. March 18-21. 1996, Mie University, Mie, Japan. IEEE, 1996:259-264.
- [15] Qian Qingwen Research on Modeling and control method of two wheels self-balancing vehicle pendulum robot [D] Harbin: Doctoral Dissertation of Harbin University of technology, 2019: 5-12.
- [16] Sphero | Connected Toys [EB/OL]. [2018-02-03]. <http://www.sphero.com/>.
- [17] KARAVAEV Y L, KILIN A A. The dynamics and control of a spherical robot with an internal omni wheel platform[J]. Regular & Chaotic Dynamics, 2015, 20(2): 134-152.
- [18] CHEN W H, CHEN C P, TSAI J S, et al. Design and implementation of a ball-driven omnidirectional spherical robot[J]. Mechanism & Machine Theory, 2013, 68(68):35-48.
- [19] He Y Y, Li Y Z, Wu J X, Liu X J, Yao Y A. Design and Mobility Analysis of a Multi-mode Two-wheel Mobile Robot. Journal of mechanical engineering, 2019, 55 (23): 83-92.
- [20] Li yezhuo Research on configuration design and performance of reconfigurable multi-mode ground mobile robot [D] Beijing: Doctoral Dissertation of Beijing Jiaotong University, 2018: 93-103.
- [21] XIONG Xiao Teng. Drive mechanism and experimental study on tiny wheeled robot based on liquid metal [D]. Haerbin: Harbin Institute of Technology, 2020.
- [22] ZHOU Wei, SHI Weiren, LI Jiangbo, et al. MSTRbot: A small scout robot[J]. Robot, 2011, 33(5): 592-598.
- [23] Liu W. Mechanism analysis and research of omnidirectional wheel driven spherical robot [D]. Beijing: Beijing Jiao tong University, 2017.
- [24] ZHAI Meili. Research on single-loop 6R linkage rolling mechanism [D]. Beijing: Beijing Jiaotong University, 2014.
- [25] Huang Zhen, Zhao Yong sheng, Zhao Tieshi. Advanced space mechanism [M]. Beijing: Higher Education Press, 2nd Edition, 2014.
- [26] Cui J K. Flexible workspace of 3-RRR planar parallel robot [J]. Journal of Shanghai University of technology, 2005 (4): 365-368.
- [27] Tang X Q, Shao Z F, Tang L W, etc. A modular rotary drive unit with gravity adjustment function: China. 201410357304.3[P] 2014.11.05.
- [28] SONG S M, WALDRON K J. Machines that walk: The adaptive suspension vehicle[M]. Cambridge: MIT Press, 1989.
- [29] Ruan X G, Cai J X, Li X Y, Zhao W. Research and design of two wheeled balancing robot [M]. Beijing: Science Press, 2012.
- [30] Pu L G, Chen G D, Wu L Y. Mechanical design [M]. Beijing: Higher Education Press, 9th Edition, 2013.
- [31] Wang F C. DESIGN AND PERFORMANCE ANALYSIS OF ALL-TERRAIN WHEEL MOBILE ROBOT[D]. Chengdu: Southwest Jiao tong University, 2018.
- [32] Wu Y T, Wu Y, Wu D L, X D, etc. Design analysis of a new variable diameter wheel [J]. Mechanical equipment, 2017, 1672-3872 (16): 044-01.