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Design and stability analysis of a wheel-track robot

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***Abstract* - The wheel-track robot is a new type of mobile robot combining a wheel and a track in a single component, which can quickly switch between in wheel mode and track mode. The wheel-track mobile robot system is proposed in this paper, comprising two operation modes, including wheel motion and track motion. And the dynamic stability analysis is a strong basis on structure design of the robot. As well as the two modes of the robot turning experiments contrast. The result shows that theoretical analysis and the robot's design are reasonable. The robot mechanism is simple and compact, and it has a good practical value and application prospect.**

Index Terms–Mobile robot, Wheel-track, System design, Stability analysis.

I. INTRODUCTION

Up to day, there have been numerous studies on the mobile robots since they can help human perform the dangerous missions in complex and unpredictable environments, such as planetary exploration, intelligence and reconnaissance, anti-terrorism, and rescue, and so on[1-3]. For example, when a sudden disaster happens, it is required that the robot should go through the irregular terrain quickly and arrive at its destination in time. If the robot had a poor ability to overcome the obstacles, it would fail to finish its work because it possibly wanders or runs aground in a place. Therefore the robots should have prominent flexibility and traversability. In such situations, various robots have been developed. Generally, the track mechanism and the hybrid mechanism are more adaptive to the rough terrains. Since it has the advantages such as excellent stability, low terrain pressure and simple control system, the tracked-type robots have been widely applied in irregular environments, and one kind is called "transformable track robot". For example, CALEB-2 [4], VSTR [5], VGTV [6], Single-Tracked [7], ROBHAZ-DT [8], NEZA-I [9] and some others belong to this kind of robots. They are designed to maximize flexibility and adaptability to rough terrains by adjusting configuration of tracks. They can reduce the energy consumption by minimizing the contact length with the ground. A novel transformable wheel-track robot has been developed as shown in figure1 and the robot prototype is mainly analysed in this paper.

II. MECHANICAL STRUCTURE OF THE ROBOT

Generally, a wheel mechanism has good performance in turning flexibility and energy efficiency, and a track mechanism has prominent off-road mobility. Therefore, the transformable wheel-track mechanism is chose as the mobile mechanism. As shown in figure1, the robot mainly consists of a control box, two symmetric transformable wheel-track units and a sub-arm equipped with a single-direction wheel. The track in track mode is much longer than in wheel mode, so the track should be made of a material with a low elastic modulus, but the mesh between track teeth and the gear ring requires a kind of high elastic modulus material to avoid slipping. This paper presents a retractable track assembled by the rubber timing belt shown in figure 1, which is as long as the envelope of opened double four-bar linkage mechanism.

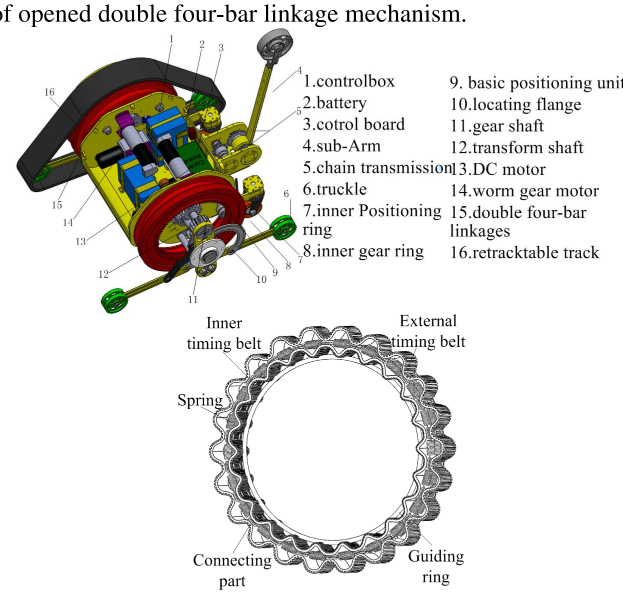

Fig. 1 Mechanical structure of the robot.

III. CONTROL SYSTEM OF THE ROBOT

The robot control system adopts hierarchical structure, composed of smart board and control board, complishing collaborative human computer interaction, external environment detection and pose control function as shown in figure2. The command is input intelligent plate by the operator according to the change of external environment through the wireless terminal, through the wireless terminal is sent to the control board to analyse, controlling 2 DC gear motor and 3 worm gear motor movements, so as to realize the control of the robot's pose. Pose information is got through real-time sensor sensing robot connected on the control board gyro internal and this information by the smart board is feedback to the operator, reflecting in the PC man-machine

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interface. The operator according to the feedback information and real-time environment resets robot pose requirements and requirements through the PC interface or the remote control are sent to the robot end. In the process of mobile robot, the external sensor, infrared ultrasonic probe will detect some external environment information sent to the control board to assist the operator some obstacle avoidance work.

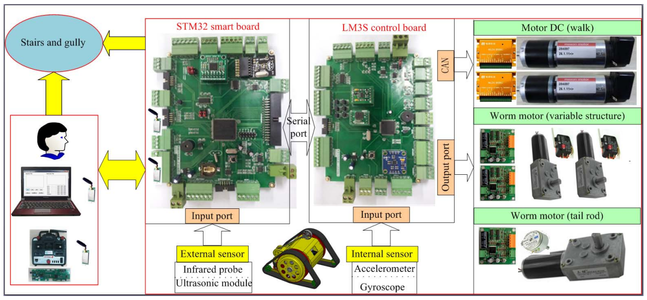
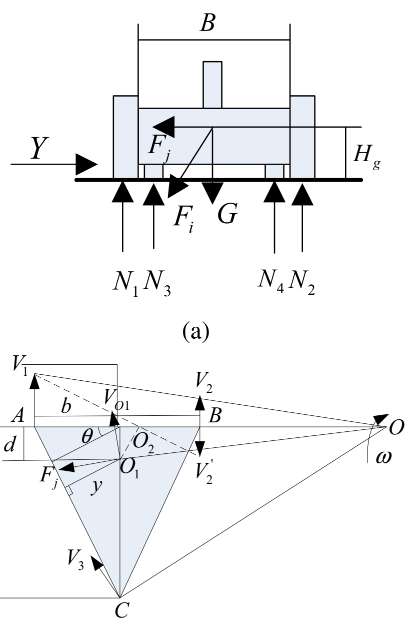


Fig.2 Control system of the robot.

IV. Robot stability analysis

A. Analysis of the dynamic stability of the robot level road surface



(a)

(b)

Fig.3 Analysis on forces and velocities when swerving rapidly on horizontal road surface

H_g —Height of centre of gravity

Y —Lateral friction force

F_i —inertia force

G —gravity

As shown in figure 3(b), assuming $V_1 > V_2$,the robot turning right, the centre distance l_1 between front wheel and rear wheel shaft is known. The centre distance of two front wheel is b . The distance centre of gravity O_1 from the centre line of the front wheel shaft is d . The rear two universal wheels are equivalent to a wheel on the centre pivot point. So the speed of the three wheels are respectively V_1, V_2, V_3 ,The robot body centroid in the domain of pedal support is O_1 .The centroid velocity is V_{O1} .Three wheel speed instantaneous centre is O or O_2 .(When V_1 and V_2' are in the opposite direction, Speed instant centre is O_2 on the centre line of the front wheel shaft. Otherwise, it is O on the extension line of the centre line of the front wheel shaft.) In condition the robot steering around the instantaneous velocity centre, the speed is relatively small when the robot reaches the required range, so the inertia force which is not enough to cause the body tilting. In the case of a sudden change in the high-speed mobile, due to the inertia, the two rounds into the reverse speed need some time, so the inertia force generated is not enough to cause the body tilting. Therefore, this paper will not analyse the above two cases. The main analysis is the situation the robot around the extension line of the instantaneous velocity centre O .

$OB = x$, $OO_1 = r$ .The vertical distance O_1 to the boundary AC is y , because $d << r$, so assuming the vertical angle of inertia force F_i and O_1 to boundary AC is always θ .(θ is half of an isosceles triangle ABC vertex $\angle C$), Centrifugal inertia force for high speed steering.

$$F_i = \frac{GV_{O1}^2}{gr} \times \cos\theta \tag{1}$$

By the principle of triangle similarity

$$y = \frac{(l_1 - d)b}{\sqrt{4l_1^2 + b^2}} \tag{2}$$

With movement speed increasing or turning radius decreasing, centrifugal inertia force increasing, medial wheel to ground load continuously decreases until zero, reaching the critical state of body of the lateral overturned relation

$$F_i \times H_g = G \times \frac{(l_1 - d)b}{\sqrt{4l_1^2 + b^2}} \tag{3}$$

The type (1) types by type (3), without the occurrence of rollover velocity

$$V_{O1} \le \sqrt{\frac{(l_1 - d) \times b \times g \times r}{H_g \times \cos\theta \times \sqrt{4l_1^2 + b^2}}} \tag{4}$$

Lateral force may also be greater than pavement lateral adhesion and make the body produce sideslip and sideslip critical state is (ϕ is the adhesion coefficient)

$$F_i = G\phi \tag{5}$$

By formula (9) and (5) available, no slip velocity is

$$v' \le \sqrt{gr\phi} \tag{6}$$

In order to make sideslip before rollover occurs, should meet the following relations

$$\sqrt{gr\phi} \le \sqrt{\frac{(l_1-d)\times b\times g\times r}{H_g\times\cos\theta\times\sqrt{4l_1^2+b^2}}} \tag{7}$$

$$\cos\theta = \frac{2l_1}{\sqrt{4l_1^2+b^2}} \tag{8}$$

$$\frac{b\times(l_1-d)}{2\times H_g\times l_1} > \phi \tag{9}$$

Because the moving speed of the robot is fast, the stability becomes worse at the time of rapid steering, so It is necessary to determine the relationship on the centroid between the turning radius of curvature r and V_1 ,(assuming $V_1 > V_2$). In the case of a certain turning radius, the maximum speed can be traveling, the robot does not turn over, so as to determine a minimum speed as the motor set speed, to ensure the safety of driving.

The first analysis $r > b$ of the situation, from the speed instant centre method

$$\frac{V_{O1}}{r} = \frac{V_1}{b+x} \tag{10}$$

Getting the turning radius r by a right angled triangle relation shown in figure 3(b):

$$r^2 = \left(x+\frac{b}{2}\right)^2 + d^2 \tag{11}$$

Integrated (4), (10), (11), the elimination x and V_{O1} , the relationship between the type V_1 and r can be as follows

$$V_1 = \frac{\left(b+2\sqrt{r^2-d^2}\right)}{2r}\sqrt{\frac{g\times r\times b\times(l_1-d)}{2l_1\times H_g}} \tag{12}$$

Similarly, in the case of $b/2 < r < b$ the relationship between V_1 and r is

$$V_1 = \left(b+2\sqrt{r^2-d^2}\right)\sqrt{\frac{g\times y}{4r\times H_g\times\cos\theta'}} \tag{13}$$

the formula (2) is given . At this time θ' can no longer be approximated by θ , the trigonometric functions available

$$\cos\theta' = \sqrt{\frac{y^2}{(l-d)^2}+\frac{r^2-d^2}{r^2}} \tag{14}$$

The steering radius r is the independent variable. The step size is 0.001 . By numerical calculation, in the range $b/2 < r < 10m$, in the normal turning radius, the minimum speed is also required to achieve $2m/s$,the robot will be turned over. Therefore, in practical design, the maximum speed of the robot is determined as $1m/s$, so as to ensure that the robot does not appear tilting.

B. Analysis of the dynamic stability of the robot in emergency braking on the horizontal ground

The emergency brake is also an important factor affecting the dynamic stability of the robot in the high-speed road. In this paper, the stability criterion, the maximum speed into the set, verify that it is stable. The condition of emergency braking is related to the position of the centre of gravity of the robot body, the geometry dimension and the road condition. The following basic assumptions are made at the time of the discussion, (1) the robot is traveling at the level of the road, with a large attachment coefficient. (2) the braking condition of both sides of the driving wheel is the same, only the longitudinal stability is considered. (3) when the emergency brake, cutting off the power, brake torque to achieve the maximum value of the moment, the wheel completely slip. Emergency braking dynamic stability can be divided into two stages: first stage is from the start of braking to velocity zero, namely body around the angular velocity of the overturning pivot from zero to maximum ,the second stage is to continue to rotate around the pivot point under the action of inertia moment.

(1)First stage of dynamic stability

The motion differential equation of the body around the pivot point

$$I\theta'' = mR\sqrt{a_1^2+g^2}\sin(\theta+\alpha-\beta) \tag{15}$$

I is the moment of inertia as the body around the fulcrum. The mass of the body is m . R is the distance from the centre of mass O to the pivot point, $a_1 = V/t_b$ is the average acceleration.(The braking time is t_b when the body speed is V in the front of the brake.)

$$\alpha = \tan^{-1}\frac{L}{2H_g}, \beta = \tan^{-1}\frac{g}{a_1} \tag{16}$$

L is the track length.

According to the principle of function transformation, the kinetic energy at the beginning of the braking, in the end of the braking,a part of the ground resistance to overcome the negative work, and the other part of the rotation around the fulcrum to rotate the work done.

$$\frac{1}{2}mV^2 = mg\phi S + \frac{1}{2}I\theta'^2_{\max} \tag{17}$$

ϕ is the adhesion coefficient,

$S = \frac{1}{2}Vt_b$ is the braking distance.

Integrated (15) to (17) and initial conditions $\theta_0 = 0$ and $\theta_0^{'} = 0$, at the end of the first phase the braking angle

$$\theta_1 = \cos^{-1}\left[\cos(\alpha-\beta) - \frac{V(V - g\phi t_b)}{2R\sqrt{\left(\frac{V}{t_b}\right)^2 + g^2}}\right] - (\alpha-\beta) \tag{18}$$

(2)Second stage of dynamic stability

After brake, due to the gravity effect, the angular velocity of the rotation of the body around the pivot is gradually reduced, and the rotation angle will increase until the angular velocity is zero

$$I\theta^{''} - mgR\sin\left[90^0 - (\theta+\alpha)\right] = 0 \tag{19}$$

Given initial conditions $\theta_0 = \theta_1$ and $\theta_0^{'} = \theta_{\max}^{'}$, when $\theta = 0$, the maximum rotation angle of the body around the pivot point can be obtained.

$$\theta_{\max} = \sin^{-1}\left[\sin(\theta_1+\alpha) + \frac{V(V - g\phi t_b)}{2gR}\right] - \alpha \tag{20}$$

Substituting $v = 1m/s$ into formula (20) was $\theta_{\max} + \alpha << 90^0$ without tipping. Through the analysis of the stability of the robot body in some extreme cases, demonstrating the feasibility of the structural design.

From the above stability analysis of overturning, sideslip critical state relations can be seen, by lowering the centre of gravity height, increasing two wheelbase were advantageous to the stable of the robot body.

V. Experiment

A. Robot prototype

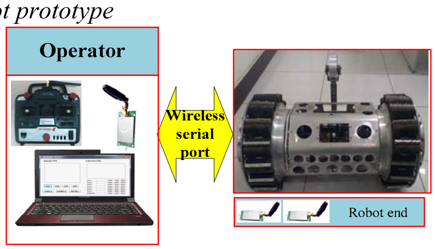


Fig.4 Robot prototype

Wheel-track variable structure mobile robot experimental system includes robot platform and user control terminal, as shown in figure 4. The operator through the remote controls robot wheel and track switch, tail rod rotation and forward backward position transformation, All attitude data during operation are sent to the computer PC interface through the wireless transmission module, including the attitude data of the wheel / track robot when it runs.

B. Turning experiment

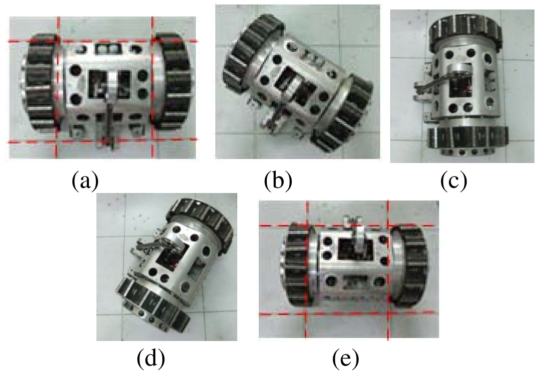


Fig.5 Wheel mode turning

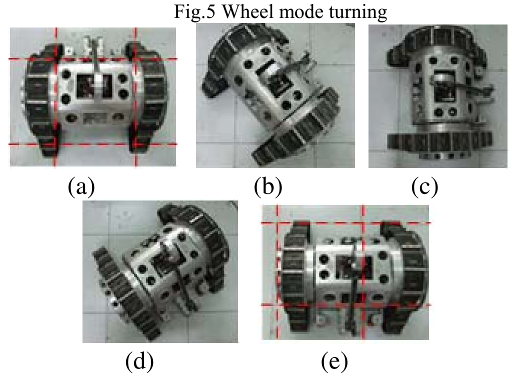


Fig.6 Track mode turning

In order to facilitate comparison, selecting the floor of the gap as a reference line. From figure 5(a) (e) and figure 6 (a) (e) contrast, the lateral sliding of the wheel in the turning process is much smaller and more accurate control is got in the wheel. From figure 7 can be seen at the same speed, the energy consumption of the track is greater than that of the wheel and the impact load is larger than that of the wheel. In the same turn mode, the demand torque increases with the increase of the turning speed.

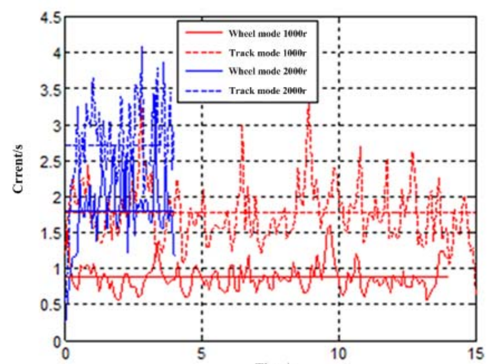


Fig.7 Comparison of turning current at different speeds under different modes

VI. Conclusion

This paper proposes a wheel-tracked mobile robot system, comprising two operation modes, including wheel motion and track motion. And the dynamic stability analysis is completed, providing a strong basis on structure design of the robot. The turning experiment of the robot on two modes contrasts. The robot mechanism is simple and compact, and it is characterized by flexible, fast movement and high efficiency in performance. It has a good practical value and application prospect.

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