Analysis of Over-Obstacle Robot with Left and Right Wheel Sharing one Shaft

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Keywords: mobile robot, in-phase, over-obstacle, swerve.

Abstract. The wheeled robot whose left and right sides are in phase (L&R in-phase) is superior to the one whose both sides are not in getting over obstacles. Nevertheless, the wheeled robot has to abandon its routine swerve way depending on speed difference of the left and right wheels. In this paper, we present two methods of swerve, one is terms with different friction coefficient on both sides and the other is differential wheel diameter. The quadruple wheeled robot makes its first two wheels revolving and the rest couple reversing. With such rotating mode, there exists a slight deviation [1] on both sides in every cycle because of its different parameters. After several periods, the wheeled robot swerves as instructed. Furthermore, we perform a series of experiments to test this structure we have proposed how the obstacle climbing capability and swerve efficiency are. We also compare the results with the performance of conventional structure whose left and right wheels are out of phase

Introduction

Robot is becoming increasingly coupled with the physical world. It is very common and contagious that the robot appears in such situations as forest fires, earthquake accident, etc, and substitutes for the man to carry on rescuing. When disasters occur, people urge to perceive what about the scene on earth is, in order to collect information constantly, mitigate disasters [2] and rescue the wounded. To address this demand, scientists must design a kind of over-obstacles mechanism which has been termed robot in rough terrain.

When it comes to rough terrain robot [3], people typically think of wheeled mobile robot, tracked mobile robot, legged mobile robot and complex mobile robot that do feature and matter respectively. Tracked robot equipped with sophisticated elements rolls into the ruins as easily as flat ground, while wheeled robot cannot. But it will take much more energy than the latter to fulfill its task. Because of inherent complexity, legged robot can walk through terrain efficiently at the cost of walking inefficiently on flat ground and controlling complicatedly. It has been proved that the wheel, which was created 3000 years ago, is the most efficient travel mechanism among caterpillar track and leg. We are most likely to be concerned about the simple structure and control of wheeled robot, though its ability of getting over obstacle is less than the other two mentioned. Our key insight is to strive for a new solution in which both high over-obstacle ability and walking efficiency are performed.

In this paper, we present our work on proposing a novel structure that is called L&R in-phase and realizing its swerve. L&R in phase has been guaranteed absolutely by sharing a transmission shaft. With motors' cooperation, the output of them is converged. It is obvious that the converged is superior in getting over obstacles than that not. However, it is troublesome for wheeled robot with L&R in phase to swerve as ordered because of giving up speed difference of the left and right wheels. The quadruple wheeled robot whose forward two and backward two wheels are in phase respectively is mainly analyzed. The final aim is to make a better use of two couples of wheels which respectively stand on the two diagonal lines. Therefore, a mechanism is proposed in which a pair of wheels with different friction coefficients or diameters share one shaft. We can implement novel turn gaits even though the left and right wheels rotate with the same angular velocity.

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Organization of the Text

The Design of Robot Platform. In general, the quadruple wheeled robot is equipped with four motors, and each motor resolves one wheel separately. It is flexible because of every motor's own being controlled, and control complexity appears with it. Obviously, it is insufficient for the robot to fulfill basic walking on the flat ground perfectly. Note that we are focusing on its ability of getting over obstacles [4].

Fig. 1 shows the mechanisms of wheeled robot we proposed. We can clearly see that the forward two wheels are sharing one transmission shaft resolved by two motors, instead of being driven separately, and so are the backward two. Besides, to turn normally and effectively, we adopt a novel diagonal differential instead of bilateral differential of robot body. Diagonal differential is implemented as follows.

The two road wheels at the end of shaft are different in wheel diameter while the two wheels on diagonal line are the same. Alternatively, different friction coefficients are permitted in the two wheels at the end of shaft.

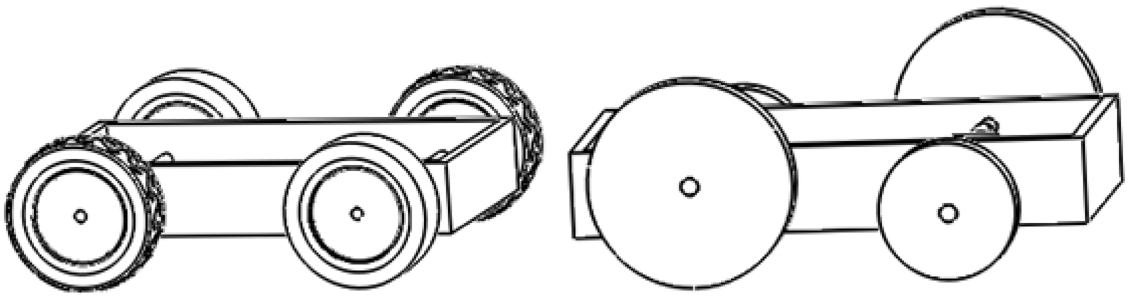

Figure 1 3D-Mode

Obstacle Performance Analysis. For the convenience of research, we assume that the deformation between road wheels and ground or obstacles will be ignored. We also take no account of the friction and deformation among components [5].

To improve its adaptability in the terrain, the forward right driving wheel is set a bulge, and correspondingly, so is the left at the same position. Here, we will make further illustration that the robot with L&R in phase has higher ability in crossing obstacles than that not. We will take continuous stairs as an example to analyze its performance of obstacle negotiation concretely. Hence, let's define coordinate system O-XZ locating at a vertex of stationary stairs, which is in the first stair and connects with flat ground.

Firstly, let's denote the point where the bulge stands key point (KP). When climbing the first stair, the driving wheel will naturally revolve around KP. Suppose the point of contact between wheel and stairs is key point. Fig. 2 shows the concrete analysis of sufferance forces [6]. But, we had better start with figure 1, which depicts the lifting of front wheels. Let's name the states depicted by solid line and dotted line as stage 1 and stage 2 respectively. The slope of inclination angle of β is defined as the angle between line O_1O_2 and line $O_1^{'}O_2^{'}$. θ can be stated as the angle between the line composing $O_1^{'}$ and the key point P and vertical line. So we can have the relation equation from stage 1 to stage 2.

$$l\sin\beta = R\sin\alpha + R\cos\theta \tag{1}$$

After calculating, β can be expressed by θ as

$$\beta = \arcsin\frac{R\left(\sin\alpha + \cos\theta\right)}{l} \tag{2}$$

Where l is the distance from O_1 to O_2, and α is the angle between line O_1P and horizontal line. α is a constant if the wheel diameter and the height of stair are known.

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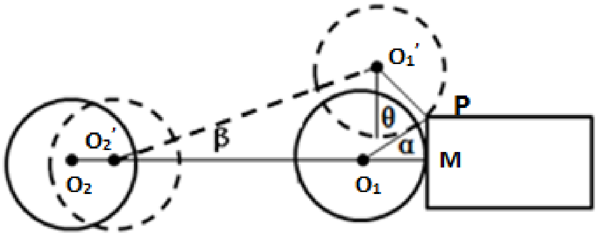

Figure 2 Over-obstacle

Fig. 2 shows the simplified model of over-obstacle, aiming at getting the relation between β and θ. As can be seen in the Fig. 3, we can easily get the coordinates of centroid which are represented as

$$\begin{cases} X_m = -R - \frac{1}{2} l \cos\beta \\ Z_m = R + \frac{1}{2} l \sin\beta \end{cases} \tag{3}$$

Where X_m and Z_m lie in the X axis and Z axis respectively in the O-XZ coordinate system. The result of Quadratic Differential from Eq. 3 is readily available as following

$$\begin{cases} \ddot{X}_m = \frac{1}{2} l \left(\dot{\beta}^2 \cdot \cos\beta + \ddot{\beta} \cdot \sin\beta \right) \\ \ddot{Z}_m = \frac{1}{2} l \left(\ddot{\beta} \cdot \cos\beta - \dot{\beta}^2 \cdot \sin\beta \right) \end{cases} \tag{4}$$

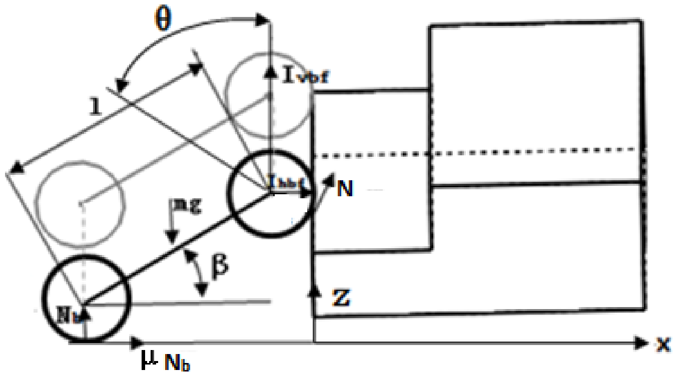

Figure 3 Force Analysis on Step

In fact, the wheeled robot is climbing obstacle when its physical centroid is fluctuating. We will view the body and backward wheels as a intergated whole as the rear wheels have little effect on obstacle negotiation. Thus, we further model kinematics and illustrate equations composing of interaction forces. I_{vbf} and I_{hbf} are forces of vertical and horizontal direction respectively from body. N is symboling of interaction force between bulge and stair and its magnitude is decided by driving torque. N_b is regard as supporting force and μ is friction coefficient. After corresponding components are depicted in detail, we clearly have (according to d'Alembert principle)

$$\begin{cases} \mu N_b + N\cos\theta + I_{hbf} = m\ddot{X}_m \\ N_b + N\sin\theta + I_{vbf} - mg = \lambda m\ddot{Z}_m \end{cases} \tag{5}$$

Where mg is the weight of body, and θ is what it used to be as above mentioned. Additionally, $\ddot{X}_m$ is the summation of the original and the part circle motion causes.

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$$\begin{cases} \ddot{X}_m = -R \cdot \omega^2 \cdot \sin\theta + R \cdot \dot{\omega} \cdot \cos\theta + \frac{1}{2} l \left(\dot{\beta}^2 \cdot \cos\beta + \ddot{\beta} \cdot \sin\beta \right) \\ \ddot{Z}_m = \frac{1}{2} l \left(\ddot{\beta} \cdot \cos\beta - \dot{\beta}^2 \cdot \sin\beta \right) \end{cases} \tag{6}$$

Most of all, λ is quality coefficient and must meet condition 0<λ<1. We consider a scenario where the forward right wheel is on the stair while the counter is on the ground alternatively the opposite if L&R out-phase. Here λ is very small and the wheel on the ground may wait for right phase to climb the stair. On the contrary, if L&R in-phase, the forward wheels will be on the stair because of lateral symmetry and λ is closer to 1 much bigger than before. The driving torque is converged at any time and it is obviously superior to that not converged, that is to say, L&R out-phase.

Swerve Analysis. The wheeled robot is different from ordinary cars equipped with steering. For steering purpose, driving wheels equally divided into two groups, on either side of robot, vary in speed when every one of all 4 wheels is equipped with a motor alone. Ordinarily, bilateral differential is widely used. However, a new mechanism with L&R in-phase is giving up the bilateral differential because of the front two wheels driven by motors. Diagonal differential is proposed at the right time. Here are two specific constructions, one is designed by different diameter, and the other is different friction.

Designed by Different Diameter. L&R in-phase and out-diameter has been introduced in section Introduction. Though there exist differences in wheel diameters, the bottom points of all 4 wheels are in a plane. As we can see in the figure 4, suppose X-axis positive direction is front of wheeled robot, and wheel with smaller diameter is on the left and the bigger is on the right (right is the bigger). The rest couple is the opposite. Let's denote the bottom point of front right wheel is M and lies in the X-axis. The bottom point of back right wheel is O and regarded as the center of the coordinate system. Suppose wheels revolve in direction as shown in figure and angular velocity is ω. Let V1 and V2 stand for the line velocity of W1 and W2. And the points O and M are instantaneous centers of velocity of corresponding two wheels. So we can have

$$\begin{cases} V1 = R_1 \bullet \omega \\ V2 = R_2 \bullet \omega \end{cases} \tag{7}$$

Where R_1 is the radius of back right wheel, and R_2 is the radius of front right wheel with the constraint $R_1<R_2$. It's worth mentioning that V1 is opposite direction to V2. Logically, the resultant velocity of right half of this robot is towards negative direction of X axis since it is rigid structure [7] . Similarly, the counterpart is towards positive direction of X axis. Both sides are different in velocity because of the difference of diagonal wheels. It does really realize what we want. So it can swerve successfully as ordinary wheeled robot.

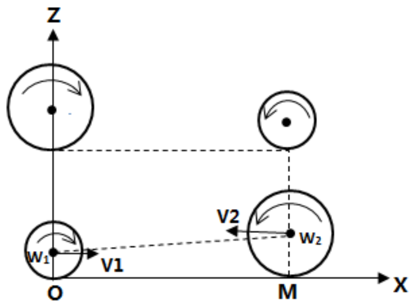

Figure 4 Locomotion Model

Designed by Different Friction Coefficient. The mechanism with L&R in-phase and out-friction is presented in section Introduction. Certainly wheels' diameter can be the same but what is different are the factors that generate tremendous change in friction. As we known, it is friction that leads to

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swerve ultimately. The wheeled robot is in pure roll due to friction [7]. If there exists a scenario where slide occurs during pure roll, we will utilize the slide occurring on either side to turn [8]. Friction forces must differ remarkably, and only in this way can this side of large friction get another side slid. Here we will give the relationship between motor torque and friction coefficient.

In figure 5, we can clearly see stress analysis one of the wheels represented. We assume the wheel moves in a straight line and T stands for torque of driving motor. Let's denote a and a_c are angular velocity and horizontal acceleration. Suppose F_N and F are support force and friction separately. So we can have differential equations for planar motion of rigid body.

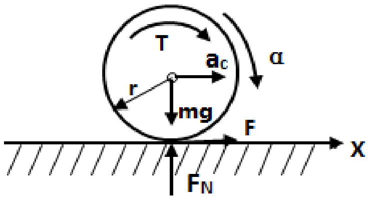

Figure 5 Kinematic Model on Ground

$$\begin{cases} ma_{cx} = F \\ ma_{cy} = F_N - mg \\ m\rho_c{}^2\partial = T - Fr \end{cases} \tag{8}$$

Where a_{cx} and a_{cy} represent components of X and Y axes, respectively. ρ_c is the radius of gyration. We assume that only horizontal movement is permitted. That is to say, it meets a_{cy}=0 and a_{cx}=a_c. Thus, $a_c = \dfrac{Tr}{m\left(\rho_c{}^2 + r^2\right)}$ is obtained easily and there obviously exist two conditions such as $F = ma_c$ and $F_N = mg$ according to Kinematics. Note that it must meet this condition $F \le f_N$ if we have a situation of pure roll, where f_N is the product of friction coefficient and gravity. We can clearly obtain relation that can be formulated mathematically as

$$T \le \frac{3}{2}\mu rmg \tag{9}$$

Where ρ_c is a constant value, $\rho_c = \dfrac{\sqrt{2}}{2}r$, when the wheel is homogeneous material. Slide is in terms of relations between torque and friction. It is one side sliding and another rolling that we utilize to swerve because resultant velocity of sliding side is bigger than rolling with the same angular velocity.

Experiments and Results. We have a test to verify the method we have proposed. Table 1 shows the experiments results that get from comparison between L&R in-phase and L&R out-phase. We make the 4-wheel vehicle climbing up the step and repeat it 100 times. Let's define this situation where it cannot climb over a given period of time such as 3 cycles is unsuccessful. Waiting time represents the interval between arriving and starting to climb averagely.

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Table 1 Experiment Results

	Over-obstacle			Swerve	
	Waiting Time/s	Success	Efficiency	Offset/m	Time/s
In-phase	1.03	100	97%	0.17	5.75
Out-phase	1.15	87	75%	0.08	4.46

In the experiment, the coefficients of the static friction were distinctly different , the height of the step was 110mm(a little higher than the radius of wheels), and we assumed that ground surface is as possible as smooth .

We have recorded the vehicle with L&R in-phase could get on the step each time within a desired predetermined time . 97 in 100 was successful in one peroid and 3 times in two peroids. 1.03 seconds, the average waiting time, were took to succeed in climbing. However, another vehicle with the same conditions except L&R out-phase failed to climb 13 in 100 times. And during negotiation stage, there were 13 times to spend 2 peroids,the rest spending 1 peroid. Surely, its average waiting time was 1.15 seconds. According to fractional steps principle, after succeeding in climbing, we will consider the waiting time efficiency. Here let's denote success probability was expressed by SP $=\frac{\text{Success}}{\text{Total}}$,waiting time efficiency as WT = $\frac{\text{real average waiting time}}{\text{theoretical average waiting time}}$, where theoretical average waiting time is 1 sencond. Thus, the final efficiency was formulated by E=SP*WT . The final data was demonstrated in Table 1 above , over-obstacle section.

We would take two main factors for consideration, one is swerve time and the other is offset which is the distance from rotating center to the original center of body. The 4-wheel drive vehicle was assembled whose wheel radius is 100mm and the vehicle with L&R in-phase owned wheels of which radius were 70mm and 150mm seperately. Theoretically, it would spin around under either bilateral differential of diagonal differential condition. In other words, the offset distance should be 0m. People could not stand some situation where the vehicle took long time to succeed in swerving. But the data recorded in this experiments illustrated the difference from vehicles with in-phase and out-phase. Especially, the swerve time of R&L in-phase was a little longer than R&L out-phase but surely accepted by people .

In conclude, this comparison from above table indicates vehicle in-phase are more efficient than out-phase, and time it spends on swerving is accepted, though longer than out-phase.

Conclusion

In this paper, we are aiming at turning of wheeled vehicle with L&R in-phase because of its high ability in getting over obstacles. We present a novel principle which is called diagonal differential. We also propose corresponding mechanism and conduct experiments to verify its feasibility. However, the research carried out has some unresolved constraints. The bigger the difference of wheels diameter or friction is, the more obvious effect it shows. We will use notch wheel instead of small diameter or friction, which is a transition form from space to time.

Acknowledgements

This work is financially supported by “Fundamental Research Funds for the Central Universities of China” (XDJK2016E071).

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