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INNOVATIVE DESIGN OF A ROUGH TERRAIN NONHOLONOMIC MOBILE ROBOT

Arman Hajati*, Mansour Nikkhah-Bahrami*, and Hami Golbayani†

* Mechanical Engineering Department
School of Engineering, University of Tehran
North Kargar Ave. 11395-515 Tehran, Iran
e-mail: ahajati@ut.ac.ir

† Mechanical Engineering Department
KhajeNasir University of Technology 15875-4416 Tehran, Iran
e-mails: mbahrami@ut.ac.ir, golbayani_h@yahoo.com

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Abstract. *In this paper, an innovative mechanism to improve the step-climbing ability of a nonholonomic mobile robot is presented. Two auxiliary wheels are employed to provide additional traction force; consequently, the step-climbing of the robot is enhanced without any special actuator or complex control strategy. The enhancement in the step-climbing ability of the system is shown by dynamic analysis of the innovative system and the typical one. Based on this design, a prototype of a mine-sweeper robot has been constructed and its performance has been verified through multiple experiments.*

1 INTRODUCTION

A typical nonholonomic mobile robot (unicycle robot) consists of two differential-drive wheels on the same axle and one castor wheel. Wheeled mobile robots are the optimal solutions for well-structured environments like roads or flat and regular terrains. However, in outdoor applications, their mobility becomes noticeably limited and depends highly on the typical size of the obstacles they encounter. Adding real step climbing abilities to a wheeled robot often requires special actuators or complex control strategies [1, 2, and 3]. Other robots, such as walking machines and caterpillars, are well adapted to unstructured environment and can be readily used in such conditions.

Dynamic analysis of step climbing sequence for two-wheel-driven and four-wheel-driven cars has shown a higher performance for the latter. While the step climbing procedure for unicycle robots is similar to that of a 2WD car, use of a 4WD mechanism is preferred for step-climbing purposes. On the other hand, using a 4WD mechanism increases the control complexity and also decreases the maneuverability. Therefore, the idea of upgrading a unicycle robot to a 4WD mechanism for the step-climbing sequence is proposed.

2 SYSTEM DESCRIPTION

Two auxiliary wheels are employed to achieve an enhanced ability for the step-climbing sequence by providing additional traction force. The wheels, normally detached from the ground because of an initial clearance, are activated automatically when they reach the step. Therefore, in normal conditions they have no effect on the system's controllability and maneuverability and help the robot to pass the step by providing extra traction force. These two wheels are connected to the differential drive wheels using timing belt, hence no additional electrical motor is needed.

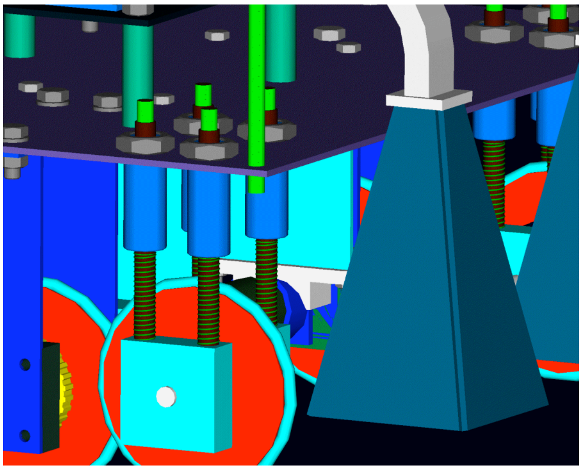

Figure 1: Auxiliary Wheels.

The use of springs and guide rods, as shown in figure 1, provides auxiliary wheels a self-activating mechanism. Therefore, without any dedicated actuator or complex control procedure, step-climbing ability of a unicycle robot is enhanced to that of a 4WD one.

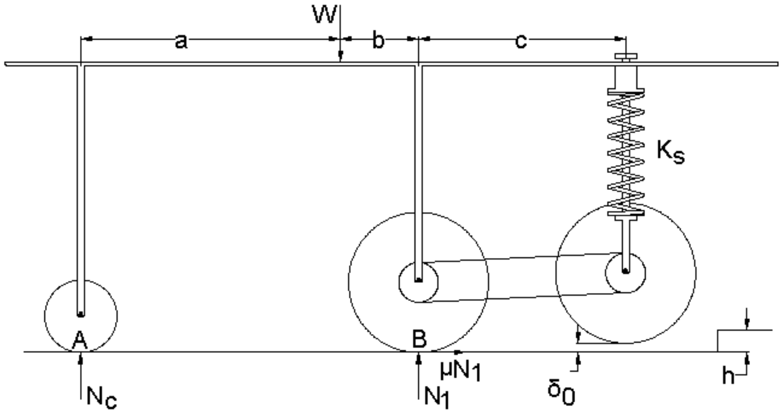

Figure 2: Schematic Diagram of the Proposed Mobile Robot.

The design process consists of determining the system's parameters, which are given in Table 1 and shown in figure 2.

W	total weight of the robot
$F_{preload}$	spring constant
δ_0	passive wheels clearance from the surface
h	height of the step
μ	coefficient of friction
N_1	surface reaction force to driven wheels
Nc	surface reaction force to castor
D	diameter of the driven/passive wheels
d	diameter of the castor

Table 1. Definitions of symbols and the parameters

There are some facts which must be considered in the design process: while crossing the obstacles, the higher the $\frac{D}{h}$ ratio, the more improvement of the system performance; but using larger wheels will cause an increase in robot size and also friction torque on motors.

3 DYNAMIC ANALYSIS

In order to analyze the performance of the system and to select the optimum parameters for the system, a dynamic analysis of the system has been done. The maximum step-climbing ability of the system can be determined by analyzing the forces on the robot while passing the step. The main difficulty for the system in passing the steps is the reaction force of the step on the robot which prevents the robot's motion. However, in spite of the negative force exerted on the robot, the robot can pass the step if it has sufficient velocity. But, it makes an impact force which is undesirable. Therefore, the failure criteria would be the inadequate traction force of the robot in at least one of these conditions. It means that we would like the robot to be able to pass the step smoothly without initial velocity. The maximum height of the tolerable step for the robot can be determined by assuming the magnitude of the friction force to be maximal and the traction force of the robot is cancelled out completely by the reaction force of the step.

3.1 Case I: Auxiliary Wheels - Crossing the Step

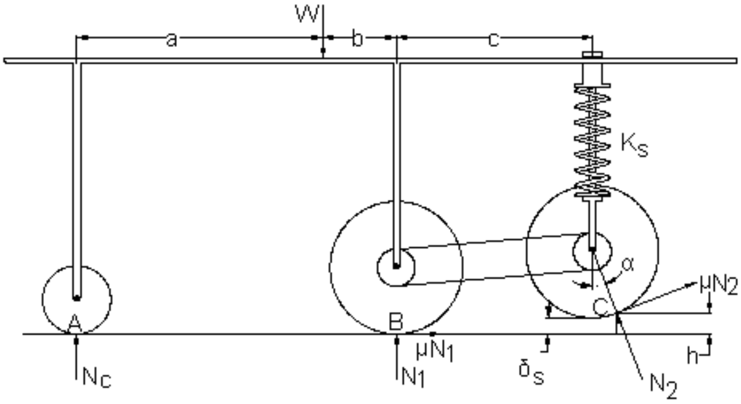

Figure 3: System's Free Body Diagram - Case I

Crossing the auxiliary wheels over the step is one of the most critical situations of the robot as it shown in figure 3. The main points should be considered are the optimum spring constant and initial state of the front wheels. In other words, spring hardness imposes a vertical force while the front wheels climb the steps canceled out by the step reaction force. To solve this problem, we have used a soft spring for suspension which is mounted with an initial preload. By this mean, the system exerts an identical force, equals to the preload, regardless the amount of the wheel's deflection.

These reaction forces are composed of normal force N_2 and subsequent friction force which magnitude is μN_2. Consequently, these forces have components in x-direction may spoil robot moving and must be calculated.

$$\text{Spring force:} \quad N_2 \cos\alpha + \mu N_2 \sin\alpha = F_{preload}$$
$$\Rightarrow \quad N_2 = \frac{F_{preload}}{\cos\alpha + \mu \sin\alpha} \tag{1}$$

Robot's equilibrium equations:

$$\Sigma F_x = 0 \quad \Rightarrow \quad \mu N_1 - N_2 \sin\alpha + \mu N_2 \cos\alpha = \mu N_1 + \frac{F_{preload}(\mu\cos\alpha - \sin\alpha)}{\cos\alpha + \mu\sin\alpha} = 0 \tag{2}$$

,

$$\Sigma F_y = 0 \quad \Rightarrow \quad N_1 + N_c + F_{preload} = W \tag{3}$$

,

$$\Sigma M_C = 0 \quad \Rightarrow \quad N_c\left(a + b + c + \frac{D}{2}\sin\alpha\right) - W\left(b + c + \frac{D}{2}\sin\alpha\right) + N_1\left(c + \frac{D}{2}\sin\alpha\right) - \mu N_1 h = 0 \tag{4}$$

Considering the geometry, we have:

$$\cos\alpha = \left(\frac{\frac{D}{2}+\delta_s - h}{\frac{D}{2}}\right) \Rightarrow \alpha = \cos^{-1}\left(\frac{\frac{D}{2}+\delta_s - h}{\frac{D}{2}}\right) \quad (5)$$

The angle of normal force with vertical direction in the wheel α is an important parameter because of its effect on x-direction resultant of step on robot.

3.2 Case II: Driven Wheels - Crossing the Step

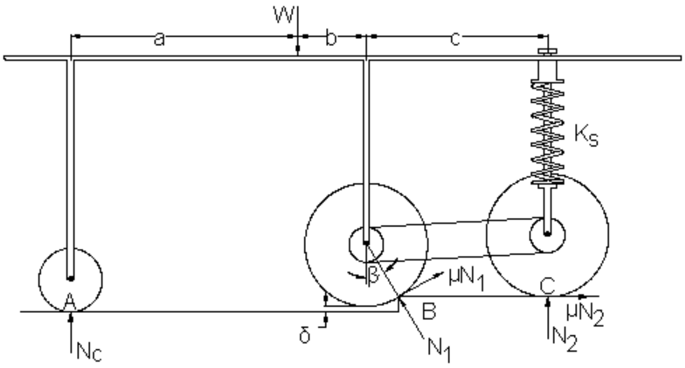

Figure 4: System's Free Body Diagram - Case II

The free body diagram of the robot while driven wheels are crossing the step is shown in figure 4. It is notable that we can observe the functionality of passive wheels and their benefit for robot traction in this stage.

$$\Sigma F_x = 0 \quad \Rightarrow \quad \mu N_1 \cos\beta - N_1 \sin\beta + \mu F_{preload} = 0 \quad (6)$$

,

$$\Sigma F_y = 0 \quad \Rightarrow \quad N_c + F_{preload} + N_1 \cos\beta + \mu N_1 \sin\beta = W \quad (7)$$

, and

$$\Sigma M_B = 0 \quad \Rightarrow N_C\left(a+b+\frac{D}{2}\sin\beta\right) - W\left(b+\frac{D}{2}\sin\beta\right) - F_{preload}\left(c-\frac{D}{2}\sin\beta\right) = 0 \quad (8)$$

in which a new term δ_{def} is added in eq. (6). It is because of deflection of robot as a result of its geometry condition. Driven wheels are climbing the step, in such a way that castor remains on the ground and the robot chassis makes an angle with horizon as shown in figure 5.

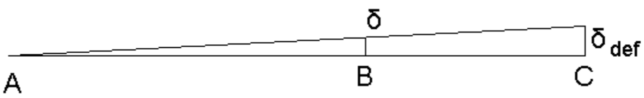

Figure 5: The amount of rising of robot head when its driven wheels climb up

Then we have:

$$\delta_{def} = \left(\frac{a+b+c}{a+b}\right)\delta \quad (9)$$

Considering the wheels geometry, we have:

$$\cos\beta = \left(\frac{\frac{D}{2} + \delta - h}{\frac{D}{2}} \right) \tag{10}$$

3.3 Case III: Castor - Crossing the Step

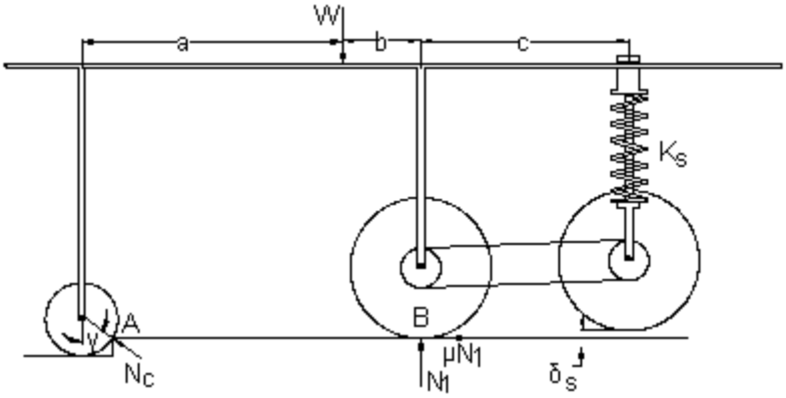

Figure 6: System's Free Body Diagram - Case III

Another critical condition occurs when the castor crosses the step as shown in figure 6. In this case, the driven wheels traction force is the most important factor. Since castor is a free rotating wheel, no friction force exists at contact point, and the only existing force is normal force which has a negative component in x direction; therefore, it is a disadvantage for robot's moving; consequently, it is much better to locate the C.G. of the robot in such a way that it's reaction force at castor would be a small value.

$$\Sigma F_x \geq 0 \quad \Rightarrow \quad \mu N_1 - N_c \sin\gamma \geq 0 \tag{11}$$

,

$$\Sigma F_y = 0 \quad \Rightarrow \quad W - N_c \cos\gamma - N_1 = 0 \tag{12}$$

,

$$\Sigma M_A = 0 \quad \Rightarrow N_1 \left(a + b - \frac{d}{2} \sin\gamma \right) - W \left(a - \frac{d}{2} \sin\gamma \right) = 0 \tag{13}$$

and we have,

$$\cos\gamma = \left(\frac{\frac{d}{2} - h}{\frac{d}{2}} \right), \sin\gamma = \sqrt{1 - \left(\frac{\frac{d}{2} - h}{\frac{d}{2}} \right)^2} \tag{14}$$

4 RESULTS

The proposed system has been implemented as a minesweeper mobile robot, which is shown in figure 7. The actual parameters of the robot are listed in Table 2.

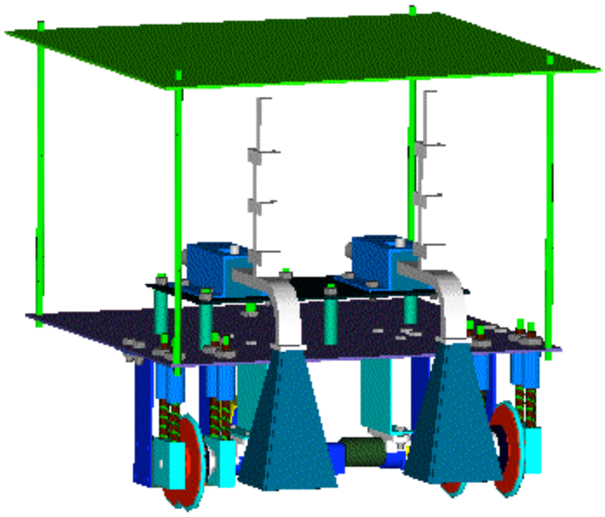

Figure 7: Minesweeper Mobile Robot

d	6cm
D	9cm
μ	0.5
δ_0	2mm
a	30cm
b	5cm
c	10cm
W	100N
$F_{preload}$	35N

Table 2. Actual Parameters.

The performance of the proposed mobile robot and traditional unicycle robot, shown in figure 8, is compared in figure 9. We can see a considerable enhancement in system's performance.

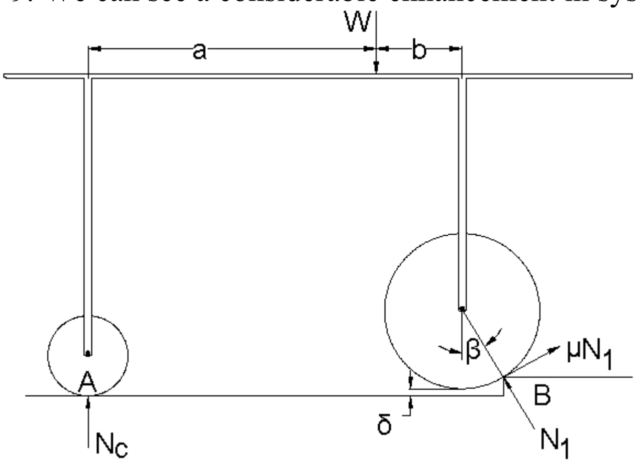

Figure 8: Schematic Diagram of the Unicycle Mobile Robot.

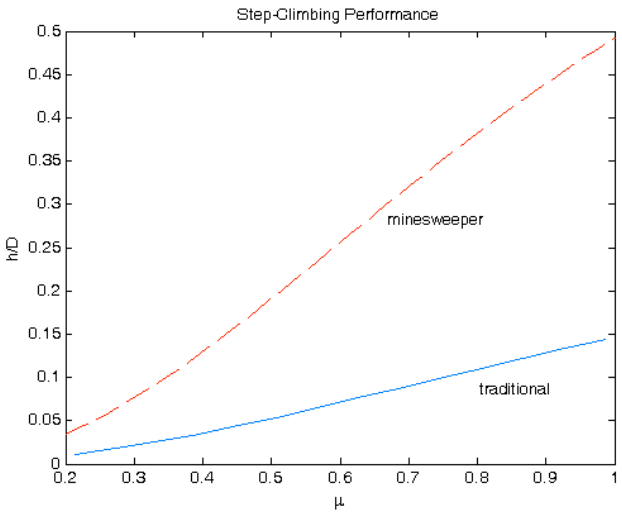

Figure 9: Step-Climbing Ability of the Proposed Robot and Traditional Unicycle Robot.

5 CONCLUSIONS

In this paper, an innovative mechanism was proposed to enhance the step-climbing ability of traditional unicycle mobile robots. Two auxiliary wheels were employed to increase the traction force of the robot while passing the step. The effect of these auxiliary wheels was studied by dynamic analysis of the system. The improvement in system's step-climbing ability can be easily seen in figure 9. It shows that this ability has been nearly tripled by means of auxiliary wheels without increasing system's control complexity or employing extra actuators. The proposed system was successfully implemented on a minesweeper mobile robot of Tehran University.

REFERENCES

[1] C. Balaguer, A. Gimenez, A. Jardon *Climbing Robots' Mobility for Inspection and Maintenance of 3D Complex Environments.* Autonomous Robots, March 2005.

[2] D. Bevly, S. Dubowsky, C. Mavroidis *A Simplified Cartesian-Computed Torque Controller for Highly Geared Systems and its Application to an Experimental Climbing Robot* Dynamic Systems, Measurement and Control Journal, ASME, 2000.

[3] T. Bretl, S. Lall, J.C. Latombe, S. Rock *Multi-Step Motion Planning for Free Climbing Robots*, *Algorithmic Foundations of Robotics*, Utrecht/Zeist, The Netherlands, July 2004.