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Mechanims for Preventing Traction Loss in Mobile Robots Operating on Sparingly Flat Surfaces

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***Abstract* – Wheeled robots that traverse across flat surfaces encounter a loss of traction due to irregularities in the surface plane. This causes the robot to deviate from its path, thus requiring constant adjustment in its direction and speed. Existing solutions for this problem involve complex and bulky suspension systems that affect the robot mobility and increase power consumption. This paper presents a compact and efficient mechanism that helps to prevent the loss of traction in mobile robots.**

Keywords – Mobile Robot, Flat Surface, Traction Loss, Wheel Slip, Suspension.

I. NOMENCLATURE

f	Degree of freedom
n	Number of links
p	Number of lower pairs
h	Number of higher pairs
I	Moment of inertia
y	Distance from neutral axis
σ	Allowable stress
S_1	Shear force at pivot point
S_2	Shear force at spring end
S_3	Shear force at wheel end
N_w	Normal force on wheel
R_p	Reaction force at pivot
δ	Deflection
τ	Allowable shear stress
P	Equivalent load
V	Race rotation factor
X	Radial load factor
Y	Axial load factor
C_o	Static load capacity
C	Dynamic load capacity
L_{10}	Life in million revolutions
K	Wahl factor
C_s	Spring index
D	Mean coil diameter
N	Number of active coils

II. INTRODUCTION

Robotics has become an integral part of almost all industrial processes. One of the most extensively used robots are the stationary ‘pick and place’ robotic arms that are deployed in manufacturing and assembly lines for performing specific tasks. Another category of robots popular in manufacturing units are the mobile robots. These robots are comprised of a platform and a locomotion system that helps to move the robot through its surrounding environment. They can be wheeled or legged robots that operate on the ground or aerial robots that have propellers for flight.

The use of such mobile robots for material transportation is now a common feature in the process industry. These robots are usually four wheeled machines that trace a white strip drawn on the shop floor. Such line tracing robots are useful for tasks involving fixed paths and are not greatly affected by any bumps or depressions on the floor. But for robots that operate with a greater autonomy or use a different form of feedback for determining their path, irregularities in the floor surface can significantly add to the complexity of path planning. Moreover this problem is increasingly prominent in remote controlled robots. Here the motions of the robot are controlled by a human operator and therefore any form of slippage significantly compromises the ease of operation. A robot that is commanded to move in a straight line by the operator, may deviate sideways if any of its wheels losses contact with the ground at certain points during the travel time.

This leads to a motion that is constantly corrective and never reaches a stable equilibrium or a minimum potential point. It requires a control that works on minimizing the error function for obtaining the desired motion. Such a control has a high power consumption and is highly iterative. Therefore it is necessary to reduce the slippage and loss of traction for allowing the error function to reach its minima in minimum amount of time. Several models have been proposed for addressing this problem. But very few focus on the motion of manually controlled mobile robots on flat surfaces that closely represents the conditions in a material handling workshop. In this paper we will discuss different cases of operation on flat surfaces and how each can be tackled. We will also test the postulated mechanism for preventing traction loss and compare it with previously proposed solutions.

III. LITERATURE REVIEW

One such model presented in [1] is a two degree of freedom suspension system for minimizing slip on uneven terrain. Movement is allowed in the vertical as well as the lateral plane. It also utilizes a torus shaped wheel that can maintain contact with the ground even in a tilted position. The two degrees of freedom are achieved through a four bar mechanism called the double four bar suspension. This mechanism demonstrates lower slip on uneven terrain while tracing straight and curved paths. But its motions are superfluous on a flat surface. The

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design of a similar suspension model is analyzed in [2]. It calculates the damper and spring coefficients required to sustain the irregularities of an uneven terrain. The system of two dashpots and a spring was able to scale obstacles of 80mm height and the stresses experienced during this motion were studied. This system showed high power requirement at higher speeds.

The most common approach to tackling rough terrains is the utilization of a control model. Paper [3] considers the dynamics of the robot in a 2D plane. It considers different contact angles at each wheel to calculate the ideal torque requirement of each wheel. Therefore it maintains the desired speed while minimizing the power consumption. But this model is only applicable in cases where the chassis roll angle is constant. On the other hand, [4] employs a third order under-actuated dynamic system. Here the second order non holonomic constraints do not reduce the state space and asymptotically stabilize the motion of the robot. It also establishes an extremum seeking control for sharp turning operations. But the time taken by the system to converge exponentially is dependent on the magnitude of error that has to be first controlled physically.

But [6] presented a model that was not based on torque distribution and slip measurement. It studied the properties and geometry of the terrain using a Kalman filter to determine the wheel contact angles. This model was more efficient in improving mobility than individual wheel control models. An extension of this model in [7], implemented a sensor triggered reactive control for high speed mobile robots. It determined the factors governing performing of high speed tasks in rough terrains.

In an ideal case a wheel is assumed to roll without slipping. But there exists a significant degree of slip in practical applications. Slippage in motion of omni-directional robots is discussed in [5] where a dynamic slip model is determined to measure friction coefficients and the factors governing the introduction of slip. Building on this study, we aim to physically reduce the loss of traction and establish a correlation with the dynamic slip model.

IV. LOSS OF CONTACT

B A wheel is said to have lost traction when the normal force acting on the wheel becomes zero or its coefficient of friction with the surface becomes zero. This causes the wheel to freely rotate in air without contributing any force towards the motion of the robot. This tends to imbalance the forces generated by the rest of the wheels hence changing the resultant force vector.

Along with the surface properties, the probability of loss of traction at a wheel is also governed by the position of center of gravity of the robot. As most mobile robots are used for carrying materials, the position of their center of gravity can vary according to the placement of loads. For a robot to remain stable, the projection of its center of gravity onto the horizontal surface, should lie within a region called the support polygon.

A support polygon is a region formed by the points of contact between the robot and the ground. For a robot with just one wheel the support polygon becomes a point. Similarly for a robot with just two wheels, the support polygon is nothing but a line. But for three or more wheels, we get a polygon with number of sides equal to the number of wheels.

For a robot with one or two wheels, the probability that the projection of center of gravity lies on the stable region is infinitesimally small. But for a robot with three wheels, there can be numerous points of stability inside the support polygon.

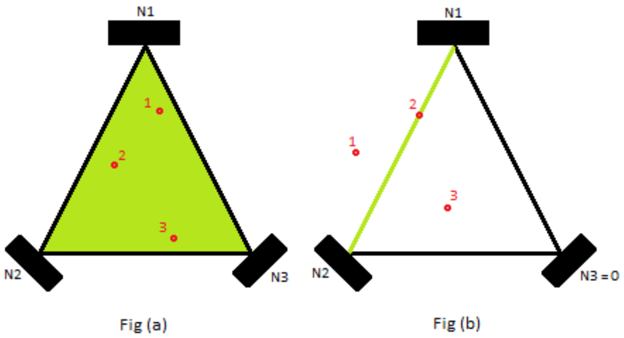

Fig.1. Support polygon for three wheeled robot

The green portion in figure 1 represents the stable region. If the projection of center of gravity lies on points 1, 2, 3 or the infinite other points inside the green triangle in Fig-a, the robot is in stable equilibrium. When one of its wheels loses contact with the ground, its normal force becomes zero (N3 = 0) and the support polygon becomes a line. Only if the point of center of gravity lies exactly on point 2 in Fig-b the robot can remain stable. But if it lies in the region of point 3, the wheel will come back in contact with the surface. Therefore for a three wheeled robot that is stable, loss of contact would be minimum.

Now, for a four wheeled robot, when one of its wheels loses contact with the ground, the support polygon becomes a triangle.

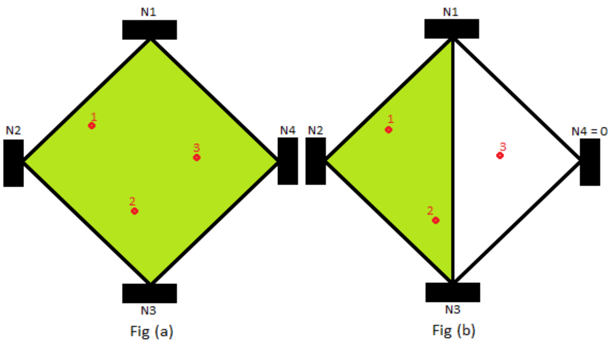

Fig.2. Support polygon of four wheeled robot

If the position of center of gravity of the robot lies at point 3, the wheel will return to ground. But if the center of gravity lies around points 1 and 2, the wheel will remain suspended in the air. Therefore there exist several cases of equilibrium with one wheel not in contact with the ground. The fundamental principle being the existence of other local minima that ensure the stability of the robot even while some its wheels are ungrounded.

V. DESIGN PROCEDURE

If the path of a robot is fixed, one can use a PID control that minimizes an error function to correct its path. But the position and magnitude of the load carried by a mobile robot can vary and thus causes the center of gravity to constantly change its position. This makes it extremely difficult to determine the proportional, integral and derivative parameters required by a PID control that will converge quickly.

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The crests and depressions on a seemingly flat surface have a vertical displacement of not more than 5mm. Therefore the adjustment required in the vertical direction is minimal and thus a bulky suspension mechanism is unmerited. We have proposed an arrangement that comprises a spring actuated revolute pair that can be easily incorporated in the design of mobile robots. This kinematic pairing helps to physically eliminate the loss of contact and in turn reduces the slippage, making it easier for a control to obtain the desired trajectory.

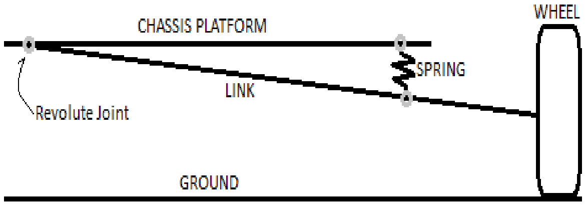

Fig.3. Schematic of kinematic pair

A. Kinematic Analysis of Links

To determine the degrees of freedom we applied an altered form of the Kurtzbeg equation:

$$f = 3(n-1) - 2p - h \tag{1}$$

By substituting n=2, p=1 and h=0 we get the degree of freedom as 1. This DOF is the rotation of link in the vertical plane. To ensure that the wheel does not tilt more than 2˚ for a vertical wheel displacement of 5mm, the link length can be determined as:

$$l = d/\sin(\theta) \tag{2}$$

Taking d=5mm and θ = 2˚we get that the length of the link should be more than 150 mm.

B. Structural Analysis of Links and Shafts

The link bearing the motor and wheel is acted upon by the spring and the reaction forces generated by the weight of the robot. It is necessary to select a link cross-section that can sustain these forces without undergoing bending failure.

$$I = \frac{M * y}{\sigma} \tag{3}$$

M is the maximum bending moment acting on the link. The bending moment is maximum where the shear stress becomes zero. We can calculated the shear force at the pivot point, the point of spring action and the location of wheel as follows:

$$S_1 = N_w - k\delta \tag{4}$$

$$S_2 = N_w \tag{5}$$

$$S_3 = R_p - k\delta \tag{6}$$

Using these values we plot a shear force diagram and a bending moment diagram, to calculate the maximum bending moment acting on the link.

The shaft inside the bearing is subjected to loading in the shear plane and its diameter can be calculated as:

$$d_{shaft} = \sqrt{\frac{R_p}{2\pi\tau}} \tag{7}$$

The diameter of the shaft should be equal to more than the calculated diameter.

C. Bearing Selection

Almost complete weight of the robot acts across the revolute joint. Therefore it is necessary to select a bearing that can carry this radial load and provide a sufficiently long life. To estimate the total equivalent load on the bearing we used:

$$P = VXF_r + YF_a \tag{8}$$

The factors X and Y depend on the ratios ${}^{F_s}/_{F_r}$ and ${}^{F_a}/_{C_o}$. We also determined the life of bearing in million revolutions and calculated the dynamic load capacity as:

$$C = P(L_{10})^{1/3} \tag{9}$$

Lastly we select the bearing having the required dynamic capacity from bearings catalogue.

D. Spring Design

The function of the spring is to keep the wheel pushed towards the ground and therefore we require a compression spring. The different dimensions of the spring we calculated as:

$$d_{spring} = \sqrt{{}^{8PKC_s}/_{\pi\tau}} \tag{10}$$

$$D = C_s * d \tag{11}$$

$$\delta = {}^{8PD^3N}/_{Gd^4} \tag{12}$$

$$l_{free} = l_{solid} + l_{gap} + \delta \tag{13}$$

A list of these specifications is used to manufacture the spring of required stiffness.

VI. MODELLING

According to the aforementioned procedure, following dimensions were determined for generating the CAD model of the mobile robot.

TABLE I. DESIGN DATA TABLE

Parameter	Value
d_{shaft}	20 mm
b_{link}	50 mm
h_{link}	40 mm
l_{link}	500 mm
$h_{platform}$	20 mm
D_{spring}	20 mm
d_{spring}	1.6 mm

Kinematic analysis was performed for highest and lowest values of wheel displacement.

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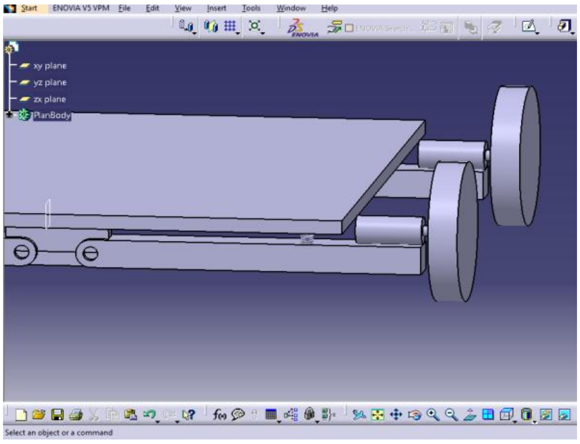


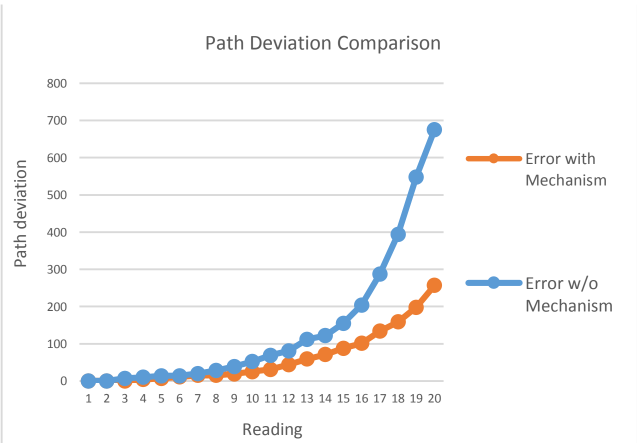
Fig.4. CAD modelling of mechanism

VII. RESULTS AND DISCUSSION

A three wheeled mobile robot was constructed for testing the proposed mechanism. A radiac coupling was also introduced in the wheel shaft for absorbing the vibrations generated by the omni-directional wheels.

Fig.5. Three wheeled mobile robot

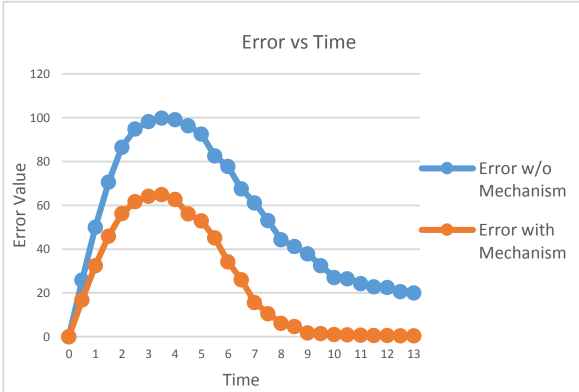
The robot was instructed to follow a straight line without any feedback control circuit and suspension mechanism. The robot showed an exponential deviation from the desired trajectory as it moved farther away from the starting point. This was due to the rotation of the robot about the wheel experiencing loss of traction.



Graph.1. Deviation from desired path

As seen in the graph 1, the use of the proposed suspension mechanism reduced the magnitude of error between the observed and desired path. Also as the load on the robot was increased the deviation of the robot from the desired path reduced. But in a four wheeled robot, increase in the load can lead to greater deviation because of greater unbalanced moments.

A control loop was introduced to correct the path of the robot. The control took feedback from a gyrometer, compass and accelerometer arrangement. Without the suspension mechanism the control failed to minimize the error function in required time. But as seen in figure 7, with the use of the suspension mechanism the error function was able to converge in few seconds.



Graph.2. Error function

VIII. CONCLUSION

Operation of mobile robot on a flat surface is less rigorous than operation on a rough, uneven surface. Therefore it requires minimal vertical adjustment to eliminate the loss of contact. The proposed mechanism duly serves the purpose without affecting the mobility of the robot. Other suspension mechanisms used in robots operating on rough terrain have superfluous degrees of freedom and hence not efficient on seemingly flat surfaces.

We can see from the results that this mechanism helps to reduce the traction losses and eliminates loss of contact. It also helps the PID control to converge faster and execute the desired trajectory. It is easier and cost effective to incorporate such a mechanism into industrial mobile robots that operate on shop floors. Speed of execution being of utmost importance in material handling units, elimination of loss of contact proves to be a vital factor. Also further research into the compatibility of this mechanism with different dynamic control models can help in determining the most optimum control strategy.

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