



MODELS OF ROBOT'S WHEEL-MOVER BEHAVIOR ON FERROMAGNETIC SURFACES

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Abstract: The mobile robots which can move on complicated working surfaces play a significant role in the automation of various technological processes, in particular, ship repair, fire fighting, inspection of welding quality, rescue operations, etc. This work is a continuation of the authors' investigation of the mobile robot's moving on inclined and vertical ferromagnetic surfaces based on a magnetically operated wheel-mover. Special attention is paid to constructing magnetically operated wheel-mover with twelve legs and modeling of the robot's wheel-mover behavior in different working modes including investigations of the wheel-mover center trajectory, behavior of control signals, etc. Geometrical dependences between a number of wheel-mover legs and deviation of the wheel center path from horizontal line are described. In the present article the modeling results for movement of the wheel-mover on both plain and non-plain surfaces are discussed. For this purpose, the mathematical model of the wheel-mover was created and analyzed and the results were verified using a simulation approach.

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1. INTRODUCTION

Robotics, automation and information technologies correlate with production, culture, sport, life science [1] and have very great prospects in different fields of human activity [1, 2].

Industrial robots and specialized robotic systems play a significant role in the automation of different industrial technological processes [2, 3] in manufacturing, even under various dynamic and uncertain conditions [3]. One of the most important robotics tasks is to control the robot movement [4-6] in an environment with complicated working surfaces [7, 8], with dynamic obstacles and when

(a) the mass of manipulated object is unknown [9],

(b) the robotic system has non-stationary parameters,

(c) the mission of the robotic system can be changed online [3, 10].

The tasks and missions of robotic systems define their construction peculiarities and the diversity of their types [2, 7, 8]. Examples are planar robots [11], manipulators with parallel kinematic structure [12], dual arm robot manipulator [13], robots with multi-arm structure [14], mobile robots [15-18], etc.

In various industrial branches such as shipbuilding, processing (cleaning, mounting of dowels and explosive devices, firefighting, dyeing, inspection and diagnostics, welding, cutting and polishing and desalination of the ship hulls) of large surfaces or in tight places, human life and health are at risk. The use of mobile robots (MR) increases the productivity as well as has a positive impact on the health of employees.

2. RELATED WORKS AND PROBLEM STATEMENT

As the MR can be used in shipbuilding and ship repair, it makes sense to use magnetically operated principles and devices [19, 20] in particular, magnetically operated plates and clamping devices. This restricts the range of MR application and requires a powerful clamping force. A magnetically operated wheel-mover (WM) [21] allows the MR to move on surfaces that can be inclined at an arbitrary angle and even have non-planar shape.

The investigations of an interaction between magnetic driver and ferromagnetic surface are discussed in [22]. It is based on the calculation of magnetic field parameters for various thicknesses of

the layers and creates a mathematical model as well as an algorithm for calculating the mechanical interaction with the permanent magnets.

In [9] authors propose new solutions to creating and improving slip displacement sensors in applications to measure contact forces in robotic systems. In [23, 24] a neuro-fuzzy observer of the clamping force was created and the energy efficiency and reliability of the MR moving process was improved.

In [25] the author analyzed current multifunctional MR, such as [26, 27], which can move on inclined and vertical surfaces. Analysis of [7, 8, 21, 25-27] shows that researching of robots with magnetically operated clamping devices is very important and promising for the automation of technological processes in the ship repair industry.

Present researches deal with the development of the structures of MR's intelligent control system [5, 28], the selection of the most acceptable control system components (based on FPGA, for example [29, 30]), the control algorithms and devices testing in order to model and implement them [31, 32] and consideration of the possibility to reconfigure the control system according to a dynamic environment with unknown obstacles or to allow MR's mission to change over time.

Processing of the operations mentioned in the introduction often requires rather high position accuracy of the installed equipment. It is also assumed that most of the operations need to be performed on a curved surface. But there are no research results about meeting these requirements for the WM. This paper aims at considering the mathematical model of the magnetically-operated WM and its behavior on planar and non-planar surfaces and developing approaches for satisfying the equipment requirements.

3. STRUCTURE OF MAGNETICALLY-OPERATED WHEEL-MOVER

The structure of the magnetically-operated wheel-mover [19, 20] considered in this paper is presented in Fig. 1.

The wheel-mover has N uniformly allocated spokes 1-4, each with a hinged 5 electromagnet foot 6 that can extend and shorten individually. The length of the legs lies within $[R_{min}, R_{max}]$.

- Rotation is induced by changing the lengths of the spokes.
- Two magnets are attached to a surface 7 permanently.
- It is assumed that the magnets do not slide on the surface.

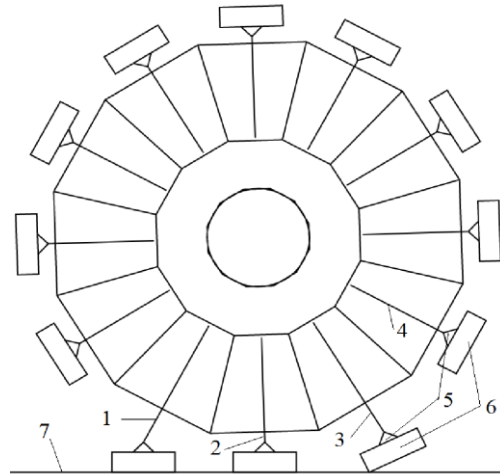


Fig. 1 – The wheel-mover with 12 legs (magnets).

It is supposed that several WMs will be connected to a MR's body similarly to conventional wheels with active suspension.

4. DESCRIPTION OF A SINGLE STEP OF THE WHEEL-MOVER

The WM proceeds in individual steps, where each step is made while two spokes are attached to the ground. This section summarizes the results from [29] and continues them by considering features of the WM's movement in the single step case.

4.1 PATH OF THE WHEEL CENTER

In [29] the authors obtained conditions on the possible positions of the WM's center O during a single step when two magnets A, B are connected to the surface. The wheel center O lies on the circumcircle of the triangle ABO (Fig. 2) described by formula:

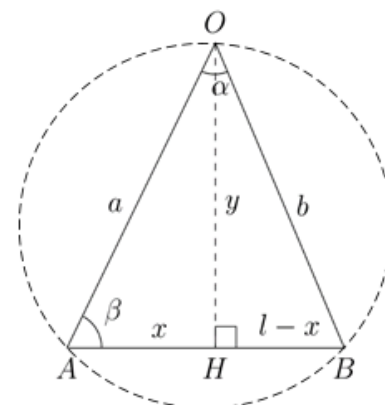


Fig. 2 – Triangle and circumcircle defined by adjacent legs.

$$\left(x - \frac{l}{2}\right)^2 + \left(y - \frac{l}{2 \tan(\alpha)}\right)^2 = \left(\frac{l}{2 \sin(\alpha)}\right)^2. \quad (1)$$

As the path of the center of the WM consists of arcs, it cannot move parallel to the surface. Fig. 3 shows a circumscribed circle of the triangle and the arc O_1O_2 of typical positions of O on a plain surface.

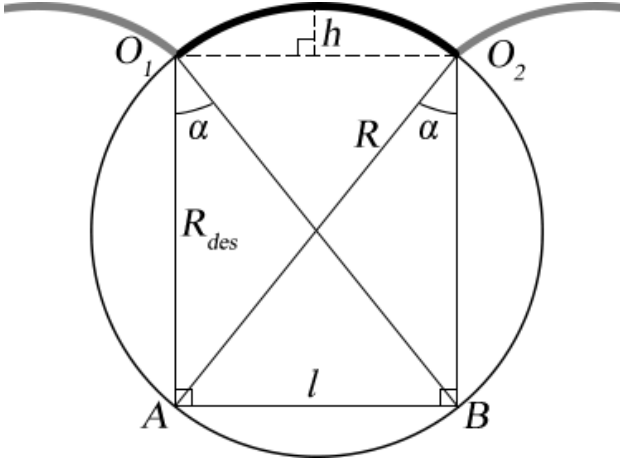


Fig. 3 – Possible positions of the wheel center.

Fig. 4 illustrates the effect of non-constant distance between surface and center of a WM with 12 legs, 8 legs, and 6 legs and $R_{des} = 50$ units.

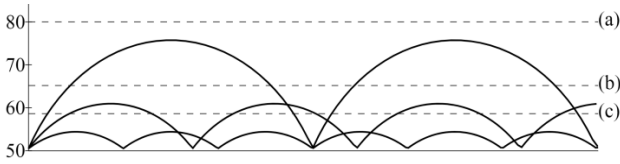


Fig. 4 – Paths in the plane of the wheel center for 6 legs (a), 8 legs (b), and 12 legs (c).

The position of the WM is parametrized in [29] by the angle β . Of course, there is no direct actor on β but by varying the spoke lengths a and b , it can be affected. In [29] the lengths of the spokes were calculated as

$$a = l \frac{\sin(\beta+\alpha)}{\sin(\alpha)} \quad b = l \frac{\sin(\beta)}{\sin(\alpha)}. \quad (2)$$

4.2 CHANGES OF Y-COORDINATE OF THE WM CENTER ON A PLAIN SURFACE

It is assumed that the robot with the WMs will be equipped with the necessary tools. In general, correct processing requires a constant distance between the surface and the equipment. By the construction of the WM this is not possible directly and it is necessary to add mechanical components to compensate for the ripple in the distance. It would be very useful to know the bounds on the ripple at an early design stage.

Figure ABO_2O_1 in Fig. 3 is a rectangle, hence $AB = O_1O_2 = l$ holds and the height h of an arc O_1O_2 is given by

$$h = R - \sqrt{R^2 - \frac{l^2}{4}} = \frac{l}{2} \cdot \frac{1 - \cos(\alpha)}{\sin(\alpha)} \quad (3)$$

where $R = l/(2\sin(\alpha))$ is radius of the circumscribed circle. By the WM construction $\tan(\alpha) = AB/O_1A = l/R_{des}$, where R_{des} is a minimal desired leg length during movement on the plain surface. Hence

$$h = R_{des} \frac{1 - \cos(\alpha)}{\cos(\alpha)} = R_{des} \left(\frac{1}{\cos\alpha} - 1 \right). \quad (4)$$

Fig. 5 illustrates (4) for fixed $R_{des} = 100$ units and different number of legs N . Note that $\alpha = \frac{2\pi}{N}$. It is seen that the ripple increases in a small number of legs N to rather big values. Thus, for restricting the ripple at design stage one might need to fix a minimal N satisfying this restriction. E.g., twelve legs, which are used in the simulation, provide a change in the y -coordinate of 7.74% of R_{des} . A compensating structure which can extend up to 8% of R_{des} is sufficient to move the robot body parallel to the surface.

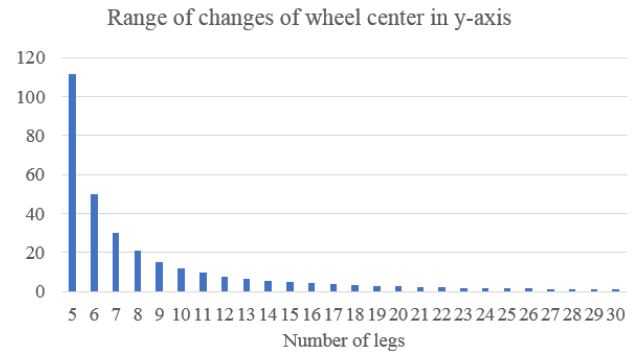


Fig. 5 – Range of changes of y -coordinate for $R_{des}=100$ units and different number of legs N .

4.3 CONSTANT HORIZONTAL SPEED

Such processes as welding, cutting and dyeing are very sensitive to speed changes and require a constant speed in a fixed direction. The latter can be provided by special devices compensating unintended movements like the vertical ripple. A constant speed on the other hand can be achieved correspondingly by parameterizing the leg lengths in time.

From Fig. 2 it is obvious that the variables x and y can be expressed in terms of a and β by $x = a\cos\beta$ and $y = a\sin\beta$. Horizontal speed is given using addition theorems of trigonometric functions as

$$\dot{x} = \left(-a\sin\beta + \frac{\partial a}{\partial \beta} \cos\beta \right) \dot{\beta} = \frac{\cos(2\beta+\alpha)}{\cos\alpha} l \dot{\beta} \quad (5)$$

with $\frac{\partial a}{\partial \beta} = l \frac{\cos(\beta+\alpha)}{\sin \alpha}$ from (2). This is non-constant for constant angular speed $\dot{\beta}$ which was used in the first implementation of the simulation. Thus, by applying a non-constant angular velocity $\dot{\beta}$ one can obtain a constant horizontal speed $\dot{x} = v$. By integrating (5) from t_0 to t , one obtains

$$v(t - t_0) = \frac{l(\sin(2\beta(t)+\alpha) - \sin(2\beta(t_0)+\alpha))}{2\cos \alpha}. \quad (6)$$

This leads to the result

$$\beta(t) = \frac{\arcsin \frac{l \sin(2\beta(t_0) + \alpha) + 2v(t - t_0)\cos \alpha}{l} - \alpha}{2} \quad (7)$$

with $\beta(t_0)$ the angle at the start of the step depending on the configuration of the WM.

5. THE WM ON NON-PLANAR SURFACES

Using the WM only on planar surfaces severely limits its scope of operation. Therefore, the features of the WM's movement on non-planar surfaces should also be considered.

To move over longer distances, the WM must make steps to proceed. Each such step is a single step as discussed above. At the end of each step, the WM must have extended one spoke until it touches the surface at some point C . To make the step, the rearward spoke must be deactivated and the new-in-contact spoke must be activated. It is assumed that this switch happens instantaneously. As a result of the switching the points A and B as well as angle β are redefined to the former points B and C and the corresponding angle to reflect the newly activated

spokes.

5.1 MOVING THE WHEEL ON NON-PLANAR SURFACES

In the planar case the switching of the magnets was timed in such a way that after each switch one spoke was perpendicular to the surface. This can be seen in Fig. 6, which shows the angle β that is within the interval $[\frac{\pi}{2} - \alpha; \frac{\pi}{2}]$ for each step.

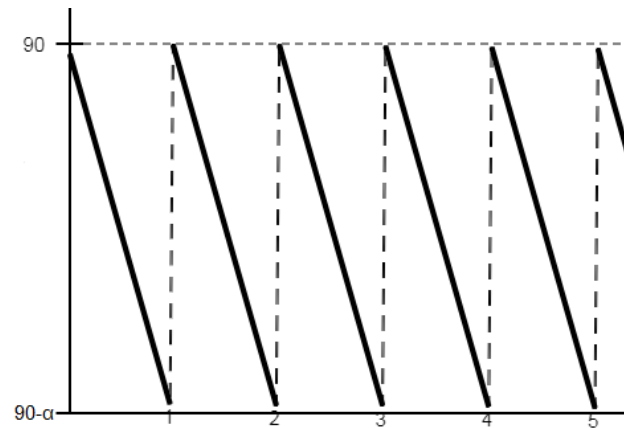


Fig. 6 – Changing the angle β on plain surface.

In the non-planar case, the angle β does not in general start each step at $\beta = \frac{\pi}{2}$ as sketched in Fig. 6. Instead the value of the angle β and position x at start of each single step must be adopted to the orientation of the WM accordingly.

Moving on a concave surface restricts the interval within which it lies during a single step compared to the planar case. On a convex surface the interval increases. Fig. 7 shows the example result of moving on a non-planar surface.

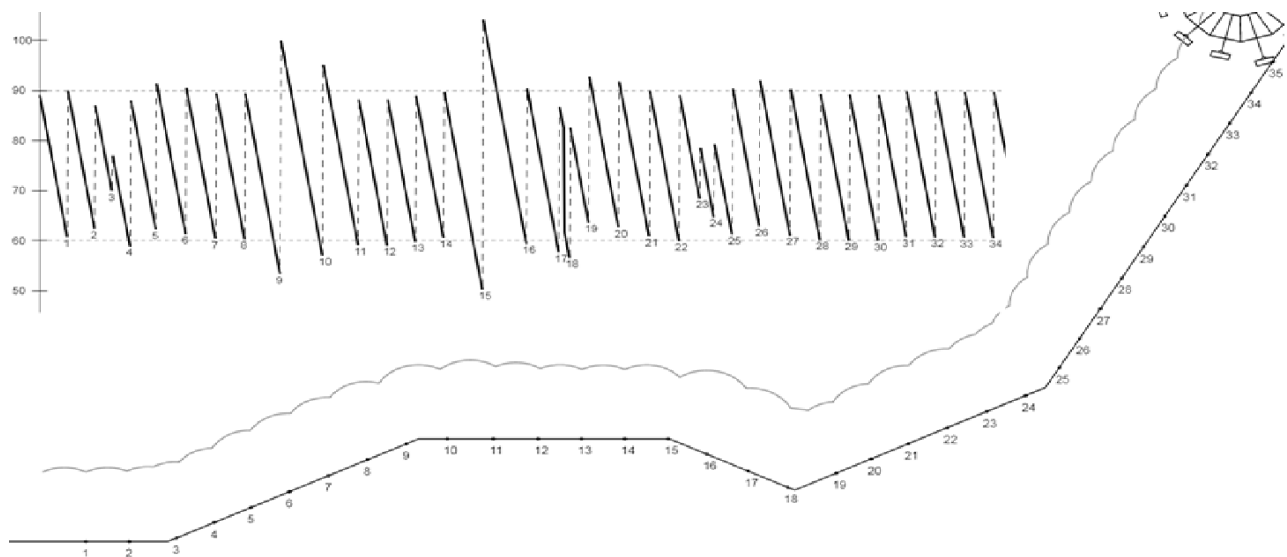


Fig. 7 – Changing the angle β on non-plain surface for the wheel with twelve legs.

5.2 CRITICAL CURVATURE OF A NON-PLANAR SURFACE

In this section the authors investigate how much curvature of the surface is allowed, so that the WM can still pass over it.

In [29] it was considered that the WM moves over a convex corner (see Fig. 8) and a critical bend angle described by

$$\phi_{crit} = 2\alpha + 2\arcsin\left(\frac{1}{p}\right) \quad (8)$$

where $p = \frac{R_{max}}{R_{min}}$ the ratio of the radii of maximally and minimally extended spokes was calculated.

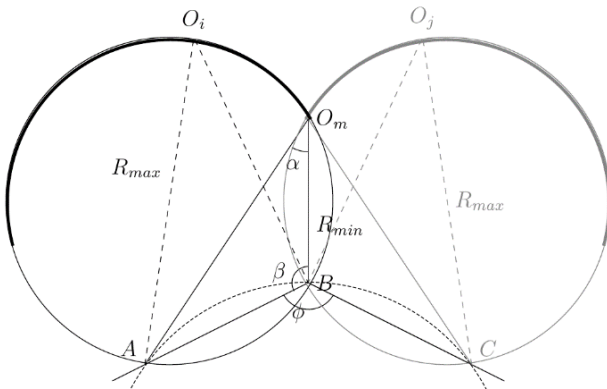


Fig. 8 – Movement of the wheel over the bend.

It is generally accepted to describe a surface geometry by its curvature. The curvature $k = \frac{1}{R}$ is defined as the reciprocal of the radius R of a circle Γ that approximates the surface at the particular point.

The curvature of the surface must not exceed a critical curvature $k_{crit} = \frac{1}{R_{crit}}$. This is the case if all of the points A, B, C lie on the circle (c.f. Fig. 8). Its radius is then given according to the law of sines by

$$R = \frac{AB}{2\sin\left(\frac{\pi-\phi}{2}\right)} = \frac{AB}{2\cos\left(\alpha+\arcsin\left(\frac{1}{p}\right)\right)}. \quad (9)$$

Applying the law of cosines to the triangle ABO_m leads to

$$AB^2 = R_{min}^2 + p^2 R_{min}^2 - 2pR_{min}^2 \cos(\alpha). \quad (10)$$

Value λ is defined as: $\lambda = \frac{R_{min}}{R} = kR_{min}$. Setting (10) in (9) leads to

$$\lambda = \frac{2\cos\left(\alpha+\arcsin\left(\frac{1}{p}\right)\right)}{\sqrt{1+p^2-2p\cos(\alpha)}}. \quad (11)$$

It is favorable to maximize λ as this will allow a fixed-sized wheel to pass by a surface of maximal curvature. Note that the problem can be scaled: For a fixed number of legs N with scaled R_{min} the WM can pass an appropriately scaled circle Γ .

The function $\lambda(p, N)$ is shown in Fig. 9. According to it, the pretended statement that the larger the leg extension coefficient p is, the more curved the to-be-passed surface can be, is wrong if the legs must be extended completely. For each N there is a critical relative curvature $\lambda_{crit}(p)$ that represents the maximum relative curvature that the WM can pass. This maximum lies at $p = p_{crit}(N)$. Values $p > p_{crit}(N)$ do not allow to pass a higher curvature. E.g. for the WM with $N = 20$ legs the maximal $\lambda_{crit} = 1.63$ is located at $p_{crit}(20) = 1.391$. Hence, the legs will extend only up to 39.1% of R_{min} . Even any larger extension coefficient $p > p_{crit}(20)$ will not allow the WM to pass by a relative curvature $\lambda > \lambda_{crit} = 1.63$.

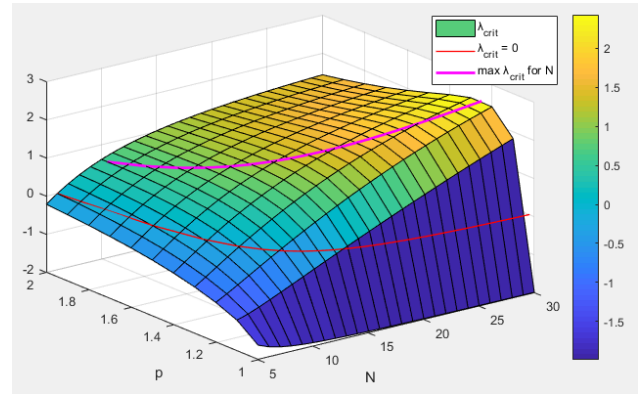


Fig. 9 – The relative curvature $\lambda_{crit}(p, N)$.

6. CONCLUSION

In this work the authors have considered the mathematical model of the magnetically-operated WM and its behavior on planar and non-planar surfaces. These improvements include a sketched scheme to allow the WM to move with a speed whose projection on the planar surface is constant in time. Furthermore, a design tool is given to approximate the possible WM's size considering a given curvature of the surface.

This research was used to improve the simulation of the movement of the WM for different configurations. It can serve as a basis for creating a real automated control system of the wheel-mover and mobile robot.

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