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Highly passable propulsive device for UGVs on rugged terrain

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Abstract. One of the priority functional tasks of both industrial and mobile robotics is to perform operations for moving payloads in space. Typically, researchers pay attention to control the movement of the robot on different soils. It is necessary to underline the specificity of the movements of mobile robots, the main functional purpose of which is the movement of different objects. Unlike other robot applications there is the fact that transported cargo may have different mass-dimensional characteristics. The payload should be comparable to the mass of the mobile robot. This article addresses the issue of passability on rough terrain for a mobile robot performing the transport task and proposed a technical solution in the field of mechanics of propulsion to improve propelling of the traction wheel of the mobile robot with the ground.

1 The problem statement

A number of robotics research centers investigate transportation task performed by group of robots. This includes a number of scientific problems to be solved [1-3]. The interaction between the mobile robot's mover and the ground is a key factor to perform the mobile robot's passability.

In mobile robotics, the transportation operations are associated with the planning of the trajectory of movement for both the mobile robot and a payload. There are many factors that influence the formation of control, both at the stage of motion planning, and at the stage of maneuvering. Among these factors, we can point the main ones:

- the effect of distributed load on the propulsion of a mobile robot,
- special requirements for cargo transportation (orientation in space, vibration, speed and acceleration requirements),
- the influence of soil parameters on the passability of the mobile transport platform,
- force effects on the structural elements of the robot during movement, caused by external factors.

Among those for single robot-transporter the following tasks were solved: consideration of geometrical and inertia properties of the object to be transported, object's slippage effect referring to UGV, consideration of undulations of ground while keeping desired orientation of transported object, interaction of soil with wheels. These tasks were discussed throughout scientific community during last 15 years [4, 5]. However, we have not met such solutions for coordinated transportation task performed by a group of robots.

In order to effectively fulfill the transportation task mobile robot requires information about the type of soil, the irregularities of the surface, information about moving and stationary obstacles. Thus, the solution of this task should be comprehensive and take into account significant number of factors.

Coordinated transportation task implementation resembles communication coverage task by a group of robots. A potential fields approach for this task was proposed and discussed in [4].

In practice there are also a lot of cases of transporting deformable loads. This is a case of [5] which discusses transportation of deformable load by a group of wheeled UGVs equipped with manipulators. There they study centralized and decentralized control approaches. An algorithm presented there secures obstacle avoidance for both static and dynamic obstacles. A remarkable point is that during whole transportation task a desired shape of deformable load is secured.

The tire is the communication element between the robot and the ground. Through tires all the forces and torques influence on the system during acceleration and deceleration of the robot. The tire takes the action of lateral forces, keeping the robot on the operator selected trajectory. Therefore, the physical conditions of the tire friction with the road surface define the boundaries of the dynamic loads acting on the mobile robot.

The dependence of the pressure in the contact area q_t on the geometric parameters of the tire is shown in Figure 1. This dependence is given in accordance with variation of the width and height of a wheel's tire of the robot.

The pressure in the contact area q_t depends on a number of parameters. It is expressed as follows:

$$q_t=\pi h_g \frac{(p_0+p_w)}{2_b}\left(\frac{B}{H}+\frac{3H}{2B}\right)\left(1-\frac{h}{B}\right). \qquad (1)$$

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Here p_0 is the pressure caused by the stiffness of the tire carcass on the ground, 105 Pa; p_w is the internal air pressure in the tire, 105 Pa; b is width of the tire tread, m; B – width of the profile of tire, m; H is the height profile of the tire, m, h_g is the track depth, h is magnitude of wheel's bending.

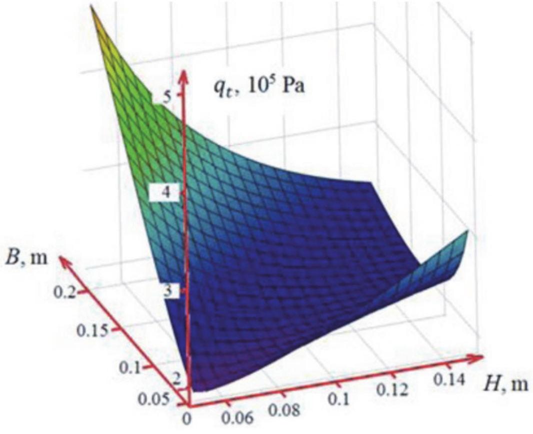

Fig. 1. The dependence of the pressure in the contact area from the geometric parameters of the tire.

Here one can see that the slight increase of the height of the tire profile with increase of the width of the tire profile leads to increase of the internal air pressure in the tire. Further increasing of the height of the tire profile with increase of the width of the tire profile decreases the internal air pressure in the tire.

Figure 2 shows the change of resistance coefficient *f* depending on the magnitude of wheel's bending h and on the load. The soil type on which the robot moves through influences on the resistance coefficient *f*.

After determining the soil type, the control system of the robot can generate the necessary control for drive system of the robot to overcome the possible obstacles, or to plan a new trajectory, avoiding the dangerous area. The resistance coefficient is determined as follows:

$$f = 3.5 p_0 y h^2 (B^2 + 1.5H^2) \frac{B - 0.3h}{PHB^2} 0.6qz \frac{b + b_{ki}}{p}. \qquad (2)$$

Here y is the coefficient of free traction; P is payload, H; q is roughness vertical coordinate, m; z is RMS displacement value; b_{ki} is the width of the tire tread, m.

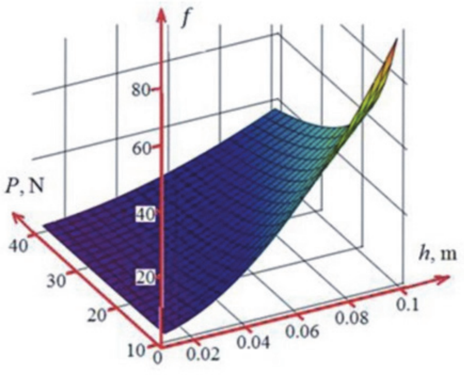

Fig. 2. The resistance coefficient change depending on the magnitude of wheel's bending and on the load.

Figure 2 presents increasing of the wheel's bending according to the quadratic law with the increasing of the resistance coefficient and payload. As it can be seen from (2), the rolling resistance coefficient depends more on the geometry of the tire in the contact zone than on the payload value.

The dependence of the load on the wheel from deformation of the tire and the soil type is shown in Figure 3. The payload also influences the parameters of the wheel and, as a consequence, its interaction with the soil.

$$p = \frac{Eh_g}{\frac{2Eh_g}{p p_{so}} arctg \left(\frac{p(H_g - h_g)}{2b_t} \right) + ab_t arctg \frac{H_g - h_g}{ab_t}}. \qquad (3)$$

Here E is deformation modulus; h_g is the track depth; H_g is the depth of soft soil layer; p_{so} is inner pressure; b_t is tread width; $a = 0,64(1 + b_t / H_g)$ is passability coefficient.

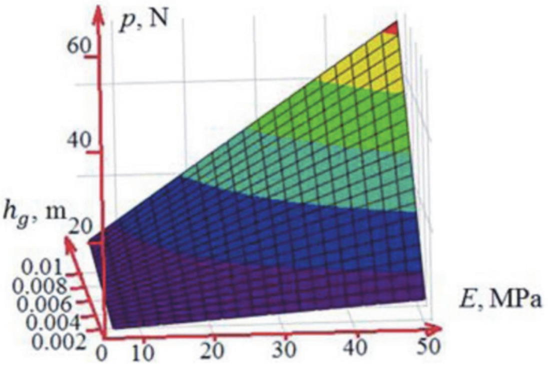

Fig. 3. The dependence of the axial load from deformation of the tire and the soil type.

When the load increases than the area of contact with the surface increases too, but in loose soil it can lead to slippage and penetration of the wheel into the soil with the formation of ruts.

The idea is to combine round wheels of mobile robot as the most effective movers on the plain areas and legged movers designed for overcoming obstacles and rough terrain.

Moving through cross-country mobile robot meets different types of the ground. That specifies the degree of the grousers' rotation. That changes different ground-wheel's interaction parameters such as width and height of a wheel's tire, pressure in the contact area, the resistance coefficient, the track depth and magnitude of wheel's bending.

Balanced action of the forces is controlled in the process of moving. Suppose that the wheels of the robot equipped with spikes. The change of direction of any object can only be achieved by the application of additional external forces. The robot is subjected on many forces when driving.

Thus tires perform important functions: every change of speed or movement direction of the robot causes the reactive forces.

In this paper we presented some simulation results that can be used in motion planning for a group of robots, considering target trajectory, type of load, load distribution among agents, type of terrain and specifics of soil (Fig. 1-3). During transportation different robots involved in the coordinated movement of a particular cargo may be located on different type of soil. Thus, in order to ensure the coordinated movement of cargo, it is necessary to take into account the interaction between each mover of each robot of the group with the ground. This is discussed in more detail in [4] and [5].

Research and development of wheel devices for various mobile robotic platforms are carried out by many research groups in different countries. Analysis we have done has shown that for motion planning and control for group-based transportation usually assumptions are done which are far from reality in cross-country conditions. E.g. wheel-soil interaction is not considered or soil considered being non-deformable, only slippage factors are considered, some works include only 2 robots into transportation. Some studies do not include practical experimentation.

Recent studies [6] for improving traction-coupling properties of a wheel, have led to the development of the anti-skid device that provides the mover to move on soils with low passability. Depending on the slippage factor, rotation of the segmented disc fixes its parts in a certain position relatively to the wheel axis; the device pushes the anti-skid elements out, which increases the adhesion to the ground. The disadvantage of this design is the lack of automation and adaptation to the actual soil parameters.

Another solution [7] is the construction of the wheel containing the soil hooks (grousers), as well as the mechanism of extension of the soil hooks with limiters (Fig. 4).

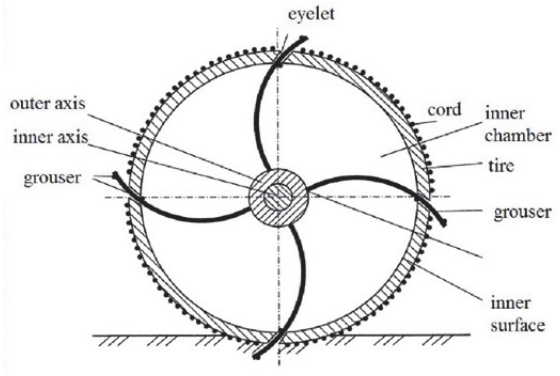

Fig. 4. Wheel with grousers.

However, the design of this device does not allow improving the adhesion to the ground during the reverse movement of the wheel, which is essential for using in mobile robotics.

Researchers are also interested in the development of wheel rotation algorithms in the slippage and towing. Work [9] proposes the method of controlling the thrust of a wheeled robot with a console suspension when moving on rough soils. The purpose of the proposed method is to reduce the slippage of wheels. The method is based on measuring the contact angle between the wheel and the ground using wheels of special design (tactile wheel), equipped with tactile sensors. The sensors are located on the wheel's rim, which allows fixing the point of contact with the ground wheels (Fig. 5).

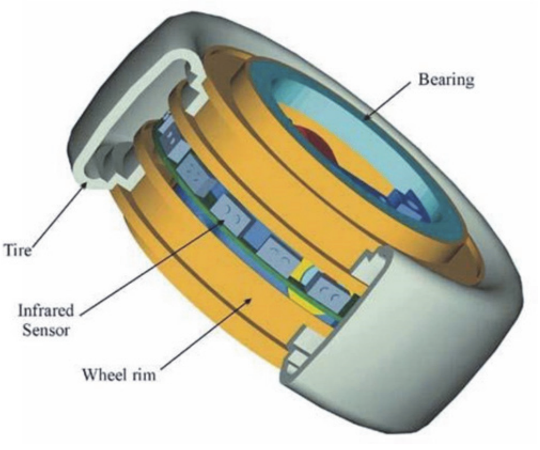

Fig. 5. Wheel equipped with tactile sensors.

The presented technique makes it possible to exclude complex models of interaction between the wheel and the surface, parameters of which are often unknown. The authors note the advantage of the presented method of steering the wheels torque in comparison with the traditional speed control. However, the work did not consider the interaction with deformable soils or grass.

Another way of solving the problem of increasing the robot's passability is the creation of a wheel-walking mover. The work [10] describes a transformable wheel shown in Figure 6. These wheels allow the robot to move steadily on a flat surface, using a conventional round wheel, and overcome obstacles as wheel-stepping machines.

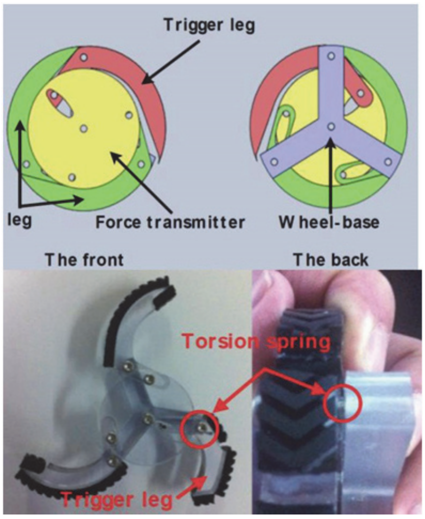

Fig. 6. Transformable wheel.

The advantage of this mover is the ability to overcome obstacles and to move in a loose environment (grass, swamp), but the disadvantages of the design can be attributed to the inability to set the amount of disclosure blades. As a result, this solution does not provide the ability to adapt the movement to different types of deformable soils.

In addition to devices that improve adhesion to the round, different methods andalgorithms for determining the parameters of the soil on which the robot moves are being developed. One of such methods is the Generalized Newton Raphson (GNR) method, which allows determining all the necessary parameters of the soil for the formation of the traction force. This method was considered in [8]. This method requires calibration and preliminary adjustment of the control system for a specific type of surface.

2 The proposed design of the mover for the mobile robot

In terms of this work a new propulsion system was developed. While moving on various soils this propulsion system may function in 2 modes: rotating and stepping. This allows combining high robot velocity with improved cross-country ability.

The proposed solution is to equip the wheels of the robot with additional blades that improve the coupling properties of the wheel with the ground. At the same time, unlike other similar solutions, the proposed scheme implies a mechanism for adapting the degree of extension of the blades depending on the nature of the actual interaction of the wheel with the ground. The general scheme of a wheel is shown in Figure 7. The mover consists of a disk 1 and connected to it retractable soil hooks (blades) 2. Each hook is provided with two rods 3 and 4 fixed on it at a distance from each other. One end of the first rod 3 is connected to disk 1, and the other end of the other rod 4 is connected to the plane mounted on the disk of the rotating element 5. All rotating elements 5 are connected by kinematic coupling 6, and one of them is equipped with a drive.

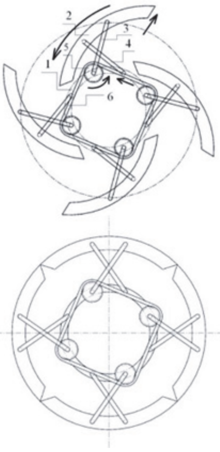

Fig. 7. Proposed schematic design.

A feature of the proposed wheel design is receiving and processing the information from the built-in bend-sensors (Fig. 8) located on the inner surface of the flexible blades. They measure the level of vertical deflection of the tire relative to the unloaded condition of the blade. The vertical deflection of the blade depends on the level of rigidity of the surface (soil), on which the robot moves and the rigidity of the blade itself.

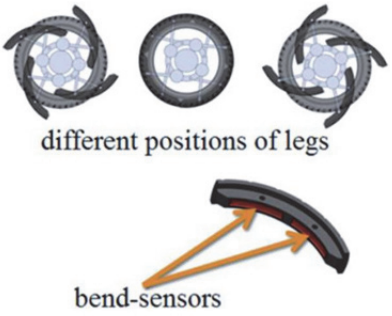

Fig. 8. Proposed design of the wheel.

When the robot moves over rough terrain, the control system is checking the soil type in database and, based on the vertical tire deflection value obtained from the bend-sensors, determines the most appropriate parameters. Depending on the type of soil, the speed of rotation and the applied torque of each wheel are adjusted, which reduces the probability of slipping. It is possible to make a map of the terrain for one mobile robot, which will be useful for other robots in the group, and contributes to the efficiency of movement and overcoming possible obstacles for all robots in the group (Fig. 9).

Fig. 9. Overview of the device.

Thus, the use of bend-sensors in the proposed configuration allows to calculate the reaction forces in the contact area and to adapt the mover to the type of soil with the extraction of the flexible blades outside from the wheel to the desired value.

Robot's movers are equipped with bend-sensors located on the inner surface of the flexible blade. They measure the change in the vertical deflection of the wheel giving the command to change the configuration of the wheel [11]. The smaller the value of the vertical deflection, the less the force of adhesion of the wheels with the surface movement. The second condition for changing the configuration of the wheel is to reduce the torque on the shaft of the developed mover, which may indicate its slippage or blocking due to external factors [12].

It was experimentally shown [11] that the coefficient $m(\lambda)$ of the longitudinal friction force is subject to Gauss law, i.e.

$$m(\lambda) = m_c e^{-(l^2)} / b = m_c \exp(-(\lambda^2)/b), \tag{4}$$

for b=0,26, if m_c J 0,9.

This coefficient is determined by the following ratio:

$$\lambda = \frac{j\ P_c \text{-} v_p}{\max\,(v_{p_I} f\ R)}.$$

Here j is the angle of rotation of the wheel, v_p is the linear speed of the robot's wheel, R is the radius of the wheel, m_c is the static friction coefficient. Slippage is absent, if $\dot{\mathrm{v}}_\mathrm{p} = \dot{\mathrm{v}}_\mathrm{c} = \ddot{\varphi}\mathrm{R}$. In the case of the movement with slippage $\mathrm{v}_\mathrm{c} = \dot{\varphi}\mathrm{R} > \mathrm{v}_\mathrm{p}$. Linear velocity v_p of the robot equals the linear velocity v_c of the wheel under absence of slipping. The driving moment causing slippage can be found as follows:

$$\mu_k = \mu_c\, exp(-(\lambda^2)/b)\, GR \tag{5}$$

For the wheel rolling without slipping requires that the adhesive force satisfies the condition $F_s \geq \left(R_x{}^2 + R_y{}^2\right)^{1/2}$, here R_x – the tangential reaction force from the ground, R_y – the transverse reaction force from the ground. Considering that $F_s = R_z{}^2 \varphi_x{}^2$, we may obtain $R_y \leq \left(R_z{}^2 \varphi_x{}^2 - R_x{}^2\right)^{1/2}$, that is, the transverse force applied to the wheel and not sliding, the greater the force of adhesion of the wheel to the ground than the less the tangential reaction of the road, φ_x – coefficient of longitudinal adhesion of the wheel to the surface.

The evaluation of robot passability in the group is necessary to identify impassable areas and further form the optimal route or restrictions for other mobile robots in the group. This parameter for the all-wheel-drive mobile robot can be obtained as follows:

$$\Pi = \frac{\mathrm{G_i V_1 q_1}}{\mathrm{G V_2 q_2}} \tag{6}$$

here $\mathrm{G_i}$ – payload on the wheel, obtained by bend-sensors, G – mass of the $\frac{1}{4}$ robot, $\mathrm{V_1}$ – the desired speed of the wheel, $\mathrm{V_2}$ – the real speed of the wheel in the coordinate system associated with the object, and calculated through the instantaneous center speeds, $\mathrm{q_1}$- power consumption of the electric motor in ideal conditions, $\mathrm{q_2}$ – power consumption of the electric motor in real conditions.

3 Conclusion

The proposed technical solution in the field of propulsion mechanics improves the adhesion of mobile robot wheel to the ground. It can significantly improve the technical characteristics of the mobile robot on the parameter of passability. A distinctive feature of the proposed solution is the ability to adapt the degree of extension of the soil hooks (blades) depending on the type of the soil.

The proposed design of the mover should keep the average speed for certain mobile robot in group under rough conditions of the cross-country territory. This leads to increasing of passability for the whole group and increasing efficiency for joint transport task solution.

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