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Development of a Mobile Reconfigurable Mecanum Robot with a Locking Device of Rollers

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Abstract— **This paper presents the design and analysis of an omnidirectional reconfigurable wheeled robot capable of switching between omnidirectional and conventional wheeled mode. We have developed a new pneumatic locking mechanism of rollers for the mecanum wheel. In the mecanum mode, the robot can perform holonomic movements, and in the wheeled platform mode, it can overcome inclined surfaces and perform more energy-efficient movements. In addition, the locking device allows the robot to brake faster compared to other mecanum robots. Unlike other works describing the reconfigurable structure of the mecanum wheel, this work offers a new design characterized by the simplicity of the mechanism and does not require the location of active reconfiguration elements inside the wheel itself. The paper describes the design concept and presents the mechanism for locking rollers. The study evaluates the use of the developed robot in various scenarios, including movement on an inclined surface, sudden braking on a plane and an inclined surface, and also analyzes the energy efficiency of the resulting solution for some operating scenarios. The experiments carried out confirm that this mobile platform, when switching mode, is able to move on surfaces with a large angle of inclination and perform more effective deceleration on both flat and inclined surfaces.**

I. INTRODUCTION

Mobile robotics is one of the fastest expanding fields of scientific research. This is due to their versatility and the ability to help or completely replace a person in difficult and dangerous fields of activity. In addition, the integrated use of mobile robots can significantly improve the efficiency of work in various industries [1], [2].

Currently, one of the most common types of mobile robots is wheeled mobile robots. This type of robots has gained great popularity due to their energy efficiency, relatively high speed and low production costs [3]. Wheeled mobile robots can use various mechanical structures as wheels. An interesting example of a wheeled mobile robot is an omnidirectional robot that uses omnidirectional wheels as movers [4], usually of mecanum or omni-type. Due to the design feature, mobile robots on omnidirectional wheels are able to perform movements of complex mechanical nature (holonomic) without the use of steering mechanisms, which makes them extremely efficient in space-constrained environments, e.g., such robots show good results as transportation agents in indoor logistics. In addition, the elimination of steering mechanisms significantly reduces production costs.

Nevertheless, for all their advantages, omnidirectional wheel platforms have a number of substantial disadvantages, such as high demands on the working surface. Furthermore, mecanum platforms are an incompletely driven system, since the rollers that make up the wheel are free to rotate about their axis. Thus, the inability to directly control the state of the object creates a number of difficulties: slippage, inability to move on an inclined surface and low energy efficiency of operation in some modes. One of the possible solutions aimed at overcoming the disadvantages of omnidirectional platforms described earlier is the creation of a reconfigurable robot combining the capabilities of conventional wheeled and omnidirectional robots [5].

The development and research of reconfigurable robotic systems is one of the directions of modern robotics [6]. Currently, there are reconfigurable solutions using an omnidirectional configuration as the wheelbase [7], [8], [9]. However, all of them are aimed at creating a reconfigurable robot capable of moving in wheeled robot mode or in walking mode. These solutions are aimed at the possibility of robots functioning on rough terrain, overcoming obstacles, for example, steps. However, these solutions still restrict movement on inclined surfaces and demand substantial resources (such as additional engines for both reconfiguration and movement). Moreover, walking robots consume significantly more energy than wheeled robots. For instance, in papers [10] a structure is attached to the wheeled platforms, including the mecanum platform, which allows it to be held on an inclined surface with the help of additional force developed by the propellers. This solution has shown its effectiveness, but it is not applicable for large mobile platforms carrying a payload.

In this paper, a reconfigurable robot is defined as a technical vehicle capable of changing its configuration from an omnidirectional mobile platform to an all-wheel drive configuration without steering mechanisms when a control signal is applied.

This study is motivated by previous work aimed at increasing the applicability of omnidirectional platforms [11]. The paper presents a new design for controlled restriction or complete locking of the mecanum wheel rollers. The main difference of this solution is the use of a pneumatic system, simplicity of design and lack of requirements for the presence of control and regulating elements in the wheel. The proposed design is realized in a reconfigurable mobile robot. The study suggests areas and scenarios where this

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solution can be implemented. Based on the proposed areas of operation of the developed design, a series of experimental studies has been carried out, confirming the proposals put forward.

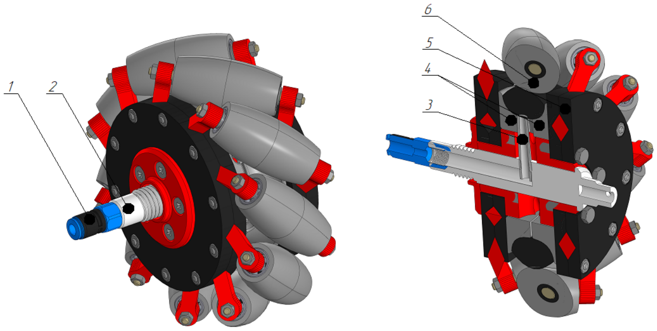
This paper is organized as follows. Section II presents the design concept and detailed mechanism of the locking device of rollers. Section III presents the structure of the robot. This section also describes the design parameters of the robot. Section IV proposes the areas and scenarios in which the use of the proposed solution will reduce the basic disadvantages of omnidirectional platforms. Section V describes the design of experiments for each of the previously discussed research areas. The section also presents the results of the experiments. Section VI concludes the paper.

II. MECHANISM OF LOCKING OF ROLLERS

The locking of the rollers of the mecanum platform enables to reconfigure the platform from an omnidirectional to a regular four-wheeled one. This solution improves energy efficiency when driving in a straight line [5], in addition, this method reduces the requirement for the slope of the work surface. There is a solution [5], which is most often referred to in works devoted to improving the quality of omnidirectional platforms. A significant disadvantage of this solution is the inability to uniformly affect the rollers with the necessary force (the rollers are either locked or unlocked) and the need to place the actuators with the entire locking periphery inside the wheel.

This paper proposes another solution inspired by the design of a tire-pneumatic coupling [12]. In this invention, compressed air in an inner tube with friction pads is used to lock the coupling halves relative to each other and to transfer torque from one shaft to another.

In the papers [11], [13] mecanum wheels have been developed, characterized by the use of more accessible production equipment. The proposed design allows using the free volume inside the wheel to accommodate the locking system of rollers. Fig. 1 shows a 3D model of the obtained solution.



1 – Rotatable push-in fitting; 2 – shaft with a hole for air supply and venting; 3 – nipple; 4 – limiter for laying the inner tube; 5 – inner tube; 6 – wheel roller.

Fig. 1: 3D model of mecanum wheel with the locking device of rollers

The resulting device operates as follows. The compressed air enters the inner tube (5) through the rotating sealed push-in fitting with a bearing (1) located on the wheel rotation axis through the nipple (3). The nipple (3) is part of the inner tube (as in bicycles) and is screwed into the shaft (2). The inner tube (5) inflates, expanding uniformly and acting on the wheel rollers (6). An example of the change in volume from pressure in the inner tube is shown in Fig. 2. Parameters of the mecanum wheel with the locking device of rollers are presented in Table I.

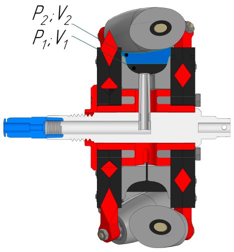


Fig. 2: Changing the volume of the inner tube

TABLE I: Parameters of the wheel with roller locking device

Wheel radius, mm	89
Wheel width (excluding wheel shaft), mm	64
Wheel width, mm	147.5
Wheel weight, kg	1.3
Weight of locking device elements, kg	0.2
Roller radius (max.), mm	14.5
Roller material	plastic
Inner tube volume, l	0.111
Minimum time to fully inflate the inner tube, s	0.135

This solution differs from analogs in its ability to reduce the influence of rollers on the kinematics of the mobile robot. When the rollers are fully locked, the wheel turns from a mecanum wheel into a regular wheel. At the same time, this design lacks active elements in the wheel itself (drives, sensors, controllers, etc.), and all necessary controls are placed on the platform (Section III).

III. ROBOT DESIGN

A diagram of the reconfigurable platform is shown in Fig. 3. The system consists of four main parts. The upper level of control and the vision system are implemented on a desktop computer. The platform itself [11] consists of a frame of aluminum profiles, a single-board computer, a control board, four stepper motors and their drivers, as well as two batteries. The wheels presented in the section II are mounted in the platform. The pneumatic part includes a compressed air source (in this work, the compressor is stationary, but a portable compressor can be used for real robots), a filter regulator and a valve block. Control and power relays are used to monitor the condition of the inner tubes of the wheels. The compressed air flow rate is controlled by a one-way flow control valve. It can be installed for each wheel and adjusted so that they are balanced (the inflating time of each wheel coincides with the others), however, in our case we use one shared one-way flow control valve. The fourth part of the platform consists of sensors. Various sensors can be installed in the mobile robot, our complex uses an IMU sensor to determine the angle of inclination (in a real robot it can be used for automated control of inner tubes) and a pressure sensor.

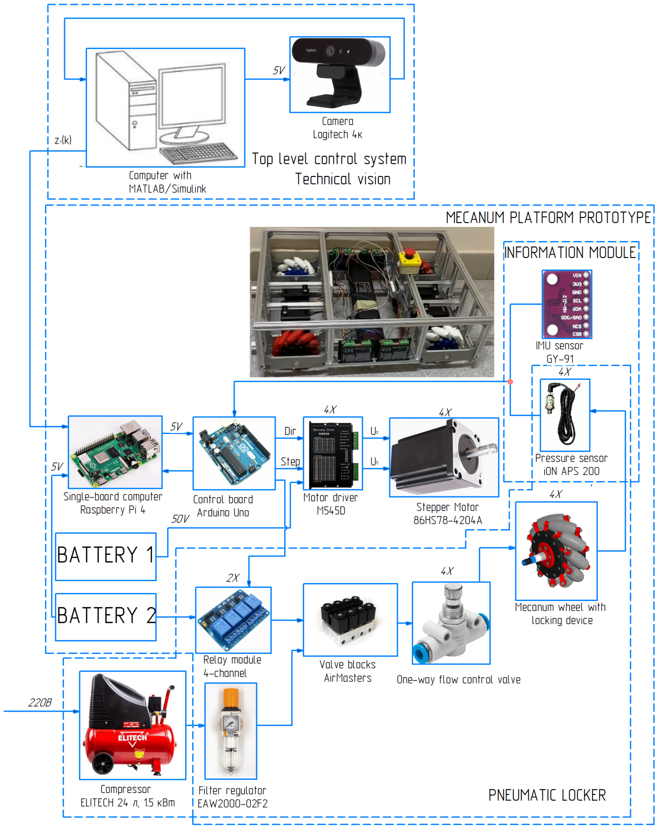


Fig. 3: The diagram of the reconfigurable robot

The design of the platform developed during the research is shown in Fig. 4.

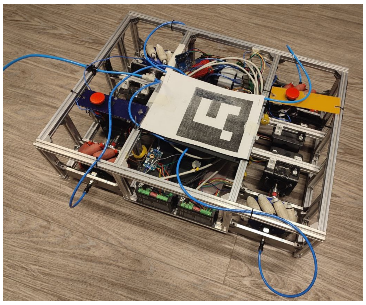
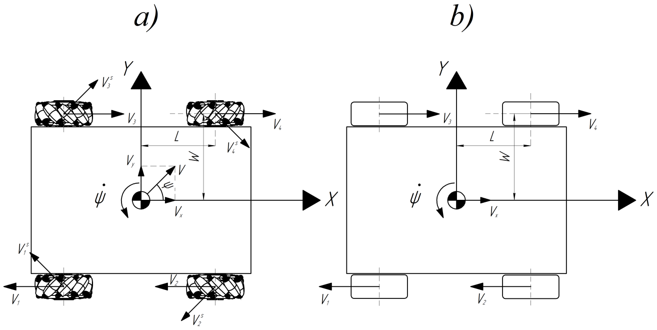


Fig. 4: The design of the developed platform with width 566mm, length 752mm, height 370mm and weight 40kg

Fig. 5 shows the kinematic scheme of the developed mobile robot. The velocities are directed according to the positive direction of rotation of the stepper motors.



a) kinematic scheme of the mecanum platform

b) kinematic scheme of the regular wheeled robot

Fig. 5: Kinematic model of the robot

According to [14] and taking into account the X-type arrangement of the wheels, we obtain the following equation for the kinematics of the mecanum platform

$$\begin{bmatrix}\omega_{1w}\\ \omega_{2w}\\ \omega_{3w}\\ \omega_{4w}\end{bmatrix} = \frac{1}{R}\begin{bmatrix}-1 & 1 & -L-W\\ -1 & -1 & -L-W\\ 1 & 1 & -L-W\\ 1 & -1 & -L-W\end{bmatrix}\begin{bmatrix}V_x\\ V_y\\ \omega_z\end{bmatrix}.$$

With the rollers locked, the kinematics of the mobile robot can be described as follows

$$\begin{bmatrix}\omega_{1w}\\ \omega_{2w}\\ \omega_{3w}\\ \omega_{4w}\end{bmatrix} = \frac{1}{R}\begin{bmatrix}-1 & -L-W\\ -1 & -L-W\\ 1 & -L-W\\ 1 & -L-W\end{bmatrix}\begin{bmatrix}V_x\\ \omega_z\end{bmatrix},$$

where $\omega_{iw} = V_{iw}/R$ – angular velocity of the i-th wheel, L and W – the half-length and half-width of the platform, respectively, R – wheel radius, V_{iw} – linear speed of the i-th wheel, V_x, V_y, ω_z – linear and angular velocities of the center of the mobile robot, respectively.

Thus, the reconfiguration changes the kinematics of the platform, making it possible to switch between holonomic and nonholonomic movements.

IV. ANALYSIS OF THE RECONFIGURABLE PLATFORM

A. *Movement on an inclined surface*

High work surface requirements are a known problem with omnidirectional platforms. In addition, mecanum platforms have difficulty moving on an inclined surface (when the gravity component along the slope exceeds the rolling friction limit between the rollers and the slope, the robot loses the ability to control its own motion state) [15].

Theoretically, with locking device of rollers, we are able to increase this limit within certain boundaries. Consider the motion of the platform on an inclined surface. The calculation scheme for the wheel of the mobile platform is shown in Fig. 6.

A force acts on the platform, causing it to roll down a slope due to its own weight. In this case, each wheel will have only a quarter of the mass of the platform

$$F_w = \frac{m}{4} g \cos\alpha.$$

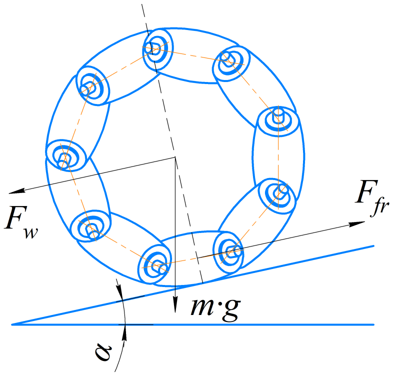


Fig. 6: Wheel force diagram

The frictional force counteracts the force considered. The type of friction force will vary depending on the inflation level of the wheel inner tube:

1) inner tube is not inflated — friction force is equal to the rolling friction force F_r;
2) inner tube is inflated, but rollers are not completely locked — friction force is the sum of rolling friction force F_r and friction force of the inner tube against the roller F_t;
3) inner tube is inflated and rollers are completely locked — friction force is equal to the roller sliding friction force F_s.

$$F_{fr} = \begin{cases} F_r, & \text{if } P < P_{eff} \\ F_r + F_t, & \text{if } P \geq P_{eff} \text{ and } F_r + F_t < F_s \\ F_s, & \text{if } F_r + F_t \geq F_s \end{cases},$$

where P is the pressure inside the inner tube, P_{eff} is the minimum effective pressure (so that the inner tube starts to touch the roller preventing its rotation).

B. Safety

Currently, omnidirectional platforms are most commonly used in indoor environments. For this purpose, the space is designed with mecanum robots in mind. In this case, flat surfaces with a non-slip coating are used. However, the safety of cargo transportation remains an important issue. Omnidirectional platforms are distinguished by their load capacity. However, when transporting bulky loads with an offset center of gravity, the platforms have to move at a reduced speed. Increasing the speed of the platform can cause the rollers to slip and the platform with the load to skid. In this case, the rollers may continue to rotate around their axis, causing the platform to move by inertia even if the drives are stopped or reversed.

Separately, it is worth highlighting works that propose to use omnidirectional platforms outdoors [16], [17]. Using mecanum platforms in non-deterministic environments not designed for them increases the risk of robot failure or poses a danger to others. Slippery surfaces can throw the robot out of control. The presence of small stones, sand, and dirt can cause the rollers to become locked, altering the platform's kinematics.

Special attention should also be paid to areas where the mecanum platforms are used as a part of a wheelchair or rehabilitation unit [18]. Safety is crucial in these areas, but the underactuated character of mecanum platforms makes it impossible to ensure safe movement, particularly on inclined surfaces.

C. Energy efficiency

Despite its advantages, mecanum platforms consume more energy than traditional wheeled robots due to their unique wheel design [19], [20].

On inclined surfaces, omnidirectional robots require more energy than calculated [15]. Using the robot in conventional wheeled mode can reduce energy consumption in some operations. The energy cost of locking and unlocking all wheels with pneumatic system involves a control relay (1.4 W) and a valve block (33.6 W), with up to 10 cycles per minute. Switching energy consumption

$$E = P \cdot t \cdot n,$$

where E – energy [J], P – power [W], t – time [s], n is the number of switching operations.

Locking the rollers requires 175 J, unlocking – 700 J. Energy consumption for inflating the wheel inner tubes: the initial volume is 0 liters, the final volume is 0.111 liters, with a total of 0.444 liters. The duration of module switching on is 2s. The compressor capacity is 198 l/min, power – 1.5 kW. Air can be supplied to the inner tubes in 0.135 s. Considering the number of cycles, pumping air is 2025 J. The total energy for inflation the inner tubes 10 times per min is 2900 J or $0.8 \cdot 10^{-3}$ kW·h. The resulting value can be reduced by adjusting the one-way flow control valve and using another compressor.

Thus, we can assume that it is possible to solve the problem of planning the trajectory of a mobile robot with the pneumatic locking mechanism so that the platform functions in the mode of a conventional wheeled robot when performing simple movements (forward and backward on inclined and flat surfaces). This will significantly reduce the platform's power consumption and increase its energy efficiency, which is important for big warehouses with a large fleet of robots. It will also increase the autonomy of omnidirectional platforms operating outdoors.

V. EXPERIMENT AND RESULTS

A. Experiment setup

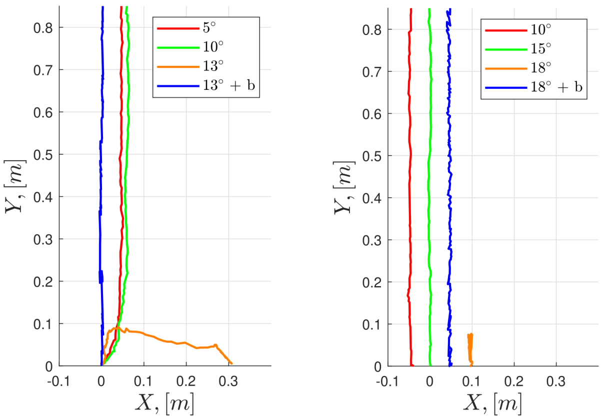
The experimental study is conducted on the robot shown in Fig. 4. The working surfaces are plywood, which simulates a slippery surface, and linoleum, which acts as an ideal working surface for the roller material used. The inclined surface is fixed in place. The inclination angle is measured using an IMU sensor. The position of the platform is determined using a computer vision system and an ArUco marker. The manual remote control mode is used to move the platform on the inclined surface. The automatic control mode is used for the task of stopping at a point.

B. *Movement on an inclined surface*

The study tests the possibility of upward movement on an inclined surface with a gradual increase in the angle of inclination. Plywood is used as a working surface for this experiment.

Fig. 7 (a) shows the results of the experiment. As can be seen from the graphs, the work surface inclination limit for the robot in the mecanum mode is 13°. At the same time, the platform with locked rollers is able to rise at the given angle. In addition, the platform moves smoother in the conventional wheeled robot mode.

Next, the work surface was changed to linoleum, but the course of the experiment was not changed. The results are presented in Fig. 7 (b).



(a) Plywood (b) Linoleum

"+ b" – with locked rollers.

Fig. 7: Movement on an inclined surface

The graph shows that the inclination limit for the robot in mecanum mode is 18°. At the same time, in the conventional wheeled platform mode, the robot is able to overcome this incline. It can also be observed that the platform moved flatter on this surface. Further increasing the angle does not allow the robot of any configuration to drive on the surface due to the limited resources of the actuators.

The next experiment tests the possibility of the robot being on an inclined surface without sliding down. The experiment was conducted on linoleum. The results of the experiment are shown in Fig. 8.

From the experimental results, it can be seen that the platform in the conventional wheeled robot mode is able to stay on an inclined surface of 25°. The platform rolls down diagonally, when the rollers are unlocked,

C. *Braking*

The experiment tests the possibility of braking the mobile platform on an inclined surface and on a plane by locking the rollers. Plywood was used for the experiment as a more slippery surface for the greatest clarity (the experiment can be repeated on linoleum, but this will require a huge load on the platform or increase the angle of inclination).

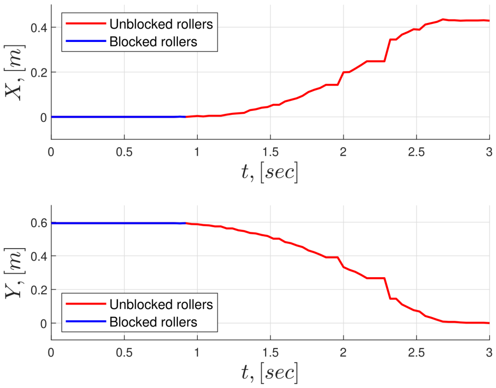


Fig. 8: Descent from an inclined surface at the angle of 25°

Fig. 9 shows a graph of the platform braking on a flat surface. The graph shows that the platform was able to brake faster when using the locking device of rollers. It is important to note that the trajectory change is due to the uneven inflation of the inner tubes of each wheels, since a single one-way flow control valve was used in the experiment.

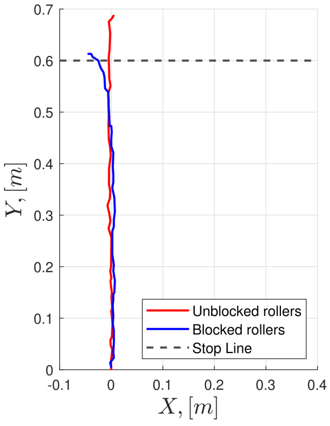


Fig. 9: Braking on a flat surface

During emergency braking on a given line, the braking distance of the platform with timely locked wheels is shorter than the braking distance of the platform in mecanum mode.

In the next experiment, the robot was placed on top of an inclined surface at the angle of 15 degrees. Initially the rollers were partially locked to prevent the robot from rolling down too fast. Then, the robot began to roll downhill due to its own weight, with the wheel drives locked (motor shafts not rotating). Next, the locking device of the rollers was activated. The rollers were unlocked back after the robot stopped. The results of the experiment are shown in Fig. 10.

As can be seen from the results of the experiment, the robot started to roll down the inclined surface until the rollers were completely locked. The platform continued to move diagonally down the inclined surface after unlocking the rollers

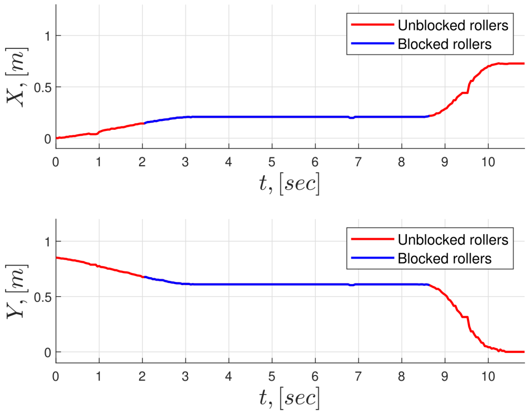


Fig. 10: Braking on an inclined surface at the angle of 15°

VI. CONCLUSIONS

In this work, we presented a new mechanism for locking the mecanum wheel rollers and its implementation on the mecanum platform. The robot can reconfigure between omnidirectional and conventional wheel mode to traverse inclined surfaces, be able to brake more efficiently, and perform more energy-efficient motion. Compared to other locking mechanisms of rollers, the proposed system is characterized by its simple design and does not require control elements embedded in the wheel. The energy input for reconfiguration is calculated and the force diagram is proposed to demonstrate the change of forces while using the locking device of rollers. A series of experiments have been carried out to prove the effectiveness of the obtained solution. The developed platform with the included locking device can drive on the inclined surface at the angle of not less than 18° and move off at an angle of not less than 25°. Meanwhile, these results are not available for the same platform without using the locking mechanism. In addition, experiments demonstrating the possibility of realizing braking both on an inclined surface and on a plane have been carried out in the paper. In our future works we plan to improve the developed design: the stepper motor will be replaced by a DC motor in order to test the energy efficiency of the obtained solution. Also in the future, we plan to investigate control algorithms to synthesize a regulator to achieve controllability on a sloping surface using switching and feedback control from a pressure sensor. Finally, to increase the service life of the inner tube, it is planned to add friction pads or a transformable wheel to the design of the locking device of rollers, which will act as a layer between the inner tube and the wheel rollers.

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