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Transport platform stabilization mechanism using controlled suspension

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ABSTRACT

In this paper the authors present the development of a novel transport mechanism designed to perform gravity survey work on difficult terrain. Thus, in the first part of the paper the authors present review and analysis of existing patents and commercial developments of transport platforms capable of stabilizing loads while travelling in urban environments with potholes and steps. In the second part we present technical solution of a steerable suspension with a torsion bar as an elastic element based on the elimination of the drawbacks of the existing developments. The core feature of this development is the potential ability to adapt the suspension to different types of surfaces by changing the elastic characteristics of the torsion bar. We also propose an alternative to the generally accepted kinematic scheme by using a conical gearbox, which allows to achieve a tight arrangement of suspension mechanisms within the dimensions of the transport platform. In addition, authors propose the stabilization mechanism, that allows to change the clearance of the transport platform and provides stabilization of the gravity exploration research equipment, characterized by sensitivity to deviations from the vertical.

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1. INTRODUCTION

The automation of technological processes is becoming more and more embedded in a wide range of production areas nowadays. Mobile robots are frequently used to address a wide range of tasks such as terrestrial and planetary exploration, forestry, agriculture, mining industries, and reconnaissance [1], [2]. In many cases mobile robots are carrying a variety of tools in dangerous, harsh, and unstructured environment [3]. Gravity exploration tasks could be cited as an example of such application.

Gravity exploration is one of the geophysical methods of examining the surface layer of the Earth's crust for the purpose of prospecting and exploring mineral deposits [1]. One of the main equipment used in this field is the gravimeter - a device for measuring the gravitational acceleration. The result measurements are presented as isolines on a topographic map and help to indicate deposits based on gravitational anomalies.

Gravimetric measurements require substantial preparation. Firstly, manual adjustment of the three set screws is required at each side to bring the main gravimeter plane to the strict horizontal position and set the tilt sensitivity of the gravimeter to its minimum [4]. Secondly, due to the variability of elastic properties of sensitive systems' material, all gravimeters have zero-point drift reaching 0.1-0.2 mGal per day [5]. If gravity measurements are made at the same observation point for a long time, zero-point drift occurs and the range of measured values could become even larger than the gravity anomalies of interest [6]. Also, the proper choice of location is important. The surface with small deviations is selected for the installation of the gravimeter due to the fact that measurements on hilly terrain require more careful preliminary analysis of the topographic map, clearing and horizontal alignment of the selected areas in order to improve the quality of the measurements.

Reudink *et al.* [7] studied several Scintrex CG-5 gravimeters' susceptibility to tilt and found that an exceedance of more than 6° for a few minutes biases the initial observations by tens of μGal. The bias in the observations decreases logarithmically as a function of time. Knowledge of this logarithmic decay time is crucial for planning field observations as it limits the time required for the instrument to stabilise within the noise level. The recovery time is linear to the duration of the instrument tilt and can take several hours. Given that it might require up to 30 min to obtain readings at a point, this time may not be sufficient for automatic stabilization.

Application of wheeled mobile robots (WMR) to the task of gravimetric exploration could significantly shorten time frame of measurement without increasing zero-point alignment inaccuracy. Controlled suspension (CS) allows taking measurements on steep slopes with a slope angle of 16°-20° [8] while stabilising the gravimeter and preventing a slope of more than a couple of degrees. Therefore, it is possible to achieve a deviation small enough to be automatically compensated by the internal stabilization systems of the gravimeter.

Gravity surveying takes place in various natural conditions. Thus, changing the ground clearance allows WMR to adapt to new terrain features, for example, when moving from grassy to stony ground. Mobile wheeled robots are most frequently implemented for delivery either in laboratory and warehouse environments or in urban environments. Therefore, proper stabilization mechanism would allow to widen WMR's field of application by providing it with ability of adaptation to a wide range of road conditions.

2. METHOD

Analysis of existing solutions allows us to distinguish two main types of WMR suspensions: independent and dependent in Figure 1. The independent type includes-balance, spring and combined, which uses a combination of diverse types of elastic elements. Typical passive adaptive suspension structures are rocker-bogie suspension [9] and, parallelogram suspension (for in-pipe robots) [10], [11]. Active suspension [11] approach implies changing the suspension configuration by actuation. WMRs with active suspension may also use elastic elements as additional dampers. Dependent suspension is an old-fashioned technology gradually abandoned by manufacturers due to its high rigidity, slippage and steering problems. It has been replaced by independent suspension, in which the wheels of one axle are disconnected from each other and changing the position of one wheel in general has no effect on another. Alternative popular solution in robotics is the tracked chassis. It has high cross-country capability, but it has a significant disadvantage-it is difficult to maintain the horizontal orientation of the body on surfaces with high elevation difference. Each type of suspension has its own benefits and drawbacks, but the current improvement of control systems and the cost reduction of mechanical components allows to combine different types of suspension thereby compensating for the disadvantages.

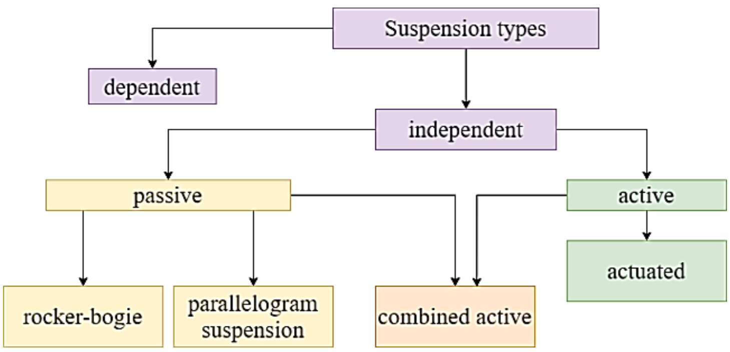


Figure 1. Classification of WMR suspension types

Mobile robotics in many ways began with space missions and the technologies used there. The rocker-bogie suspension without an elastic element was developed by NASA for Mars rovers in 1988 [12],

[13]. However, this passive surface-adaptive suspension mechanism is subject to negative impulse oscillations under its own weight and is structurally incapable of providing automatic body horizoning when required to account for initial measurement equipment deflections.

On the contrary, an active system controls the vertical movement of the wheels relative to the body. In recent years, commercially successful designs have used actuators to reconfigure the chassis, greatly increasing the complexity of the mechanics and control system. Yandex Rover's balanced steerable suspension with each axle elastically connected to its frame is based on this principle [14]. The drive on the balancer linking the first and second wheel axles allows rover to overcome curbs, but, due to the lack of drives on the rear wheel axles, the body tilts backward.

SameDay Bot [15] uses a different combination of drives for active stabilization. This WMR successfully traverses steps due to the additional raised third wheel axle and also has a separate stabilization system for the body. The additional stabilization mechanism significantly increases the height of the SameDay Bot to 1.5 meters. It is due to the high tipping moment that this robot is not designed for travelling over rough terrain.

Passive suspension is based on elastic elements such as springs, torsions, air bags, and hydro-pneumatic systems. Various springs are most common choice for passive suspension due to simplicity of overall design. However, despite that, modern robotics designers are experimenting with other types of elastic elements, incorporating them into new designs.

A transport platform that uses air springs for constant horizontal alignment even during crossing uneven surfaces and pits is known [16]. The controlled shock absorbers designed in the form of paired pneumatic cylinders with displacement sensors. The pneumatic actuator is incapable of providing continuous control and low positioning accuracy makes continuous adaptation to changing terrain conditions impossible. Proposed design additionally requires regular inspections and repairs, which can be detrimental to the autonomy and mobility of the transport platform.

A similar concept has been presented in [17]. Each wheel of proposed mechanical system is mounted on a separate controllable shock absorber mounted on the body and having its own distribution and control equipment. The linear movement of the actuator changes the distance between the wheel and the housing. In the event of tumbling into a pit this distance increases, leaving the WMR in a horizontal position. Also, similar to the design described in [16], authors use a pneumatic cylinder in suspension, which significantly limits the stroke of the shock absorbers. Both solutions are designed for urban or laboratory conditions and unacceptable for various natural environment.

3. RESULTS AND DISCUSSION

3.1. Proposed design

Based on a comparative analysis of commercial and patented WMR suspensions, the article proposes a mechanism of controlled independent torsion bar suspension, with a rocking of the balancers in the longitudinal plane of the transport platform (TP). The general view of the transport platform with the developed steerable suspension is shown in Figure 2. As a result of the independent modular design, the CS allows one to compensate roll along the longitudinal axis and pitch along the transverse axis of the TP at a maximum angle of 22°.

When selecting an actuator for the active component of the suspension, the advantages and disadvantages of each type were considered: hydraulic, pneumatic, electric actuator [18]. The hydraulic cylinder is not suitable for the developed stabilization system due to low maintainability and possible leakage of working fluid. The pneumatic cylinder is difficult to ensure smooth operation. The safest and easiest to maintain is the electric actuator [19], [20], [21].

Figure 3 shows the kinematic diagram of a suspension module. Taking into account the width of the platform and the size of the selected equipment, the arrangement of all kinematics in one line for two suspension modules simultaneously is impossible. In order to rationally use the space on the platform, servo drives (1, 2) were placed along the platform above the bevel gear (4). The transmission of rotational motion is carried out through a spur gear (3). An elastic coupling with a sprocket (5) ensures alignment of the cylindrical shafts of the gearbox (4) and the torsion bar (6). The balancer (8) is fixed to the platform surface through radial bearings (7) located in the cup.

The model of one suspension module corresponding to the kinematic diagram is shown in Figure 4. Figure 4(a) shows the external view of the 3D model and the direction of torque transmission from the gearmotor and to the balancers indicated with arrows. Figure 4(b) shows a view in the plane perpendicular to the rotation of the balancer. Proposed WMA suspension system combines four such modules on a single platform and correspond to the following characteristics: i) overall dimensions: 890×729 mm, ii) weight: 65 kg, iii) load capacity: 20 kg, and iv) clearance: 201 mm.

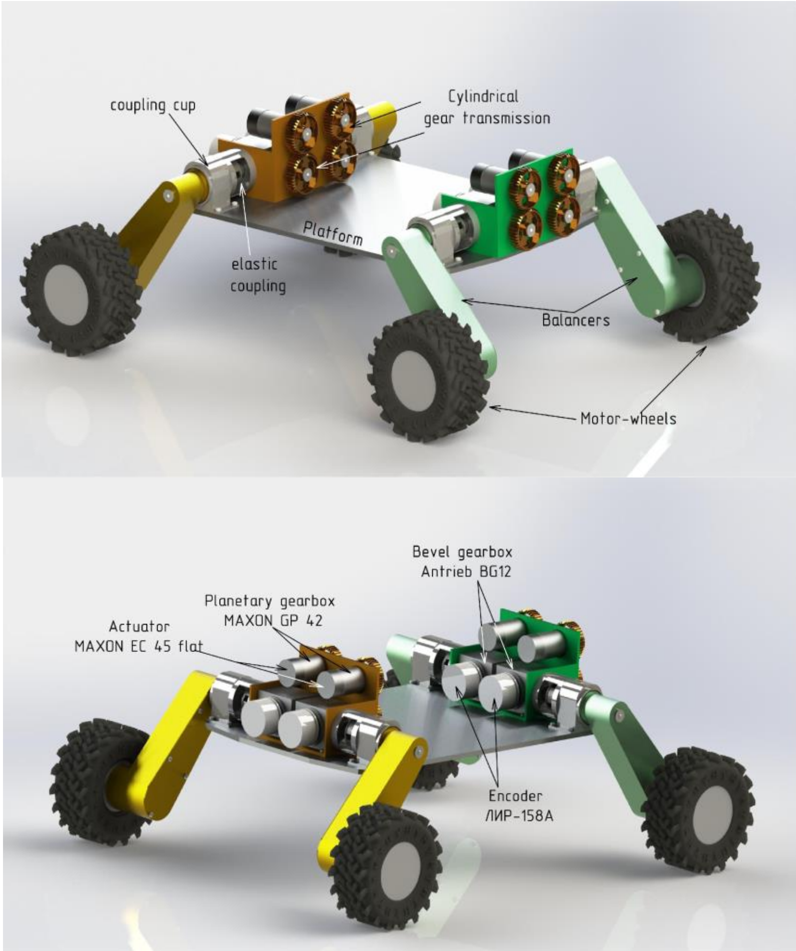


Figure 2. General view of the developed TP with CS

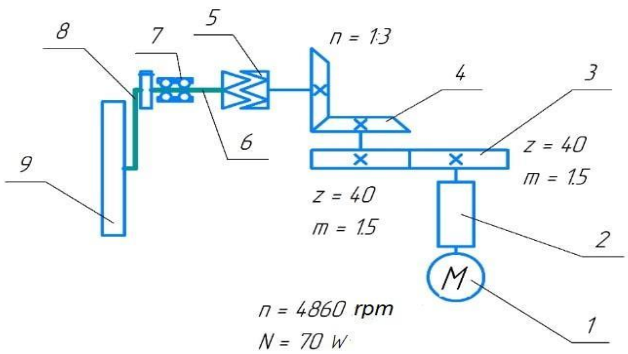


Figure 3. Kinematic diagram of the UE module

In order to determine the speed of the drive, it is necessary to determine the maximum angular velocity of rotation of the platform when approaching an obstacle. The parameters that are used in all further calculations are shown in Table 1. The angular velocity reaches its maximum at the moment when the front wheels hit the inclined surface. The platform tilt angle $\varphi(x)$ (1) depends on the distance x (where $x = 0 \dots d$) according to the following:

$$\varphi(x) = \alpha - arcsin(\frac{x \cdot sin(\alpha)}{d}) \tag{1}$$

Thus, the angular velocity (2) of the WMR's platform rotation about the pitch axis:

$$\Omega_y(x) = \frac{d\varphi}{dt} = -\dot{x}\frac{sin(\alpha)}{d\sqrt{1-\frac{x^2 sin^2\alpha}{d^2}}} \quad (2)$$

As shown in (2) the angular velocity reaches its maximum at $x = d$. During this period of time, the control system corrects the inclination of front balancers. During movement on a horizontal plane the speed of the WMR can reach V_{max}, but when hitting an inclined surface, the speed should be decreased by the control system for more than twice. The angular velocity of the balancer rotation ω (3) during collision with an inclined plane at an angle of α can be described as (3).

$$\omega = \frac{(V_{max}/2)\ .tg(\alpha)}{d} \quad (3)$$

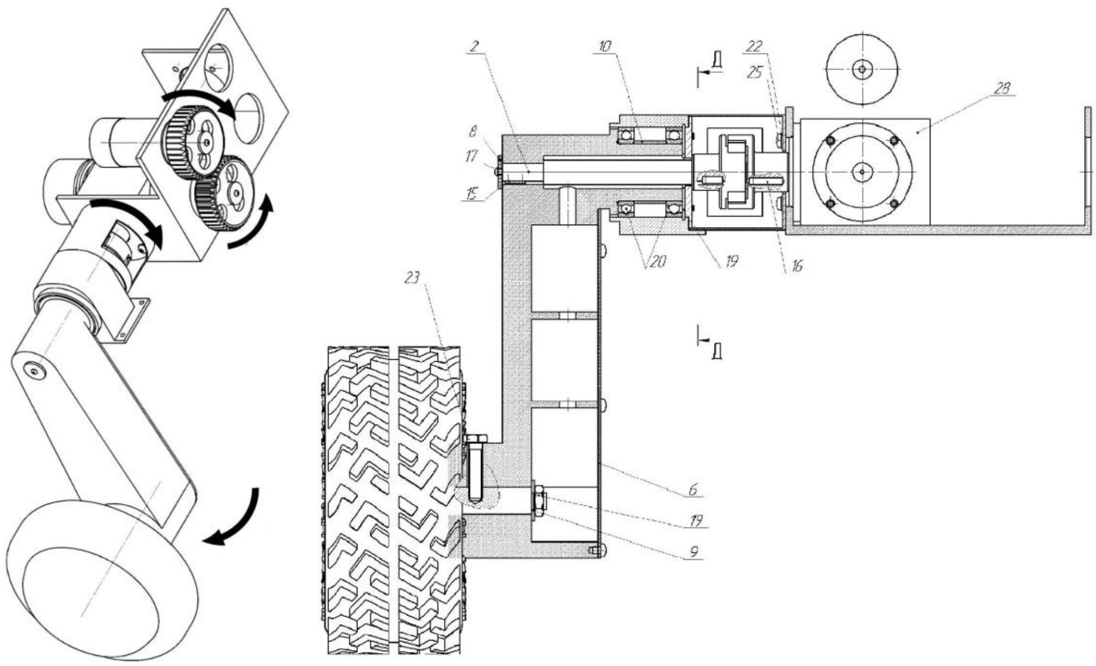
To further define the torque on the output shaft of the planetary gearbox, it is necessary to know the force acting on the end link of the balancer due to the mass of the entire platform. The mass acting directly on this section is the total mass excluding the mass of the balancer, wheel motor and tire (4). It is expressed as (4).

$$T_1 = \frac{M - m_t\cdot n - m_b\cdot n}{n} gr \quad (4)$$

The resulting torque of the output shaft strength calculation of the torsion beam could be performed to ensure the functionality of the system. Torsion shafts are made of spring steels due to their relatively small torsional stiffness and high elasticity, in particular, steel 50XFA with elasticity modulus G was chosen for the presented design. For the designed construction torsional stress (5) and twisting angle (6) are within the norm[22]:

$$\tau = \frac{16\cdot T_1}{\pi\cdot d^3} < [\tau_{norm}] \quad (5)$$

$$\theta = \frac{32T_1\cdot l\cdot 180°}{\pi^2 d^4 G} < [\varphi_{norm}] \quad (6)$$



(a) (b)

Figure 4. Display of one balancer module as (a) a 3D model and (b) sectional drawings

Table 1. Parameters of calculation

Parameters	Meaning	Value
	Determining the required angular velocity	
d	Length of the platform	0.7 [m]
α	Obstacle inclination	20 [°]
ω	The angular velocity of the balancer rotation	5.4 [rpm]
V_{max}	Maximum speed	2.2 [m/s]
M	Total mass of the transport platform with load	85 [kg]
m_t	Total weight of one motor-wheel and tire	5 [kg]
m_b	Total weight of one balancer	2 [kg]
n	Number of wheels	4
r	Moment arm	0.2 [m]
T_1	Torque acting on one actuator in relation to the total mass	28.9 [Nm]
	Calculation of the torsion bar's strength	
l	Torsion bar working length	90 [mm]
d	Torsion bar diameter	16 [mm]
G	Elasticity modulus of steel 50XFA	1324 [MPa]
τ	Torsional stress	70 [MPa]
$\boldsymbol{\tau_{norm}}$	Norm torsional stress	1000 [MPa]
θ	Twisting angle	14.2 [°/m]
$\boldsymbol{\theta_{norm}}$	Norm twisting angle	15 [°/m]
	Calculation of the power of the gearmotor and selected components	
P_n	Load power at the output shaft	20.7 [Wt]
η_{gb1}	The efficiency of the planetary gearbox;	0.72
η_{gb2}	The efficiency of the bevel gearbox	0.97
η_b	Efficiency of one pair of rolling bearings	0.995
P_C	Calculated drive power	29.86 [Wt]
ς	Safety factor	2.5
P_r	Required drive power	65.7 [Wt]
P_M	MAXON motor power	70 [Wt]
T_M	MAXON nominal torque	0.134 [Nm]
n_M	MAXON motor speed	2540 [rpm]
η_M	MAXON efficiency factor	0.84
i_0	Final transmission ratio of the motor- output shaft chain	450
i_p	Transmission ratio MAXON GP 42 planetary gearboxes	150
η_p	MAXON GP 42 efficiency factor	0.64
n_i	Speed of the output shaft of the planetary gearbox	16.3 [rpm]
T_L	Torque of the output shaft of the planetary gearbox	10.9 [Nm]
i_g	Gear ratio angular gearbox Antrieb: Series BG12	3
η_g	Angular gearbox Antrieb: Series BG12 efficiency factor	0.98
n_{out}	Output shaft speed	5.4 [rpm]
T_{out}	Output shaft moment	32.5 [Nm]

3.2. Calculation of the power of the gearmotor and selected components

Based on the data from the previous section, an energy calculation was carried out to determine the required motor power and select gearboxes[23]. This calculation involves determining the load from the end link to the drive, taking into account accuracy factors, safety factors, and ratios. The calculated power at the output shaft (7) considers the efficiency of all components in the circuit from the motor to the load:

$$P_C = \frac{T_1 \cdot \omega \cdot \varsigma}{\eta_b \cdot \eta_{gb1} \cdot \eta_{gb2}} \quad (7)$$

where η_b is the efficiency of the planetary gearbox, η_{gb1} is the efficiency of the bevel gearbox bevel and η_{gb2} is the efficiency of rolling bearings, ς - safety factor.

In order to find a suitable actuator in the MAXON catalogue [24], the drive power (8) was multiplied by the safety factor $\varsigma = 1.2 \ldots 2.5$. To withstand dynamic load, this value is chosen closer to the upper threshold. The calculated required drive power (6) allows the selection of a suitable actuator - MAXON EC 45 flat drive with P_M, nominal torque T_M, nominal speed n_M, maximum efficiency η_M. Since the motor is pre-selected, the transmission ratio of the motor-output shaft chain (8) can be obtained as (8):

$$i_0 = \frac{n_m}{\omega} \quad (8)$$

Considering this value, a MAXON GP 42 planetary gearbox and an angular gearbox Antrieb: Series BG12 [25] with ratios of i_p and i_g, respectively, were selected. The bevel gearboxes are shown in Figure 2 in each suspension module. Further calculations are aimed at confirming the correct selection of drive and gearboxes by calculating the output speed and torque at the planetary gearbox output (n_L, T_L) to the angular gearbox shaft (n_{out}, T_{out}). The output shaft speed of the planetary gearbox and bevel gearbox accordingly expressed as (9).

$$n_L = \frac{n_M}{i_p} \qquad n_{out} = \frac{n_L}{i_g} \tag{9}$$

The torque of the output shaft of the planetary and bevel gearbox are calculated respectively as (10):

$$T_L = T_M i_p \eta_M \qquad T_{out} = T_L i_g \eta_g \tag{10}$$

In addition to a reduction shaft and boosting shafts of opposite rotation, the gearbox has an additional shaft for measuring output speed with the LIR-158A encoder, which increases compactness and makes it easy to take measurements. The characteristics of the selected components allow to achieve the required compensated angular velocity of the platform (3). The resulting torque T_{out} at the output is greater than the required torque T_1, which means that the selected components of the overdrive circuit are correct.

4. CONCLUSION

This article proposes a novel steerable suspension with a torsion bar for each wheel. The mechanical design of the proposed mobile robot is presented and the selection of components of the suspension system is carried out. The proposed mechanism finds potential applications in terrain exploration and equipment stabilization, such as cameras and measuring devices. Control suspension has the following advantages over other types of WMR suspensions: i) independent adjustment of the distance between each wheel and the WMR body achieved by the combination of active and passive elements in the suspension design; ii) compensation of both longitudinal and transverse vibrations; iii) reduction in inertial vibrations of the platform compared to passive balance suspension; iv) high cross-country ability compared to other wheeled robots due to the absence of limitation on wheel diameter and linear drive stroke; v) the ability to work in both urban and hilly terrain; vi) the ability to perform measurements on inclined surfaces up to 20° and minimize possible errors associated with post-processing of the obtained data for gravity survey; vii) increase in ground clearance of the WMR due to simultaneous lifting of the front and rear balancers; and viii) increase of WMR load capacity at stabilization.

The disadvantages of this system include the high cost of components, which depends on the mass of the load and the weight of the transport platform itself during manufacturing, as well as the complexity of the control system being developed. The main modelling problem is the difficulty in accounting for deflection, which depends on the torque applied to the torsion. The moment of the reaction force of the support is different depending on the angle of tilt of the balancer and is maximum at the moment of greatest distance from the base. Further experimental studies are required to select the optimal parameters of the control system when the TP is travelling on different types of soil, as well as to investigate the possibility of selecting a more suitable material for the torsion bar.

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