

K. SOKÓŁ^{1*}, M. PIERZGALSKI¹

AN INFLUENCE OF THE MATERIAL PROPERTIES ON THE ENDURANCE OF THE SELF-ADJUSTABLE ROCKER-BOGIE SUSPENSION

In this paper one presents the new concept of a rocker-bogie suspension where the suspension members can change their length. As a result of this action the frame with suspension is able to adjust to the specific environmental conditions. The main problem with the designed suspension system is a fact that with an extension of the suspension members their slenderness increases as well as final displacements. The solution of this problem is not so simple because the construction must meet the specific requirements due to participation of the mobile platform in different competitions. In the presented results of numerical simulations one shows an influence of the different materials on stress and displacements magnitudes of suspension members when the mobile platform hits an obstacle. This situation allows one to test different engineering solutions in the worst case scenario when suspension elements may be damaged. Finally the optimum design is presented.

Keywords: rocker-boogie, suspension, rover, mobile platform, FEM analysis

1. Introduction

In many scientific departments the design and experimental works on mobile platforms are performed. Their use is very wide, from large-scale warehouses through gardens or military use. The investigations on platforms can be divided into two main sections. In the first one, engineers are focused on the mechanical design of construction and FEM simulations, while in the second the investigations on control units are done. In book written by Giergiel, Hendzel and Żylski [1] one can find information related to the design and steering techniques of mobile robots. Giesbrecht [2] have presented overview of high-level path planning methods used in mobile robotics with special emphasis on outdoor actions. Similar studies were done by Bunyamin, Wan, Sariff and Mohamad [3]. Their paper was focused on the bug algorithm family which is a local path planning algorithm. Cook [4] combined in one book all main problems in robot motion: control, navigation and remote sensing.

Platforms available on the market [5] have a suspension system analogous to the one installed in regular vehicles. This solution has advantages, such as simple construction and low costs of production but also has disadvantages like limited mobility in the rough terrain and easy overturn. This is due to the fact that the

used suspension systems are not able to adapt to variable conditions. As a confirmation of this statement one can quote paper written by Mucha and Kuś [6], where authors have built a mobile platform for exploration purposes with simple suspension system. Mucha [7] has also presented detailed description of an analysis of FEM simulation of main components of this platform.

The mobile platform presented in this paper has a unique engineering solution due to the possibility of change of the distance between the external axles by almost 100% and is a development of the platform subjected to numerical and experimental tests described in [8,9]. Such an advanced design allows not only for a dynamic change in the length of individual members depending on the space available during the mission but most importantly it allows one to control the location of the center of gravity so that the platform can overcome very sloping obstacles and move in terrain of different height relative to longitudinal axis of symmetry.

The theoretical, numerical and experimental studies were performed on motion of rovers and mobile platforms in different terrain. Ishigami, Nagatani and Yoshida [10] have presented two control approaches for rovers moving in sandy terrains. Both methods (thrust cornering and sensor based feedback control) where experimentally tested with the use of four-wheeled rover.

¹ CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, DEPARTMENT OF MECHANICS AND MACHINE DESIGN FOUNDATIONS, 73 DĄBROWSKIEGO STR., 42-201 CZĘSTOCHOWA, POLAND

* Corresponding author: sokol@imipkm.pcz.pl



In these extensive considerations one have presented advantages and disadvantages of both methods. Yoshida et al. [11] have studied dynamics, control and navigation of lunar rover. The main goal was to test slip-based control effectiveness in experimental studies. Interesting investigations were done by Aizawa et al. [12] where one can find results of studies on designing of lunar rovers for high work performance. It is worth to mention that in all the above studies non-adjustable suspension systems were considered as well as an influence of material used was not also discussed.

The main purpose of this study is to find the best material (Aluminium 6060 T66 or Steel S235 or Titanium grade 1) for the suspension units which when fully extended have high slenderness and are subject to significant displacements when hit the obstacles. The decision on the use of those materials was done on the basis of the availability of profiles required in the production of the platform.

2. Geometrical model of a frame with suspension

The mobile platform consists of six independently driven wheels and six independently controlled suspension members. Electric motors with planetary gears are used to drive and adjust the suspension system. In addition, an encoder is attached to each of them to inform the control unit about its current status. The analysed platform with general dimensions is shown in Fig. 1.

The designations in Fig. 1a. stand for: 1,2 – suspension arms; 3,4,5 – wheels with electric motors; 6 – main frame; 7 – differential bar; 8 – electric motors for suspension control.

3. Assumptions

Before entering the design phase, several assumptions were made. The most important of them include:

- initial wheelbase from 500 mm up to 1000 mm,
- width not greater than 1000 mm,
- total weight of a frame and suspension units less than 50 kg (with motors, wheels and electronic equipment).

Knowing that the platform will be field tested inter alia in the URC (University Rover Challenge) [13] challenges the above assumptions were made on the basis for the competition regulations.

4. Simulations results

In the simulations the worst possible case was considered – one wheel hits the obstacle with the fully extended suspension made of: Titanium grade 1, Aluminium 6060 T66 or Steel S235. The preliminary studies have shown that materials like ABS (Acrylonitrile butadiene styrene) can't be used due to high overall displacements of suspension parts. The calculation model includes gravity force and a force of 100[N] which simulates the mass of additional equipment (electronics, batteries, wires).

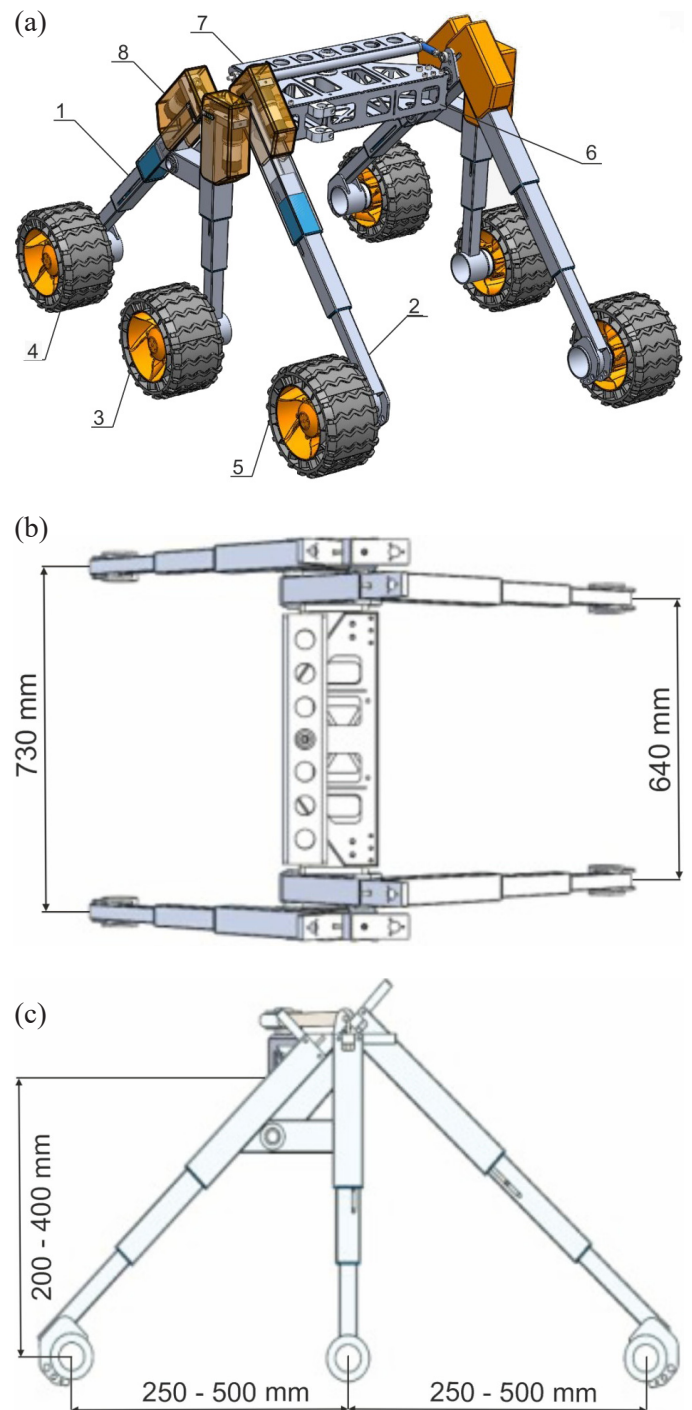


Fig. 1. Dimensions of a frame with suspension (views: isometric (a), top (b) and side (c))

During creation of simulation scenarios the simplification was done on the basis of which the impact force was derived on the basis of the equality of kinetic energy and work written in the form:

$$F = \frac{mV^2}{2x} \quad (1)$$

This simplification gives greater magnitude of F than in the case in which the elasticity is taken into account. The impact force F is applied in some distance from the model in order to

simulate the hit with outer part of the wheel what requires greater durability of suspension members.

The force F is determined from Eq. (1) where m is the mass of the platform, V is the maximum speed and x is the value of the platform displacement after hitting the obstacle. The value of x takes into account tire deflection and compensation of backlash resulting from inaccurate workmanship of components and applied tolerances. It was assumed that: $m = \text{construction_mass [kg]} + 28.4 \text{ [kg]}$ (additional elements required for platform operation), $V = 2 \text{ [m/s]}$, $x = 0.08 \text{ [m]}$. Finally the impact force was obtained. The boundary conditions and the applied loads are presented in Fig. 2.

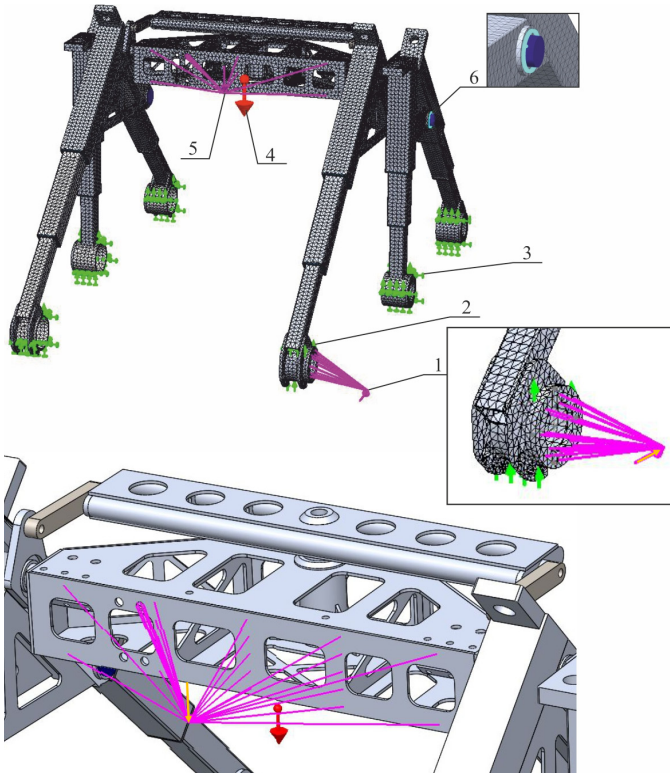


Fig. 2. Boundary conditions (green), loads (yellow and red) and pin connection of suspension parts (blue)

The boundary conditions (Fig. 2) were defined as:

- vertical translations for the wheel hitting the obstacle are equal to zero (point 2),
- other wheels have deprived translations and rotations in all directions (point 3).

The force F (yellow arrow in point 1 – Fig. 2.) determined on the basis of Eq. 1 was applied at the wheel mounting place and shifted by the distance of the drive set width (point 1). In the place of connection of the small and large swingarms, a pin joint simulating a rotary pin was used, which is illustrated in close-up (point 6). The real platform also contains inter alia electrical equipment and wiring what is simulated by means of the force applied to the front part of the frame (point 5). The gravity force was marked in point 4. A solid mesh with an element size of 3.6 mm and a tolerance of 0.18 mm was superimposed on the calculation models. The size of the elements was selected experi-

mentally. The percentage of elements (estimated by tools available in SolidWorks) with an aspect ratio less than 3 is 98.3, and the percentage of elements with an aspect ratio above 10 is 0.01. These values confirm that the mesh imposed on the model is correct [14]. The parameters of the computational model are as follows: number of nodes – 168074; number of elements – 955910.

Based on the computational model one has prepared the FEM analysis scenarios. In each of them one has used different material for the suspension members. In Table 1 the properties of materials used in this study are presented. In order to compare the investigated parameters the Table 2 was created where the maximum: von Mises stress, resultant displacement and equivalent strain as well as total mass (without additional equipment) are given.

TABLE 1

Material properties of the considered materials

Material		Aluminium 6060 T66	Steel S235	Titanium grade 1
Yield strength	[N/m ²]	$1.60 \cdot 10^8$	$2.35 \cdot 10^8$	$2.2 \cdot 10^8$
Tensile strength	[N/m ²]	$1.70 \cdot 10^8$	$3.6 \cdot 10^8$	$3.45 \cdot 10^8$
Longitudinal elasticity modulus	[N/m ²]	$6.95 \cdot 10^{10}$	$2.1 \cdot 10^{11}$	$1.05 \cdot 10^{11}$
Poisson ration		0.33	0.28	0.34
Density	[kg/m ³]	2700	7800	4510

TABLE 2

Simulation results

Material	The maximum von Mises stress [N/mm ²]	Maximum resultant displacement [mm]	The maximum equivalent strain	Construction mass [kg]
Aluminium 6060 T66	185.454	5.434	0.00452	15.19
Steel S235	239.654	2.677	0.00359	31.77
Titanium grade 1	202.979	4.306	0.00414	20.94

The first set of results (von Misses stress) is plotted in the Fig. 3a-c.

On the basis of the results it can be stated that not all chosen materials are suitable for adjustable rocker – boogie suspension system. When Aluminum 6060 T66 is used the maximum stress exceeds the yield strength. This phenomenon is caused by a stress concentration in a construction notch (enlarged view in Fig. 3a). The location of the highest stresses is the same for all tested materials. One can predict that in a real construction the notch will be slightly reduced by a weld which will create a fillet between perpendicular surfaces. It can be assumed that a prototype construction made of Aluminum 6060 T66 should not be omitted and is worth further experimental testing due to lowest total mass as well as easy accessibility of construction profiles. In a construction made of Steel S235 (Fig. 3b) the total mass exceeds the assumptions while stress is the lowest. In this case an intensive optimization should be implemented in order to obtain the correct mass of mechanical design. When

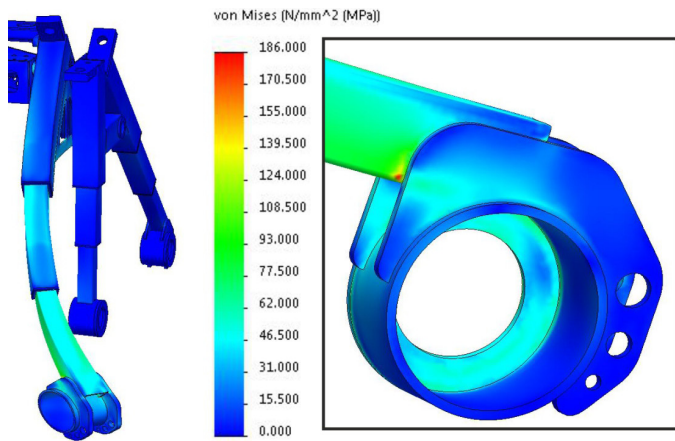


Fig. 3a. The von Mises stresses of construction from Aluminum 6060 T66

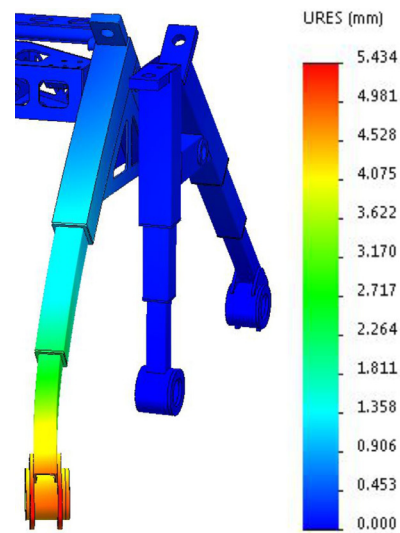


Fig. 4a. Displacements of construction from Aluminum 6060 T66

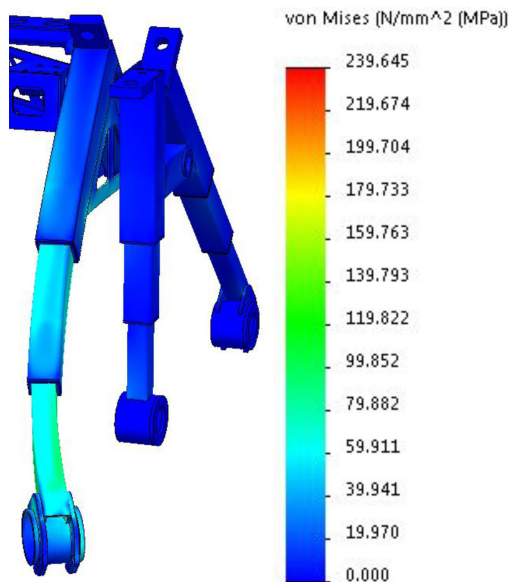


Fig. 3b. The von Mises stresses of construction from Steel S235

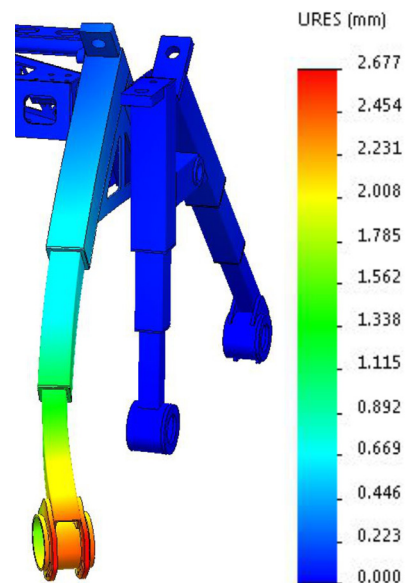


Fig. 4b. Displacements of construction from Steel S235

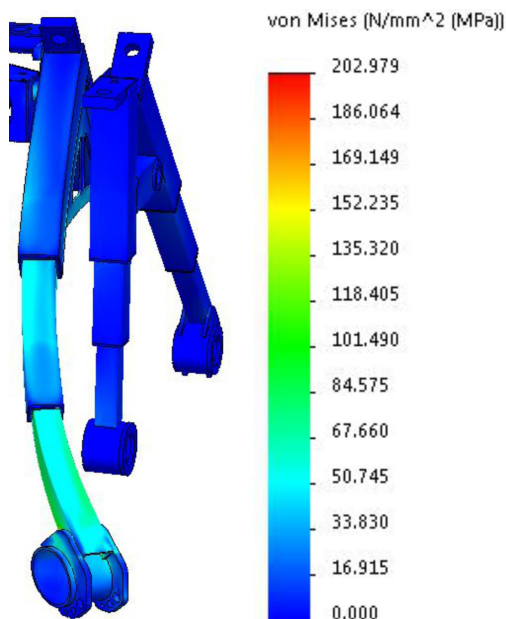


Fig. 3c. The von Mises stresses of construction from Titanium grade 1

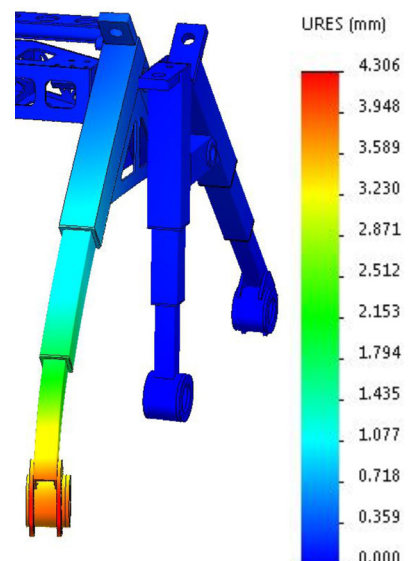


Fig. 4c. Displacements of construction from Titanium grade 1

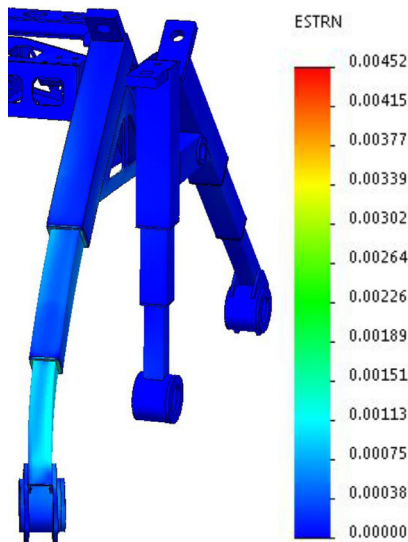


Fig. 5a. Strains of construction from Aluminum 6060 T66

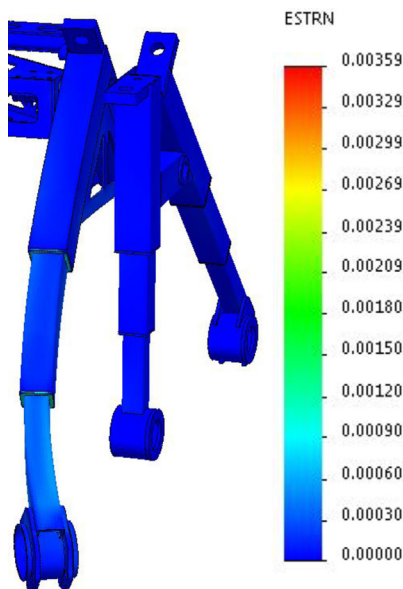


Fig. 5b. Strains of construction from Steel S235

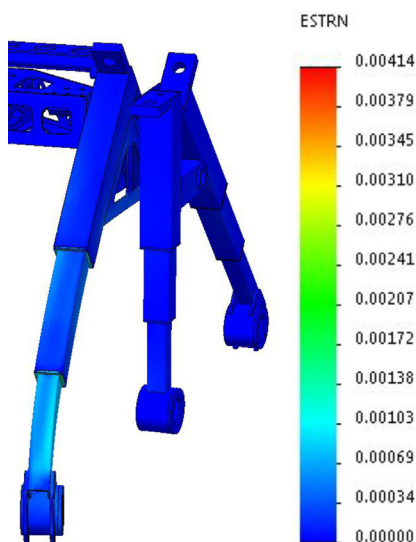


Fig. 5c. Strains of construction from Titanium grade 1

Titanium grade 1 (Fig. 3c) is taken into account the maximum stress is slightly lower than for Steel S235 as well as the total mass is almost 17% lower (see Table 2). In the other fragments of analyzed suspension systems the stress distribution is similar. The differences in the magnitudes of calculated stresses result from different material properties of the analyzed materials.

When the results of displacements are discussed it must be emphasized that the applied load was acting on the fully expanded suspension unit (which has the highest slenderness) with a total length in this case greater than 640 mm (measured along the axis of suspension arms). In this part of studies the lowest displacements are found for Steel S235 (Fig. 4b) material, which are almost 1.6 times lower than in a construction made of Titanium grade 1 (Fig. 4c) and almost 2 times lower than in use of Aluminum 6060 T66 (Fig. 4a). The distribution of the displacements is similar in all considered cases.

The strains are plotted in Figs. 5a-c. The lowest ones were found in a construction made of Steel S235 (Fig. 5b) while the greatest in one made of Aluminum 6060 T66 (Fig. 5a). The strains magnitudes for Titanium grade 1 were between ones calculated for Steel S235 (lowest) and Aluminum 6060 T66 (greatest). The strains distribution is analogous to the previously presented results.

5. Conclusions

It can be concluded that the suspension made of Steel S235 will be the best in terms of strength of the designed mobile platform but it does not meet all the design assumptions. The mass of the mobile platform made of Steel S235 is much greater the mass of one made of Aluminum 6060 T66. The mass reduction will be a great challenge and it can't be sure of success. The construction made of Titanium grade 1 has some advantages in relation to Steel S235 such as lower mass. However, the displacements are slightly greater at similar stress distribution. Construction made of Titanium grade 1 profiles will be the most expensive and problematic during construction. The most interesting material for mobile platform suspension seems to be Aluminum 6060 T66 due to fact of lowest mass, accessibility of profiles as well as easy final product manufacturing despite some material limitations. The problems with stress concentration which are pointed in this study can be overcome during manufacturing and should be verified in the prototype field tests.

In the future one should also perform fatigue and vibration frequency studies [14] as well as work cycle optimization [15] of the working suspension what is very important in such a construction. The suspension system presented in this paper opens the new areas of future investigations.

Acknowledgement

The studies presented in this paper are financed by Czestochowa University of Technology 1-100/3010/2020.

REFERENCES

- [1] M. Giergiel, Z. Hendzel, W. Żylski, Modelowanie i sterowanie mobilnych robotów kołowych, PWN (2013) in polish.
- [2] J. Giesbrecht, Global path planning for unmanned ground vehicles. Defence R&D (2004).
- [3] N. Buniyamin, N. Wan, N. Sariff, Z. Mohamad, Int. J. Sys. App. Eng. Dev. **5** (2), 151-159 (2011).
- [4] G. Cook, Mobile Robots Navigation, Control and Remote Sensing, John Wiley & Sons (2011).
- [5] P.E. Sadin, Robot mechanisms and mechanical devices illustrated, The McGraw-Hill Companies Inc. (2003).
- [6] W. Mucha, W. Kuś, Exploration mobile robot, project and prototype, in: J. Awrejcewicz, R. Szewczyk, M. Trojnacki, M. Kaliczyńska.
- [7] W. Mucha, Mod. Inż. **48**, 92-98 (2013).
- [8] M. Pierzgalski, K. Sokół, D. Cekus, J. Eng. Mech. (2019), DOI: 10.21495/71-0-283
- [9] P. Ptak, M. Pierzgalski, D. Cekus, K. Sokół, Procedia Eng. (2017), DOI 10.1016/j.proeng.2017.02.215
- [10] G. Ishigami, K. Nagatani, K. Yoshida, J. Field Rob. **26** (3), 264-286 (2009), DOI 10.1002/rob.20277
- [11] K. Yoshida, T. Watanabe, N. Mizuno, G. Ishigami, Slip, traction control and navigation of a lunar rover, in: Proceedings of the 7th International Symposium on Artificial Intelligence, Robotics and Automation in Space, NARA, Japan, May 19-23, 2003.
- [12] J. Aizawa, N. Yoshioka, M. Miyata, Y. Wakabayashi, Designing of lunar rovers for high work performance in: Proceedings 5th International Symposium on Artificial Intelligence, Robotics and Automation in Space, NARA, Japan, 1-3 June, 1999.
- [13] <http://urc.marssociety.org/home/urc-news>, accessed: 10.07.2020
- [14] http://www.tu.kielce.pl/~rokach/instr/mes_siatki.htm
- [15] D. Cekus, D. Skrobek, T. Zajac, A dynamic analysis of an industrial CNC plotter. Engineering Mechanics 2016, 2016, 109-109.
- [16] B. Posiadała, M. Tomala, D. Cekus, P. Waryś, Int. Jo. Dyn. Ctrl. **3**, 94-99 (2014).