Research of Various Magnetic Systems Used in Autonomous MegaSumo Robots

Paulina Łapińska, Marcin Dziubek, Łukasz Kotarski, and Rafał Grądzki
Faculty of Mechanical Engineering, Bialystok University of Technology, Bialystok, Poland
Email: lapinskapaulina96@gmail.com, m_dziubek97@wp.pl, kotarskil@interia.pl, r.gradzki@pb.edu.pl

***Abstract*—The paper is continuation of work on research of magnetic systems used in MegaSumo robots. The article describes comparative research of two configurations of neodymium magnets arrangement. The tests were carried out for the common attraction of magnet sets. Two versions of magnet arrangement were compared - the first version was arranged in an alternating polarization configuration of magnets, while the second was arranged to create a Halbach array. The tests included simulations in the COMSOL program and tests on the MTS 858 TABLE TOP SYSTEM machine.**

***Index Terms*—autonomous robot, sumo robot, magnetism, magnet, halbach array**

I. What Is a MegaSumo Robot?

Sumo is Japanese national sport where wrestlers are attempting to force opponents out of the dohyo. Same concept is moved to the sumo robots battles. Centuries-old tradition of Japanese martial art is coupled with modern technologies to create challenging competition for engineers around the world. The rules for sumo robots battles are straightforward – one autonomous robot (Fig. 1) shall force the other robot out of the circle ring. Sumo robots competition is divided in several categories depending on the dimension and weight of the vehicle. The most popular and therefore most competitive category is MegaSumo class, where floor of the robot cannot exceed the dimensions of 200 by 200 mm and weight of 3000 g.

Figure 1. Autonomous MegaSumo robot.

Manuscript received April 5, 2019; revised May 9, 2020.

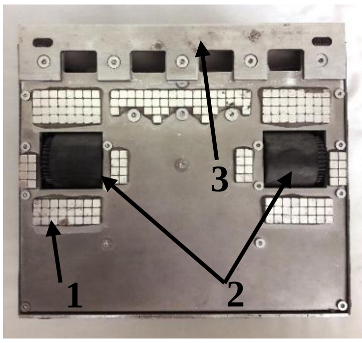

Figure 2. View of the current magnetic system of the MegaSumo robot (1 -magnets; 2 – wheels; 3 - plough).

Compact construction of the robot has all the necessary elements for autonomous work including skeleton, drive systems, sensors, electronic system batteries and magnetic system. The magnetic system of the MegaSumo robot is shown in Fig. 2. [1]-[3]

The magnetic system will provide the robot's adhesion to the metal dohyo on which he moves. The perfect attraction to the mat will make sure that no opponent will be able to drive under the robot. Therefore, the most vulnerable areas are around the wheels and the plough (front main blade), so it is crucial that most of the magnets are placed in those sections. [4], [5]

II. Research Objects

5x5x5mm neodymium magnets made of material designated N52 (NdFeB) were tested. Their nominal attraction force specified by the manufacturer is approx. 1.6 kg / item. The exact parameters of the magnet are shown in Table I. Single magnet is shown in Fig. 3. [6]

TABLE I. Magnet Parameters

Dimensions [mm]	5 x 5 x 5
Material	Neodymium (NdFeB)
Magnetising	N52
Weight [g]	0.94
Magnetization [kA/m]	875
Remanence [T]	1.47
Holding force [kg]	Ab. 1.6

Permanent magnet strength can be described as a ability to move other objects. This is determined as the force of attraction or repulsion, depending on the direction. To describe magnets strength’s Maxwell equation (1) can be used:

doi: 10.18178/ijmerr.9.5.739-744

$$F = \frac{B^2 A}{2\mu_0} \qquad (1)$$

where:

- F – strength (N),
- A – cross-section of the magnetic pole field (m2),
- B - magnetic induction produced by a magnet (T),
- $\mu_0 = 4\pi * 10^{-7}$ – permeability ($H * m^{-1}$).

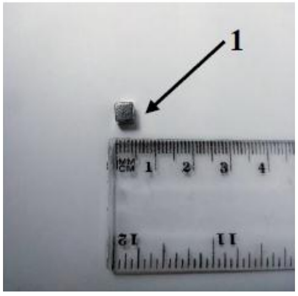

Figure 3. 1 - Single neodymium magnet.

It is not a straightforward task to determine the force between a permanent magnet and a ferromagnetic material at any given distance. It is possible to estimate the value by the use of complicated simulations but most magnet manufacturers conducts experimental tests to figure out the actual value of attraction force. [8]

Two configurations of magnet arrangement were prepared. First of them was based on Halbach array, which is a special arrangement of permanent magnets. This magnets distribution allows to enhance the magnetic field on one side of the array. The arrangement diagram and magnetic field distribution is presented in the Fig. 4.

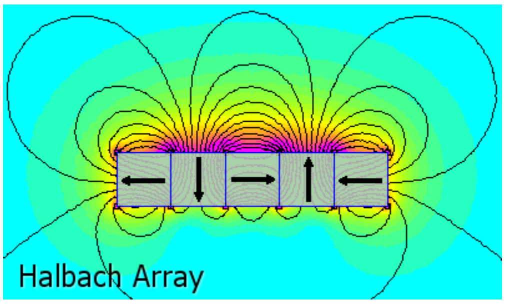

Figure 4. Halbach array scheme [9].

Second configuration of permanent magnets is using alternating polarity concept. The diagram of this arrangement is shown on Fig. 5. This type of configuration enhances the magnetic field in the near neighborhood of magnets while distributing the field evenly.

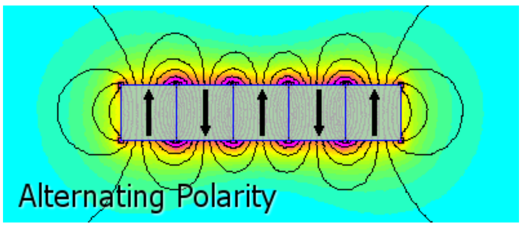

Figure 5. Alternating polarity scheme [9].

III. Computer Simulation

To simulate forces that occurring in both magnet arrangements COMSOL Multiphysics program was used. The simulations were carried out with „Magnetic Fields, No Currents" mode and static simulation type. „Extra fine" mode was used to perform those simulations. The magnetic field produced by the magnets can be described with the following equation (2):

$$B = \mu_0 (H + M) \qquad (2)$$

where:

- M – value of magnetisation (kA/m),
- μ_0 – magnetic permeability,
- H – magnetizing field (kA/m).

According to parameters Table I of used neodymium magnets value of magnetisation equals to 875 kA/m. Simulations were carried out with magnetic permeability set to 1 (vacuum conditions). There are no currents, therefore H = 0.

The two magnet arrangement schemes presented earlier were built for two different quantities. The first of them contained 200 neodymium magnets, the second one contained 100 of them. Both systems were created in COMSOL Multiphysics program and their model is visible in Fig. 6 and Fig. 7.

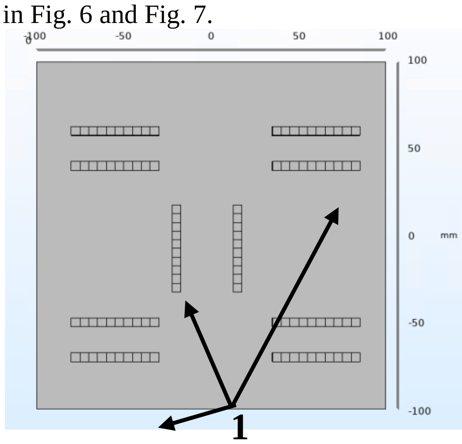

Figure 6. Created system for 100 magnets for the robot floor (1 – magnets).

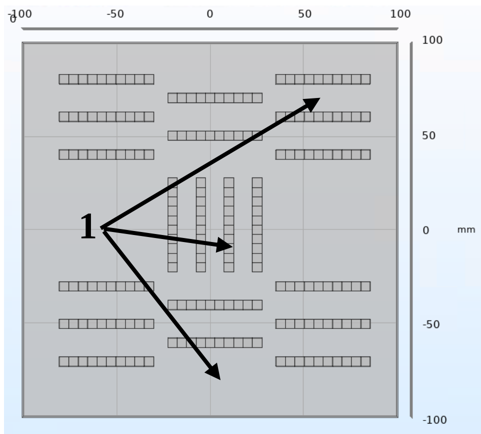

Figure 7. Created system for 200 magnets for the robot floor (1 – magnets).

When creating the magnetic system of a sumo robot, it is assumed that it should have about 2000 N of attraction force on the ring, and one neodymium magnet has about 10 N capacity. So, theoretically, 200 pieces of magnets are needed to get the desired force. This was the reason for choosing the system with 200 magnets. A system with 100 magnets was created to confirm the test results. In the case of the Halbach array and alternating polarity, the models created in the program looked the same.

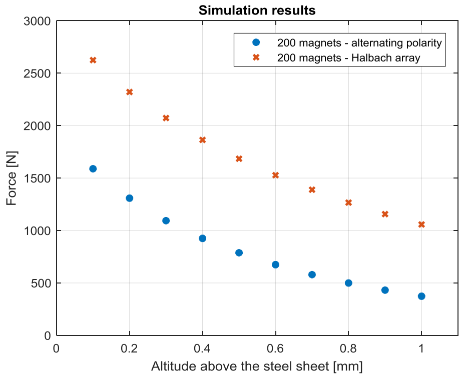

Figure 8. Simulation results for 200 magnets.

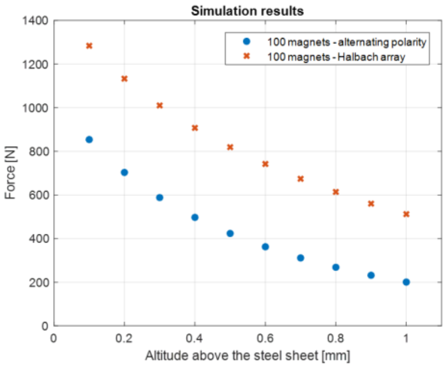

Figure 9. Simulation results for 100 magnets.

TABLE II. SIMULATION RESULTS FOR 200 MAGNETS

Distance	Halbach array	Alternating polarity
mm	F [N]	F [N]
0.1	2624.658	1588.905
0.2	2320.612	1308.324
0.3	2072.31	1093.866
0.4	1863.806	924.885
0.5	1684.514	787.9425
0.6	1527.466	674.2686
0.7	1389.044	579.3249
0.8	1266.126	499.4286
0.9	1156.353	431.6223
1	1057.622	373.4322

TABLE III. SIMULATION RESULTS FOR 100 MAGNETS

Distance	Halbach array	Alternating polarity
mm	F [N]	F [N]
0.1	1283.787	1588.905
0.2	1133.0102	1308.324
0.3	1010.226	1093.866
0.4	907.3274	924.885
0.5	819.075	787.9425
0.6	741.9446	674.2686
0.7	674.0602	579.3249
0.8	613.9076	499.4286
0.9	560.0664	431.6223
1	512.0408	373.4322

After conducting the first simulations for 200 magnets, the intended effect was achieved (Fig. 8). With the same number of magnets, a greater attraction force was obtained for the Halbach array than for alternating polarity. In the case of a Halbach array, it is more similar to a linear function. Magnets arranged in an alternating polarity gave results that follow the model of a logarithmic function (it has more dynamic value change than in the case of the Halbach array).

100 magnets were tested to confirm the results (Fig. 9). In the case of Halbach array and alternating polarity arrangement, the points are arranged in the same way with the difference that the achieved force values are lower. However, the strength in the case of the Halbach array is much higher than for alternating polarity arrangement.

The simulation results are presented in Table II and in Table III.

IV. EXPERIMENTAL TESTS

To verify the credibility of given simulation real research was carried out. Both magnet arrangements were tested using MTS 858 TABLE TOP SYSTEM testing machine (Fig. 10). All necessary parameters have been measured and saved in data files for further analysis.

This research was conducted by lifting magnet configurations from a 10mm steel plate (Fig. 11). Tearing distance was set from 0 to 1.4 mm in case of alternating polarity, while Halbach array was tested in 0 to 1 mm range. Frequency of data reading was 25 Hz. The increment during tearing was equal to approximately 0.001 mm. To reduce the impact of other factors that could affect the reality of the results the surface of the steel plate has been cleaned of impurities and leveled.

Figure 10. MTS 858 table top system.

Figure 11. Top view of a steel plate.

The systems created earlier in the COMSOL Multiphysics program for 200 and 100 magnets have been reconstructed (Fig. 12 and Fig. 13). The magnets have been glued with resin to a rigid structure that will allow the system to be detached from the metal plate.

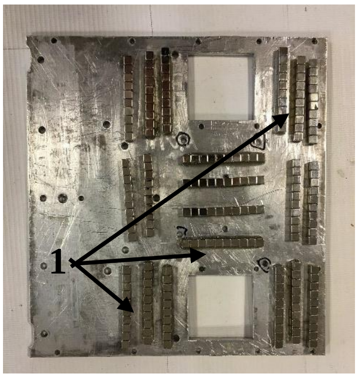

Figure 12. Created system for 200 magnets (1 - magnets).

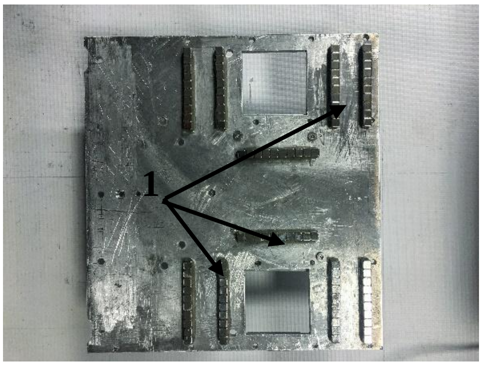

Figure 13. Created system for 100 magnets (1 - magnets).

Systems with 200 magnets were subjected to the experiment. The graphs in Fig. 14 show that more force had to be used to detach the magnets arranged in a Halbach array. The maximum force used to detach the system in the Halbach array was 2617.4N. For alternating polarity, the same force was 1592.8N. This is over 1000N difference. As the distance increased, the Halbach mesh force was much higher than the alternating polarization force.

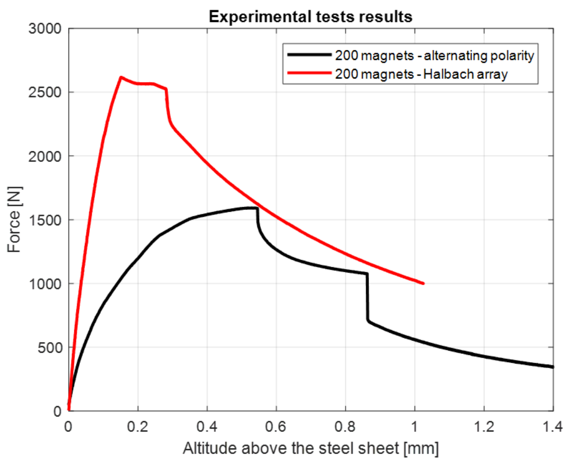

Figure 14. Created system for 100 magnets.

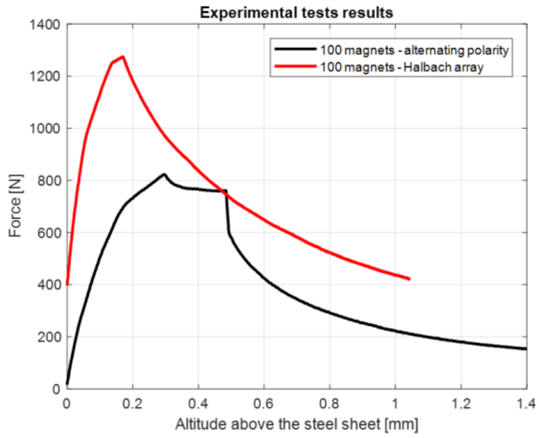

Figure 15. Created system for 100 magnets.

Then, 100 magnet systems were subjected to the experiment. As in the previous case, the force needed to detach the Halbach array is much bigger. Its maximum value is 1274.8N, and when placing magnets in alternating polarity the same force is 822.7N. The experiment graphs are shown in Fig. 15.

Comparing the results of the experiments, it can be seen that using 100 magnets in the Halbach array achieved results are very comparable as for 200 magnets in the alternating polarity arrangement. The difference is only 318N.

V. Comparison of Results

On the Fig. 16 - 19, it can be seen that the maximum force obtained during the simulation is comparable to that obtained during the experiment.

The results of the simulation in the case of Halbach's array do not differ much from the results of the experiment. They even coincide with them (Fig. 16). This does not happen in systems with alternating polarity, but the calculated maximum force is comparable.

In the case of the Halbach array, it will hold the robot closer to the mat than placing them in alternating polarity. Strength when using Halbach array even over a distance of 1mm is over 1000N.

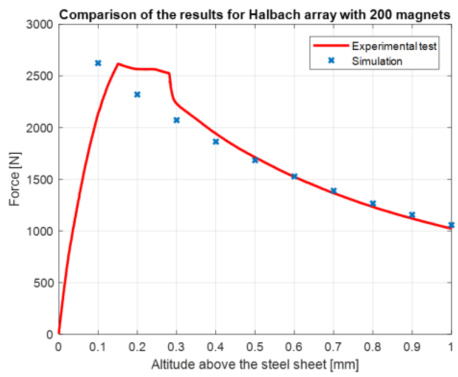

Figure 16. Comparison of the results for Halbach array with 200 magnets.

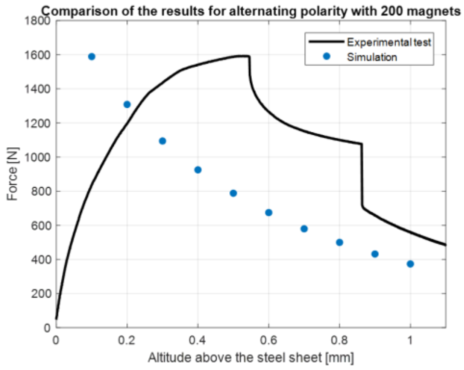

Figure 17. Comparison of the results for alternating polarity with 200 magnets.

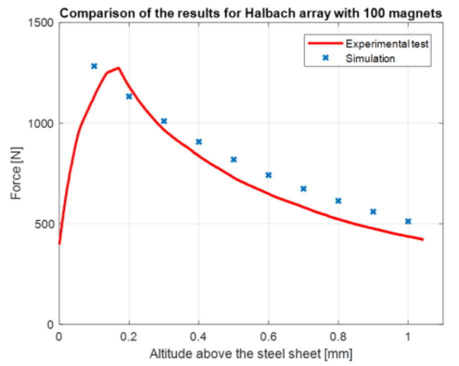

Figure 18. Comparison of the results for Halbach array with 100 magnets.

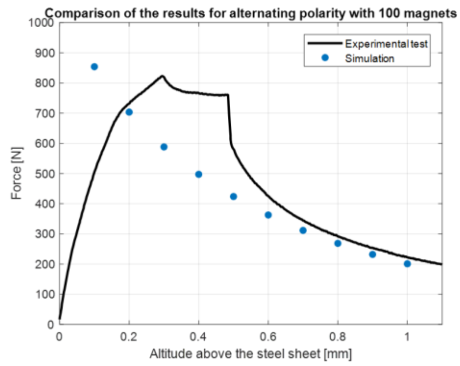

Figure 19. Comparisonda of the results for alternating polarity with 100 magnets.

VI. Conclusions

The use of Halbach's array brings many benefits over the alternating polarity arrangement. Halbach has more similar characteristics between the simulation and the experiment, therefore it is less complicated to conduct simulation tests of various patterns of the arrangement of magnets, their number and position. One of the disadvantage of Halbach's array is very difficult arrangement of magnets.

The study shows the differences between the tested configurations. There is a significant difference between the Halbach array and the alternating polarization arrangement in achieved holding force with equal number of magnets. When we compare the results of Halbach array and alternating polarity for a different number of magnets (in the case of Halbach array - 200 magnets, for alternating polarity - 100 magnets) we get only 300N difference. This allows reducing the number of magnets, while maintaining a similar attraction force to the steel ground. However, it should be noted that an equal number of magnets were used. By manipulating their quantity, it is possible to optimize the structure in such a way to achieve desirable force while retaining the weight as low as possible. This increases the possibility of using a stronger drive system or more durable construction materials in the MegaSumo category robot.

Also noticeable is the difference in the distance of the magnets from the ground at which the maximum value of attraction force is achieved, and how the change of distance affects the value of force. In the case of Halbach array, the distance at which the attraction force reaches its maximum is much smaller than in the alternating polarity arrangement.

Based on the advantages and disadvantages of both configurations, the magnet arrangement can be individually selected for the construction solutions used in the robot, thanks to which the selection of the configuration and the number of magnets becomes a lesser limitation taken into account during the robot construction stage.

In the future, this work will help optimize the weight of the new design. New magnet arrangements will be tested using a carbon fiber floor. Testing the various arrangements and the number of magnets will allow to observe the behavior of the robot and many other important factors.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Łukasz Kotarski was responsible for conducting simulations in COMSOL Multiphysics software. Marcin Dziubek carried out experimental research of magnets arrangement. Paulina Łapińska made charts from the obtained research results and wrote the content of the article. Rafał Grądzki coordinated the team's work and assisted in creating the article. The final version of the article has been accepted by all authors.

Acknowledgment

The project is funded by the Ministry of Science and Higher Education of Poland under the "Najlepsi z najlepszych! 4.0" program.

References

[1] Ł. Kotarski, M. Wysocki, R. Grądzki, P. Łapińska, "Research of magnetic system applied in autonomous MegaSumo robots," *in Proc. 2019 20th International Carpathian Control Conference (ICCC)*, Krakow-Wieliczka, Poland 2019, pp. 1-5. https://doi.org/10.1109/CarpathianCC.2019.8765950.

[2] P. Wasilewski, K. Chojnowski, R. Grądzki, "Autocalibration of gyroscope based two-step regulator for autonomous vehicles," *in Proc. MATEC Web of Conferences*, vol. 182, Article Number: 01030 (2018), https://doi.org/10.1051/matecconf/201818201030

[3] K. Chojnowski, P. Wasilewski, R. Grądzki, "Movement modeling of mobile robot in MegaSumo category," *in Proc. AIP Conference Proceedings 2029*, 020010 (2018); https://doi.org/10.1063/1.5066472

[4] M. Dziubek, M. Klimowicz, R. Grądzki, "Evaluation of temperature changes of a loaded DC motor in autonomous mobile robots," *in Proc. 2019 20th International Carpathian Control Conference (ICCC)*, Krakow-Wieliczka, Poland 2019, pp. 1-5. https://doi.org/10.1109/CarpathianCC.2019.8766058.

[5] K. Falkowski, *Passive magnetic suspensions*, Military University of Technology, 2016.

[6] H. Kronmüller, S. Parkin, *Handbook of Magnetism and Advanced Magnetic Materials*, 5 Volume Set, John Wiley & Sons, 2007.

[7] K. Halbach, *Design of Permanent Multipole Magnets with Oriented Rare Earth Cobalt Material*, Nuclear Instruments and Methods, 1980.

[8] J. L. Coulomb, "A methodology for the determination of global electromechanical quantities from a finite element analysis and its application to the evaluation of magnetic forces, torques and stiffness," *IEEE Transactions on Magnetics*, vol. 19, no. 6, pp. 2514–2519, 1983.

[9] https://www.kjmagnetics.com/blog.asp?p=halbach-arrays

Paulina Łapińska, Bialystok (Poland), November 4, 1996, Control System and Robotics student at the Bialystok University of Technology. Bachelor's degree in Control Systems and Robotic at the the Bialystok University of Technology, Poland, Bialystok, 2019.

Copywriter. She works for the iAutomatyka.pl company in Bialystok. In 2018, an internship at ANLAP. Co-author of the article "Research of magnetic system applied in autonomous MegaSumo robots" presented on 20th International Carpathian Control Conference (ICCC), 26-29 May 2019, Krakow-Wieliczka, Poland.

Marcin Dziubek, Augustow (Poland), September 26, 1997 Control System and Robotics student at the Bialystok University of Technology. Mechatronics technician at Augustowskie Centrum Edukacyjne, Poland, Augustow, 2017.

Łukasz Kotarski, Augustow (Poland), June 8,1997,Control System and Robotics student at the Bialystok University of Technology. Mechatronics technician at Augustowskie Centrum Edukacyjne, Poland, Augustow, 2017.

He worked as electrical equipment fitter at AGRIM-TEC company. Co-author of the article "Research of magnetic system applied in autonomous MegaSumo robots" presented on 20th International Carpathian Control Conference (ICCC), 26-29 May 2019, Krakow-Wieliczka, Poland.

He worked as serviceman of measuring and control machines in British American Tobacco in Augustow. Co-author of the article: „Evaluation of temperature changes of a loaded DC motor in autonomous mobile robots" presented on 20th International Carpathian Control Conference (ICCC), 26-29 May 2019, Krakow-Wieliczka, Poland.

Rafał Grądzki, Mońki (Poland) December 22, 1984. In 2012 in Bialystok University of Technology finished PhD thesis in technical sciences in the field of machine construction and operation.

He works as assistant Professor of the Faculty of Mechanical Engineering at the Bialystok University of Technology since 2012. Research subjects: technical diagnostics of bus engines, shafts, examination of potential reliability and safety level demonstrated by technical objects and autonomous robots. The most important publication 27. R. Gradzki, P. Z. Kulesza, B. Bartoszewicz, "Method of shaft crack detection based on squared gain of vibration amplitude", Nonlinear Dynamics, 2019, Volume 98, Issue 1, pp 671–690. https://doi.org/10.1007/s11071-019-05221-0.