Research of Hybrid Magnetic System Used in Autonomous MegaSumo Robots

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***Abstract*—The article describes the research of a hybrid magnetic system consisting of neodymium magnets arranged in a Halbach array, combined with electromagnets. The system had been applied to an autonomous MegaSumo robot. Application of the system is intended to enable control of a robot adhesion to the mat that the robot moves on during fights. As a part of the electromagnet selection process, simulation tests had been conducted. Simulations were targeted to analyse the influence of changing quantities of electromagnet coils and core radius on attraction force. After the electromagnets selection, the hybrid magnetic system had been created, consisting of 60 neodymium magnets and two electromagnets. The system had been tested with MTS 858 Table Top System machine. The experiment showed that the use of a hybrid solution brings many benefits, and in certain situations its capabilities significantly exceed the standard solution. In addition, during the tests, it was possible to determine the optimal number of turns of the electromagnet coil on the basis of optimization tests.**

***Index Terms*—autonomous robot, sumo robot, magnetism, electromagnet, magnet, Halbach array**

I. Introduction

MegaSumo robots are autonomous structures that compete in competitions based on traditional sumo wrestlers fights. They move on a steel dohyo, which is why the vast majority of constructors of MegaSumo robots use magnets in their structures to increase the adhesion on the mat. The classic solution used in the vast majority of designs found at competitions is to arrange neodymium magnets individually or in groups while maintaining alternating polarity. The only exception is the UK team of builders, which used an electromagnet instead of permanent magnets. Their solution was based on a single, large electromagnet, which was turned on at the beginning of the fight and turned off only after its end. However, the robot constructed in this way moved very slowly around the dohyo and was vulnerable to enemy attacks from the side and the back. Based on the observations of the world's leading robots, it was noticed that the highest positions in the competition are occupied by structures that move very dynamically, achieve full speed in a short time and react almost immediately to every enemy move. Thus, slow construction is doomed to failure. The robot is constructed based on one large electromagnet also had another serious drawback - while maintaining the same attraction force, the electromagnet is much heavier than permanent magnets. Moreover, the electromagnet, which remained on throughout the fight, generated a point focus of the attractive force. The lack of its distribution evenly over the entire surface of the robot's floor forced the use of larger, and therefore heavier, motors driving the robot. These are the issues that impose construction restrictions when designing the remaining robot components due to the maximum weight of the robot being 3000g. [1], [2]

The research carried out earlier based on which the articles [3]-[5] were created drew the Authors' attention to the correctness of using both electromagnets and permanent magnets. However, it was necessary to choose the right proportions between both types.

The combination of both types of magnets (neodymium and electromagnets) would allow us to adjust the attraction force of the robot to the mat. The operation of such a solution would be based on switching on two smaller than the electromagnets mentioned above using signals from the microcontroller controlling the operation of the entire system.

The electromagnets would be turned on when the distance sensors detect an enemy that is below the distance range that would be taken into account when programming the microcontroller. Then, during a confrontation with the opponent, the robot would temporarily have a significantly increased adhesion against the dohyo.

In the proposed solution, when the electromagnets remain off, compared to the classical solution, the resistance forces resulting from the adhesion of the robot's razor and wheels to the dohyo significantly decrease. Therefore the robot gains speed while driving at a safe distance from the opponent.

II. Research Objects

The magnets most frequently used in MegaSumo robots constructions are neodymium NeFeB magnets [3] with dimensions 5x5x5mm. The nominal value of the attraction force is 1,6kg/item. Exact parameters from the manufacturer's data are shown in Table I.

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TABLE I. NEODYMIUM MAGNETS 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

In previous work, the authors have researched the reduction of the number of neodymium magnets installed in the robot. The research focused on the use of the Halbach array, which properly polarises the direction of propagation of the magnetic field generated by the magnets. Such a system of magnets allowed to maintain a similar force of attraction with a significant reduction in their number, which also translates into weight savings, which can be used in other elements of the structure [4]-[7].

Since the total weight of the robot cannot exceed 3000g, the use of electromagnets in the robot's magnetic system is associated with the removal of a significant amount of material from the robot's floor and the use of the previously mentioned Halbach array so that the total weight of the robot complies with the competition regulations.

Electromagnet selection was conditioned with three factors:
- electromagnet size;
- attraction force;
- coil inductance (the factor which determines the time that magnet requires achieving the maximum attraction force).

To keep the structure as stiff as possible, it was assumed that the diameter of the electromagnet could not exceed 40mm. However, to avoid modifying the arrangement of the remaining structural elements of the robot, the permissible height of the electromagnet was 20mm.

III. SIMULATIONS

The theory of electromagnetism used in the article was based mainly on Maxwell's equations [8], [9]. The most important of these was Faraday's law of electromagnetic induction. The law states that electric current is conducted in a closed circuit, exposed to a changing magnetic field [10], [11].

$$\oint_L \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt} \oint_S \mathbf{B} \cdot d\mathbf{s} \tag{1}$$

where:
- L – any closed contour;
- E – vector of electric field strength [V/m];
- S – area stretched on any closed contour L;
- B – magnetic field induction vector [T].

Another important law was the Ampere law extended by Maxwell, which describes the relationship between the flow of current and the alternating magnetic field and the produced magnetic field [12], [13].

$$\oint_L \mathbf{B} \cdot d\mathbf{l} = \mu I + \mu\varepsilon \frac{d}{dt} \oint_S \mathbf{E} \cdot d\mathbf{s} \tag{2}$$

where:
- L, E, S, B – exact as in equation 1;
- μ - magnetic permeability of the medium [H/m];
- I – total current flowing through the surface S stretched on any closed contour L [A];
- ε – electric permittivity of the medium [F/m].

The above laws are the foundations of theorems on which COMSOL Multiphysics modelling the operation of an electromagnet was based [14].

In order to model and test the electromagnet, its parameters should be taken into account:

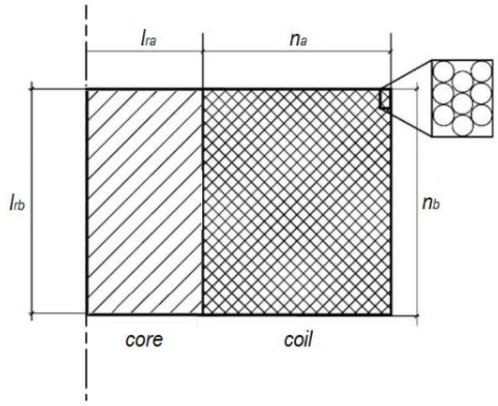

Figure 1. Electromagnet – cross-section.

where:
- n_a – the numer of turns in one layer along the horizontal axis;
- l_{ra} – core thickness [m];
- l_{rb} – core length [m];
- n_b – number of turns in one layer along the vertical axis.

To examine the value and distribution of forces, an electromagnet model [15] was modelled in the COMSOL Multiphysics program. The electromagnet winding was converted from multiple circular sections to a simplified rectangular section corresponding to the real areas of the windings (Fig. 1). The simplification was applied due to the small differences in the cross-sectional area between the solutions. However, it significantly shortened the simulation time, and the accuracy of the results remained at a very high level. The model of the electromagnet is shown in Fig. 2 and Fig. 3.

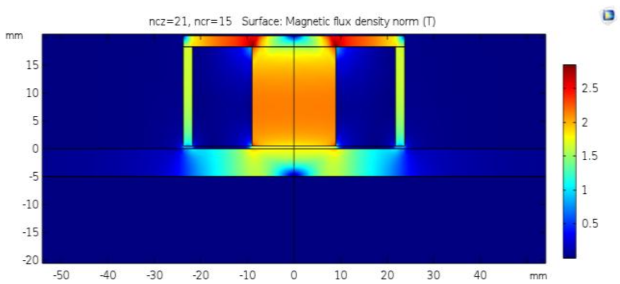

Figure 2. 2D cross-section of the electromagnet model.

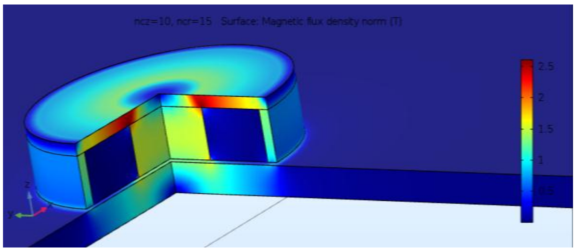

Figure 3. 3D cross-section of the electromagnet model.

Fig. 2 shows the distribution and intensity of the magnetic field inside the electromagnet and in the substrate. The housing used in the electromagnet directs the propagation of the magnetic field while preventing it from affecting the other components of the robot - the magnetic field does not interfere with the operation of the control electronics and sensors (Fig. 3).

The magnetic field generated by the electromagnet depends on the number of turns and the intensity of the flowing current. The simulation aimed to select the electromagnet parameters such that for the above assumptions, in terms of dimensions, the highest possible magnetic field strength was achieved. An essential parameter of the electromagnet related to its operation is its induction. Due to the high speed at which the robot moves, the time to achieve full attraction must be as short as possible.

To fully use the potential of the electromagnet, the distances between its core and the ground were minimised for the robot's design. This dependency determines the method of mounting the electromagnet to the robot's body.

The article presents only the range of results relevant for further research (simulations were carried out in a much broader range of input data).

Below are presented simulations for seven different core radius (from 3 to 14 mm, every 1 mm) with the same winding, and then the results for the same core diameter of 9 mm, but with a different number of turns (Tab. II, Tab. III).

TABLE II. SIMULATION RESULTS WHEN CHANGING THE CORE DIAMETER

The radius of the electromagnet core	Attraction force (N)	Coil resistance (DC) (Ω)	Coil inductance (H)
3	25,1527	0,2637	0,001354
4	52,8073	0,3024	0,002285
5	92,4095	0,3413	0,003422
6	141,0657	0,3797	0,004699
7	190,0237	0,4183	0,005959
8	230,6313	0,4572	0,007123
9	**262,5543**	**0,4956**	**0,008188**
10	286,8313	0,5342	0,009177
11	315,2056	0,5728	0,010452
12	338,1733	0,6114	0,011603
13	362,2347	0,6523	0,012753
14	388,2542	0,6886	0,013904

TABLE III. RESULTS OF THE SIMULATION OF THE CHANGE IN THE NUMBER OF COILS ON THE RADIUS

Number of turns in the horizontal axis	Attraction force (N)	Coil resistance (DC) (Ω)	Coil inductance (H)
5	131,7484	0,2388	0,003412
6	165,5354	0,2975	0,004473
7	198,8458	0,3599	0,005624
8	231,2018	0,4259	0,006867
9	**262,5548**	**0,4956**	**0,008188**
10	292,8458	0,5689	0,009591
11	321,8358	0,6459	0,011059
12	349,1837	0,7265	0,012587
13	372,4712	0,8108	0,014167
14	395,5065	0,8987	0,015807
15	416,5802	0,9903	0,017498

The above simulation results show that the more the coil has turns and the more current flows through it, the stronger the magnetic field of the electromagnet. On the other hand, the induction of the coil is so low that its influence can be neglected when selecting the magnet.

The highest efficiency, while maintaining the assumed maximum dimensions, without the need to reduce the stiffness of the structure and without affecting the operation of other components, was achieved by an electromagnet with the following parameters:

- numbers of turns at height – 21;
- number of turns on the radius – 9;
- radius of the electromagnet core - 9mm.

IV. EXPERIMENTAL TESTS

The conducted simulations provided the data needed for the correct selection of the electromagnet. They made it possible to approximately predict the effects of introducing the electromagnets into the system (approximate value of the increase in the pressing force of the robot to the mat). It was necessary to verify the correlation between the simulation calculations and the actual results. For this purpose, a structure consisting of two electromagnets with parameters determined in the simulation section and sixty neodymium magnets arranged in a Halbach array was made. The system constructed in this way was subject to further stages of the verification of the force of attraction. Conducting practical tests will allow predicting the behaviour of the structure placed in the Mega Sumo robot during a fight, and will also allow to roughly determine the benefits of using such a solution during sumo fights. Based on the research to date, the authors of the article noticed that the results from the tensile tests give a reliable translation into the real Mega Sumo structures.

To check how the developed magnetic system will behave on a real robot, the MTS 858 Table Top System machine was used (Fig. 4).

The test sample was built based on a 6mm thick aluminium sheet, imitating the floor of the MegaSumo robot (Fig. 5) The aluminium used in the construction does not affect the operation of the magnets. For the tensile tests, the positioning of the magnets on the aluminium plate was changed about the arrangement on the robot's floor - the even distribution of the magnets made the magnets lift simultaneously and evenly [16].

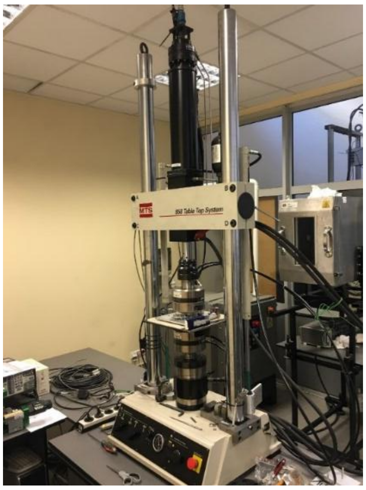

Figure 4. MTS 858 Table Top System.

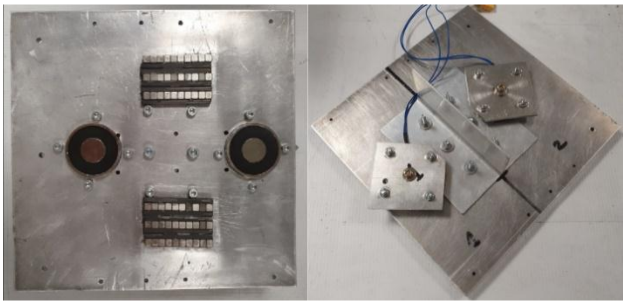

Figure 5. The system built for tensile testing.

The constructed system was pulled away from a 10mm thick steel plate. The data recording rate was 25 Hz, and the lifting pitch was about 0.001mm. The tensile test data was saved for further analysis. To minimise error introduced by uneven sample surfaces, both the steel plate and the surface of the magnets were aligned and cleaned. Despite the initial distance of the magnets from the steel plate of 0mm, the graphs show an apparent increase in the magnetic force of attraction. However, it is the result of the deformation of the material from which the test system was built.

The test was performed for two cases - with off and on solenoids. In this way, the attraction force of the robot was simulated while driving around the ring and in close quarters.

During the extraction of a sample made of only 60 permanent magnets arranged in a Halbach array, the highest value that was recorded was approx. 846N - this corresponds to 86 kg of the robot's attraction force on a dohyo made of magnetic steel (Fig. 6). These data correspond to the values obtained during the tests described in the article [5] (per 1 magnet - a factor of approx. 150% compared to the traditional arrangement with the same number of magnets).

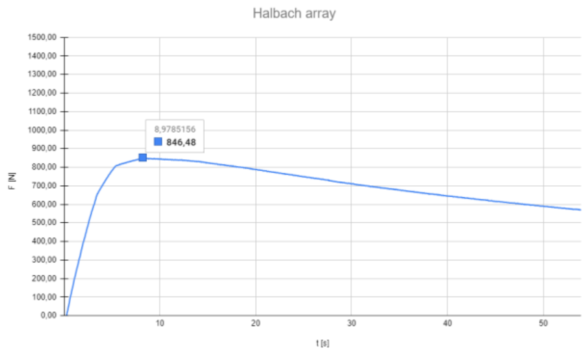

Figure 6. Graph of the force of attraction during a tensile test with the electromagnets off.

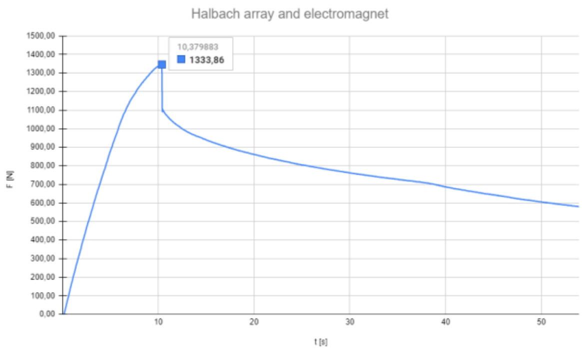

Figure 7. Graph of the attraction force during a tensile test with the electromagnets on.

The result of the distraction of the sample with the electromagnets turned on coincides with the expected effect from the simulation results. During the sample pulling test with the electromagnets turned on, the maximum force of attraction was 1333.86N (Fig. 7), which gives the robot approx. 136 kg attraction force against the dohyo. The difference between the attracting force of the system obtained in the two pull-off tests is 487.38N, which corresponds to approx. 24.9 kg of additional adhesion generated by a single electromagnet, therefore switching on the electromagnets results in an increase of the attraction force by 37%.

V. CONCLUSIONS

The use of a hybrid magnet system in the MegaSumo category robot allows for a dynamic change of the adhesion of the robot to the mat. The electromagnets used in the construction of the robot, supporting the work of permanent magnets, enable the increase of the robot's speed while performing manoeuvres bypassing the opponent and maintaining the full attractive force during a collision with him - just like in a traditional solution. This solution also makes it much easier to adapt the robot to a dohyo made of materials of different quality and varnish. Damage resulting from peeling off the paint layer before the collision disqualifies the robot from the fight, and those caused during the collision are not taken into account. Since with the proposed solution, the chance of damage to the dohyo occurs only during the collision - the risk of disqualification was avoided.

In a robot in this category, the nominal operating parameters of the engine are often deliberately exceeded. The increase in the current flowing through the windings occurs as a result of adding additional resistance from the attraction force of the magnets in the traditional solution. Moving away from the engine's endurance limit may cause permanent structural damage and prevent further participation in the competition. The consequence of reducing the resistance during manoeuvring is also a significant relief of the motors used in the robot's construction - less current that flows through the winding of the motors. Then the risk of winding damage is reduced. This is crucial in a fight that is longer than usual. [17]

The attraction of the robot to the dohyo can be changed from 846N to 1334N within a fraction of a second, and vice versa. It has a diametrical impact on the robot's capabilities. Thanks to the possibility of any change in the adhesion of the structure, the characteristics of the robot can change between fast and agile, and slower but firmly pressed. The benefits of using a hybrid magnet system may, in the future result in the popularisation of this solution in the MegaSumo robot competition. Depending on the designer's intention, the system can be freely modified, adapting the robot to the intended fighting style. The authors envisage application for the hybrid solution mainly in robots that are characterized by achieving very high speeds - within 5-7 m/s. This will allow them to maintain their agility and predisposition to perform fast maneuvers, as well as increase their chances of facing slower robots with greater attraction force.

The differences between the simulation results and the haul-off tests result from losses caused, among others, by heating of the windings of electromagnets and internal defects of the materials used for their construction.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Marcin Dziubek carried out experimental research of magnets arrangement. Michał Falkowski was responsible for conducting simulations in COMSOL Multiphysics software. Paulina Łapińska did a theory overview and wrote the content of the article. Rafał Grądzki coordinated the team's work and assisted in creating the article. All authors have accepted the final version of the article.

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REFERENCES

[1] 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.

[2] S. Jeong, H. Choi, S. Young Ko, J. Park, S. Park, "Remote controlled micro-robots using electromagnetic actuation (EMA) systems," in *Proc. Biomedical Robotics and Biomechatronics (BioRob) 4th IEEE RAS & EMBS International Conference*, 2012, pp. 482-487.

[3] J. Coey, *Magnetism and magnetic materials*, Cambridge University Press, 2009.

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

[5] K. Halbach, *Design of permanent multipole magnets with oriented rare earth cobalt material*, Nuclear Instruments and Methods, 1980.

[6] P. Łapińska, M. Dziubek, Ł. Kotarski, and R. Grądzki, "Research of Various Magnetic Systems Used in Autonomous MegaSumo Robots," *International Journal of Mechanical Engineering and Robotics Research*, 2020, vol. 9, no. 5, pp. 739–744. http://doi.org/10.18178/ijmerr.9.5.739-744.

[7] R. D. Brewer, K.E. Loewke, E. F. Duval, J.K. Salisbury "Force control of a permanent magnet for minimally-invasive procedures", in *Proc. 2nd IEEE RAS&EMBS international conference on biomedical robotics and biomechatronics*, 2008, pp. 580–586.

[8] Smajic. J, *How to perform Electromagnetic Finite Element Analysis*, NAFEMS, 2016.

[9] D. S. Jones, *The theory of Electromagnetism*, PERGAMON PRESS, 1964.

[10] J. C. Mallinson „On-sided Fluxes – A magnetic curiosity?", *IEEE Transactions on Magnetics*, 1973, pp. 678-682.

[11] D. K. Cheng, *Field and Wave Electromagnetics,* Addison-Wesley Publishing Company, 1992.

[12] E. M. Purcell, *Electricity and magnetism,* Cambridge Univ. Press, 2012.

[13] P. Tripler, *Physics for Scientists and Engineers: Electricity, Magnetism, Light, and Elementary Modern Physics,* W. H. Freeman, 2004

[14] M. Tabatabaian, *COMSOL for Engineers*, Mercury Learning & Information, 2015.

[15] A. W. Mahoney, D. L. Cowan, K. M. Miller, J. J. Abbott (2012), "Control of untethered magnetically actuated tools using a rotating permanent magnet in any position.", in *Proc. Robotics and automation (ICRA), IEEE international conference*, 2012, vol. 20, pp. 3375–3380.

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

[17] M. Dziubek, M. Klimowicz, R. Grądzki, "Evaluation of temperature changes of a loaded DC motor in autonomous mobile

robots, " in *Proc. 20th International Carpathian Control Conference (ICCC)*, Krakow-Wieliczka, Poland, 2019, pp. 1-5. https://doi.org/10.1109/CarpathianCC.2019.8766058.

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