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INVESTIGATION THE FEASIBILITY OF COMPLEX CIRCULAR MOTION OF IMPLANTS IN MAGNETIC STEREOTAXIS SYSTEMS

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Анотація: У даній роботі ми досліджуємо можливість управління круговим рухом імплантату безконтактним способом шляхом контролю зміни зовнішнього магнітного поля в магнітній стереотаксичній системі. Зміна зовнішнього магнітного поля була змодельована за допомогою комп'ютерних симуляційних експериментів, щоб контролювати круговий рух невеликого постійного магніту безконтактним способом, і в реальному експерименті система ковзання була оснащена великим постійним магнітом для формування зовнішнього магнітного поля, а робота системи ковзання контролювалася мікроконтролером Arduino. Перевірено результати комп'ютерно-імітаційних експериментів та уточнено доцільність безконтактного керування круговим рухом імплантату.
Ключові слова: здоров'я людини, магнітне поле, програмне забезпечення COMSOL, постійні магніти, мікроконтролери Arduino, біомедична система.
Abstract. In this paper, we explore the feasibility of controlling the circular motion of the implant in a non-contact manner by controlling the change of the external magnetic field in a magnetic stereotaxic system. The change of the external magnetic field was simulated through computer simulation experiments, so as to control the circular motion of a small permanent magnet in a non-contact manner, and in the actual experiment, the slide rail system was equipped with a large permanent magnet to form an external magnetic field, and the operation of the slide rail system was controlled by an Arduino microcontroller. The results of computer simulation experiments were verified, and the feasibility of non-contact control of the circular motion of the implant was clarified.
Keywords Human health, Magnetic field, COMSOL Software, Permanent magnets, Arduino microcontrollers, Biomedical system.

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1. INTRODUCTION TO MAGNETIC STEREOTAXIC SYSTEMS

The magnetic stereotactic system [1-3] is a neurosurgical method that is in the experimental research stage. The central idea is to provide non-contact control of the implant into the skull through an external magnetic field and guide it along a pre-designed path to a lesion located in the deep structure of the brain tissue, where it can be given hyperthermia or drug delivery through a catheter.

Compared to traditional neurosurgical interventions [4-6], the magnetic stereotactic system can perform multiple simulations before surgery to establish multiple surgical pathways, and with its non-contact control of the implant, the implant can reach almost any location in the brain tissue along any path, with minimal damage to the surrounding tissues along the implant's path. Since the implant is completely controlled by a computer-controlled external magnetic field, the interference of human factors is greatly reduced. As a result, magnetic stereotactic systems have emerged as one of the least invasive and most promising methods for neurosurgical interventions [12, 13-19].

Early magnetic stereotactic systems consisted of large solenoid coils and metal implants, in which the strength of the external magnetic field generated by the solenoid coils was determined by the amount of current passing through the coil, but the magnitude of the current was difficult to control, which made it difficult to accurately control the implants. With the rapid development of science and technology, people's research on magnetic stereotactic system has also made new progress with the support of new technologies and new materials [14, 20-25].

Due to the high similarity between MRI and magnetic stereotaxic systems, as permanent magnet MRI [7,8] is widely recognized in the world, it has inspired us to directly use permanent magnet materials as the external magnetic field generator of magnetic stereotaxic systems to control implants without contact. Through previous studies, we have verified that it is completely feasible for large permanent magnets to be used as external magnetic field generators to control the spatial displacement of implants without contact [9,10].

However, spatial displacement alone is not enough, we need to design a route for the implant that allows the implant to move along the designed route by controlling the external magnetic field. Therefore, in this study, we plan to control the implant in a circular motion. First, we need to perform simulations on a computer using the COMSOL software [11,12], and then conduct practical experiments to verify the simulation results.

2. SIMULATION EXPERIMENT

Experimental Purpose: Non-contact control of small permanent magnets[13] for circular motion.

Experimental design: In the software, a three-dimensional spatial coordinate system is established, a small permanent magnet is set in the center of the three-dimensional space, and a large permanent magnet is set on the +X, +Y, -X, and -Y axes, respectively, and the distance of the four large permanent magnets from the center position is equal. Set the parameters of large and small permanent magnets based on real material data and build a geometric model. It should be noted that in this simulation experiment, boundary conditions need to be set for small permanent magnets. Based on the results of previous studies, we set up a movement scheme for large permanent magnets: the first large permanent magnet moves 0.05 [m] after the second large permanent magnet starts to move to the center position, the third large permanent magnet moves to the center position after it moves 0.05 [m], and the fourth large permanent magnet starts to move to the center position after it moves 0.05 [m].

Geometry parameter settings:

(1) Large permanent magnet diameter d_ion=100[mm]=0.1[m];

(2) Large permanent magnet thickness t_ion=20 [mm]=0.02[m];

(3) Small permanent magnet diameter d_NFB =1[mm]=0.001[m];

(4) Small permanent magnet thickness l_NFB=2[mm]=0.002[m];

(5) The maximum radius of motion of a small permanent magnet is 0.1 [m], so we set a cylinder with a radius of 0.1 [m] and a height of 0.5 [m] as the boundary of the small permanent magnet centered on the origin of the three-dimensional space;

(6) The initial positions of the four large permanent magnets are set as follows: Distance from the center position of the large permanent magnet on the +X axis: dis_ion1 = 0.41 [m]; Distance from the large permanent magnet to the center position on the -Y-axis: dis_ion2=0.41 [m]; Distance from the center position of a large permanent magnet on the +X-axis: dis_ion3=0.41 [m]; Distance from the large permanent magnet to the center on the -Y axis: dis_ion4=0.41[m];

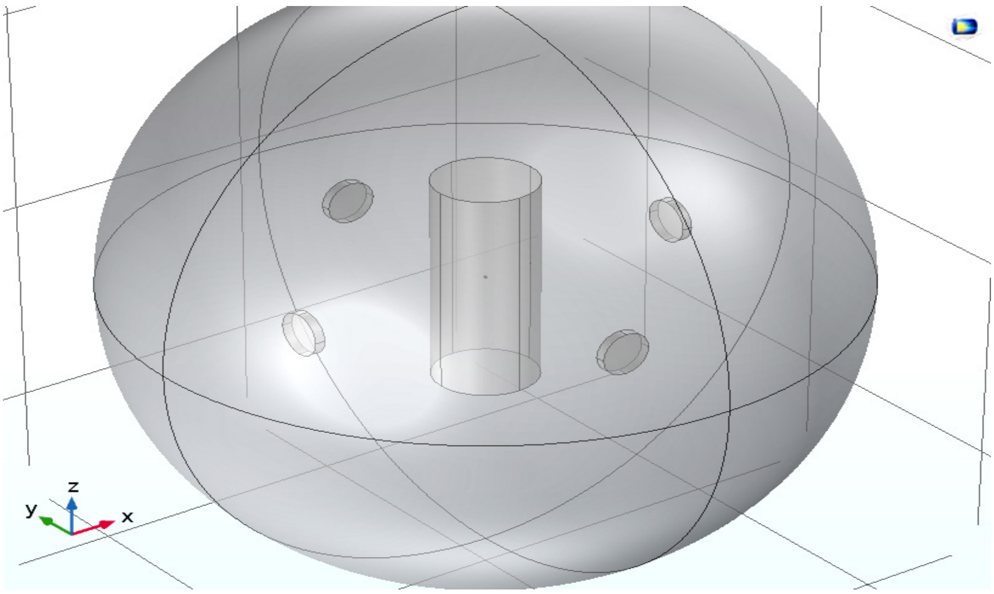

Figure 1 – Geometric model of a magnetic stereotaxic system in 3D space

Material Properties Settings (NdFeB permanent magnets):
(1) Conductivity σ=1/1.4[uohm*m][S/m];
(2) Relative permittivity ε_r=1 [1];
(3) Recovery permeability μ_{rec}=1.02;
(4) Residual flux density norm $\|B_r\|$=1.3[T];
Perimeter space (air) :
(1) Conductivity σ=0[uohm*m][S/m];
(2) Relative permittivity ε_r=1 [1];
(3) Recovery permeability μ_{rec}=1;

The above material properties are assigned values and can be modified according to the actual material properties.

The large permanent magnet that is an external magnetic field generator device has no current passing through it, and the magnetic field generated by it is a constant magnetic field, and the physics we choose is "Magnetic Field, No Current (MFNC)", so the required formula is retrieved from the software library by the physics itself, we only need to select the option of residual magnetic flux density in the magnetization model of the constitutive relation B-H, and the selected residual magnetic flux density is calculated as follows:

$$\mathbf{B} = \mu_0 \mu_{rec} \mathbf{H} + \mathbf{B_r} \tag{1}$$

$$\mathbf{B_r} = \|\mathbf{B_r}\| \frac{\mathbf{e}}{\|\mathbf{e}\|} \tag{2}$$

Where B is the magnetic flux density, μ_0 is the vacuum permeability, μ_{rec} is recoil permeability, B_r is residual flux density, $\|B_r\|$ is residual flux density norm, e is residual flux direction.

After running the program, in order to more intuitively display the magnetic field range, intensity and magnetic field line distribution of large permanent magnets, we need to adjust the contrast of the drawn image, and set the ratio of the magnetic field strength to the color of the image. Finally, tick the option to draw magnetic field lines.

After running the program, the four large permanent magnets move to the center position in turn, the magnetic field of the large permanent magnet located on the +X axis first touches the small permanent magnet located in the center position, and the small permanent magnet is affected by its magnetic field and moves towards the large permanent magnet on the +X axis until it is blocked by the boundary and stays on the boundary. The large permanent magnet on the +X axis continues to move towards the center position until it reaches the limit distance and begins to move away from it, at which point the large permanent magnet in the other three directions continues to move towards the center position.

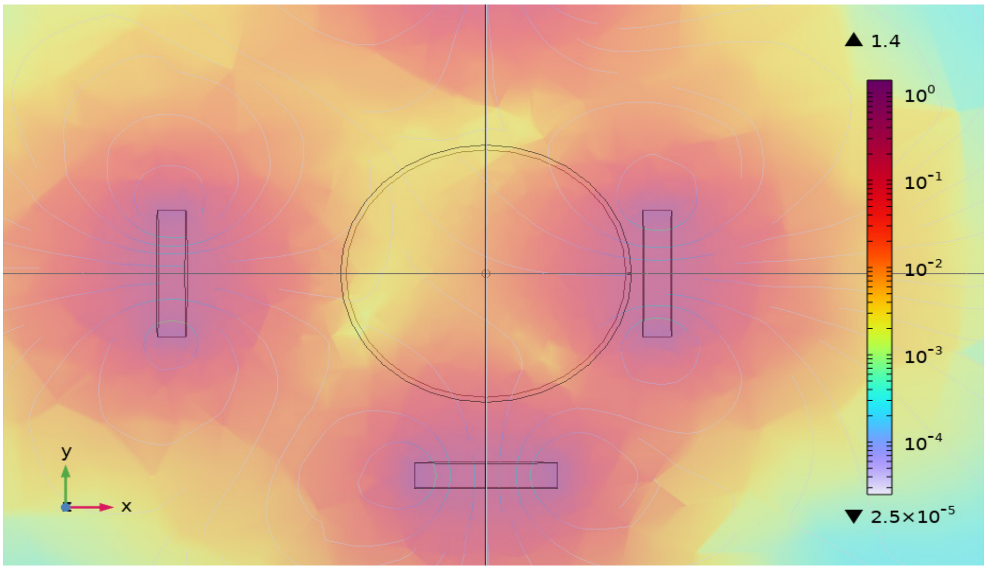

Figure 2 – The small permanent magnet stays at the boundary position, close to the large permanent magnet on the +X axis

After that, the distance from the large permanent magnet on the -Y axis to the center position is less than the distance from the large permanent magnet on the +X axis to the center, i.e., dis_ion1>dis_ion2, the small permanent magnet is affected by the magnetic field of the two large permanent magnets and begins to move along the boundary towards the large permanent magnet on the -Y-axis.

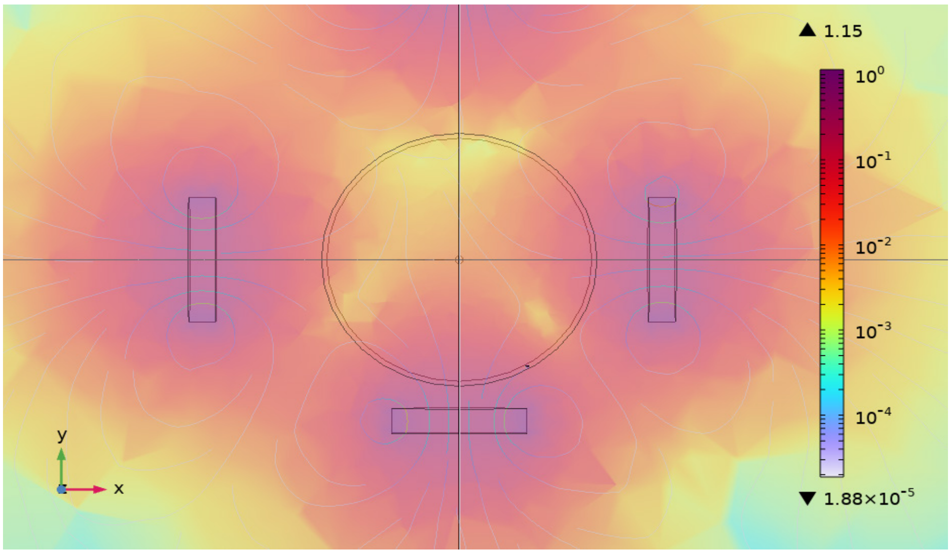

Figure 3 – Small permanent magnets move along the boundary towards large permanent magnets on the -Y axis

The small permanent magnet is captured by the magnetic field of the large permanent magnet on the -Y axis and stays at the boundary of the large permanent magnet close to the -Y axis. When the large permanent magnet on the -Y axis reaches the limit distance, it begins to gradually move away, at this time, the two large permanent magnets on the -X, +Y axis are still approaching the central position, and the same as in the previous stage, when the distance from the large permanent magnet on the -Y axis to the center position is greater than the distance from the large permanent magnet on the -X axis to the center position, that is, dis_ion2>dis_ion3, the small permanent magnet is affected by the magnetic field of the two large permanent magnets and begins to move along the boundary towards the large permanent magnet on the -X axis.

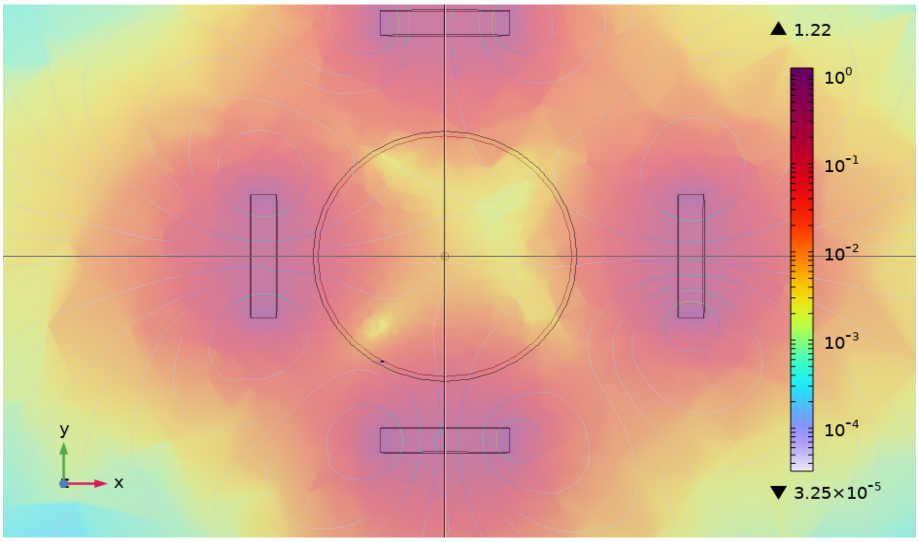

Figure 4 – The small permanent magnet moves along the boundary towards the large permanent magnet on the -X axis

After that, the small permanent magnet is completely captured by the magnetic field of the large permanent magnet on the -X axis and stays at the boundary. As the large permanent magnet on the -X axis reaches the limit distance and begins to move away from the center, the large permanent magnet on the +Y axis is still moving towards the center. When the distance of the large permanent magnet on the -X axis from the center position is greater than the distance of the large permanent magnet on the +Y axis from the center position, i.e., the dis_ion3>dis_ion4, the small permanent magnet is affected by the magnetic field of the two large permanent magnets and begins to move along the boundary towards the large permanent magnet located on the +Y axis.

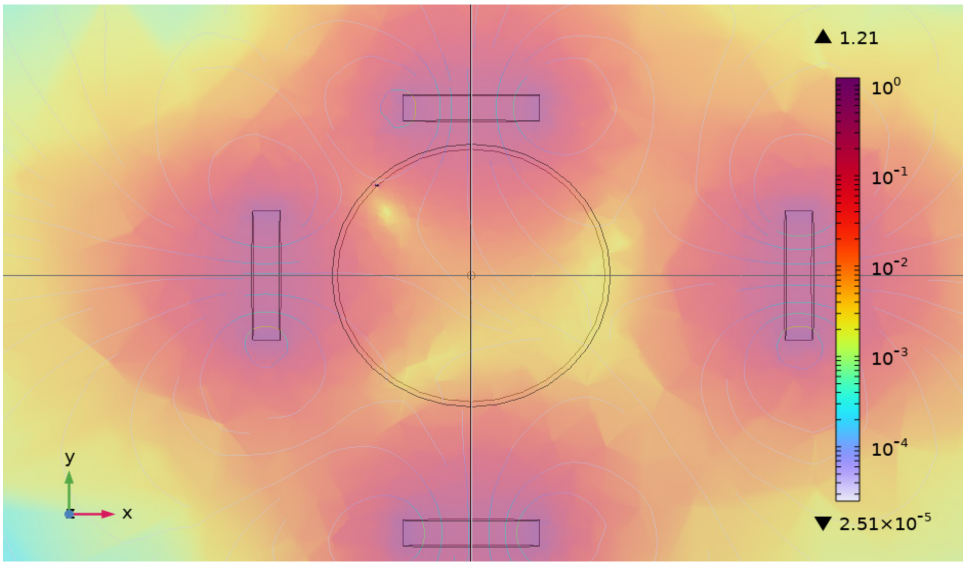

Figure 5 – The small permanent magnet moves along the boundary towards the large permanent magnet on the +Y axis

The magnetic field of the large permanent magnet on the +Y axis completely captures the small permanent magnet, and the small permanent magnet eventually stays at the boundary position of the large permanent magnet. As the large permanent magnets on the +Y axis begin to move away from the center after reaching the limit distance, the small permanent magnets remain at the boundary position.

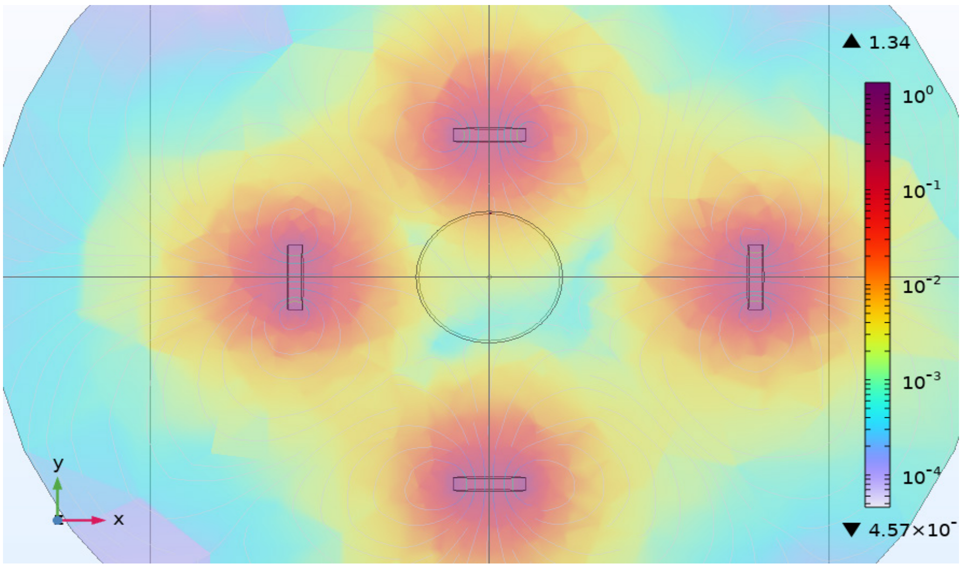

Figure 6 – The small permanent magnet stays at the boundary position

After that, the large permanent magnets on the +X axis return to the initial position and move to the center position again, and the other large permanent magnets return to the initial position and move to the center position again. When the large permanent magnet on the +X axis comes into contact with the small permanent magnet located on the boundary of the +Y axis, the small permanent magnet begins to move towards the large permanent magnet on the +X axis, and when the small permanent magnet reaches the upper boundary position on the +X axis, it means that the small permanent magnet completes a circular motion within the boundary.

Analysis of simulation experiment results

Through simulation experiments, we can clearly see that when the distance relationship between two adjacent large permanent magnets and the center position changes, that is, one large permanent magnet gradually moves away, and the other large permanent magnet gradually approaches the center position, and the distance of the large permanent magnet gradually away from the center position is greater than the distance of another large permanent magnet gradually close to the center position, the magnetic field line near the small permanent magnet changes significantly, which indicates that the direction of attraction of the small permanent magnet changes, which provides power for the arc motion of the small permanent magnet.

This shows that when the four large permanent magnets move sequentially to the center of the three-dimensional space at intervals of 0.05 [m], the changes in the external magnetic field generated during their operation can control the circular motion of the small permanent magnets along the boundary in a non-contact manner. This provides a theoretical basis for subsequent practical experiments.

3. PRACTICAL EXPERIMENTS

In the computer simulation experiment, we can clearly see that when the large permanent magnet on one side moves, the external magnetic field of the magnetic stereotaxic system changes significantly, so in the simulation experiment, we need to form a platform that can carry the large permanent magnet to move, and realize the precise control of the platform movement through the controller.

In computer simulation experiments, we simulated four large permanent magnets sequentially close to the center, so that the small permanent magnets could move in a circular motion through the change of the external magnetic field. Therefore, in the actual experiment, we need to assemble four sets of slide rail systems to carry four large permanent magnets for movement.

Each rail system consists of an Arduino microcontroller [14, 15] control, stepper motor controller, external power supply, and ball screw slides with 57x56 stepper motors. Connect the slide rail with the stepper motor to the stepper motor controller [16, 17], then connect the Arduino microcontroller and the stepper motor controller with the common yang method, turn on the external power supply, and finally connect the computer and the Arduino microcontroller through the data line, so far, a set of slide rail system is completed.

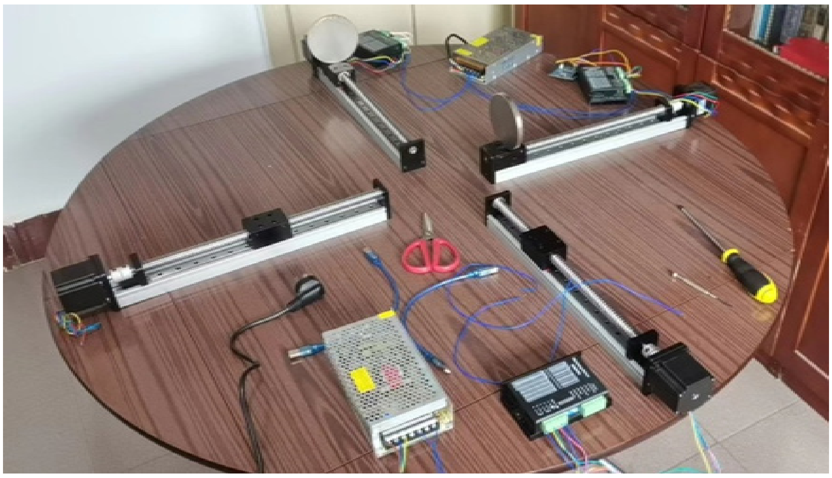

Figure 7 – Four sets of slide rail systems

In this practical experiment, in order to simulate the working environment of the implant entering the skull, we prepared a 5% gelatin [18, 19] solution, when the gelatin solution was prepared and poured into a cylindrical container with a diameter of 0.2 [m], when the gelatin solution cooled to a loose jelly shape, the small permanent magnet was put into the center of the container, and after running the program, the first slide rail system was connected, and after it ran 0.05 [m], the second slide system was turned on, and it ran again for 0.05 [m] Finally, the third slide rail system is connected, and after it runs for 0.05 [m], the fourth slide rail system is finally connected. At this point, the four large permanent magnets mounted on the slide move at regular intervals towards the container in the center.

As the first large permanent magnet gradually approaches the center, the small permanent magnet is affected by its magnetic field and moves towards the first large permanent magnet until it is blocked by the container and stops moving.

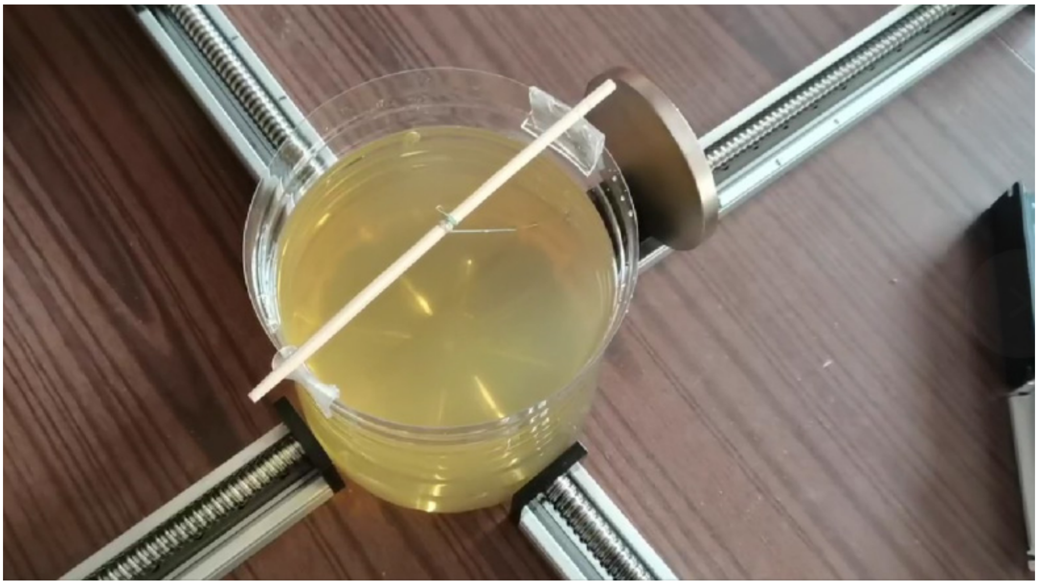

Figure 8 – The small permanent magnet moves towards the first large permanent magnet

After that, the first slide system starts to return after operating to the limit distance, i.e. the first large permanent magnet begins to gradually move away from the container. At this time, the large permanent magnets carried by the second slide system are still moving towards the container, until the distance between the first large permanent magnet and the container is greater than the distance of the second large permanent magnet from the container, and the small permanent magnets are affected by their magnetic field and begin to move along the inner wall of the container towards the second large permanent magnet.

Figure 9 –The small permanent magnet moves along the inner wall of the container towards a second large permanent magnet

As the second large permanent magnet reaches the limit distance and begins to gradually move away from the container, the small permanent magnet stays on the inner wall of the container near the second large permanent magnet.

Figure 10 – The second large permanent magnet begins to gradually move away from the container

At this time, the third large permanent magnet gradually approaches the container, until the distance between the second large permanent magnet and the container is greater than the distance between the third large permanent magnet and the container, the small permanent magnet begins to move along the inner wall of the container to the third large permanent magnet until it stays on the inner wall of the container and is close to the third large permanent magnet.

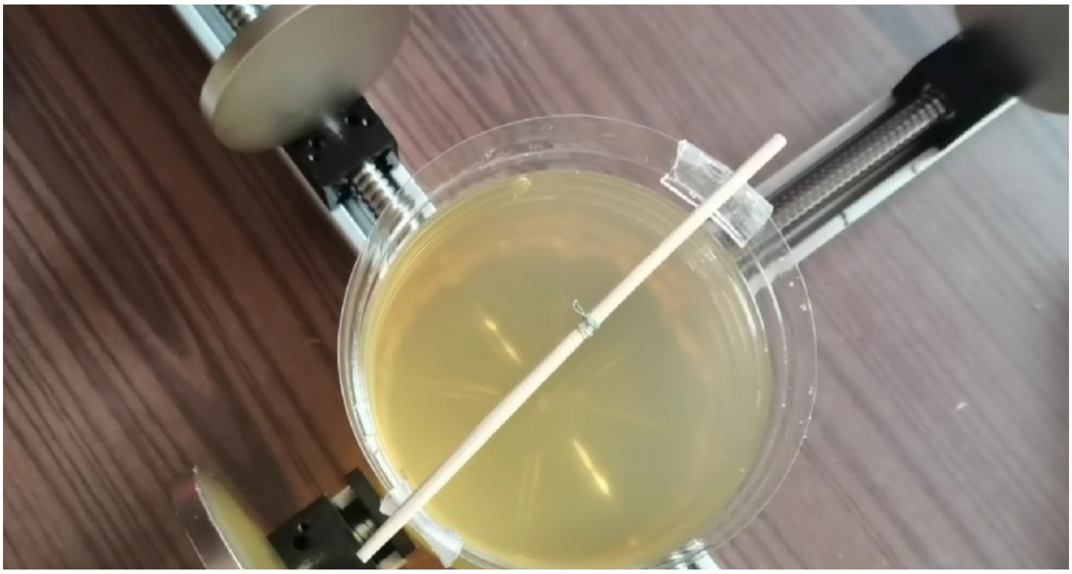

Figure 11- The small permanent magnet stays near the third large permanent magnet

As the third large permanent magnet reaches the limit distance and begins to gradually move away from the container, the fourth large permanent magnet is also gradually approaching the container, until the distance between the third large permanent magnet and the container is greater than the distance of the fourth large permanent magnet from the container, the small permanent magnet begins to move along the inner wall of the container towards the fourth large permanent magnet.

Figure 12 – The small permanent magnet moves along the inner wall of the container towards the fourth large permanent magnet

As the fourth large permanent magnet reaches the limit distance and begins to move away from the container, the small permanent magnet remains at the boundary.

Fig 13. The small permanent magnet stays on the inner wall of the container.

After that, as the fourth large permanent magnet gradually moves away, the small permanent magnet still stays on the inner wall of the container, until the first large permanent magnet approaches the container again, and the small permanent magnet is affected by its magnetic field, moves towards the first large permanent magnet, and is finally blocked by the container and stays close to the position of the first large permanent magnet on the inner wall of the container. It is also advisable to consider the possibility of using a complete system for telemedicine applications [20, 21].

IV. Experimental conclusions

In the computer simulation experiment, we set the four large permanent magnets that make up the external magnetic field to move to the center of the three-dimensional space at a certain distance in the software, so as to control the small permanent magnets by changing the external magnetic field in a non-contact way. Through simulation experiments, we can clearly see that when a large permanent magnet begins to gradually move away from the center position, and the large permanent magnet on the adjacent side is still gradually approaching the center position, and the distance between the first large permanent magnet and the center position is greater than that of the second large permanent magnet, dis_ion1>dis_ion2 that is, the direction of the magnetic field around the small permanent magnet changes, and the small permanent magnet begins to move along the boundary to the second large permanent magnet, and so on, until the small permanent magnet completes circular motion. This shows that it is theoretically feasible for small permanent magnets to move in a circular motion under non-contact control.

In the actual experiment, we assembled four slide rail systems to carry four large permanent magnets, which were controlled by an Arduino microcontroller, and the four slide rail systems were activated sequentially at certain intervals, so that the four large permanent magnets were sequentially close to the container containing the gelatin solution at certain intervals. Through practical experiments, we can intuitively see that when the distance relationship between two adjacent large permanent magnets and the center position changes, that is, one large permanent magnet begins to gradually move away, and the other continues to approach the container, and the distance between the large permanent magnet and the container is greater than the distance between the large permanent magnet and the container, the small permanent magnet moves along the inner wall of the container to the gradually approaching large permanent magnet. Finally, the small permanent magnet runs around the inner wall of the container in a gelatin solution, completing a circular motion.

In this study, we investigated the feasibility of using non-contact control of the implant for circular motion in a magnetic stereotaxic system through computer simulation experiments, and verified the simulation results through practical experiments, which proved that the small permanent magnet can perform circular motion under non-contact control. This provides a theoretical foundation for the follow-up research of magnetic stereotaxic systems and provides a large number of experimental data.

REFERENCES

1. Grady S M, Howard III M A, Broaddus W C, et al. Magnetic stereotaxis: a technique to deliver stereotactic hyperthermia[J]. Neurosurgery, 1990, 27(6): 1010-1016.
2. Nelson B J, Gervasoni S, Chiu P W Y, et al. Magnetically actuated medical robots: An in vivo perspective [J]. Proceedings of the IEEE, 2022, 110(7): 1028-1037.
3. Grady M S, Howard M A, Dacey R G, et al. Experimental study of the magnetic stereotaxis system for catheter manipulation within the brain[J]. Journal of neurosurgery, 2000, 93(2): 282-288.
4. Avrunin, O., Tymkovych, M., Semenets, V., & Piatykop, V. (2019). Computed tomography dataset analysis for stereotaxic neurosurgery navigation. Paper presented at the Proceedings of the International Conference on Advanced Optoelectronics and Lasers, CAOL, , 2019-September 606-609. doi:10.1109/CAOL46282.2019.9019459
5. Avrunin, O. G., Alkhorayef, M., Saied, H. F. I., & Tymkovych, M. Y. (2015). The surgical navigation system with optical position determination technology and sources of errors. Journal of Medical Imaging and Health Informatics, 5(4), 689-696. doi:10.1166/jmihi.2015.1444
6. Avrunin, O. G., Tymkovych, M. Y., Moskovko, S. P., Romanyuk, S. O., Kotyra, A., & Smailova, S. (2017). Using a priori data for segmentation anatomical structures of the brain. PrzegladElektrotechniczny, 93(5), 102-105. doi:10.15199/48.2017.05.20
7. Moresi G, Magin R. Miniature permanent magnet for table-top NMR[J]. Concepts in Magnetic Resonance Part B: Magnetic Resonance Engineering: An Educational Journal, 2003, 19(1): 35-43.
8. O'Reilly T, Teeuwisse W M, de Gans D, et al. In vivo 3D brain and extremity MRI at 50 mT using a permanent magnet Halbach array[J]. Magnetic resonance in medicine, 2021, 85(1): 495-505.
9. Hunkun J. Explore the Feasibility Study of Magnetic Stereotaxic System / J. Hunkun, O. G. Avrunin // Optoelectronic Information-Power Technologies, vol. 45, no. 1, Sept. 2023, pp. 86-96.
10. J. Hunkun and O. Avrunin, "Possibilities of Field Formation by Permanent Magnets in Magnetic Stereotactic Systems," 2022 IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek), Kharkiv, Ukraine, 2022, pp. 1-4, doi: 10.1109/KhPIWeek57572.2022.9916450.
11. Multiphysics C. Introduction to COMSOL multiphysics® //COMSOL Multiphysics, Burlington, MA, accessed Feb. – 1998. – Т. 9. – №. 2018. – С. 32.
12. Pepper D W, Heinrich J C. The finite element method: basic concepts and applications with MATLAB, MAPLE, and COMSOL[M]. CRC press, 2017.
13. O'Reilly T, Teeuwisse W M, de Gans D, et al. In vivo 3D brain and extremity MRI at 50 mT using a permanent magnet Halbach array[J]. Magnetic resonance in medicine, 2021, 85(1): 495-505.
14. Badamasi Y. A. The working principle of an Arduino //2014 11th international conference on electronics, computer and computation (ICECCO). – IEEE, 2014. – С. 1-4.
15. Banzi M., Shiloh M. Getting started with Arduino. – Maker Media, Inc., 2022.
16. Virgala I, Kelemen M, Gmiterko A, et al. Control of stepper motor by microcontroller[J]. Journal of Automation and Control, 2015, 3(3): 131-134.
17. Avrunin O., Sakalo S., Semenetc V., Development of up-to-date laboratory base for microprocessor systems investigation, 2009 19th International Crimean Conference Microwave & Telecommunication Technology, Sevastopol, 2009, pp. 301-302.

18. Avrunin O.G. Experience of Developing a Laboratory Base for the Study of Modern Microprocessor Systems / O.G. Avrunin, T.V. Nosova, V.V. Semenets. // Proceedings of I International Scientific and Practical Conference «Theoretical and Applied Aspects of Device Development on Microcontrollers and FPGAs» MC&FPGA-2019, Kharkiv, Ukraine. – 2019. – P. 6-8.
19. Alipal J, Pu'Ad N A S M, Lee T C, et al. A review of gelatin: Properties, sources, process, applications, and commercialisation[J]. Materials Today: Proceedings, 2021, 42: 240-250.
20. Hunkun, J. i Avrunin, O. (2023) , Feasibility analysis of implant movement along arc trajectory under non-contact control in magnetic stereotaxic system //Innovative technologies and scientific solutions for industries. 2023. No. 3 (25). – P. 174–182. doi: 10.30837/ITSSI.2023.25.174.
21. Kolisnyk, K., Deineko, D., Sokol, T., Kutsevlyak, S., and Avrunin, O., "Application of modern internet technologies in telemedicine screening of patient conditions," in 2019 IEEE International Scientific-Practical Conference Problems of Infocommunications, Science and Technology (PIC S&T), (2019).
22. Sokol, Y., Avrunin, O., Kolisnyk, K., and Zamiatin, P., "Using medical imaging in disaster medicine," in IEEE 4th International Conference on Intelligent Energy and Power Systems IEPS, 287 –290 (2020). https://doi.org/10.1109/IEPS51250.2020.9263175/
23. Wójcik, W., Pavlov, S., Kalimoldayev, M. (2019). Information Technology in Medical Diagnostics II. London: Taylor & Francis Group, CRC Press, Balkema book. – 336 Pages, https://doi.org/10.1201/9780429057618. eBook ISBN 9780429057618.
24. Pavlov S. V. Information Technology in Medical Diagnostics //Waldemar Wójcik, Andrzej Smolarz, July 11, 2017 by CRC Press - 210 Pages. https://doi.org/10.1201/9781315098050. eBook ISBN 9781315098050.
25. Pavlov Sergii, Avrunin Oleg, Hrushko Oleksandr, and etc. System of three-dimensional human face images formation for plastic and reconstructive medicine // Teaching and subjects on bio-medical engineering Approaches and experiences from the BIOART-project Peter Arras and David Luengo (Eds.), 2021, Corresponding authors, Peter Arras and David Luengo. Printed by Acco cv, Leuven (Belgium). - 22 P. ISBN: 978-94-641-4245-7.

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ДОСЛІДЖЕННЯ МОЖЛИВОСТІ СКЛАДНОГО КРУГОВОГО РУХУ ІМПЛАНТАТІВ В СИСТЕМАХ МАГНІТНОГО СТЕРЕОТАКСИСУ

Харківський національний університет радіоелектроніки