Proceedings of 2016 IEEE
International Conference on Mechatronics and Automation
August 7 - 10, Harbin, China

Movement Characteristics Evaluation of the Spherical Robot Actuated by the Magnetic Field for Medical Applications

Shuxiang Guo[1,2], Nan Liang[1], Jian Guo[1*], Pengyu Liu[1], Lili Wang[3] and Gang Sun[4]

1 Tianjin Key Laboratory for Control Theory & Application in Complicated Systems and Biomedical Robot Laboratory Tianjin University of Technology, Binshui Xidao 391,Tianjin, China

2 Intelligent Mechanical Systems Engineering Department, Kagawa University, Takamatsu, Kagawa, Japan

3 Internal Medicine-Oncology, Tianjin Hospital of ITCWM Naikai Hospital,Three latitude Road 122, Tianjin, China

4 Gastrointestinal Surgery, Tianjin Hospital of ITCWM Naikai Hospital,Three latitude Road 122, Tianjin, China

**Corresponding Author: jianguo@tjut.edu.cn;liangnanzhang@163.com; guoshuxiang@hotmail.com;nkyywlili@163.com*

***Abstract* – The capsule microrobot will play an important role in the medical application such as the minimally invasive surgery in the future. In this paper, we proposed the spherical capsule robot system driven by the external magnetic field. And then we did the finite element analysis of the electromagnetic device involved in the system using ANSYS software. In the end, to verify our analysis results and establish relationship with the experimental system, we conducted the comparison between experimental results and theoretical results. In addition, the spherical robot motion was also recorded in the tube and an open plastic sink. Combining with the proposed experimental platform, we can change the orientation of the capsule robot by changing the direction of the external magnetic field and change the moving speed by changing the frequency of the external magnetic field. The driving force of the Helmholtz coil on the capsule robot can be generated along the space any direction by changing the parameters of the input signal in theory. Besides that we found that the variation tendency of the magnetic field is the same between experimental values and simulation results. We can adjust the parameters of the input current on the basis of the simulation results in order to obtain the needed external magnetic field during the actual operation. The capsule robot motion indicated that the capsule robot motion is related to other factors except the external driving force. The experiments in an open plastic cup indicated that the spherical capsule robot can actively motion along the predetermined direction in the plane. The research results in this paper will provide the strong supports for actuating the capsule robot with the external magnetic field for medical applications in the future.**

Index Terms – Capsule robot; Helmholtz coil; Finite element modeling; Medical applications

I. INTRODUCTION

Digestive diseases, such as the stomach and the colon cancer, ulcerative colitis are one of the leading causes of human death in the modern society [1]. The research on the capsule robot that can move along the organ of digestion or small area such as blood vessels has become one of the hottest research areas during the last few years. By virtue of the capsule microrobot we can timely diagnose a variety of disease and take some measures in order to cure our body. Although the capsule microrobot is a kind of effective means of inspection gastrointestinal diseases for human, the researcher have met with many difficulties in the process of optimization of the capsule microrobot, especially for the actuator and structure. As we all know, many kinds of micro actuator have been actively investigated for their potential applications to actuate up to now [2-6]. However the volume limitation of the capsule microrobot makes it intractable to integrate certain components on the microrobot body, such as the power source, the control board and the additional diagnostic equipment and so on [7]. In fact, more and more researchers are realizing that the wireless drive method of capsule microrobot is the key point to enhance the robot's feasibility and reliability. The capsule microrobot driven by the external magnetic field can not only move in the larger and the more complex area, but also it can move longer time and have higher safety. Up to now, some kinds of capsule robots and the outside magnetic field driving systems have been developed.

Zhang et al have designed and fabricated a spatial universal rotating magnetic field system using three axes orthogonal square Helmholtz coils and also derived the corresponding signal formula [8-9] on purpose for the petal-shaped capsule microrobot without the line drive [10]. The orientation of the external magnetic field could be continuous adjusted in the form of digital. The capsule microrobot could rotate along its axis and realize the change of the position and the orientation when the capsule robot accessed to the rotating magnetic field.

Carta et al designed a multi-coil inductive powering system [11] for an endoscopic capsule with vibratory actuation. In the powering module a pair of Helmholtz coil was viewed as an external primary coil, producing a relatively uniform and high-intensity magnetic field. It provided energy for the eccentric motor cooperated with the secondary coil, which guaranteed the persistence of energy and for another provided possibilities of active motion system and advanced diagnosis and treatment modules integrated on the robot body in the later study.

Guo lab proposed the hybrid wireless microrobot [12] and perfected the prototype using the rotational magnetic field driven by the 3D Helmholtz coil system [13]. In addition, considering that the safety is very important in the clinical application, they also ameliorated the Helmholtz coil with the iron core [14]. In the new driving system each of the Helmholtz coils consists of a coil and an iron core, making the external magnetic flux density promotional under the condition of the same input current compared with the Helmholtz coil without the iron core. Therefore the input current value can be greatly reduced in order to make sure the personal safety of the manipulator to a certain extent. Besides that, a novel tele-operation controller based on the RF transmission [15] for the symmetrical capsule microrobot [16] driven by the external magnetic field has been designed, providing a theoretical basis and the technical support for the remote surgery.

We have found that the external magnetic field, especially for the Helmholtz coil, has an important status in terms of driving the capsule robot motion from the above typical researches. However, there are also many technical difficulties in realizing multi DOFs locomotion of the capsule robot and obtaining stable motion by using the external magnetic field such as the control of the direction and the intensity of the external magnetic field, the complexity of the magnetic field superposition. The capsule microrobot must be safe against all possible accidents in the clinical application so that the research of the external driving magnetic field is critical. In general, the research of the capsule microrobot is still at the exploratory stage at present. We need more researches to realize the capsule microrobot flourishing the medical field in the future.

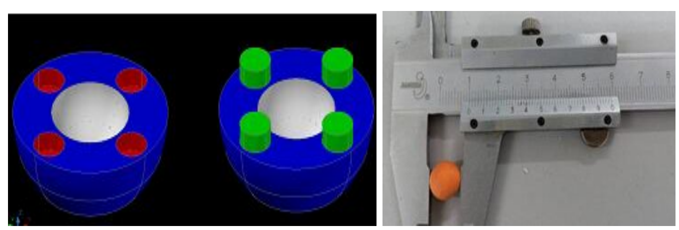
Faced with these problems, this paper focused on do a simulation of the external magnetic field generated by the Helmholtz coil, providing theoretical basis for the application of driving magnetic field before the Helmholtz coil is manufactured. Although some simulations of the Helmholtz coil have been done, most of them are implemented using Matlab [17-18]. This simulation result of Matlab is idealized, taking no account of the material properties while the result of ANSYS can not only reflect comprehensively the material properties, but also its graphic stereo sense is stronger and the vector is wider. In addition, the analysis and the snapshots of the spherical capsule robot motion prove the effectiveness of the driving force of the Helmholtz coil on the spherical capsule robot.

This paper is structured as the following. In section II, we showed the proposed spherical capsule microrobot system driven by the external magnetic field generated by the 3D Helmholtz coil. In section III, we did the finite element analysis of the electromagnetic device involved in the system using ANSYS, especially for the 3D Helmholtz coil and the coupling analysis between the Helmholtz coil and the spherical microrobot. In section IV, in order to verify our finite element analysis results and establish the relationship with the experimental system, we made the comparison between experimental results and theoretical results. In addition, the snapshots of the spherical capsule robot motion were also recorded in the tube and an open plastic sink in order to prove the correctness of the theoretical analysis and the potential of the robot motion for the medical application. The last are our conclusions and the future work.

II. System Overview

Generally speaking, the system of the capsule robot driven by the external magnetic field has two parts of the mechanism, one is the internal receiving part and the other is the outside sending part. The spherical capsule robot actuated by the external magnetic field and the proposed external driving system are shown in Fig. 1 and Fig. 2, respectively. The spherical capsule robot has the neodymium permanent magnet embedded in the body. In the system the permanent magnet was regard as the internal receiving part. The permanent magnet can produce the strong magnetic field by its own, with no need for the field winding and the coil and their power supply system. The Helmholtz coil system was regard as the outside sending part. When the current flows through a coil, the external magnetic field will be generated. If it is given the external magnetic field, it has torque to the propulsive force. However, considering that the magnetization of the permanent magnet embedded in the spherical capsule robot can be regarded as a constant, so the force situation of the permanent magnet is closely related to the magnetic field environment.

According to the relevant formula of the magnetic field generated by the Helmholtz coil [19-20], we found that the frequency and the intensity of the input current are the decisive factors for the magnetic field. Combining with the proposed experimental platform, we can change the orientation of the robot by changing the direction of the magnetic field and change the moving speed of the spherical robot by changing the frequency of the magnetic field.



(a) Sectional view of the spherical robot (b) Spherical robot prototype

Fig. 1 The spherical capsule robot driven by the external magnetic field.

Fig. 2 The Helmholtz coil driving system.

TABLE I
SPECIFICATION OF EACH HELMHOLTZ COIL

	X axis	Y axis	Z axis
Resistance(Ω)	5.52	3.29	1.86
Wire Diameter(mm)	1.8	1.8	1.8
Turns Per Coil(times)	216	174	126
Physical Radius(mm)	294.3	211.4	157.4

The parameters of the external magnetic field generated by the Helmholtz coil are determined by the input current, but considering that the proposed Helmholtz coil system in our research has been fabricated already, we can only complete the control of the external magnetic field generated by the 3D Helmholtz coil system from the input signal rather than by improving the parameters of the Helmholtz coil system . The specification of the each Helmholtz coil system is shown in Table I.

III. THE FINITE ELEMENT ANALYSIS OF HELMHOLTZ COIL

The magnetic flux density of the Helmholtz coil is complex, lacking of the elementary function expression, so that people have adopted various approximation method to study. ANSYS is the large calculation software FEM-based and the function of the electromagnetic field analysis module is perfect [21], so it is widely used in various industrial fields, such as the biomedicine.

A typical ANSYS analysis process can be divided into three steps,

A. *Modeling*

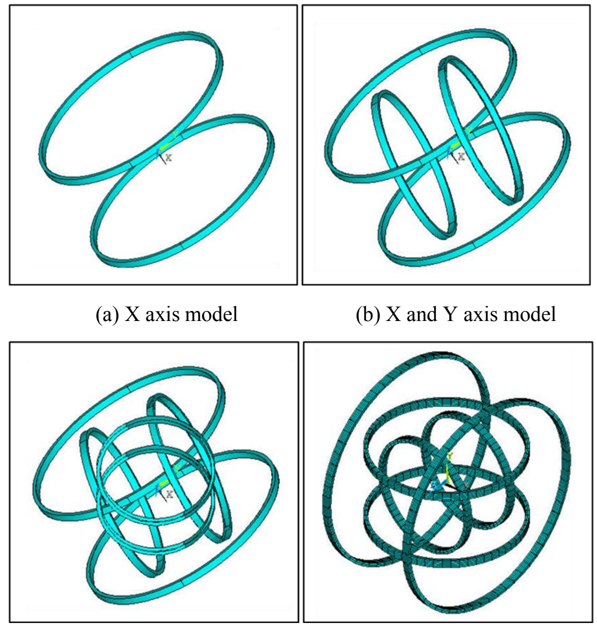
The process of modeling mainly includes the following procedures, the element type, the real constants, and the material props, the modeling and the meshing. The specific modeling process of the 3D Helmholtz coil system adopting the top-down method in this paper and the result of meshing are shown in Fig. 3. In addition, we defined the spherical air medium area whose radius is greater than X axis's around the Helmholtz coil system in order to limit the scope of the discussed external magnetic field. The finite element models of the Helmholtz coil increased the air cover under the different elements are shown in Fig. 4.

B. *Loads and Solution*

Loads and solution include the define loads and analysis options. The load refers to the boundary conditions and the external or internal force function. The main purpose of the finite element analysis is to check the response of the structure or the component to a certain load so that the specified load condition is the key step in the process of the whole analysis. In our analysis, the DOF constraints and the concentrated load for the Helmholtz coil are the main configuration. As for the solution, we need to choose the type of analysis and the solver before . In addition, in order to convert the harmonic analysis to the static analysis, the form of the input current is defined by the following Eq (1).

$$I_x = I_0 \sin(2\pi f t + \varphi_0) \quad (1)$$

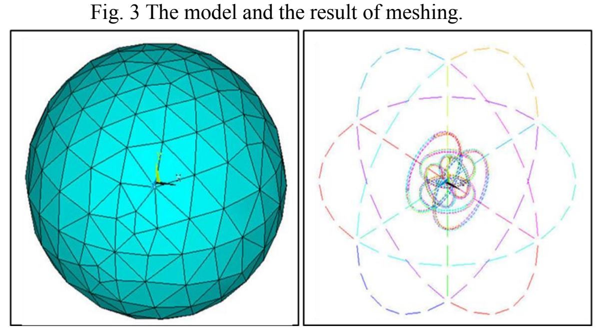
where I_0, f and φ_0 are the amplitude, the frequency and the phase of the input current, respectively.



(a) X axis model (b) X and Y axis model

(c) Helmholtz coil model (d) Result of meshing

Fig. 3 The model and the result of meshing.



(a) Area unit view (b) Lines unit view

Fig. 4 The finite element model increased the air cover.

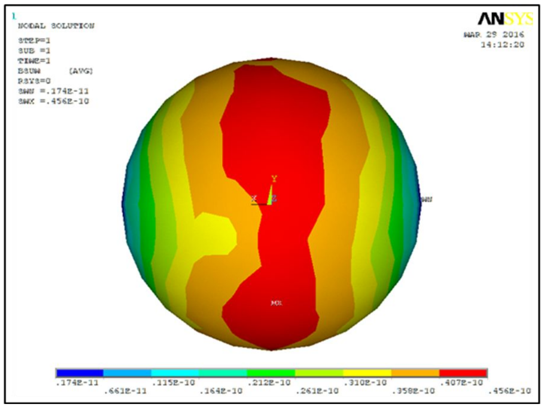
C. *General Postprocessor*

The last step of analyzing problems is the postprocessor, which is to view, analyze and handle the results of solving. The finite element analysis of the Helmholtz coil increased the air cover is shown in Fig. 5.

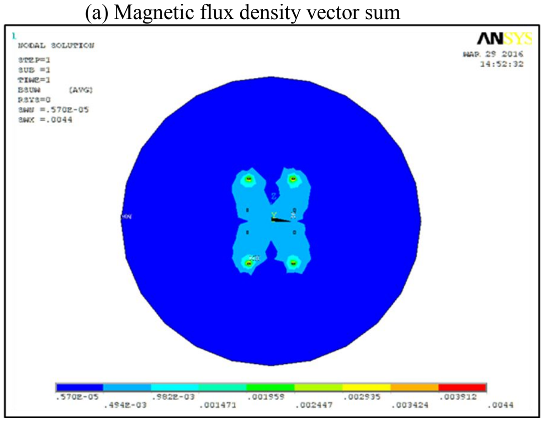
From the analysis result the external magnetic field intensity is 1.57mT. In the end, we conducted a series of more analysis by changing the parameters of the input current.

On the other hand, in order to illustrate the outside driving force of the Helmholtz coil system on the spherical capsule robot, we also did the coupling analysis between the Helmholtz coil system and the spherical robot. The spherical capsule robot is simplified as a circular permanent magnet whose radius is 3mm in this part. The result of the coupling analysis between the Helmholtz coil and the spherical robot are shown in Fig. 6.

From these figures, we can find that the driving force of the Helmholtz coil system to the spherical capsule microrobot can be generated along the space any the direction by changing the parameters of the input signal in theory. The direction and the length of the arrow indicate the direction and the strength of the coupling magnetic field force, respectively in Fig. 6.



(a) Magnetic flux density vector sum



(b) Nephogram of the magnetic field intensity

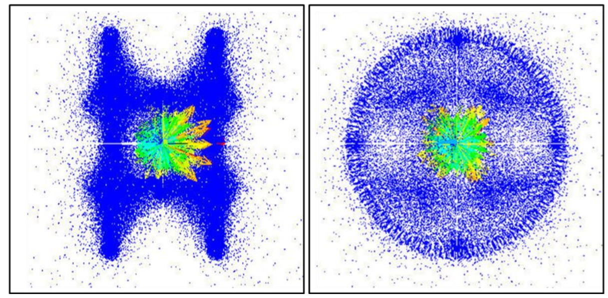
Fig. 5 The finite element analysis of the Helmholtz coil.

Considering that the volume of the embedded permanent magnet is too small and its magnetization intensity is a constant in the measurement, the driving force of the Helmholtz coil system to the spherical capsule microrobot is mainly realized by changing the strength of the magnetic field generated by the Helmholtz coil.

In addition, to make clear the relation between the input signal and the direction of the magnetic force, we did the further instruction for the synergy effect in the several typical angles as shown in Fig. 7. In these figures the direction and the length of the red arrow represent the direction of the magnetic force and the magnitude of the force, respectively. The opposite direction of the synergy effect could be obtained by changing the direction of the input signal.

IV. Experiments And Results

In order to verify our analysis results and establish the relationship with the experimental system, we make the comparison between experimental results and theoretical results. In practice, the experimental values are measured by the gauss meter and the input signal parameters were sent via a PC. The experimental platform is shown in Fig. 8. We have defined the experimental conditions in the original research before [22]. Considering that the change of the amplitude of the input signal is not big affected by the hardware circuit, we altered the frequency of the input signal in the contrast experiments. The contrast figure between experimental results and theoretical results is shown in Fig. 9.



(a) Front view (b) Right view

Fig. 6 The coupling analysis between Helmholtz coil and capsule robot.

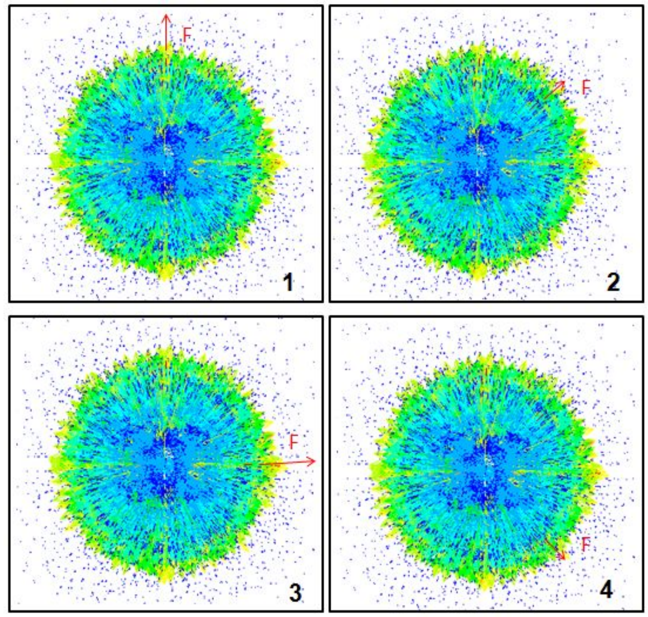


Fig. 7 The direction of the synergy effect in typical angle.

From the contrast figure, we found that the variation tendency of the magnetic field is the same between the experimental values and the simulation results. It proves the correctness of the simulation. However, there are still some differences between them. In general, the experimental values are lower than the theoretical results.

The following several reasons led to this phenomenon. First of all, the experimental system is a kind of open loop control, lacking of the feedback compensation. Besides, the accuracy of the experimental values is inferior to the theoretical values'. What's more, the parameters of the input signal didn't reach the ideal state due to the errors of the signal producing circuit and the amplifying circuit. In addition, the input signal is the constant voltage source rather than the constant flow source in the experiment. The Helmholtz coil as the inductive load is very sensitive to this difference of input source. But on the whole, we can adjust the parameters of the input signal on the basis of the simulation results to obtain the needed external magnetic field. In addition, for the sake of illustrating the effectiveness of the driving force of the Helmholtz coil on the robot, we have carried on the several tests on the capsule robot motion in the typical gradient plane and the motions in the horizontal and the vertical direction have been discussed in the original study.

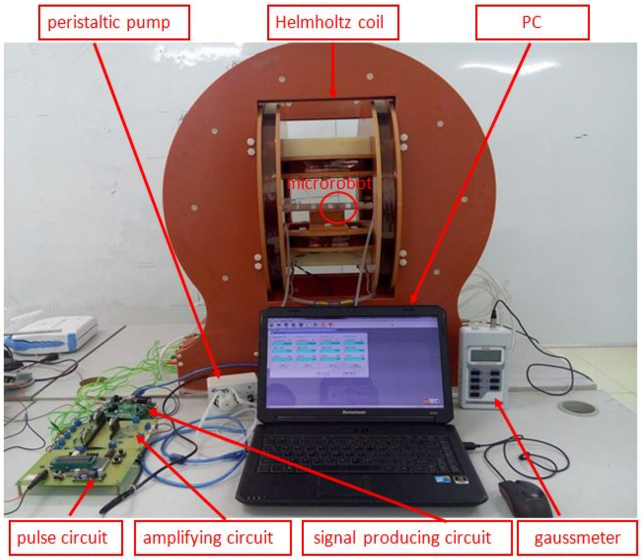


Fig. 8 The experimental platform.

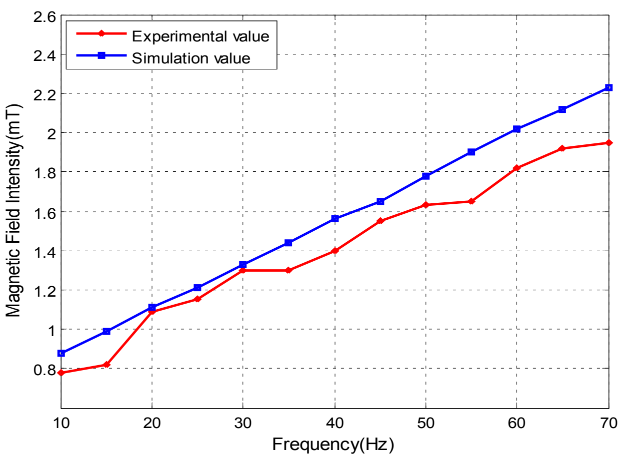


Fig. 9 Contrast figure between experimental results and theoretical results.

And we also made a schematic diagram of the spherical microrobot's speed in the different gradient plane under the condition of the same magnetic field in order to illustrate the potential of the external magnetic field in terms of actuating the spherical robot motion as shown in Fig. 10. The snapshot of the spherical microrobot motion when the angle of the inclination is equal to 30° is shown in Fig. 11. The interval time of the snapshot is about 5s for each situation.

In the Fig. 10, different color lines represent the actual speed of the spherical capsule microrobot corresponding to the different motion plane. The maximum speed of the spherical capsule microrobot are 11.2cm/s, 10.2cm/s, and 5.9cm/s, respectively, as the angle of the inclination increases in turn. The cause of the speed decline for the spherical mocrorobot is that the external magnetic field intensity generated by the Helmholtz coil is mainly caused by the frequency which affects the rotation motion of the spherical microrobot. The external magnetic field intensity is about 1.6mT when the speed of the spherical robot motion obtains the maximum value and this magnetic field intensity is not change with the angle of the inclination.

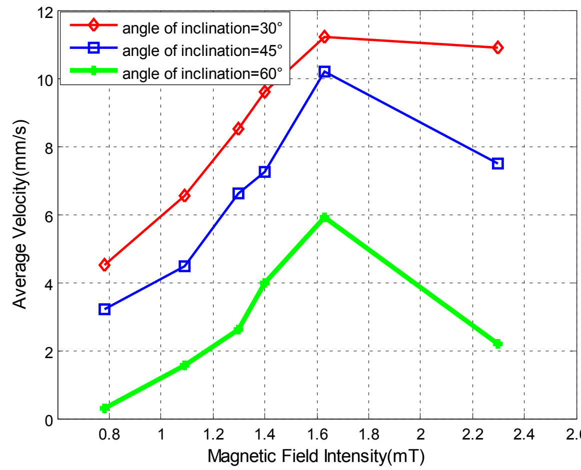


Fig. 10 Spherical robot motion in the different gradient plane

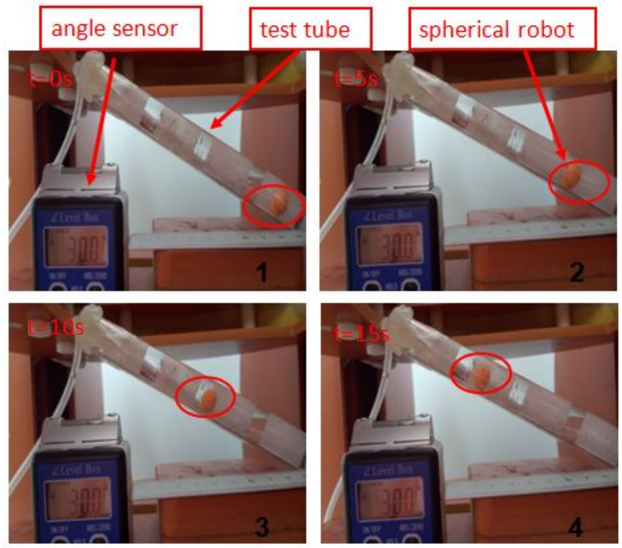


Fig. 11 Snapshots of the capsule robot motion (angle of inclination=30°).

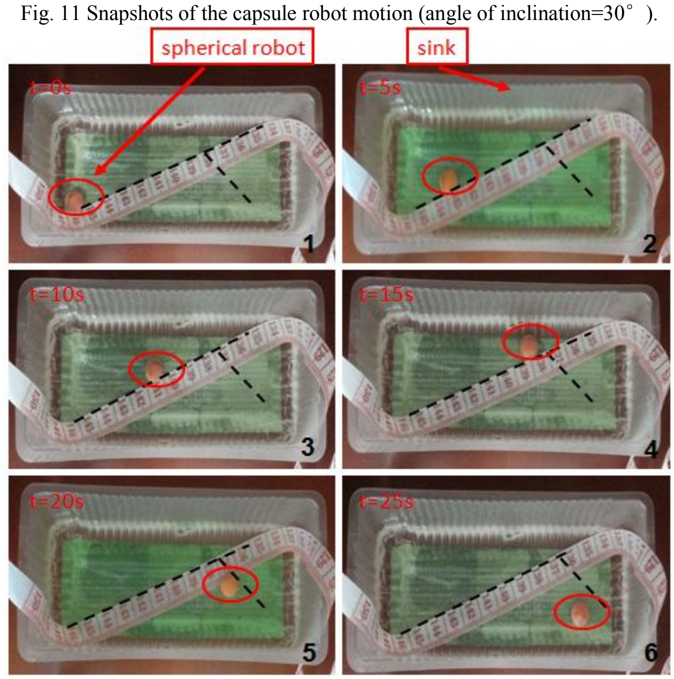


Fig. 12 Snapshots of the capsule robot along the predetermined direction.

Last, in order to show the direction of the synergy effect between the external magnetic field and the permanent magnet embedded in the spherical microrobot, we have carried on the experiments on the microrobot motion in an open plastic sink. In this part we didn't use the peristaltic pump in order to avoid the liquid leakage. The motion snapshots along the predetermined direction in the plane are shown in Fig. 12. The black dotted line represents the trajectory of the spherical robot motion.

V. CONCLUSIONS

In this paper, we proposed the spherical microrobot system driven by the external magnetic field. And we also conducted the finite element analysis of the Helmholtz coil system. In the end, in order to verify our analysis results and establish relationship with the experimental system, we made the comparison between experimental results and theoretical results.

According to the analysis of the Helmholtz coil, we have made clear that the intensity and the direction of the magnetic field are influenced by the input current parameters. In addition, the driving force of the Helmholtz coil on the spherical robot can be generated along the space any direction by changing the parameters of the input signal in theory from the coupling analysis between the Helmholtz coil and the spherical robot. The experimental values of the magnetic field intensity have the same variation tendency with analysis results. The spherical robot motion proved the effectiveness of the driving force of the Helmholtz coil on the spherical robot. However, there are other factors except the external driving force. The experiments in an open plastic sink indicated that the spherical capsule microrobot can actively move along the predetermined direction.

In the future, we will consider focusing on the functional microrobot and the remote control to the spherical robot.

ACKNOWLEDGMENT

This research is partly supported by Key Project of Scientific and Technological Support of Tianjin (15 ZCZDSY00910) and National High Tech. Research and Development Program of China (2015AA043202).

REFERENCES

[1] K. Choi, G. Jang, S. Jeon, and J. Nam, "Capsule-Type Magnetic Microrobot Actuator by an External Magnetic Field for Selective Drug Delivery in Human Blood Vessels," IEEE TRANSACTIONS ON MAGNETICS, vol. 50, no. 11, pp. 1-4, 2014.

[2] S. He, G. Yan, Q. Ke, Z. Wang, and W. Chen, "A Wirelessly Powered Expanding-Extending Robotic Capsule Endoscope for Human Intestine," International Journal of Precision Engineering and Manufacturing, vol. 16, no. 6, pp. 1075-1084, June 2015.

[3] L. Yan, T. Wang, D. Liu, J. Peng, Z. Jiao, and C. Chen, "Capsule Robot for Obesity Treatment With Wireless Powering and Communication," IEEE Transactions on Industrial Electronics, vol. 62, no. 2, pp. 1125-1133, February 2015.

[4] Z. Sun, B. Ye, Y. Qiu, X. Cheng, H. Zhang, and S. Liu, "Preliminary Study of a Legged Capsule Robot Actuated Wirelessly by Magnetic Torque," IEEE Transactions on Magnetics, vol. 50, no. 8, pp. 1-6, August 2014.

[5] J. Gao, G. Yan, Z. Wang, S. He, F. Xu, P. Jiang and D. Liu, "Design and Testing of a Motor-Based Capsule Robot Powered by Wireless Power Transmission," IEEE/ASME Transactions on Mechatronics, vol. 21, no. 2, pp. 683-693, 2016.

[6] Q. Fu, S. Guo, S. Zhang and Y. Yamauchi, "Performance Evaluation of a Magnetic Microrobot Driven by Rotational Magnetic Field," Proceedings of 2015 IEEE International Conference on Mechatronics and Automation, pp. 876-880, August 2015.

[7] H. Choi, S. Jeong, C. Lee, G, Go, K Kwon, S. Y. Ko, J. O. Park, and S. Park, "Biomimetic Swimming Tadpole Microrobot using 3-pairs Helmholtz Coils," Proceedings of 2014 IEEE RAS &EMBS International Conference on Biomedical Robotics and Biomechatronics, pp. 841-844, August 2014.

[8] Y. Zhang, H. Xie, N. Wang, L. Wang, C. Du, Y. Sun, and Z. Ma, "Design, analysis and experiments of a Spatial Universal Rotating Magnetic Field System for Capsule Robot," Proceedings of 2012 IEEE International Conference on Mechatronics and Automation, pp. 998-1003, August 2012.

[9] Y. Zhang, N. Wang, C. Du, Y. Sun, and D. Wang, "Control theorem of a universal uniform-rotating magnetic vector for capsule in curved environment," Science China Technological Sciences, vol. 56, no. 2, pp. 359-368, 2013.

[10] Y. Zhang, J. Bai, M. Chi, C. Cheng, and D. Wang, "Optimal Control of a Universal Rotating Magnetic Vector for Petal-shaped Capsule Robot in Curved Environment," Chinese Journal of Mechanical Engineering, vol. 27, no. 5, pp. 880-889, 2014.

[11] R. Carta, M. Sfakiotakis, N. Pateromichelakis, J. Thoné, D. P. Tsakiris, and R. Puers, "A multi-coil inductive powering system for an endoscopic capsule with vibratory actuation," Sensors and Actuators A: Physical, vol. 172, no. 1, pp. 253-258, 2011.

[12] Q. Pan, S. Guo and T. Okada, "A novel hybrid wireless microrobot," International Journal of Mechatronics and Automation, vol. 1, no. 1, pp. 60-69, 2011.

[13] Q. Fu, S. Guo, Y. Yamauchi, H. Hirata, and H. Ishihara, "A novel hybrid microrobot using rotational magnetic field for medical applications," Biomed Microdevices, vol. 17, no. 2, pp. 1-12, 2015.

[14] Q. Fu, S. Guo, S. Zhang, H. Hirata, and H. Ishihara, "Characteristic Evaluation of a Shrouded Propeller Mechanism for a Magnetic Actuated Microrobot," Micromachines, vol. 6, no. 9, pp. 1272-1288, 2015.

[15] J. Guo, S. Guo, and X. Wei, "A novel tele-operation controller for wireless microrobots in-pipe with hybrid motion," Robotics and Autonomous Systems, vol. 76, no. 2, pp. 68-79, 2015.

[16] J. Guo, S. Guo, X. Wei, and Y. Wang, "Development of Wireless Endoscope with Symmetrical Motion Characteristics," International Journal of Advanced Robotic Systems, vol. 11,no. 9, pp. 1-13, 2014.

[17] K. Yatabe and Y. Oikawa, "Optically visualized sound field reconstruction using Kirchhoff-Helmholtz equation," Acoustical Science and Technology,vol. 36, no. 4, pp. 351-354, 2015.

[18] R. Beiranvand, "Analyzing the uniformity of the generated magnetic field by a practical one-dimensional Helmholtz coils system," Review of Scientific Instruments, vol. 84, no. 7, pp. 1-10, 2013.

[19] Y. Zhang, Z. Su, M. Chi, Y. Huang and D. Wang, "Magnitude and Orientation Error Correction of a Superimposed Spatial Universal Rotating Magnetic Vector," IEEE Transactions on Magnetics, vol. 52, no. 5, pp. 1-9, 2016.

[20] J.J. Abbott, "Parametric design of tri-axial nested Helmholtz coils," Review of Scientific Instruments, vol. 86, no. 5, pp. 205-212, 2015.

[21] L. Liu, S. Zeng, and Y. Zhang, "Magnetic field characteristics analysis of a single assembled magnetic medium using ANSYS software," International Journal of Mining Science and Technology, vol. 25, no. 3, pp. 479-487, 2015.

[22] N. Liang, J. Guo, S. Guo and X. Wei, "Performance Evaluation of the Wireless Micro Robot in the Fluid," Proceedings of 2015 IEEE International Conference on Mechatronics and Automation, pp. 958-963, August 2015.