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# Design of a Magnetically-Driven Untethered Micro-Gripper for Drug Delivery

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***Abstract*— Micro-grippers have great potential to be used in robot-assisted surgery. They can go through small vessels and natural orifice, which makes them a good choice for drug delivery or treatment. Magnetic field can exert forces and torques that cross non-metallic substances and has no harm to organism. As a result, magnetically-driven micro-gripper can be a good candidate for clinical practice. In order to apply these advantages to drug delivery, a magnetically-driven controllable untethered micro-gripper is designed. Two small permanent magnets are assembled together with a certain angle to response the magnetic fields. Based on the principle that the magnetic fields exert torques and forces, we set up a control model of the micro-gripper. In opening and closing experiment, the current version of micro-gripper can open about 20° in a 18mT magnetic fields generated by 11A current in our coil system. Moreover, we achieve the move control of the micro-gripper. The orientation and movement can be controlled by controlling of the external magnetic field. In the movement experiment and the drug delivery experiment, the micro-gripper has shown a good performance. This study give a new research on micro-gripper used to drug delivery.**

## I. Introduction

Surgery robots have been well studied to be used in minimally invasive robot-assisted surgery [1], such as da Vinci system. However, robot-assisted surgery has many problems that need to be solved. One of the existing challenges is that the size of robot must be proper so that it won't be too big to move flexibly or too small to control [2]. What's more, when facing narrow and small workspace, traditional robots are limited by their size. Lacking of effective supplement tools, traditional robots' approaches to the workspace are limited[3], which may expose the patients to a risk of injury.

As an accurate and small tool for minimally invasive surgery (MIS), micro-robots have gained more and more attention. Biomedical micro-robots are mainly used in four fields: targeted therapy, telemetry, controllable structures and material removal [4]. They can be driven in multiple ways such as thermal [5][6], optical [7] or chemical [8]. Magnetic actuation is another method. As a kind of indirect and safe way of control, magnetic drive method has been widely studied for control of micro-robots [9]–[12]. Magnetic field based methods have a bright prospect and potential in remote control of micro-robots, since magnetic fields can achieve wireless control of micro-robots by exerting both forces and torques and cross non-metallic substances. Moreover, magnetic fields used for remote control of micro-robots do little harm to organisms because of their low strength and low frequency.

Among those micro-robots, micro-grippers have the advantages that they can achieve multiple functions and need only magnetic field. They can show a good performance in recently research. Some can use open-loop control to move big cargoes [9] and some can be folded into a really small cube [10]. However, there are still challenges for those micro-grippers. The micro-gripper for MIS is limited by its wrist and its big size[9]. The untethered reliable micro-gripper needs Special processing technology, which means that it is not easy to fabricate [10]. The two magnetic torques and forces based micro-grippers are limited by the shape of the cargoes [11]. For other micro-grippers, there are still problems such as uncoupled behaviors [15], [16]. In the field of micro-gripper, a small, general and easy-fabricated micro-gripper is required.

In addition, there are few micro-grippers used for drug delivery and the current micro-robots for drug delivery are facing with difficulties in fabrication because of the particular shapes and difficulties in selective control due to the complex structure [17].

Meanwhile, the researches of magnetic field system are making progress as well. Multi-function magnetic dynamic systems can meet different requirement. Uniform magnetic field has a maximum eight degrees of freedom in remote actuation [13] so that multiple micro-robots can be controlled in the same workspace. Moreover, a magnetic coil system developed is capable of precise control for a workspace which is big enough to carry an adult and generates a magnetic field of up to 400 mT[14].

In this paper, we explored a three-dimension magnetically-driven controllable untethered micro-gripper for drug delivery. The micro-gripper is easy to be manufactured and assembled. As shown in Fig.1, the micro-gripper is set up by 3 parts and can go through a 4mm diameter channel. The inner diameters of the vessels in heart are from $8\mu m$ to $30mm$. Among them, the diameters of Vena cava, Aorta, Vein and Medium artery are 30mm, 25mm, 5mm, 4mm, respectively [4]. Therefore, the proposed design can meet the demand of drug delivery in the vessels in heart. Control

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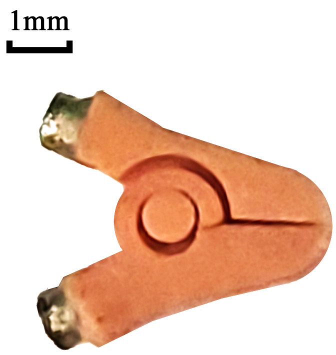


Fig. 1. Top view of the micro-gripper. It has two arms and one spindle. The magnets are attached to the arms by cyanoacrylate(CYA) glue.

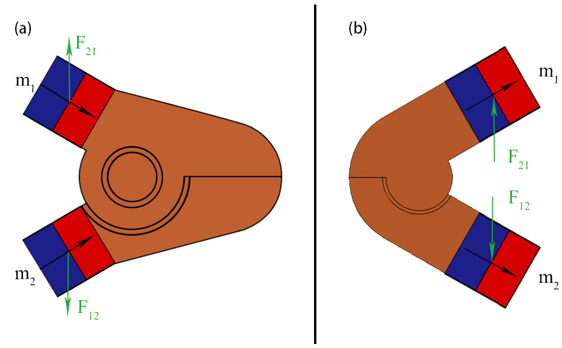


Fig. 2. Two kinds of micro-gripper design. (a) 'Normally close' gripper. Because of the repulsion between the two magnets, the gripper will keep closing without external interference. (b) 'Normally open' gripper. The gripper will keep opening without external interference.

model has been set up for the micro-gripper and experiments have been carried out to verify the model. Experimental results showed a good performance with the proposed design.

Structure of this paper is organized as follows: modeling, analysis and fabrication of the proposed design will be shown in Section II; Section III will show the electromagnetic actuation system and the control method; Experiments and results will be given in Section IV. Finally, conclusions will be drawn in Section V.

## II. Modeling, Analysis and Fabrication

This section describes in detail the design concept and process of the proposed micro-gripper. Based on the design, modeling and analysis of the function of the micro-gripper under external magnetic field will be shown.

### A. Design Concept

A magnet can be affected by an external magnetic field in terms of magnet force and torque. Based on the magnetic field superposition principle, we put forward the design concept of the magnetic driven micro-gripper by combining with the shape of clamp. As shown in Fig.2(a) and (b), two structures have been designed, namely (a) Normally close gripper since the repulsion between the two magnets will cause the gripper keep closing without external magnetic field; and (b) Normally open gripper, which will keep opening without external interference. Both of the two types can be control to open and close under controlled external magnetic field. 'Normally close' gripper is focusing on carrying while 'Normally open' gripper is focusing on grabbing. Therefore, the 'normally close' gripper design has been chosen to satisfy the aim of drug delivery.

### B. Fabricating Progress

As shown in Fig.1, the micro-gripper is structured by two arms, one spindle and two magnets. The arms and the spindle were 3D-printed from red wax, which makes it easy to manufacture and fabricate. The magnets are made of neodymium iron boride (NdFeB) N35. The gripper is 4.5mm long and the maximum width is 3.5mm. It forms a 1mm diameter sphere when fully close. The sphere allows the gripper to carry particular of drugs or even cells. The magnets are attached to the arms by cyanoacrylate(CYA) glue.

### C. Gripper Model

Based on the proposed design, the gripper can achieve 6D control: 2D orientation, 3D position and 1D open angle. They are controlled independently by the strength, direction and gradient of the applied magnetic field. Based on this principle, open and close of the micro-gripper as well as the movement can be analyzed.

*1) Open, Close and Orientation:* As shown in Fig. 3, the gripper can be controlled to open with an desired angle in predetermined direction. This can be achieved with a magnetic torque from an applied external magnetic field $\mathbf{B}$

$$\tau = \mathbf{m} \times \mathbf{B} \tag{1}$$

where $\mathbf{m}$ is the magnetic moment of the small magnet. At the same time, the two magnets also exert a torque $\mathbf{T}_m$ to each other due to their interaction with each other. By adjusting the strength of the applied magnetic field, open angle of the gripper can be controlled.

For permanent magnet, the magnetic moment $\mathbf{m}$ is

$$\mathbf{m} = \frac{1}{\mu_0}\mathbf{B}_r V \tag{2}$$

where $\mathbf{B}_r$ is the residual flux density, $V$ is the volume of the magnet and $\mu_0 = 4\pi \times 10^{-7} H/m$ is the permeability of vacuum. For $NdFeB$, $|\mathbf{B}_r| = 1200mT$. Due to the small size of the magnet, the magnetic dipole model can be used to calculate the magnetic field of the magnets. The magnetic field $\mathbf{B}$ of a magnetic dipole is depend on the magnetic moment and the cube of distance, that is

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3}\right) \tag{3}$$

where $\mathbf{r}$ is the vector from the center of the magnetic dipole to the location where the magnetic field is measured. Then,

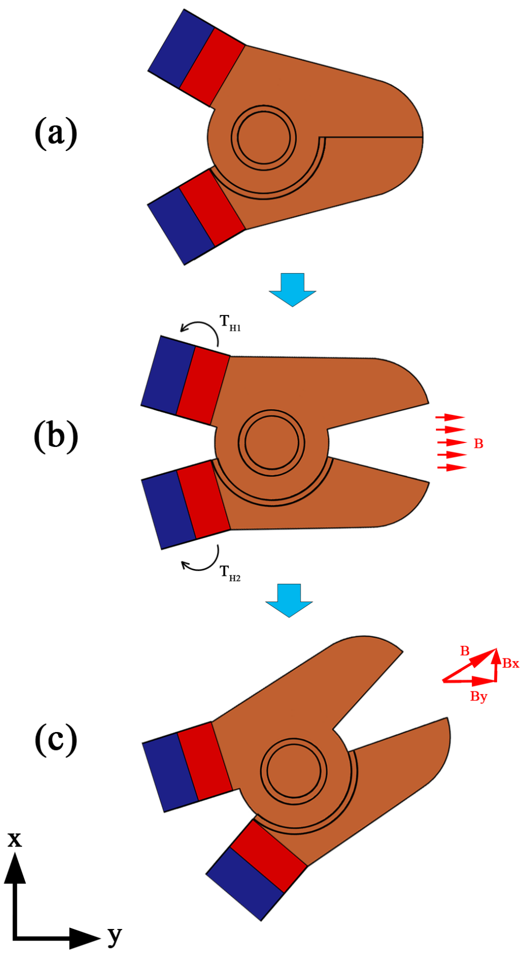


Fig. 3. Micro-gripper model.(a) No applied magnetic field. (b) A uniform magnetic field can open the micro-gripper. (c) Combined magnetic field can control the orientation of the gripper.

the torque $\mathbf{T}_m$ between the two magnets and the torque $\mathbf{T}_H$ exerts by the applied magnetic field can be calculated as

$$\begin{cases} \mathbf{T}_m = \mathbf{m} \times \mathbf{B}(\mathbf{r}) \\ \mathbf{T}_H = \mathbf{m} \times \mathbf{B} \end{cases} \tag{4}$$

Here, when we calculate the torque exerted by the magnet, we ignored the torque exerted by the force exerted by the magnet because when the open angle is not big enough, the force between two magnets is small enough to be ignored.

Therefore, for a given magnetic field $\mathbf{B}$, there will be two cases. 1) When $\mathbf{B}$ is not strong enough to overcome the repulsive torque $\mathbf{T}_m$ between the magnets, the gripper keeps close and the gripping force $F$ of the micro-gripper can be controlled, that is

$$F \cdot b = |\mathbf{T}_m| - |\mathbf{T}_H| \tag{5}$$

where $b$ is the distance from the point of force application to the spindle. And 2) when $\mathbf{B}$ is strong enough to overcome $\mathbf{T}_m$, as shown in Fig.3 (b), the gripper will open. At the equilibrium position, the sum of the torques must be zero, therefore

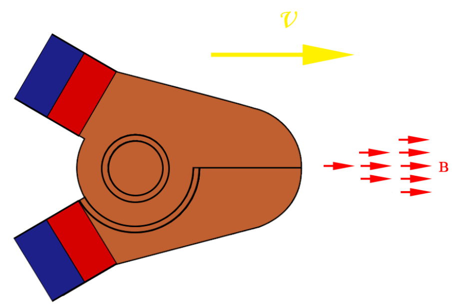


Fig. 4. The gripper moves in a gradient magnetic field.

$$\mathbf{T}_m + \mathbf{T}_H = 0 \tag{6}$$

Depending on the requirement, to achieve a given value of $F$ or open angle $\theta$, $\mathbf{B}$ can be solving by combining (5) or (6) with (3) and (4).

As shown in Fig.3 (c), the orientation of the micro-gripper is paralleled with the applied magnetic field $\mathbf{B}$ which can be calculated as

$$\mathbf{B} = B_x\mathbf{i} + B_y\mathbf{j} + B_z\mathbf{k} \tag{7}$$

With the known $\mathbf{B}$ according to the angle or force, $(B_x, B_y, B_z)^T$ can be estimated based on the desired direction.

*2) Movement:* An applied magnetic field $\mathbf{B}$ exerts a force $\mathbf{f} = \bigtriangledown(\mathbf{m} \cdot \mathbf{B})$ that can be used to move the gripper in 3D space. As shown in Fig.4, micro-gripper can be moved in a gradient magnetic field. Therefore, the force can be calculated as

$$\mathbf{F}_x + \mathbf{F}_y = \bigtriangledown(\mathbf{m} \cdot \mathbf{B}_M) = \bigtriangledown\mathbf{B}_M \cdot \mathbf{m} \tag{8}$$

Since the micro-gripper is symmetric relative to the $Y$-axis, the force in $X$ direction can be cancelled by each other. As a result, the driving force of the micro-gripper $\mathbf{F}_d = 2\mathbf{F}_y$. In order to allow the micro-gripper to move at a constant speed in the liquid, the resistance of the micro-gripper is $\mathbf{F}_d = \mathbf{F}_f$ and the viscous drag occurs when the micro-twist moves in the fluid. The can be expressed as follows

$$\mathbf{F}_f = \mu \triangle s \frac{d\mathbf{v}}{dy} \tag{9}$$

where $\mu$ is the viscosity coefficient of the fluid, and $\triangle s$ is the cross-sectional area of the micro-gripper. Since the shape of the micro-gripper is irregular, $\mathbf{B}_M$ can be obtained experimentally.

## III. Magnetic Actuation System and Control Method

### A. 3-Axis Magnetic Actuation System

As shown in Fig.5, the 3-aixs magnetic actuation system includes a 3-axis Helmholtz coils set and a 3-axis Maxwell

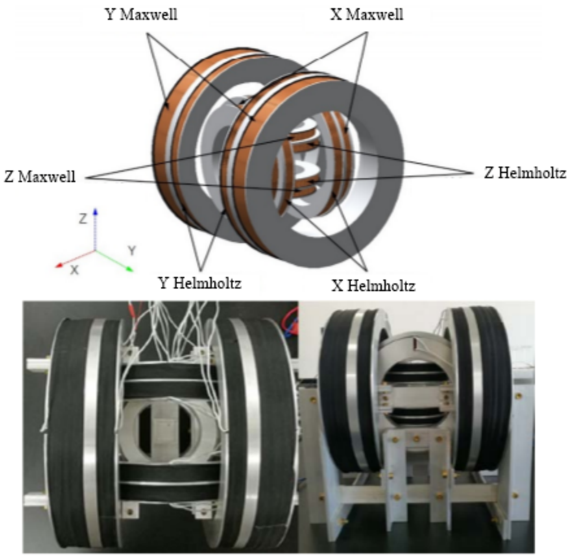


Fig. 5. System overview. Magnetization coil dynamic system is set up by 3-Axis Helmholtz Coils and 3-Axis Maxwell Coils.

TABLE I
PARAMETERS OF THE COILS

| Parameters | x | y | z |
|---|---|---|---|
| $N_H$ | 196 | 289 | 121 |
| $N_M$ | 289 | 729 | 121 |
| $r(mm)$ | 68 | 105.5 | 44 |

coils set. The parameters of the coil system are shown in Table.I.

The distance $h$ between a pair of Helmholtz coils is equal to the radius $r$ of the coil, which means a uniform magnetic field can be generated near the axial midpoint. The magnetic field of $X-$axis can be calculated as

$$\mathbf{B}_{Hx} = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 N_x I_x}{r_x}\mathbf{x} \tag{10}$$

where $\mathbf{x}$ is the unit direction vector of x-axis. Therefore, the magnetic field generated by Helmholtz coils near the midpoint is

$$\mathbf{B}_H = B_{Hx}\mathbf{i} + B_{Hy}\mathbf{j} + B_{Hz}\mathbf{k} \tag{11}$$

For Maxwell Coils, $h = \sqrt{3}r$ and a uniform gradient magnetic field can be generated near the axial midpoint. The x-axis magnetic field can be calculated as

$$\mathbf{B}_{Mx} = [g_{mx}x \quad -\tfrac{1}{2}g_{my}x \quad -\tfrac{1}{2}g_{mz}x] \tag{12}$$

$$g_{mx} = \frac{16}{3}\left(\frac{3}{7}\right)^{\frac{5}{2}} \frac{\mu_0 N_x I_x}{r_x^2} \tag{13}$$

where $N_x$ is the coil number and $I_x$ is the current. The gradient of the magnetic field is

$$\triangledown\mathbf{B}_M = \begin{bmatrix} \triangledown\mathbf{B}_{Mx} & 0 & 0 \\ 0 & \triangledown\mathbf{B}_{My} & 0 \\ 0 & 0 & \triangledown\mathbf{B}_{Mz} \end{bmatrix} \tag{14}$$

where

$$\begin{aligned} \triangledown\mathbf{B}_{Mx} &= g_{mx} - \frac{1}{2}g_{my} - \frac{1}{2}g_{mz} \\ \triangledown\mathbf{B}_{My} &= g_{my} - \frac{1}{2}g_{mx} - \frac{1}{2}g_{mz} \\ \triangledown\mathbf{B}_{Mz} &= g_{mz} - \frac{1}{2}g_{my} - \frac{1}{2}g_{mx} \end{aligned}$$

Because $\triangledown B$ is not a row full rank matrix, we can use only two of the three Maxwell coils or give another limit. Based on the above, the uniform magnetic field that generated with Helmholtz coils will be used to control the open angle and gripping force of the gripper, while the uniform gradient field from the Maxwell coils will help to move the gripper in desired direction.

### B. Gripper Controlling

As shown in Fig.6, establish a local coordinate system belonging to the micro-gripper. In the model, $\alpha$, $\beta$, $a$ are parameters defined by the gripper itself and $\theta$ is the open angle. The unit vector in direction of the two magnetic moment are $\mathbf{e}_{m1} = (\sin(\frac{\beta-\theta}{2} - \alpha), \cos(\frac{\beta-\theta}{2} - \alpha), 0)$ and $\mathbf{e}_{m2} = (-\sin(\frac{\beta-\theta}{2} - \alpha), \cos(\frac{\beta-\theta}{2} - \alpha), 0)$. Position vector $\mathbf{r} = (2a\sin\frac{\beta-\theta}{2}, 0, 0)$. Inserting these vectors into formulas in section II, we can calculate the applied magnetic field $\mathbf{B}'_{Hy}$ required to open angle $\theta$. Then, by the magnetic field transformation, we can obtain the magnetic fields $\mathbf{B}_{Hx}$, $\mathbf{B}_{Hy}$, $\mathbf{B}_{Hz}$ generated by the Helmholtz coils in $x$, $y$, $z$ directions

$$\begin{bmatrix} \mathbf{B}_{Hx} \\ \mathbf{B}_{Hy} \\ \mathbf{B}_{Hz} \end{bmatrix} = R^{-1} \begin{bmatrix} 0 \\ \mathbf{B}'_{Hy} \\ 0 \end{bmatrix} \tag{15}$$

where $R = \begin{bmatrix} \cos\angle X'X & \cos\angle Y'X & \cos\angle Z'X \\ \cos\angle X'Y & \cos\angle Y'Y & \cos\angle Z'Y \\ \cos\angle X'Z & \cos\angle Y'Z & \cos\angle Z'Z \end{bmatrix}$ is the pose matrix of local coordinate system relative to the global coordinate system (7).

Similarly, in the motion control, the required current can be calculated. When moving in the fluid, four forces will act on the micro-gripper, magnetic force $\mathbf{F}_m$, fluid drag force $\mathbf{F}_d$, buoyancy force $\mathbf{F}_b$ and gravity $\mathbf{F}_g$.

$$\mathbf{F}_m + \mathbf{F}_d + \mathbf{F}_b + \mathbf{F}_g = m\mathbf{a} = m\ddot{\mathbf{p}} \tag{16}$$

which can be expressed as

$$\begin{bmatrix} F_{mx} \\ F_{my} \\ F_{mz} \end{bmatrix} + 3\pi\mu_f Dv \begin{bmatrix} \sin\varphi\cos\tau \\ \sin\varphi\sin\tau \\ \cos\varphi \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \rho_f gV + mg \end{bmatrix} = m \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \tag{17}$$

Then, the required current can be calculated by (12) and (17).

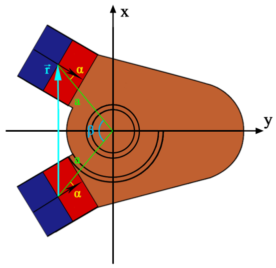


Fig. 6. The local coordinate system of the micro-gripper

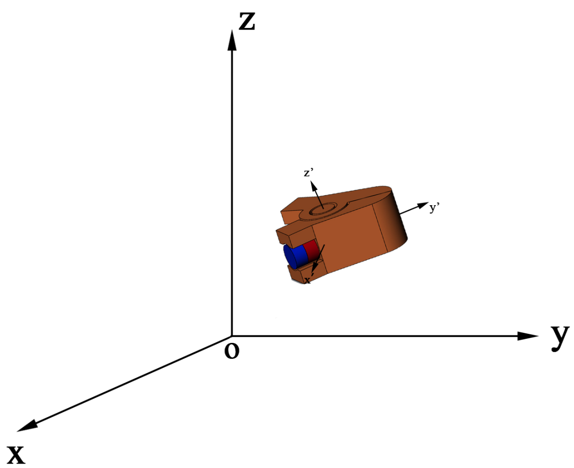


Fig. 7. The local coordinate system in the global coordinate system.

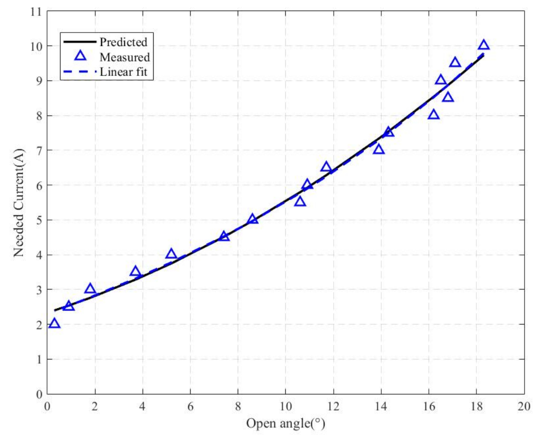


Fig. 8. Relationship between open angle $\theta$ and applied current I.

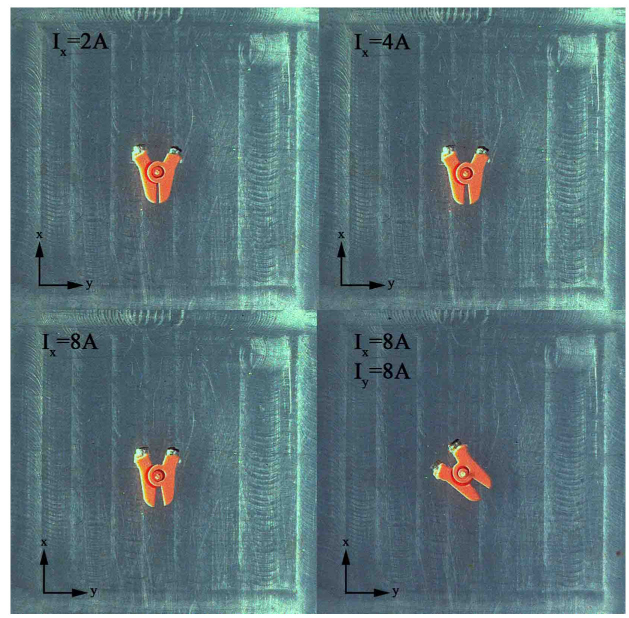


Fig. 9. Open and close experiment. With the current added from 0A to 10A, the progress is shown in the picture.

## IV. Experiment and Results

In this section, experiments are carried out to verify the accuracy of the micro-gripper model, the precision of calculating simulation and the controlling reliability of the micro-gripper. The experiments are conducted within a workspace which is a cube with 30mm long sides. And the magnetic coil system can produce a magnetic field up to 20mT with a maximum current of 10A. The position of the micro-gripper can be observed by two cameras from top and side.

### *A. Open and Close Experiment*

In this experiment, Helmholtz coils are used to control the open and close of the micro-gripper. Use the analysis in section II, a theoretical model can be obtained with the required magnetization field $\mathbf{B}$ and the opening angle $\theta$, that is

$$\mathbf{B} = \frac{K\mathbf{B}_r V \cos(\alpha - \frac{\beta-\theta}{2})}{a^3 \sin^3 \frac{\theta}{2}} \tag{18}$$

where $K(= -9.947\times10^{-3})$ is the coefficient of the function. However, because of the external interference such as viscous drag and fluid pressure, a correction coefficient should be added to the function. After calibration experiments, a correction coefficient related to the open angle is obtained

$$K_c = 0.11030\theta + 1.3481 \tag{19}$$

The designed magnetic actuation system and the micro-gripper can achieve a maximum open angle of 20°. From (10), we can change the relationship between the magnetic field and open angle into the relationship between needed current $I$ and the opening angle $\theta$. The predicted curve is shown in Fig. 8. As we loaded the current from 0A to 10A, we got a series of data. Because the predicted curve is $1/4$ cycle of trigonometric functions, quadratic fitting curve is the most suitable choice. The experiment results and the linear curve are also shown in Fig. 8. And the process of the experiment is shown in Fig. 9.

### *B. Moving Experiment*

This experiment was designed to verify the moving accuracy and the rotation reliability of the micro-gripper. Maxwell coils set is used to move the micro-gripper and the Helmholtz

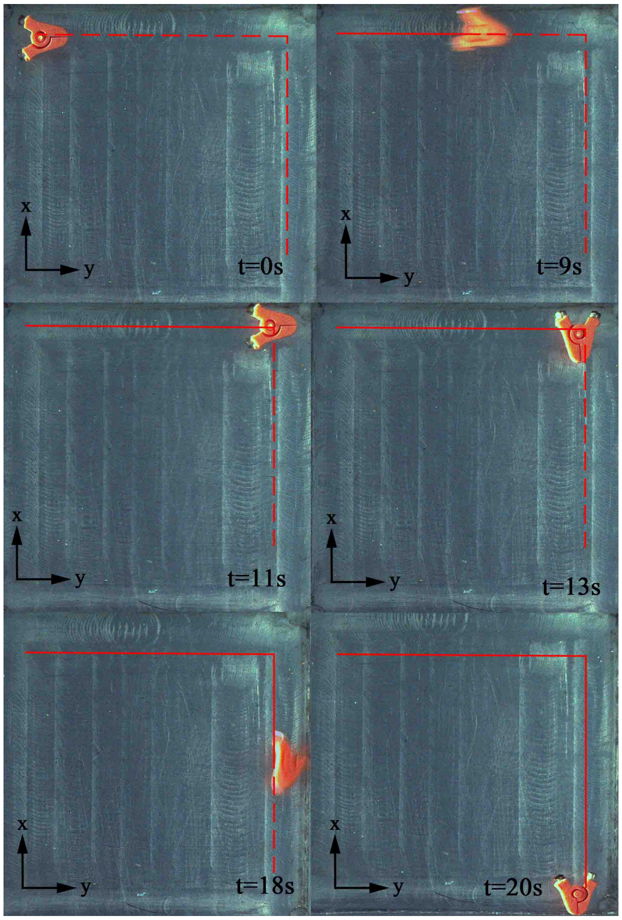


Fig. 10. Moving Experiment. Move the gripper with 2A current.

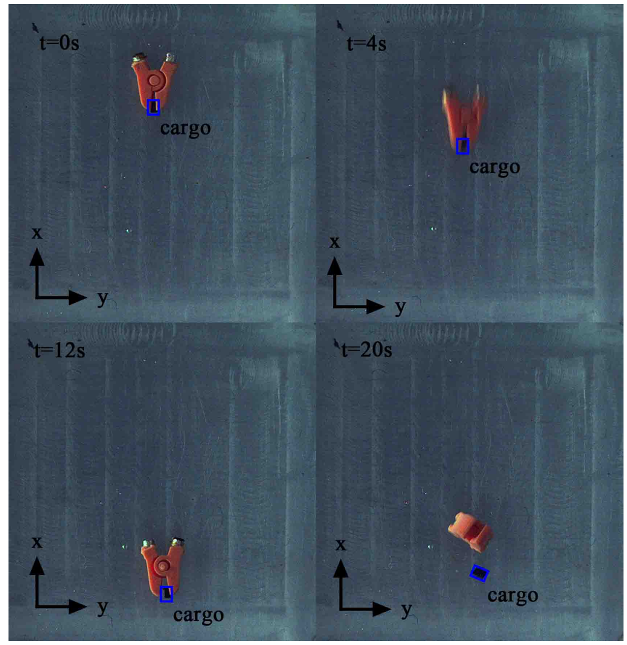


Fig. 11. Drug Delivery Experiment. The gripper carried a cargo and placed it at the designated location

coils are used to align the micro-gripper to the desired direction. Fig.10 shows a moving sequence of the micro-gripper under a current of 2A on the Maxwell Coils.

### C. Drug Delivery Experiment

This experiment is a combination of the first two experiments. The gripper is used to move a 1mm cube. As shown in Fig.11, the gripper first seized the cube and then carried it to the desired place. The cube was finally released after it reaches the destination.

## V. Conclusion

In this paper, we give a design of micro-gripper and applied it to drug delivery. A theoretical model had been set up and several experiments were performed to verify the functions of the micro-gripper. The experiment results showed that the micro-gripper was a safe and precise tool for drug deliver. In the future, we will pay attention to build a more accurate gripper model, improve the accuracy of control and apply visual feedback into the control system.

## References

[1] N. Simaan, R. M. Yasin, and L. Wang, Medical Technologies and Challenges of Robot-Assisted Minimally Invasive Intervention and Diagnostics, *Annual Review of Control, Robotics, and Autonomous Systems*,vol. 1, no. 1, pp. annurev-control-060117-104956, 2018

[2] J. J. Doulgeries, S. A. Gonzalez-Blohm, A. K. Filis,T. M. Shea, K. Aghayev, and F. D. Vrionis, Robotics in Neurosurgery: Evolution, Current Challenges, and Compromises, *Cancer Control Journal of the Moffitt Cancer Center*, vol. 22, no. 3, pp. 352-9, 2015.

[3] L. Qiao, and M. M. Souweidane, Purely endoscopic removal of intraventricular brain tumors: a consensus opinion and update, *Minim Invasive Neurosurg*, vol. 54, no. 04, pp. 149-154, 2011.

[4] B. J. Nelson, I. K. Kaliakatsos, and J. J. Abbott, Microrobots for minimally invasive medicine, *Annual Review of Biomedical Engineering*, vol. 12, no. 1, pp. 55-85, 2010.

[5] Federico Ongaro, Chang Kyu Yoon,Frank Van Den Brink,Momen Abayazid,Seung Hyun Oh,David H. Gracias, and Sarthak Misra, Control of untethered soft grippers for pick-and-place tasks, *IEEE International Conference on Biomedical Robotics and Biomechatronics*, 2016.

[6] J. C. Breger,C Yoon,R. Xiao,H. R. Kwag, M. O. Wang,J. P. Fisher,T. D. Nguyen, and D. H. Gracias, Self-folding thermo-magnetically responsive soft microgrippers, *Acs Applied Materials and Interfaces*, vol. 7, no. 5, pp. 3398-3405, 2016.

[7] Stefano Fusco, Mahmut Selman Sakar, Stephen Kennedy, Christian Peters, Salvador Pane, David Mooney, and Bradley J. Nelson, Self-folding mobile microrobots for biomedical applications, *IEEE International Conference on Robotics and Automation*, 2014.

[8] Jatinder S. Randhawa, Timothy G. Leong, Bassik Noy, Bryan R Benson, Matthew T Jochmans, David H. Gracias, Pick-and-place using chemically actuated microgrippers, *Journal of the American Chemical Society*, vol. 130, no. 51, pp. 17238-9, 2008.

[9] Cameron Forbrigger, Andrew Lim, and Onaizah Onaizah, Sajad Salmanipour, Thomas Looi, James Drake, and Eric D Diller, Cable-Less, Magnetically Driven Forceps for Minimally Invasive Surgery, *IEEE Robotics and Automation Letters*. IEEE, vol. 4, no. 2, pp. 1202–1207, 2019.

[10] Jiachen Zhang, Onaizah Onaizah, Kevin Middleton, Lidan You, and Eric Diller, Reliable grasping of three-dimensional untethered mobile magnetic microgripper for autonomous pick-and-place, *IEEE Robotics and Automation Letters*. IEEE, vol. 2, no. 2, pp. 835–840, 2017.

[11] Eric Diller, and Metin Sitti, Three-Dimensional Programmable Assembly by Untethered Magnetic Robotic Micro-Grippers, *Advanced Functional Materials*. Wiley Online Library, vol. 24, no. 28, pp. 4397–4404, 2014.

[12] Dominic R. Frutiger, Karl Vollmers, and Bradley E. Kratochvil, and Bradley J. Nelson, Small, fast, and under control: wireless resonant magnetic micro-agents, *The International Journal of Robotics Re-*

*search*. SAGE Publications Sage UK: London, England, vol. 29, no. 5, pp. 613–636, 2010.
[13] Sajad Salmanipour, and Eric Diller, Eight-degrees-of-freedom remote actuation of small magnetic mechanisms, *2018 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, pp. 1–6, 2018.
[14] Jürgen Rahmer, Christian Stehning, and Bernhard Gleich, Remote magnetic actuation using a clinical scale system, *PloS one*. Public Library of Science, vol. 13, no. 3, pp. e0193546, 2018.
[15] Aaron Becker, Yan Ou, Paul Kim, Min Jun Kim, and Agung Julius, Feedback control of many magnetized: Tetrahymena pyriformis cells by exploiting phase inhomogeneity, *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, pp. 3317–3323, 2013.
[16] Arthur W. Mahoney, Nathan D. Nelson, Kathrin E. Peyer, Bradley J. Nelson, and Jake J. Abbott, Behavior of rotating magnetic microrobots above the step-out frequency with application to control of multi-microrobot systems, *Applied Physics Letters*. AIP, vol. 104, no. 14, pp. 144101, 2014.
[17] Deasung Jang, Jinwon Jeong, Hyeonseok Song, Sang Kug Chung,Targeted drug delivery technology using untethered micro-robots: A review, *Journal of Micromechanics and Microengineering*. IOP Publishing, vol. 29, no. 5, pp. 053002, 2019.