Manipulation and Control of Microrobots Using A Novel Permanent Magnet Stage

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Abstract – This paper explores the implementation of a permanent magnet control stage for single particle and swarm control applications. The stage was designed to interact with alginate microparticles encapsulated with iron ferrite. We show that the permanent magnet stage can manipulate both single microrobots and swarms effectively.

Keywords - Cell based microrobot, Magnetic field, Motion control, Magnetic manipulation.

1. Introduction

Microrobotics is a vastly expanding and exciting field of research. Methods exist to manufacture hundreds of microscale robots using diverse array of materials and techniques [1-3]. Since microrobots are so small, they are ideal for minimally invasive medical procedures, targeted therapy, disease diagnosis, single-cell manipulation, and tissue engineering [4].

However, current fabrication constraints give microrobots little-to-no onboard computing or communication ability [3,5,6]. Instead, these microrobots are controlled externally through magnetic manipulation. Helmholtz and Maxwell coil configurations are often used for microrobot control. [7]. These systems produce a rotating magnetic field that can enable simultaneous control of three degrees of freedom (DOF). However, the use of high currents to power these systems produces heat, which can cause problems during experimentation and for the equipment [8].

Investigations into alternative methods to manipulate microrobots has recently turned to permanent magnets [8, 9]. Permanent magnets can provide the same or vastly stronger magnetic fields then those produced by coil based systems. Permanent magnets naturally produce magnetic fields and do not require external power.

In this paper, we propose a permanent magnet stage to manipulate single and swarms of microrobots. Using the magnetic gradient produced by the magnet, iron encapsulated alginate microrobots are dragged along the surface of the fluidic test chamber. The stage allows for precise control in the x-y plane.

2. Theory

2.1 Alginate microrobots

Alginate microrobots are used as the primary microrobot for this line of experimentation. The exterior of the microrobot consists of a hydrogel formed by a crosslinking process between Alginate-Na and Calcium Chloride [10]. During this process, it is possible to encapsulate iron ferrite particles if they are mixed with the Alginate-Na prior to hydrogel formation. The centrifuge based process for creating these microrobots is explored in detail in Ali et al, [7]. The alginate microrobots for this experiment had an average diameter of 300 μm.

2.2 Governing forces

As described in Gassner et al. [12], the equation for magnetic flux density of a permanent magnet is described by:

$$\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}) \tag{2}$$

where μ_0, $\boldsymbol{H}$, and $\boldsymbol{M}$ are the permeability of free space, the magnetic field, and the magnetization produced by the permanent magnet, respectively. The value for μ_0 is 1.256×10^{-6} H/m. Further analysis can be performed to find the magnetic force being exerted by the permanent magnet and displayed on the magnetic dipole moment $\boldsymbol{m}$. This can be seen in (3) below:

$$F_m = -\nabla(U) = \nabla(\boldsymbol{m} \cdot \boldsymbol{B}) = (\nabla \mathbf{m}) \cdot \mathbf{B} + \mathbf{m} \cdot \nabla \mathbf{B} \approx (\mathbf{m} \cdot \nabla)\mathbf{B} \tag{3}$$

where U represents the gradient of the magnetic dipole energy. Since the alginate microrobots encapsulate paramagnetic nanoparticles, therefore $\boldsymbol{m} = \mathcal{V}\boldsymbol{M} = \mathcal{V}\chi\boldsymbol{H}$ and the force can be rewritten as:

$$F_m = \frac{\mathcal{V}\chi}{\mu_0}(\boldsymbol{B} \cdot \nabla)\boldsymbol{B} \tag{4}$$

where $\mathcal{V}$ and χ is the volume of an alginate microrobot and the effective magnetic susceptibility, respectively. The fluid medium in this paper is a solution of Deionized Water and Tween 20, which has no inherent magnetic properties. As a result, the effective susceptibility of the medium is assumed to be 1.

These are not the only forces governing the microrobots. Drag force from surface friction is significant. At the small scale, forces such as gravity can be neglected and forces such as surface friction becomes more of an obstacle to overcome. For this reason, the drag the microrobots experience must be calculated in the total force equation. The drag force of a microrobot at low Reynolds Number [13], as is assumed when working in the microscale, can be written as:

$$F_d = 6\pi\mu\boldsymbol{V}R \tag{5}$$

where $\boldsymbol{V}$, D, and μ are defined as the velocity, radius of the microrobot, and the viscosity of the fluid, respectively. Since the fluid is remaining still in our case, the velocity is that experienced by the microrobot. When combining Eq. (4) and Eq. (5), the equation for the total force experienced by a microrobot is:

$$F_t = \frac{V\chi}{\mu_0}(\mathbf{B} \cdot \nabla)\mathbf{B} - 6\pi\mu\boldsymbol{V}R \tag{6}$$

3. Magnetic stage controller

3.1 Design of magnetic stage controller

The permanent magnet stage controller allows for a permanent magnet to move in the *xy*-plane directly below the testing area. The "Field of play," as we have termed it, describes the total accolated space the magnet can move in the *xy*-plane. The total space in the field of play, is 12 × 24 cm^2. Typically, the field of view is in the center of the field of play, which allows for the magnet to safely exit any time the magnetic field is not needed on the environment.

The magnet used in the experiments was a NdFeB, Grade N52 (KJ Magnetics, Pipersville PA, USA). With a maximum magnetic field of 14.8 T, for comparison, this magnetic flux is stronger than most applications using a Helmholtz coil system. The magnet size is 2.54 × 2.54 cm^2, with a thickness of 1.27 cm.

Using an Ardunio R3, two BigEasy Stepper Motor Drivers, and three stepper motors (Sparkfun.com); the stage was controlled through a designed graphic user interface (GUI) by way of a C++ program. Then, the Ardunio R3 generates a digital signal to BigEasy Stepper Motor Drivers in terms of the direction and number of steps. Stepper Motor Drivers controls the stepper Motors to follow the desired input rotation with a maximum acceleration.

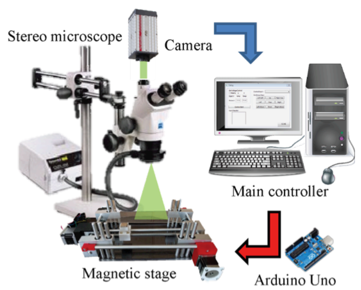

Figure 1: Experimental setup, magnetic stage controller can be seen directly below stereoscopic microscope.

4. Experimental Setup

After construction and assembly, the experiments were conducted under a Zeiss Stemi 2000-C Stereoscopic Microscope. The experimental images were observed through a Motion Pro X3 camera. All images were captured at a frame rate of 30 fps. Fig. 1 shows the experimental setup. From the initial inputs from the C++ program, the Arduino R3 relays the information to the stepper motor drivers. The control inputs passed through the drivers every 0.5 seconds. Thus, the permanent magnet moved with a velocity of 1.360 μm/s. The experimental chamber was made of Polydimethylsiloxane (PDMS). The chamber was filled with a solution of 10% Tween 20 and Deionized Water. 150 μm alginate microrobots were then inserted into the chamber. The microrobots were then manipulated in a sequential pattern.

5. Results

5.1 Motion control of single alginate microrobot

Actuation of the stage controller shows that the alginate microrobots are fully controllable. Initial commands began with a sequence of <up, right, down, left>, the alginate microrobots began to move with the magnets edge as the magnet moved in the desired direction. The alginate microrobot was manipulated to move in a square path. In this experiment, the interaction of one singular alginate microrobot was demonstrated to show the ability to overcome the drag force and the friction force of the environment. As the initial command was given the permanent magnet would move <up>, as the magnet moved over the alginate microrobot, the microrobot would not move until the trailing dipole of the magnet moved underneath. Following the magnets trailing dipole, the alginate microrobot moves to its destination. To allow the alginate microrobot to stop, the permanent magnet moves, in this case, <down> to the center of the microrobot. Through manipulation, a distance is created between the magnet and alginate microrobot, causing varied mobility depending on the robots location. .

In Fig. 3(a)-(c), a single alginate microrobot of 300 μm diameter was manipulated to spell 'SMU'. Due to the limited input direction, the heading angle for the motion of the alginate microrobot is not varied.

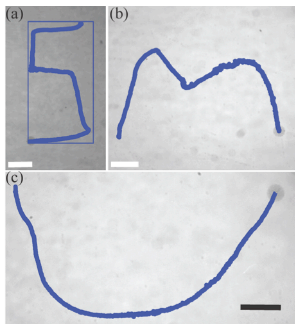

Figure 2: Single alginate microrobot controlled to spell the initials of Southern Methodist University: (a) S, (b) M, (c) U. Scale bar is 1mm

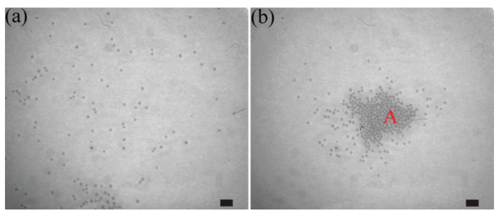

Figure 3: Gathering of an alginate particle swarm. a) shows the alginate particles spread out in the field of play. b) after several passes with the magnet, most particles are now concentrated in the center. Scale bar is 1mm

5.2 Swarming motion control

Using the suggested magnetic stage controller, it is available to move multiple alginate microrobots in a swarm. In order to swarm, the randomly distributed alginate microrobots must be gathered as a group. In the experiment, the separately located microrobots were illustrated in Fig. 3(a). Then, we located the permanent magnet at the 'A' position and the separately located individual microrobots were gathered around the 'A' position as shown in Fig. 3(b). The alginate microrobots were attracted by the magnetic field from the permanent magnet. However, the further alginate microrobot had less attraction force because of its location relative to the magnet.

Once the microrobots were gathered at the certain location, we made a swarm motion by moving the magnet. In Fig. 4(a), the more than 100 alginate microrobots were positioned at the left side. After the magnet moved toward the right side, they followed the magnet movement as shown in Fig. 4(b). As seen in Fig. 4, the drag forces of the alginate microrobots can be an issue at times. The trailing alginate microrobots of the swarm can be seen to have moved very little from the initial location of 0 s.

6. Conclusion

The proposed permanent magnet stage enables manipulation and control of microrobots. As shown in the experiments, a single microrobot can be manipulated to perform several individual tasks. A large swarm of microrobots can also be manipulated as well. As this system does not produce a rotating magnetic field, it is shown that the drag force being produced by the magnet is sufficient to control the alginate microrobot(s).

Acknowledgement

This work was supported by the National Science Foundation (IIS 1619278 and IIS 1712088)

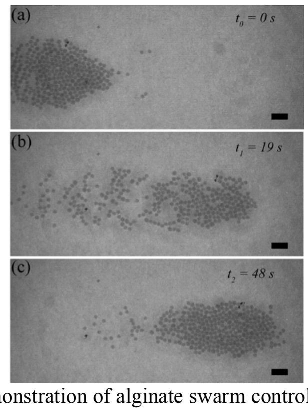

Figure 4: demonstration of alginate swarm control. a) shows the starting positon of the swarm, b) shows the swarm moving to the right with a noticeable dispersion of the swarm due to the magnetic gradient from the magnet, c) shows the final swarm re-coalescing at the end position. Scale bar is 1mm

References

[1] Rubenstein, M., Ahler, C., Nagpal, R. Kilobot: A low cost scalable robot system for collective behaviors. in Robotics and Automation (ICRA), 2012 IEEE International Conference on. 2012.

[2] Ou, Y., Kim, D.H., Kim, P.S.S., Kim, M.J., Julius, A.A., Motion control of magnetized Tetrahymena pyriformis cells by a magnetic field with Model Predictive Control. Int. J. Rob. Res., 2013. 32(1): p. 129-139.

[3] Chiang, P.-T., Mielke, J., Godoy, J., Guerrero, J. M., Alemany, L. B., Villagomez, C. J., Saywell, A., Grill, L., Tour, J. M., Toward a light-driven motorized nanocar: Synthesis and initial imaging of single molecules. ACS Nano, 2011. 6(1): p. 592-597.

[4] Sitti, M., Ceylan, H., Hu, W., Giltinan, J., Turan, M., Yim, S., Diller, E., Biomedical applications of untethered mobile milli/microrobots. Proceedings of the IEEE, 2015. 103(2): p. 205-224.

[5] Chowdhury, S., Jing, W., Cappelleri, D., Controlling multiple microrobots: recent progress and future challenges. J. Micro-Bio Robotics, 2015. 10(1-4): p. 1-11.

[6] Donald, B.R., Levey, C.G., Paprotny, I., Rus, D., Planning and control for microassembly of structures composed of stress engineered MEMS microrobots. Int. J. Robot. Res., 2013. 32(2): p. 218-246.

[7] Ali, J., Cheang, U., Liu, Y., Kim, H., Rogowski, L., Sheckman, S., Patel, P., Sun, W., Kim, M.J. *Fabrication and Magnetic Control of Alginate-based Soft-microrobots. APL (2016)*

[8] P. Ryan and E. Diller, "Five-degree-of-freedom magnetic control of micro-robots using rotating permanent magnets," *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016.

[9] A. W. Mahoney and J. J. Abbott, "Generating Rotating Magnetic Fields With a Single Permanent Magnet for Propulsion of Untethered Magnetic Devices in a Lumen," *IEEE Transactions on Robotics*, vol. 30, no. 2, pp. 411–420, 2014.

[10] Mørch, Ý .A., Donati, I., Strand, B. L., Skjåk-Bræ k, G., Effect of Ca2+, Ba2+, and Sr2+ on alginate microbeads. Biomacromolecules, 2006. 7(5): p. 1471-1480.

[11] S. Haeberle, L. Naegele, R. Burger, F. von Stetten, R. Zengerle, and J. Ducree, J. Microencapsulation **25** (4), 267 (2008).

[12] A.-L. Gassner, M. Abonnenc, H.-X. Chen, J. Morandini, J. Josserand, J. S. Rossier, J.-M. Busnel, and H. H. Girault, "Magnetic forces produced by rectangular permanent magnets in static microsystems," *Lab on a Chip*, vol. 9, no. 16, p. 2356, 2009.

[13] J. Kim and S. Lee, "Modeling drag force acting on the individual particles in low Reynolds number flow," *Powder Technology*, vol. 261, pp. 22–32, 2014.