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Manipulation and Control of Microrobots Using A Novel Permanent Magnet Stage

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Abstract - Controlling microrobots in the past have required the used of heavy coil systems and large power supply units, in this paper we show that a strong permanent magnet is sufficient for the control scheme. The development of a controlling stage was deemed to be a priority and allowed for the manipulation of microrobots, otherwise known as alginate particles or artificial cells, in the *xy*-plane. We show that the permanent magnet stage can manipulation both single microrobots and swarms. The permanent magnet stage, has the dimensions of 22.86 × 35.56 cm^2, by 15.26 cm in height. This allows for a permanent magnet to move in the *xy*-plane a total area of 12 x 24 cm^2. Additionally, the permanent magnet to be interchangeable introduces the possibility to investigate different type of magnetic fields. Our experiments were performed using a NdFeB, Grade N52 permanent magnet which provides a maximum magnet flied of 14.8 T.

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

1. Introduction

Microrobotics is a vastly expanding and exciting field of research. Engineers and scientists, through published papers displaying over decades of work, have shown the ability to manufacture large populations (102-1014) of small scale (109-106 m) robots using diverse array of materials and techniques [1-3]. Since these microrobots are so small, they are ideal for several invasive medical procedures; such as, but not limited to: minimally invasive surgery, targeted therapy, disease diagnosis, single-cell manipulation and tissue engineering [4].

These microrobots are wireless controlled through magnetic manipulation. Since microrobots are so on the micro scale provides unique challenge to control; as limits in fabrication do not allow for or have little-to-no onboard computing or communication ability [3,5,6]. Through previous work and investigation, the use of a Helmholtz or Maxwell coil systems were the controlling mechanism to manipulate the microrobots [7]. These systems produce a rotating magnetic field, that can allow for three degrees of freedom (DOF) to be used at the same time. A caveat of such investigations is the use of heavy power supplies to introduce the necessary current to produce the magnetic field. The use of high currents produce heat, which can cause problems during experimentation and for the equipment [8].

Investigations into alternative methods to perform manipulation of microrobots has recently turned to permanent magnets [8, 9]. Since permanent magnets can provide the same or vastly stronger magnetic field then those produced by the previous systems. Permanent magnets do not need current or any expensive power supplies to create a magnetic field, as these materials naturally produce one.

In this paper, we propose a new method to manipulate single and swarms of microrobots. Through the development of a permanent magnet stage, it is shown that control of microrobots in a two DOF system can be performed. Placing the experimental region on a platform with moving *x* and *y*-axes, allows for the microrobots to be dragged through the medium and to its final designation. For the investigations mentioned in [8, 9], these magnetic fields are rotating. This system moves underneath, or above the experimental region as a stationary magnet. Thus, allowing the uniform magnetic field to come from one sole source.

2. Theory

2.1 Alginate microrobots

Due to their biocompatibility, polysaccharide based hydrogels, alginate microrobots or artificial cells, are used as the primary microrobot during experimentation. The formation of the hydrogel is caused by a crosslinking process between Alginate-Na and Calcium Chloride [10]; other crosslinking agents are available, but calcium is the only one that is not harmful to the body. The encapsulated the payload can be released using chelating agents, most prominently ethylenediaminetetraacetic acid (EDTA). Using a solution of Sodium Alginate and iron oxide paramagnetic nanoparticles and interacting with Calcium Chloride, the artificial cells are created using a centrifuge method as described in previously published work, Ali et al. [7], this method can produce alginate microrobots of various diameters. Paramagnetic nanoparticles are encapsulated to allow for steerable propulsion. The governing equation for determining the size of the alginate microrobots is explained as :

$$d_p = \sqrt[3]{\frac{6\, d_n\, \sigma_p}{\rho_p\, g}} \qquad (1)$$

where d_n, σ_p, ρ_p, and g, are the diameter of the nozzle, surface tension of the alginate solution, density of alginate solution, and the applied gravitational force, respectively. The surface tension of alginate is 65.46 mN/ m [11], and a density of 1.1 g/cm^3.

2.2 Governing forces

Governing the controlling system is the permanent magnet, distributing the magnetic field upon which the microrobots are being manipulated. As described in [12] and [13], using the equation for magnetic flux density of a permanent magnet can be found as:

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

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 $\times 10^{-6}$ 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 $\boldsymbol{m}$.

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

where U represents the gradient of the magnetic dipole energy. Since the alginate microrobots encapsulate paramagnetic nanoparticles and the microrobots are in a non-magnetic fluid, therefore $\boldsymbol{m} = \boldsymbol{V}\boldsymbol{M} = \boldsymbol{V}\chi\boldsymbol{H}$. From equations (1) and (2), as well knowing the relationship of $(1 + \chi)$ as the relative permeability of the media, represented by μ_r; the force can be rewritten as:

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

where 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, this solution is shows no magnetic properties. Thus, 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 needs to be factored. 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 are experiencing needs to be calculated in the total force equation. The drag force of a microrobot at low Reynolds Number [14], as is assumed when working in the microscale, can be written as:

$$F_d = 6\pi\mu\boldsymbol{V}R \quad (5)$$

where 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 experience by the microrobot. When combining Eq. (4) and Eq. (5), the equation for the total force experienced by a microrobot to be:

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

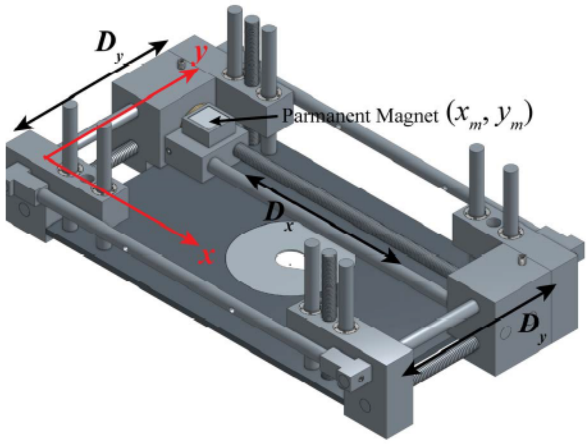

Fig. 1. Design of the magnetic stage controller

3. Magnetic stage controller

3.1 Design of a magnetic stage controller

The proposed permanent magnet stage controller would allow for interchangeable permanent magnets. This parameter of design became of utmost importance, as different application would require a different magnetic field. Depending on the size of the magnet field, the "Field of play" needs to be large enough so when the magnet is not being used, it would not interfere with any microrobot shown in the field of view. "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. The field of view, displayed through a microscope allows for movement to viewed and physically analyzed. 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 needed on the environment.

An additional parameter of the design was that the stage must work on an inverted microscope and a stereoscopic microscope. This would allow for a smaller and smaller field of view and smaller microrobots to be investigated; as inverted microscopes allow for interchangeable optics to be used, generating greater magnification than that of traditional stereoscopic microscopes. As such, there were some imitations to the size of the stage. Using a Olympus IX50 inverted microscope as the basis for the stage dimensions, the overall length of the stage comes to be 22.86 × 35.56 cm^2. The height of the stage is 15.24 cm, from the base of to the top of the *Z*-axis. Figure 1 shows the CAD model of the stage, as it would be used under a Zeiss Stemi 2000-C stereoscopic microscope.

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, the magnetic flux being produced by the permanent magnet is already 1000 times 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.

`Raw material for the stage was 6061 T-6 Aluminum (McMaster-Carr, Atlanta Ga, USA). The base is a 1.27 cm thick polycarbonate sheet. Stepper motor holders were designed in CAD and printed by using 3D printer.

3.2 Electric control system

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. Using programmed C++, it allows giving the control input signal to the Ardunio R3 by USB communication during the sampling time of 0.5 s. Then, the Ardunio R3 generates the digital signal to BigEay Stepper Motor Drivers in terms of the direction and the turn of steps. Stepper Motor Drivers controls the stepper Motors to follow the desired input rotation with a maximum acceleration.

Each input was manually entered into the C++ based GUI, then, the magnetic would move as a continuous function, or in single steps. The time step of the movement was shortened to very small value to allow the magnetic particles to move across the field of view. If the magnet moved to quickly, the particles would not react to magnetic field. A balance between speed and strength of the magnet needed to be found.

4. Magnetic stage controller

4.1 Experimental setup

As described in the previous section the permanent magnet stage that we propose was built using manufacturing equipment and a 3D printer. After constructed and assembled, the experiments were conducted under a Zeiss Stemi 2000-C Stereoscopic Microscope. The experimental images were observed

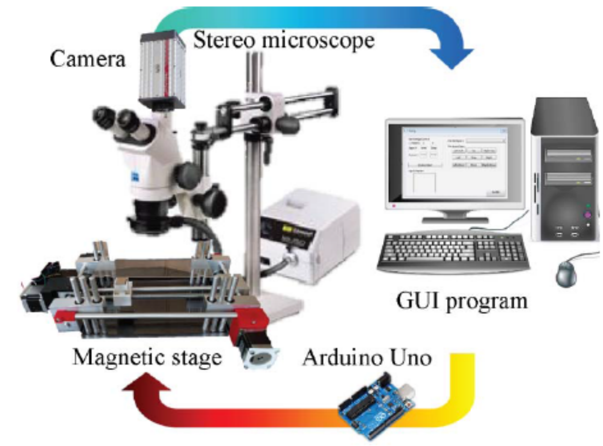

Fig. 2. Experimental setup

through a Motion Pro X3 camera. All images were captured at a frame rate of 30 fps. Fig. 2 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.

4.2 Alginate microrobots

The hydrogels are manufactured beads that are called alginate microrobots or artificial cells. Using a 27 gage needle and varying the applied gravitational force, microrobots of varying diameters were produced. Using a solution of 5% (w/v) Sodium Alginate and iron oxide paramagnetic nanoparticles 10% (w/v) and interacting with 5% (w/v) Calcium Chloride (Sigma-Aldrich, St. Louis Mo, USA), the alginate microrobots were produced. Alginate microrobots at 150 microns in diameter can be seen in Fig. 3.

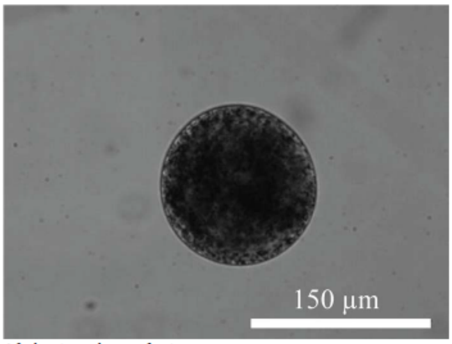

Fig. 3. Alginate microrobot

4.3 Motion control of single alginate microrobot

Actuation of the stage controller can show that the manufactured microrobots can be fully controllable. Initial commands began with a sequence of <up, right, down, left>, the alginate microrobots began to move as the magnet moved underneath. The initial position of the alginate microrobot was manipulated to create a box. In this experiment, the interaction of one singular alginate microrobot was demonstrated to show the ability to overcome the drag force using the magnetic field of a permanent magnet. Still, overcoming the drag of the alginate microrobot proved to be an individual challenge and required play with the control scheme of the permanent magnet location. The permanent magnet was initially placed in the center of the field of view. At this point the alginate microrobot would not move. As the initial command was given the permanent magnet would

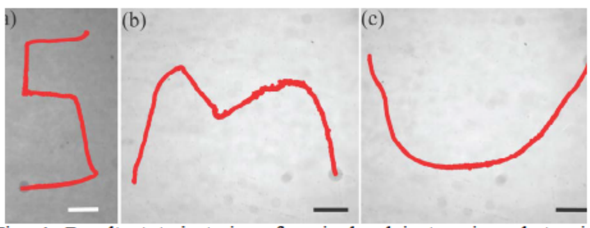

Fig. 4. Resultant trajectories of a single alginate microrobot using manual control. (a) 'S' trajectory during s, (b) 'M' trajectory during 109 s, (c) 'U' trajectory during 61 s. The scale bar represents 1 mm.

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, where the magnet moves through the field of play with a velocity of 1.36 μm/s, a distance is created between the magnet and alginate microrobot, as such the alginate microrobot followed the permanent magnet with a varied mobility. 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 aglginate microrobot is not varied.

4.4 Swarming motion control

Using the suggested magnetic stage controller, it is available to move multiple alginate microrobots and they swarm as a group. In order to swarm, the randomly distributed alginate microrobots need to be gathered as a group. The alginate microrobots in this experiment are approximately 300 μm in diameter. In the experiment, the separately located microrobots were illustrated in Fig. 5(a). Then, we located the permanent magnet at the 'A' position and the separately located individual microrobot were gathered around the 'A' position as shown in Fig. 5(b). The alginate microrobots were attracted by the magnetic field from the permanent magnet. However, the alginate

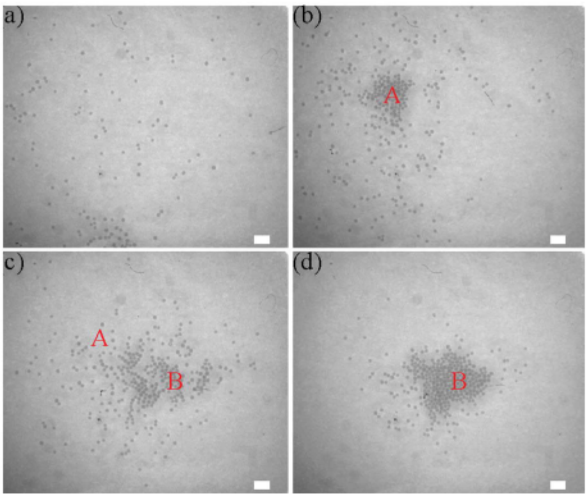

Fig 5. Building motion for swarming group of alginate microrobots. (a) Initial distribution of each alginate microrobot at 0 s, (b) The instant motion when the permanent magnet was located at 'A' position during 34 s, (c) The resultant location of alginate microrobots when the magnet was relocated the 'B' position after 45 s passed from (b), (d) The final location of all microrobots after 28 s. The scale bar represents 1 mm.

microrobot had less attracted force because of the long distance from the permanent magnet. Thus, the permanent magnet was moved to the 'B' position in order to put those alginate microrobots close to the magnet. As a result, the most alginate microrobots were gathered around the 'B' position as indicated in Fig. 5(d). As the magnet moved around the boundary of field, it will help gather all microrobot since the m can be of a strong magnetic field area.

Once the microrobots were gathered at the certain location, we made a swarm motion by moving the magnet. In Fig. 6(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. 6(b). As seen in Fig. 6, the drag forces of the alginate microrobots can be an issue at times. The trailing

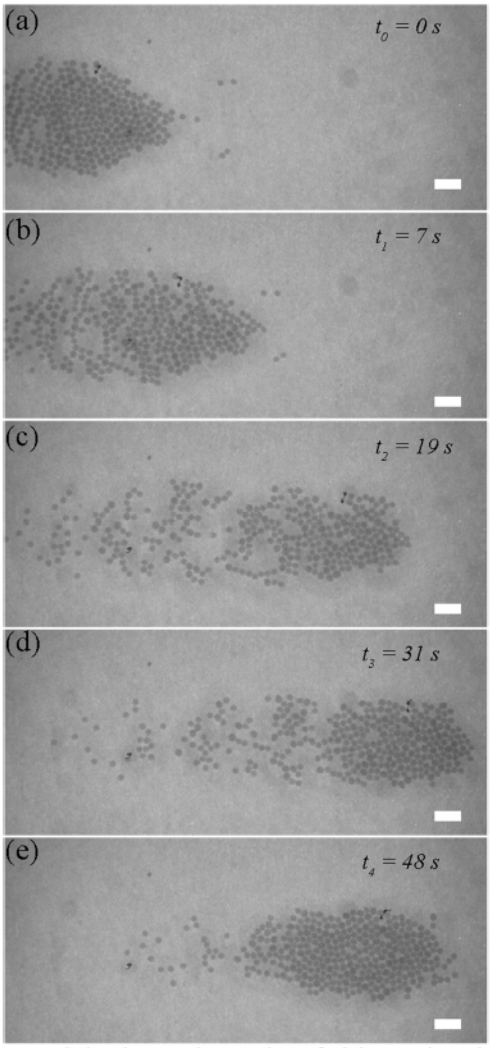

Fig. 6. Translational swarming motion of alginate microrobots. (a) Initial positions of a swarming group at 0 s, The permanent magnet headed toward the right side forward the front of alginate microrobots and the motion was shown at (b), (c), (d), and (e). The scale bar represents 1mm.

alginate microrobots of the swarm can be seen to have moved very little from the initial location of 0 s.

4.5 Transportation task using swarm motion

Following the experiments with alginate microrobot swarms, an additional task of moving a singular object was perused. In this experiment, the diameter size of the alginate microrobots are 300 μm. Using a 2.6 × 2.7 mm piece of PDMS, the alginate microrobots were then manipulated to move from their initial position seen in Fig. 7(a), as the magnet was moved from this position to is final position, the microrobots moved underneath of the PDMS piece. The some microrobots were in contact with the piece as the flow moved it across the field of view. Figure 7(d) shows the final position of the piece. The total distance the PDMS piece moved was 7.6 mm, over a 34 s span. This experiment result indicates that the swarming alginate microrobot are available to do microscale transportation task in the low Reynolds number.

5. Conclusion

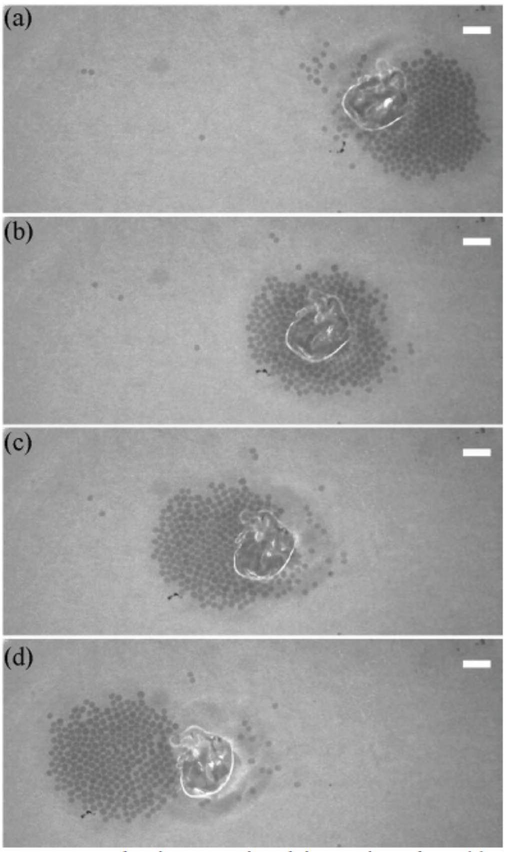

Fig. 7. Transport task using swarming alginate microrobots. (a) Initial positions of a swarming group and a PDMS chunk(0 s), (b) Transport task motion at 16 s, (c) Transport task motion at 25 s, (d) Transport task motion at 34 s. The scale bar represents 1mm.

The permanent magnet stage that we have proposed, shows the manipulation and control of microrobots can be performed. 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 enough to control the alginate microrobot.

Acknowledgement

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