INDEPENDENT ACTUATION AND MASTER-SLAVE CONTROL OF MULTIPLE MICRO MAGNETIC ACTUATORS

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ABSTRACT

We developed a new method to realize independent actuation and real-time positon control of "multiple" micro magnetic actuators. It is well known that it is almost impossible to drive a multiple number of magnetic dipoles independently in one magnetic field. To solve this problem, we developed a unique actuation/control scheme and utilized helical-shaped micro magnetic actuators and specially designed device to generate rotating magnetic fields. We succeed to obtain good experimental results to verify both theory and device. By using this system, variety of the micro actuators in many applications should be extended drastically.

INTRODUCTION

Micro actuators are used for various applications such as drug delivery and micro surgery. Micro magnetic actuators, which are controlled by an external magnetic field, are relatively safe for these applications because the magnetic field is harmless to biological tissues. In addition, their remote controllability enables in vivo actuation. Micro size actuators work in small regions, making it possible to measure the properties of tiny objects by physical contact.

The control of multiple micro magnetic actuators is a promising approach to extend the variety of their functions in many applications, for example, the delivery of different types of medicines or gripping small objects. However, multiple independent control is one of the most difficult challenges in the field of micro magnetic actuator because Helmholtz coils, which have been widely used to drive the actuators, generate only uniform magnetic fields in the workspace, and the actuators receive the same field.

Many researchers have studied multiple independent control of micro magnetic actuators. Salehizadeh et al. [1] controlled the formation of two micro magnetic spheres by using a global field and their interaction. Floyd et al. [2] controlled multiple magnetic agents actuated by the stick-slip motion. Steager et al. [3] superposed both the local and global magnetic fields, and controlled the positions of multiple magnetic agents. Wong et al. [4] controlled two magnets simultaneously in two dimensions using four coils.

There are two main categories of the actuation methods used for micro magnetic actuators. In the first method, the actuators are pulled by applying a field gradient while in the second method, propulsive force is supplied by applying a rotating magnetic field. In a micro scale region where the Reynolds number is low, it is known that the second method is more effective because the viscosity of the liquid becomes dominant [5]. In this method, the actuators are fabricated in the shape of a screw or helix and magnetized. By applying an external rotating magnetic field and torque, the actuators rotate independently, and are propelled forward. Yasui et al. [6] developed helical micro magnetic actuators with a size of 5 μm using microstereolithography and controlled single actuator by Helmholtz coils.

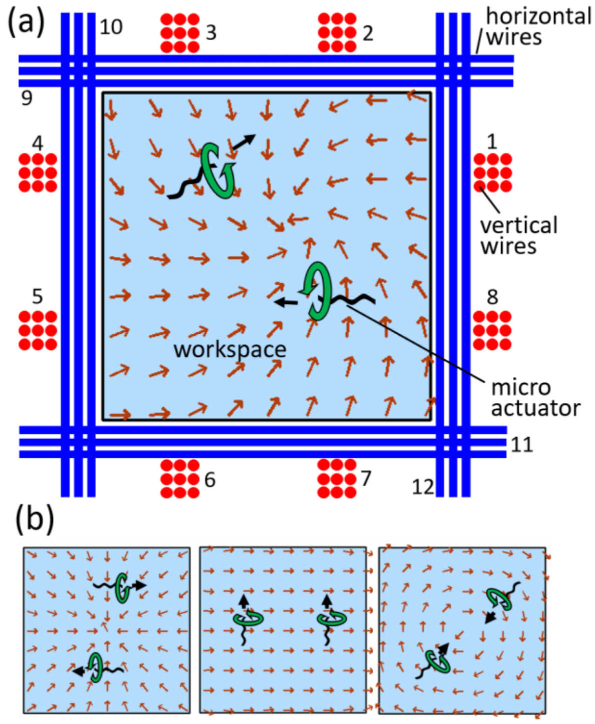

Figure 1: (a) Top view of the schematic diagram of the device and simulated magnetic fields. Small brown arrows represent the directions of the superposed magnetic field, green arrows represent the rotation of the actuators. Black arrows indicate the propulsion directions. The actuators follow different rotating magnetic fields and swim in different directions. (b) Examples of the simulation.

Several researchers have investigated multiple control methods with rotating magnetic field. Tottori et al. [7] developed helical magnetic actuators with bar-shaped heads and cross-shaped heads, and differentiated their reactions to external fields. Diller et al. [8] also differentiated the shapes and magnetization of the actuators and implemented independent control of multiple actuators. However, these methods involve the preparation of accurately fabricated agents because the difference among the actuators is the key to differentiating their motions. Moreover, the propulsion directions are restricted, which prevents arbitrary motions.

In this paper, we propose a novel actuation scheme to realize independent control of multiple helical-shaped micro magnetic actuators without Helmholtz coils. This method is able to control two helical magnetic actuators simultaneously in two dimensions by the superposing rotating magnetic fields. In this method, differentiating the properties of the actuators is not required, and it allows arbitrary motion.

METHODS

Our proposed device consists of 12 bands of wires (Figure 1 (a)). The bands are independent, and both positive and negative electrical currents can be applied. Different arbitrary magnetic fields can be generated at two arbitrary points in the workspace by superposing the magnetic fields from each band. The applied torque **T** to the actuator is expressed as:

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

where **m** is the magnetic moment of the actuator, and **B** is the magnetic field at the position of the actuator. By applying different magnetic fields at the two positions where the actuators exist, they rotate in arbitrary directions.

Eight of the 12 bands are extended perpendicular to the surface of the workspace to apply magnetic fields in the xy direction. They are numbered from 1 to 8. The remaining 4 bands are extended horizontally to the surface to apply fields in the z direction. They are numbered from 9 to 12. They are located close to the workspace, and are long enough compared to the size of the workspace. Since the remaining parts of the bands are far enough from the workspace, the bands can be assumed to be infinitely long.

The magnetic field at point p generated from the applied current at the i-th band, $B_{i,\ p}$ is derived from Ampere's circuital law:

$$B_{i,p} = \mu \frac{nI_i}{2\pi r_i(p)} \tag{2}$$

where μ is the magnetic permeability, which is approximated to μ_0—its value in vacuum. n is the number of wires in each band, and its value is always the same for all bands. I_i is the electrical current applied to the i-th band. $r_i(p)$ is the distance from the i-th band to the point p.

We aim to compute suitable currents to be applied based on the desired target magnetic fields at two points. The target fields at points p, q are defined as $\mathbf{b}_p = \{B_{p,\ x},\ B_{p,\ y},\ B_{p,\ z}\}^T$, $\mathbf{b}_q = \{B_{q,\ x},\ B_{q,\ y},\ B_{q,\ z}\}^T$, respectively. The maximum magnetic field generated from the i-th band at point p is defined as $\mathbf{b}_{i,\ p} = \{B_{i,\ p,\ x},\ B_{i,\ p,\ y},\ B_{i,\ p,\ z}\}^T$. The equations for xy values is obtained as:

$$\mathbf{b}_{p,q,xy} = \mathbf{B}_{p,q,xy}\mathbf{a}_{xy} \tag{3}$$

$$\mathbf{b}_{p,q,xy} = \begin{bmatrix} B_{p,x} & B_{p,y} & B_{q,x} & B_{q,y} \end{bmatrix}^T \tag{4}$$

$$\mathbf{B}_{p,q,xy} = \begin{bmatrix} B_{p,x,1} & B_{p,x,2} & \cdots & B_{p,x,8} \\ B_{p,y,1} & & & \\ B_{q,x,1} & & \ddots & \vdots \\ B_{q,y,1} & & \cdots & B_{q,y,8} \end{bmatrix} \tag{5}$$

$$\mathbf{a}_{xy} = \begin{bmatrix} a_1 & a_2 & \cdots & a_8 \end{bmatrix}^T \tag{6}$$

where a_i is the coefficient of the current applied to the i-th band. a_i must satisfy the restriction $-1 \leqq a_i \leqq 1$. When the coefficient is 1, maximum current is applied in the positive direction, and vice versa. This matrix equation is underdetermined. $\mathbf{a}_{xy}$ with minimum norm is obtained by solving the pseudo-inverse matrix:

$$\mathbf{a}_{xy} = \mathbf{B}^t{}_{p,q,xy}(\mathbf{B}_{p,q,xy}\mathbf{B}^t{}_{p,q,xy})^{-1}\mathbf{b}_{p,x,xy} \tag{7}$$

However, a_i in $\mathbf{a}_{xy}$ does not always satisfy the restriction $-1 \leqq a_i \leqq 1$. Therefore, $\mathbf{a}_{xy}$ is normalized as:

$$\mathbf{a}'_{xy} = \frac{\mathbf{a}_{xy}}{\max\{a_i\}} \tag{8}$$

$\mathbf{a}_z$ is also calculated as:

$$\mathbf{b}_{p,q,z} = \mathbf{B}_{p,q,z}\mathbf{a}_z \tag{9}$$

$$\mathbf{b}_{p,q,z} = \begin{bmatrix} B_{p,z} & B_{q,z} \end{bmatrix}^T \tag{10}$$

$$\mathbf{B}_{p,q,z} = \begin{bmatrix} B_{p,z,9} & B_{p,z,10} & B_{p,z,11} & B_{p,z,12} \\ B_{q,z,9} & B_{q,z,10} & B_{q,z,11} & B_{q,z,12} \end{bmatrix} \tag{11}$$

$$\mathbf{a}_z = \begin{bmatrix} a_9 & a_{10} & a_{11} & a_{12} \end{bmatrix}^T \tag{12}$$

and we obtain $\mathbf{a}'_z$ in a similar manner.

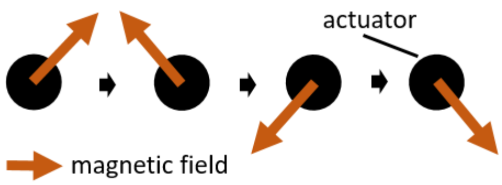

Figure 2: Four superposed magnetic fields to create rotation.

By updating these $\mathbf{b}_p$ and $\mathbf{b}_q$ each time, the desired rotating magnetic fields are generated. In this work, the rotating magnetic fields are expressed as four fields (Figure 2) for computing and transmission to generate high frequency. Fields that are 45°, 135°, 225°, 315° perpendicular to the propulsion directions are applied one after the other. Therefore, each time the positions p, q are updated, four types of $\mathbf{a}'_{xy}$ and $\mathbf{a}'_z$ are recalculated.

Figure 1 (b) shows examples of the simulated magnetic fields.

EXPERIMENT

Micro Actuator

The micro magnetic actuators were fabricated by the microstereolithography process (Figure 3) proposed by Ikuta et al. [9]. The material was made up of photo-curable resin (SCR 950), 10 wt% ferrite particles, 0.2wt% thickener (AIROSIL 300) to prevent the aggregation of the ferrite particles, and 0.008wt% microcapsules (SN-80SDE) to adjust the density. The mixed liquid was

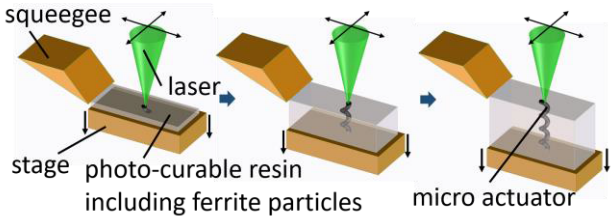

Figure 3: Fabrication process of the micro magnetic actuator by microstereolithography, which is capable of making arbitrary 3D structures.

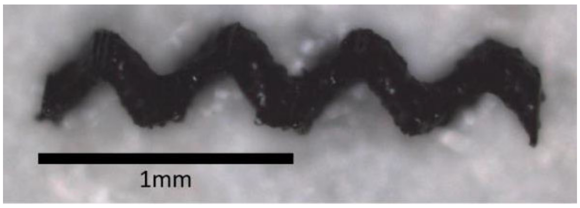

Figure 4: Fabricated helical micro magnetic actuator.

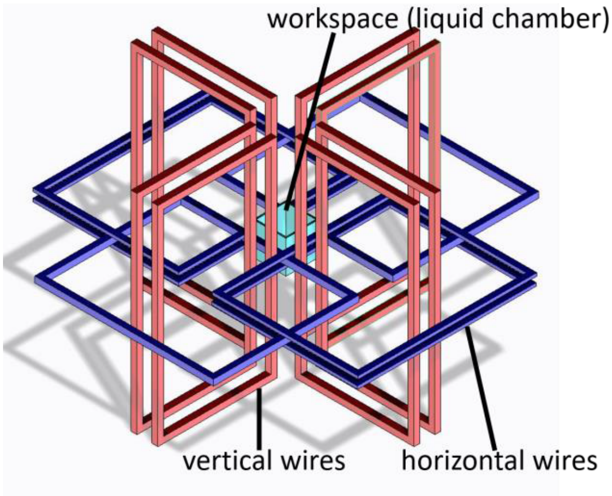

Figure 5: Structure of the actuation device.

solidified into a helical shape (Figure 4). The fabricated actuator was magnetized in a direction orthogonal to its long axis by laying it near a neodymium magnet overnight.

Actuation Device

The positions of the workspace and the bands must be accurately known since the calculated values of the currents change with respect to these positions. Figure 5 shows the structure of the device. The workspace was a cube of 10 mm. The number of wires per one band was 25, and the diameter of the wire was 0.315 mm. Bands 1–8 were arranged in a point symmetric configuration. Bands 9–12 were located at the center of the height of the workspace. Since bands 9–12 interfere with each other physically, bands 9 and 11 were separated in the upper and lower parts. Each band was rolled such that each side was 70 mm. The currents applied to the bands were controlled by Arduino Due. The currents were amplified up to 2A.

Feedback System

A camera (Grasshopper GRAS-03K2C) with a micro lens (NAVITAR TV ZOOM 7000) was placed above the device

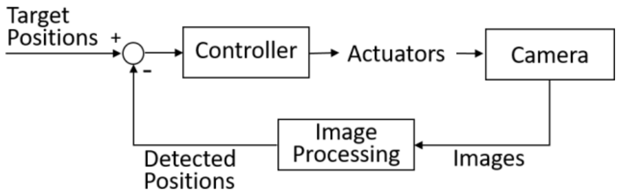

Figure 6: Schematic diagram of the feedback system.

to observe the motion of the actuators in real time. The captured images were processed by the template matching method to track the positions of the actuators. The desired rotating magnetic fields were computed based on the detected positions and the target positions, and the values of the currents were calculated using the algorithm explained in the above section. The values of the currents were transmitted to Arduino Due as signals. This feedback technique was implemented in C++. Figure 6 shows the schematic diagram of the feedback system.

Experimental Condition

To fix the height where the actuators swim, the workspace was filled with liquids, a mixture of glycerin and water (6:4), and oil (ISO VG15) to create a fluid interface in which the actuators swim. The liquids are viscous enough to weaken the gradient force by the magnetic field and to increase the propulsive force by the rotation.

The motion of two micro actuators were controlled independently and simultaneously in 2D. Two target positions were preset using our program, which move in different directions, and the actuators propelled to these positions respectively. The rotation frequency was set as 20 Hz.

RESULTS

Figure 7 (a) shows snapshots of the actuation experiment. We defined the actuators as A and B, and the target positions as A' and B'. In the images, A' moves from the upper left to the upper right, while B' moves from the lower right to the lower left.

Figure 7 (b) shows the trajectories of the actuators. Since the initial positions were arbitrary, there were large differences between the positions of the actuators and the target positions at 0 s. However, once the actuation control begins, both A and B propel to the target positions. Around 8 s, A went over A', but recovered its trajectory as a result of the implemented feedback control.

Our method did not use Helmholtz coils; therefore, the field gradient forces must pull the actuators to outside the workspace. However, the high viscous liquid weakens the influence of the forces. High viscous liquids tend to impede the rotation of the actuators, but they actually followed the 20 Hz rotating magnetic fields.

In our experiment, the actuators were propelled in different directions, although they exist in the same workspace. They followed the target positions moving in different directions. Our system controlled two magnetic helical micro actuators independently and simultaneously.

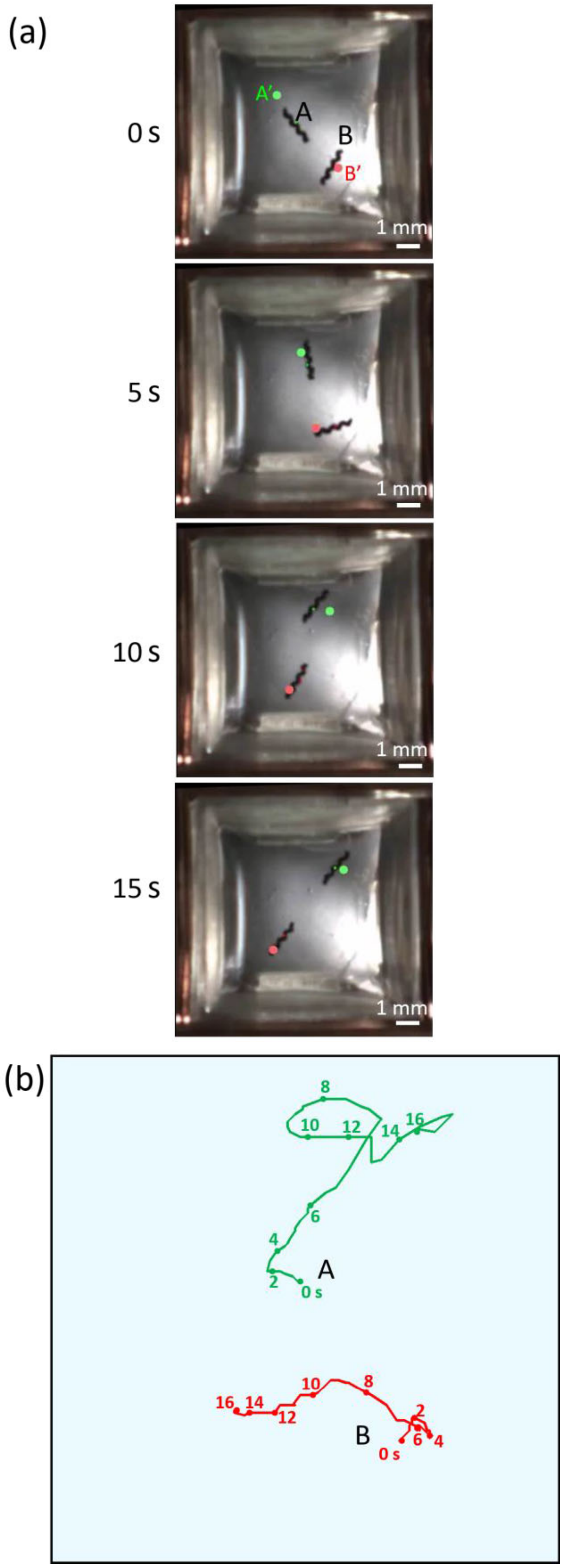

Figure 7: (a) Time series snapshots of the actuation experiment. Green and red circles are the target positions. Actuators A, B swim and follow the target positions. (b) Trajectories of the actuators. The numerical values are the time (s). Each actuator moves in a different direction independently.

CONCLUSIONS

In this paper, we proposed a new method to control multiple helical micro magnetic actuators independently. A superposition of the magnetic fields was carried out and arbitrary rotating magnetic fields were generated at two positions. We developed a device and conducted an actuation experiment in which two actuators were independently controlled. Although the actuation was limited to 2D in the experiment, the proposed device was able to generate magnetic fields in 3D space. To extend our method to 3D actuation, we must redesign a visual feedback system.

ACKNOWLEDGEMENTS

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