Sensors and Actuators A 215 (2014) 77–82

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Micro-object manipulation in a microfabricated channel using an electromagnetically driven microrobot with an acoustically oscillating bubble

Jun O Kwon, Ji Sun Yang, Jeong Byung Chae, Sang Kug Chung*

Department of Mechanical Engineering, Myongji University, Yongin 449-728, South Korea

ARTICLE INFO

Article history:
Received 15 April 2013
Received in revised form 5 April 2014
Accepted 7 April 2014
Available online 6 May 2014

Keywords:
Microrobot
Microbubble
Microstreaming
Micromanipulation
Target drug delivery

ABSTRACT

This paper presents an untethered microrobot swimming in human blood vessels through electromagnetic actuation to manipulate bio/micro-objects using an acoustically oscillating bubble attached to the microrobot as a grasping tool. First, for the three-dimensional (3D) actuation of the microrobot in arbitrarily shaped blood vessels, an electromagnetic system consisting of horizontal and vertical pairs of Helmholtz and Maxwell electric coils is designed and manufactured, and the magnetic flux density generated from the designed system is verified with theory. Using the developed electromagnetic system, the actuation of a spherical microrobot (800 μm dia.) made of a cylindrical neodymium magnet covered with clay is successfully demonstrated in *X*–*Y* and *X*–*Z* planes along with a T-shaped glass channel. Second, micro-object manipulation using an acoustically oscillating bubble is separately investigated. When a bubble is acoustically excited by a piezoactuator around its natural frequency, it oscillates and simultaneously generates microstreaming and secondary radiation force, which can be used to capture a neighboring object. The capturing distance of an acoustically oscillating bubble (550 μm dia.) and its oscillation amplitude in different frequencies and voltages are measured by using a fish egg (1 mm dia.) and high-speed camera, respectively. The capturing distance is proportional to the bubble oscillation amplitude. The maximum capturing distance and bubble oscillation amplitude ($\varepsilon = \Delta/D$) at its natural frequency (11 kHz) and 250 V_{rms} are approximately 2.3 mm and 0.13, respectively. Finally, as a proof of concept, the manipulation of a fish egg (800 μm dia.) in a microfabricated channel with tandem rectangular hills is experimentally achieved by the electromagnetically driven microrobot incorporated with an acoustically oscillating bubble.

1. Introduction

According to the 2011 World Health Organization (WHO) report, cardiovascular diseases caused by disorders of the heart and blood vessels are the number one cause of death globally. In particular, coronary arterial disease caused by the accumulation of atheromatous plaque within the walls of the coronary arteries is the most common cause of cardiovascular diseases [1,2]. Hence, various medical treatments such as coronary artery bypass graft (CABG), catheterization, and drug therapy have been developed and are currently used in hospitals. The CABG requires risky surgical procedures and long-term recovery time, whereas catheterization requires comparatively simpler surgical procedures than CABG and has a faster recovery time. However, a chronic total occlusion (CTO) of a disordered blood vessel makes catheterization difficult [1].

Although drug therapy is slow and less effective due to poor pharmacokinetics, it is the most convenient medical treatment to patients. To improve the pharmacokinetics and reduce drug toxicity, various advanced targeted drug delivery systems based on nanotechnology have been developed to supply the therapeutically active drug only to the site of disordered tissues without affecting healthy tissues [3,4]. Since the first FDA approval of a drug delivery system (Liposomal amphotericin B) in 1990, more than 10 drug delivery systems have become commercially available to treat diverse diseases ranging from cancer and fungal infection to muscular degeneration [5]. Hence, targeted drug delivery systems are widely expected to change the outlook of the pharmaceutical and biotechnology industries.

Among the numerous targeted drug delivery systems, the method based on a microrobot swimming in human blood vessels currently attracts substantial attention from the biomedical

---

* Corresponding author. Tel.: +82 31 330 6346.
E-mail address: skchung@mju.ac.kr (S.K. Chung).

http://dx.doi.org/10.1016/j.sna.2014.04.009

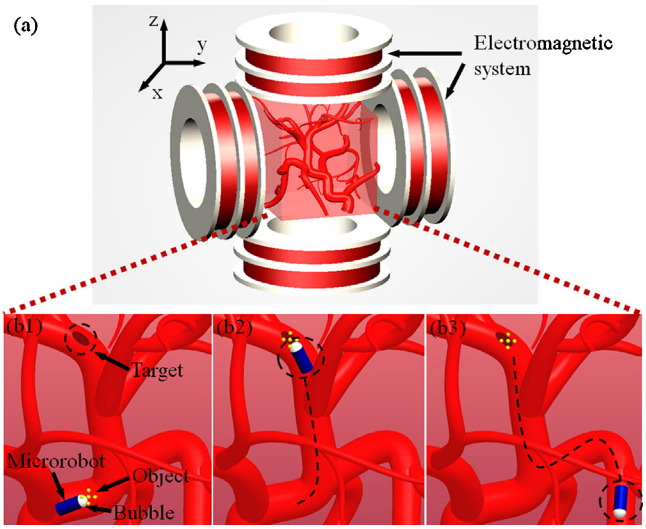

Fig. 1. Schematic diagram of micro-object manipulation in blood vessels using a microrobot incorporated with an acoustically oscillating bubble: (a) test setup; (b1–b3) micro-object manipulation in human blood vessels using the designed microrobot.

community [6,7]. Because the microrobot can access nearly every site of the human body through blood vessels, it can be applied to various biomedical operations such as targeted drug delivery, destroying blood clots for thrombolysis, and carrying electrodes for electrophysiology [8,9].

To date, several creative microrobots have been investigated and developed [10–13]. However, most micro-object manipulation processes were accomplished by physically touching and pushing the targeted objects with the microrobots, which is invasive and unreliable [14,15]. To improve the micro-object manipulation, our research group proposed a novel non-invasive micromanipulation method using an untethered microrobot with a microbubble attached to the microrobot in an aqueous medium, as shown in Fig. 1 [16,17]. The microrobot actuated by electromagnetic actuation manipulates micro-objects using an acoustically oscillating bubble, providing soft contact with the target objects and minimizing the contact damage. In our previous work, however, the microrobot actuation was limited in two-dimensional space, which would make actuation of the microrobot difficult in arbitrarily shaped blood vessels.

In this work, we develop an electromagnetic system for the three-dimensional (3D) actuation of a microrobot and experimentally demonstrate the 3D microrobot actuation in a small water chamber and T-shaped channel. Micro-object manipulation by an acoustically oscillating bubble is separately investigated by quantifying the capturing distance and bubble oscillation amplitude at different frequencies and voltages. Finally, the manipulation of a fish egg in a microfabricated channel with tandem rectangular hills filled with deionized water is achieved using the electromagnetically driven microrobot incorporated with an acoustically oscillating bubble. Note that a preliminary report on this work was presented at the International Conference on Micro Electro Mechanical Systems held in Taipei, Taiwan [17].

2. Electromagnetic system design

According to Faraday's law of induction, when an electrical current flows in a coil, a magnetic field is generated around the coil. The use of a pair of electric coils, consisting of two identical circular coils, can generate a uniform magnetic field gradient in 1D space. Furthermore, multiple pairs of electric coils can expand and control the uniform magnetic field gradient in a 3D space. The force ($\vec{F}$) acting on a magnetic object in a magnetic field can be calculated as follows [6]:

$$\vec{F} = \int_V (\vec{M} \cdot \nabla)\vec{B} dV \tag{1}$$

where $\vec{M}$ is the magnetization of a magnetic object in amperes per meter (Am^{-1}), $\vec{B}$ is the flux density of the applied magnetic field in Tesla (T), and V is the volume of the magnetic object in cubic meters (m^3).

The proposed electromagnetic system consists of horizontal and vertical pairs of Helmholtz and Maxwell electric coils, as shown in Fig. 2. The horizontal and vertical pairs of electric coils control each actuation direction of a magnetic microrobot. In particular, the horizontal pair is designed to rotate around its center using thrust ball bearings to actuate the microrobot in a 2D space. The Helmholtz coil placed inside the electric coils is used to magnetize and align the microrobot to the desired direction, whereas the Maxwell coil placed outside the electric coils is used to actuate the microrobot in an aqueous medium. Hence, by simultaneously controlling the horizontal and vertical pairs of Helmholtz and Maxwell electric coils, the microrobot can travel in a 3D space. The specifications for the electric coils used in the study are listed in Table I. For actuation of the microrobot in 3D space, six DC power supplies (6303D, Topward Co.) are used, and the motion of the microrobot is captured by a charge-coupled device (CCD) camera (EO-1312C, Edmund Optics) or a high-speed camera (Phantom Miro eX4, Vision Research Inc.) integrated with a zoom lens (VZMTM 450i eo, Edmund Optics) and saved in a PC.

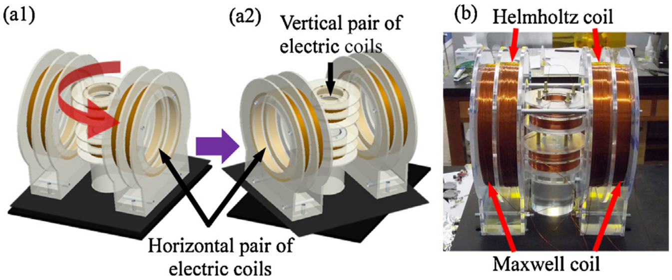

TABLE I

Coils	Horizontal		Vertical	
	Helmholtz	Maxwell	Helmholtz	Maxwell
Diameter (mm)	280		140	
Number of wire loops	390	680	160	280
Thrust ball bearing	Standard		Diameter	Height
	WBC 51124		155 mm	25 mm

Fig. 2. Design and production of the designed electromagnetic system with its specifications.

To verify the designed electromagnetic system, the magnetic flux densities generated from the horizontal and vertical pairs of Helmholtz and Maxwell electric coils are experimentally measured by a Gauss meter (SG-9115, Segye Scientific Co.) and compared with theory, which shows good agreement in a test space, as shown in Fig. 3.

3. Experimental results

3.1. Three-dimensional actuation of a microrobot using the electromagnetic system

The 3D actuation of a microrobot is tested in a water chamber ($30\ (\mathrm{L}) \times 30\ (\mathrm{W}) \times 25\ (\mathrm{H})\,\mathrm{mm}^3$) using the developed