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Theoretical analysis and simulations of micro-dosing locomotive robot with drug-release mechanism

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HIGHLIGHTS

- By taking advantage of magnetic poles, the micro-wheel is able to roll rapidly.
- Two cascaded strategies based on sliding mode control are developed and verified.
- The phenomenon of jerk can be suppressed by the dual sliding mode controllers.

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ABSTRACT

A micro-dosing system model of overall size $5 \times 5 \times 4.2$ mm^3 for drug delivery is proposed and presented. The drug delivery system mainly consists of a micro-wheel and a micro-drug release mechanism. The motion of the micro-wheel is controlled by changing the gravity center of a running disk, which is placed within the hollow micro-wheel and attracted by the actuated micro-solenoids fabricated on the inner wall of micro-wheel in shift. In addition, the micro-wheel is controlled to roll forwards/backwards to the designated location by two sliding mode control strategies: one for long-distance motion (to transport the drug to the vicinity of the spots under disease) and the other for short-distance motion (to decelerate down and stop at the exact drug-release location). On the other hand, the micro-drug release mechanism is composed by a cantilever beam and a chamber filled up by medicine. The pyramid tip of the cantilever beam deflected by the applied electrostatic force is designed to penetrate the micro-film which seals the chamber so that the medicine can be released at the specified spot. The so called "pyramid tip" is, in fact, to replace the conventional medical needle. Its profile is like a pyramid to comply with the MEMS (Micro Electro Mechanical System) fabrication process. This "pyramid" is constructed at the free end of a cantilever beam and hence named as a "pyramid tip".

1. Introduction

The concept of micro-robot by Ikuta in 1988 was initially applied in the medical science [1]. Afterwards, the micro-robots with diverse actuation methodologies were presented by numerous researchers. For example, in 1995 a medical piezoelectric micro-robot was developed by Idogaki et al. [2]. The spring, made of shape memory alloy, was employed as the actuator by Kim et al. and hence a peristaltic micro-robot for medical purpose was constructed [3]. Generally speaking, there are mainly four kinds of micro-actuators for micro-motion: electrostatic [4], electro-thermal [5], piezoelectric [6], and electro-magnetic [7–12]. In 2006, Donald presented the contemporary smallest micro-robot by utilizing the electrostatic film as the key actuator component [4]. However, the motion of the robot was considerably limited because it had to move along the conductive film. With low application value, the velocity of robot could only achieve 0.17 mm/s even under high-frequency driving voltage (up to 16 kHz). The electro-thermal micro-robot, reported by Mohebbi, was made of resistive elements [5]. Although the way of actuation was simple, the temperature of the machine was hard to control. Compared with the aforesaid actuators, the driving force generated by a piezoelectric actuator is often insufficient for practical needs on motion of robots. On the contrary, the research by employing magnetic components becomes gradually popular. Particularly, a few magnetic micro-robots controlled by the magnetic fields and Magnetic Resonance Imaging (MRI) approach have been presented in recent years [7–12].

Nowadays, the capsule endoscopes have been successfully applied for biomedical inspection. However, still there are a few significant drawbacks to be solved. For instance, the commercially-available capsule endoscopes can only move forward, mainly by the enterogastric peristalsis, and cannot pick up any specimen from the suspicious spots in a colon. Besides, the capsule endoscope is incapable of completely or partially curing. On the

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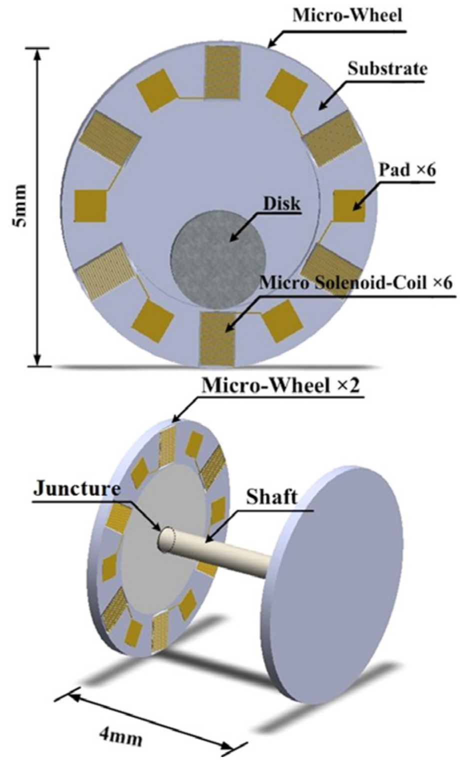

Fig. 1. Auto-rolling micro-wheel set.

contrary, instead of the proposed micro-wheel, which carries an innovative capsule endoscope manufactured by MEMS (Micro Electro Mechanical System) technique [13,14], can be moved backwards by changing the direction of applied current at magnetic poles *via* a primary magnetic field outside human body. In other words, the proposed drug-delivery micro-wheel, which mainly serves as a medicine-carrier, is incorporated with a capsule endoscope such that an innovative and active micro-dosing device can be applied to cure a certain types of disease such as colorectal cancer. Being superior to with the conventional capsule endoscope, the innovative capsule endoscope, carried by the micro-wheel, can be controlled to move forwards/backwards in various speeds. For example, by the micro-wheel, the minimal but efficient medicine required for the necessary treatment to patients can be carried to and released around the diseased spots. Different from the traditional treatment which provides the medicine by injection or swallow, the micro-dosing system enhances the absorption efficiency of the remedy and prevents cellular damage during the medication process. Besides, the micro-drug-delivery device can also provide an alternative to replace the invasive medical process such as surgery which may result in scars or cause unpredictable side effects after the treatment. Hence, a preliminary research on feasibility of automatic rolling of the proposed micro-wheel is studied and verified by theoretical analysis and intensive computer simulations. Hopefully, the proposed micro-wheel can be integrated with the capsule endoscope in the near future such that an innovative and active micro-dosing device can be applied to cure a certain types of disease such as colorectal cancer.

2. Design of drug-delivery micro-wheel

The structure of the drug-delivery micro-wheel in our work can be divided into two independent subsystems: auto-rolling micro-wheel and micro-drug release mechanism.

2.1. Auto-rolling micro-wheel

An auto-rolling micro-wheel by continuously changing the center of gravity of the micro-robot, shown in Fig. 1, is proposed and investigated in this paper. The design parameters of micro-wheel are listed in Table 1. The thickness of the wafer for micro-wheel is 0.4 mm. By assembling two micro-wheels, the SDOF (Single Degree of Freedom) mechanism can be completed so that the toppling phenomenon that will occur if there is merely one micro-wheel employed can be prevented. Before the bonding process is undertaken, a fillister, whose diameter is about 0.51 mm, is etched at the center of the glass plate by ICP (Inductively Coupled Plasma) technique. The bonding process of micro-wheel with shaft is shown in Fig. 2. The first stage, shown in Fig. 2(a), is to bond "*glass plate*" and "*micro-wheel*" together. These two objects have to be aligned and fixed in a jig frame by using EVG 610 wafer alignment system (Fig. 2(b)). Afterwards, these two objects are then delivered to EVG 520 wafer bonding system, shown in Fig. 2(c), for eutectic bonding. The gap between these two objects is gradually and very slowly reduced by increasing pressure on the hot plates so that the contact surface can be flat and homogeneous. The second stage, shown in Fig. 2(a2), is to connect "the ceramic shaft" and "already bonded micro-wheel" together by flip chip technology [15]. The actuation principle for the rolling robot, which utilizes six electro-magnetic actuators on the inner wall of the micro-wheel, is depicted in Fig. 3. Instant #1 refers to the initial state. At Instant #2, merely EM Pole #1 is energized while the other EM poles are not. At this moment, the disk inside the micro-wheel is attracted by EM Pole #1 so that the center of the entire micro-wheel is then changed to that shown as Instant #4. Instant #3 is the transient status from Instant #2 to Instant #4. Instant #1∼ Instant#4 constitutes 1/6 stroke of micro-wheel motion cycle due to EM Pole #1 energized solely. As a matter of fact, since EM Poles #1–#6 are energized in sequence (that is, $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6$), the entire cycle (that is, 360°) of micro-wheel rotation can be completed. The time interval between any two adjacent EM poles is about 2.4 s. It is noted that the power to energize the aforesaid magnetic poles can be supplied by an energy-transmitter outside the patient's body in a wireless manner [13,14]. Moreover, various MEMS-based energy harvest devices for the human body have been available in the commercial market [16]. By applying a wireless magnetic-energy transportation technique, shown in Fig. 4, the voltage can be induced at the secondary winding of the coil (receiver) while the primary winding of the coil (transmitter) is set up outside the human body. The fabrication of micro-solenoid for preliminary study is shown in Fig. 5. The U-shaped trench is constructed by a hydrofluoric acid–nitric acid–acetic acid (HNA) isotropic etching process. The appropriate mixture ratio of HNA etchant in this work is $HF:HNO_3:CH_3\ COOH = 2:7:1$ [17]. For the "conventional" 3D electro-magnetic pole, the required fabrication process is much more complicated and a few potential defects, e.g., a certain degree of void embedded within the electro-plated copper wire is usually present owing to the design of high-aspect-ratio trench for housing of the copper wire, shown in Fig. 6(b). Therefore, in order to prevent the potential voids within the electro-plated copper wire and simplify the fabrication procedure, a "U-shaped" 3D electro-magnetic pole by isotropic etching technique, shown in Fig. 6(a), is proposed in our work [18]. The merits of the obtuse-angle trenches (i.e., non-vertical wall) for the housing of copper wire in the "U-shaped" 3D electro-magnetic pole are: (i) to increase the contact angle of the wire against the trench so that the potential voids within the electro-plated copper wire can be prevented and (ii) to be able to fabricate via and copper wire of 3D electro-magnetic poles by merely a single photo-mask.

Then copper coils and Electrode Pads 1–6 are deposited onto the silicon substrate by electroplating. The dimensions of the coil