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Planar Navigation Algorithm of Magnetic Dipole Microrobot by Three External Electromagnets

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ABSTRACT: Recently, magnetic microrobots have attracted much attention in biomedical applications due to their minimally invasive features. One of the challenges in this field is about in-vivo autonomous control of microrobots to reach a predefined target. In concern to the submillimeter size of the microrobots, their position and orientation are controlled by an external magnetic field which is generated by permanent magnets or electromagnets. One of the advantages of using electromagnets to produce an external magnetic field is the ability to control the magnitude and orientation of the magnetic field by manipulating the electrical current of each electromagnet. In this study, by using Maxwell's equations and considering the microrobot as a point dipole, the exerted force and torque relations are driven as a function of electromagnets' electrical current. Moreover, a navigation algorithm is proposed to guide the robot through unknown obstacles without planning the whole path. Furthermore, the driven equations and designed algorithms are validated by simulating the microrobot's motion using MATLAB software, which confirms the effectiveness of using three electromagnets to control an electromagnet microrobot's planer motion.

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1- Introduction

Recently, minimally invasive surgery is preferred because of shorter recovery time. As a result, microrobots have shown their application in the field of medical science due to their small size, which brings them the capability of moving through veins and reaching hard to access targets even during open surgeries [1].

Microrobots are actuated in a variety of ways: piezoelectric, thermal, chemical, optical, and bacterial, but the magnetic technique is biocompatible for in-vivo use. Moreover, the safe penetration of magnetic fields into biological tissue, makes it an excellent candidate for in vivo applications [2].

The position and orientation of the microrobot are controlled by the intensity and direction of the external magnetic field, which can be produced by permanent magnets or electromagnets. In this study, in order to create the required magnetic field, electromagnets are used due to their flexibility in controlling the magnetic field by adjusting their current. In 2010, Kummer et. al. designed a system of eight electromagnets called OctaMag to manipulate the intraocular microrobots for retinal procedures [3].

The main limitations of microrobot's guidance are the confined workspace of electromagnets and the restricted view-angle of the imaging system (trade-off between view-angle and resolution). In most studies, a primary path is defined to reach the goal, and closed-loop control is applied to track the path [4]. Due to varying environments, this technique requires continuous updating of the defined path which increases the calculation cost. Therefore, in this study, the trajectory of the microrobot is controlled based on its current position of it and its distance to the goal.

The main contributions of this paper are the design of a behavior-based controller to reach the goal in an unknown environment without the need for a predefined path, and exploiting three electromagnets to generate the external magnetic field which expands the working space of the entire system.

2- Methodology

2- 1- Magnetic modeling

Taking into account the small size of the microrobot, in this study, it is modeled as a point magnetic dipole. Applying the Maxwell equation and assuming a uniform magnetic field in the workspace, the applied force on the microrobot can be written as Eq. (1). where M is the magnetic moment vector of the microrobot, B_x and B_y are the derivatives of the magnetic field vector at microrobot's position with respect to x and y respectively, and F_x and F_y are the applied magnetic force in x and y direction to the microrobot.

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} M.(\nabla B_x) \\ M.(\nabla B_y) \end{bmatrix} \tag{1}$$

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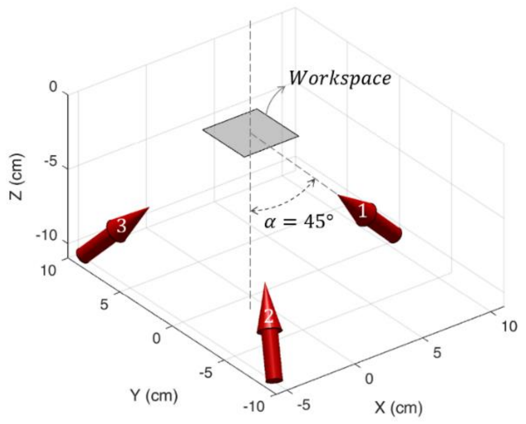

Fig. 1. Electromagnets' configuration

Considering the electromagnets, the magnetic field can be expressed as a function of coils' current as:

$$B(P)=\beta(P)I \tag{2}$$

where $B(P)$ is the magnetic field vector at the microrobot's position, I is 3×1 matrix of the coils' current, $\beta(P)$ is a 3×3 matrix that its *i*th column is described as the magnetic field of *i*th coil at the point P if its current is 1 A.

Fig. 1 depicts the configuration of the electromagnets.

2- 2- Navigation algorithm

To assure reaching the goal while avoiding obstacles, three different strategies are designed: 1) Go To the Goal (GTG), 2) Obstacle Avoidance (OA), and 3) Follow Wall (FW). Then, a hybrid automata model is proposed to form the switching logic between the three strategies [5]. The σ is introduced to omit the GTG behavior while the microrobot is reaching an obstacle. The microrobot's distance from the obstacle is $\|e_{OA}\|$, d_{OA} is the allowable distance with obstacles that controls the OA behavior, $0<\alpha_\sigma<1$ defines the minimum distance with the obstacles to ensure smooth switching behavior, and $\alpha_{FW}>1$ is the parameter to control the FW behavior.

$$\sigma=\begin{cases}1 & \alpha_{FW}d_{OA}\le\|e_{OA}\| \\ \dfrac{\|e_{OA}\|-\alpha_\sigma d_{OA}}{(\alpha_{FW}-\alpha_\sigma)d_{OA}} & \alpha_\sigma d_{OA}\le\|e_{OA}\|<\alpha_{FW}d_{OA} \\ 0 & \|e_{OA}\|<\alpha_\sigma d_{OA}\end{cases} \tag{3}$$

$$u_{GTG-OA}=\sigma\times u_{GTG}+u_{OA}+u_{FW} \tag{4}$$

Therefore, when the microrobot reaches an obstacle, the controller tries to avoid the obstacle by increasing the intensity of the FW behavior and decreasing the intensity of GTG. This strategy results in moving around the obstacle while proceeding to the goal. In the worst-case scenario, if the microrobot's velocity is too high and it reaches the blue region in Fig. 2, the only behavior will be the OA to guarantee the non-collision path.

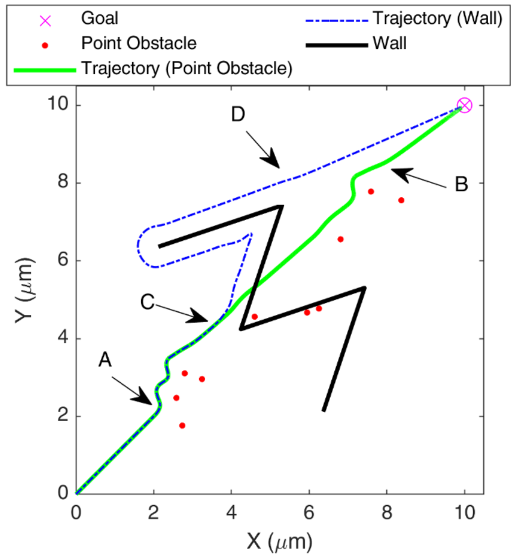

Fig. 2. Robot's trajectory while passing the obstacles to reach the goal

2- 3- Controller design

Considering the design navigation algorithm, which results in a smooth velocity profile by benefiting from soft switching, the proportional controller is implemented:

$$m_0\begin{bmatrix}\ddot{x}\\ \ddot{y}\end{bmatrix}=\left[K_p\right]_{2\times2}\left(u_{GTG-OA}-V\right)_{2\times1} \tag{5}$$

where m_0 is the microrobot's mass, $\left[K_p\right]_{2\times2}$ is the matrix of proportional controller's coefficient , V is the 2×1 vector of the microrobot's actual velocity, and u_{GTG-OA} is the desired velocity of the microrobot designed by the proposed behavior-based method.

3- Results and Discussion

Fig. 2 depicts the trajectory of the microrobot in two cases: 1) it is only facing the point obstacles (the green line) and 2) there exists a wall as well (the dashed blue line). The robot starts from the origin by the GTG behavior. When it reaches the first point obstacle (A), it passes the obstacle by moving around it by means of FW behavior and repeats this strategy anytime that it sees an obstacle until point B where there is a clear straight path to the goal. In the case of facing a wall (C), it starts to move around the wall in one direction until it finds a clear path (D).

4- Conclusions

Due to changing environment surrounding the microrobot, a novel behavior-based navigation algorithm is proposed to reach a goal without the need for any predefined path. The controller computes the required magnetic field and three coils are used to generate it. The performance of the designed controller is verified through the simulation of two different scenarios. The results confirm that the microrobot can path any form of obstacle and reach the goal in an unknown environment. As a result, the proposed algorithm can be used for drug delivery, cancer treatment, and target therapy.

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