Implementation of an MRI-guided Trajoctery for an MRbot

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***Abstract*— Advances in surgical methodologies have become evident over the past few years. Many technologies have been proposed to enhance processing accuracy and cost efficiency. Magnetic Resonance Imaging (MRI) was developed originally for surgical planning, but now its potential further spans intra-operative procedures. MR scanners generate magnetic fields that could efficiently manipulate tiny ferromagnetic objects within the human body to deliver treatment drugs for specific internal organs. MRI can thus be used as a closed-loop feedback controller for small mobile objects known as MRbots (short for magnetic resonance robots). This paper displays an attempt to implement a navigational framework for MRbots using reasonable computational resources. The navigational platform implemented here is focused on creating a navigational plan for an MRbot through a virtual blood vessel, starting from path planning and up to trajectory control using magnetic field gradient as the control input. Moreover, the used methodology is verified through Python numerical simulation. The results proved to be satisfactory.**

Keywords*— *Surgical Simulation, Millirobots, MRI-guided intervention, Kinematics, Discrete-time control

I. INTRODUCTION

In recent years, real-time magnetic resonance imaging (MRI) has become a crucial tool in invasive medical procedures. Magnetic resonance targeting (MRT), a magnetic manipulation-based technology, has emerged as a promising method for delivering therapy to specific areas of the human body by infiltrating foreign objects into the natural pathways of blood vessels [5]. The MRI system can function as both a sensor and an actuator to guide ferromagnetic materials, such as magnetic microbots, through the bloodstream [2]. The propulsion of a fleet of such entities represents a unique paradigm of robotic swarms actuated by a single magnetic source [2]. The development of MRI-guided untethered ferromagnetic beads and microbots has provided an opportunity for the development of minimally invasive and highly targeted medical interventions.

Several research studies have investigated the modeling, control, and path planning of MRbots. Chanu et al. [1] adapted the clinical MRI software environment for the real-time navigation of an endovascular untethered ferromagnetic bead for future endovascular interventions. Mathieu et al. [2] proposed a method of propulsion for a ferromagnetic core through magnetic gradients generated by an MRI system. Felfoul et al. [3] developed an in vivo MR-tracking system based on magnetic signature selective excitation. Additionally, preoperative planning and modeling of control for MRI-guided milli-robots have been investigated [4].

Challenges remain in the field of molecular MRI, including the need for more sensitive probes and imaging techniques [5]. Furthermore, the control of MRbots presents challenges, such as the need for robust and efficient algorithms to control their motion [6]. Diffusion-weighted MRI and functional MRI have been used to elucidate the cognitive control network [7].

In this paper, we propose a novel approach for MRbot navigation that utilizes magnetic field gradients as control inputs. This approach involves creating a navigational plan for an MRbot through a virtual blood vessel, starting from path planning and up to trajectory control. The proposed methodology is verified through a numerical simulation using Python, and the results demonstrate the efficacy of the approach.

II. METHODOLOGY

A. System Model

Initially, a numerical model of the second order was formulated based on the dynamic equations of motion established by Newton's second law. The MRbot that moves through the bloodstream is subjected to two forces. The primary force is generated by the magnetic field gradient exerted on the particle, and it can be computed using the subsequent formula:

$$F_{mag} = \frac{4}{3} M\pi R_{sphere}^3 G \tag{1}$$

, where M is the magnetization of the sphere at saturation, R_{sphere} is the sphere radius and G is the control gradient vector. The second force acting on the MRbot is due to resistive drag and is proportional to the relative velocity of the particle with respect to the bloodstream. This force can be expressed as:

$$F_{drag} = \frac{-1}{2} C_d \rho A |V_{blood} - V_c| \tag{2}$$

, Here, C_d is the drag coefficient, ρ is the density of blood (1025 Kg/m^3), V_{blood} is the velocity vector of blood flow, and V_c is the current velocity vector of the MRbot. The absolute value indicates that the drag force always acts in a direction opposite to the particle's velocity vector [4]. One can express the overall force acting on the MRbot as the sum of the magnetic force and the drag force, i.e.,

$$F = F_{mag} + F_{drag} \tag{3}$$

This formulation leads to the differential equation model of the MRbot motion.

$$\frac{dV_c}{dt} = \frac{F}{\frac{4}{3}\rho\pi R_{sphere}^3} \quad (4)$$

The mass of the particle in terms of its radius and density is represented by the denominator of the right-hand side of the equation. To simulate the model numerically, the continuous differential equation is transformed into a discrete difference equation using Euler's discretization formula [5]. The discretized form is as follows:

$$V_c = V_{c-1} + \frac{F}{\frac{4}{3}\rho\pi R_{sphere}^3}\Delta t \quad (5)$$

$$X_c = X_{c-1} + V_{c-1}\Delta t \quad (6)$$

The simulation algorithm can be formulated using the following equations, where V_c is the current velocity vector of the robot, V_{c-1} is the past velocity vector of the robot, Δt is the simulation sampling time, X_c is the current pose vector of the robot, and X_{c-1} is the past pose vector of the robot.

While *time is less than simulation time* **do**

Get **G**;

$\boldsymbol{F_{mag}} = \frac{4}{3} M\pi R_{sphere}^3 \boldsymbol{G}$;

$\boldsymbol{F_{drag}} = \frac{-1}{2} C_d \rho A |V_{blood} - \boldsymbol{V_c}|$;

Compute resultant force: $\boldsymbol{F} = \boldsymbol{F_{mag}} + \boldsymbol{F_{drag}}$**;**

Update system states $\boldsymbol{V_c}$ and $\boldsymbol{X_c}$**;**

end

Algorithm 1: Pseudocode of numerical simulation

B. *Path Planning*

The first step in the MRbot's navigation process involves generating multiple scans of the human body using an MRI. These scans are then analyzed by specialized software programs that digitize the analog information obtained from the MRI scans. The digitized images comprise of volume units called voxels, which are analogous to pixels in 2D images. To create the desired path for the MRbot, the voxel segments are interpreted to construct the entire path. Safety and accuracy are of utmost importance, and several precautions need to be taken. The particle path must be defined within a safety zone, also referred to as the guidance corridor. Figure 1 illustrates the guidance corridor and the safe zone where the MRbot is allowed to travel.

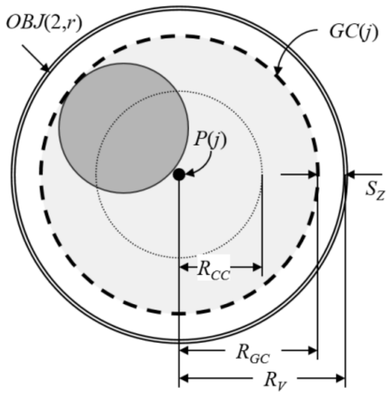

Fig.1 Blood vessel cross-section, From the segmented vessel OBJ (2, r) are extracted the Path P(j) and the virtual guidance corridor GC(j) (dashed circle) is generated with a safety zone SZ (Figure adapted from [6])

To model the path of the MRbot in 3D space, direction angles of the vector and the curvature of the path are used. In the current implementation, a semi-circular trajectory is simulated, which can be fully modeled using only two dimensions within a specific 3D plane. Thus, it is possible to model the path in terms of the semi-circle radius and the vector inclination with respect to the x-axis.

$$X_{voxel_i} = \begin{bmatrix} r.\cos(\theta_i) \\ r.\sin(\theta_i) \\ 0 \end{bmatrix} \quad (7)$$

, The desired robot poses at the beginning of voxel i, denoted by X_{voxel_i}, is calculated using the semi-circular trajectory formula. The semi-circle is prescribed within the x-y plane, where r is the semi-circle radius and θ_i is the angle, the vector makes with the horizontal x-axis. Since the semi-circle is confined to the x-y plane, the z-axis component is set to zero. The range of θ_i is from zero to 180 degrees for a semi-circular trajectory, as illustrated in Figure 2.

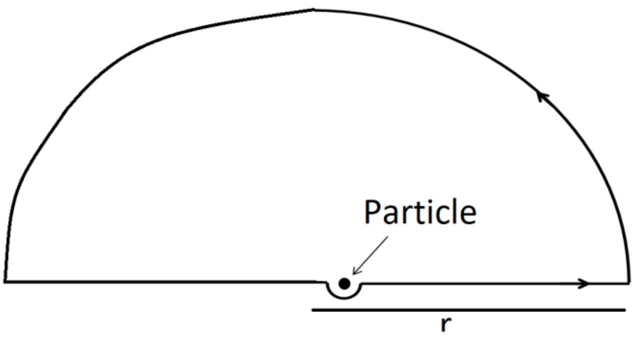

Fig.2 Particle path sample

To achieve the desired velocity profile for the MRbot, it is crucial to set the initial and final velocities to zero magnitude. Moreover, the velocity magnitude within voxel segments should be maintained as close as possible to the target velocity, which is defined by a predetermined function or equation. This ensures that the MRbot moves smoothly and uniformly through the blood vessel.

$$V_{target} = \frac{V_o}{1+\frac{1}{k_o r}} \cdot \frac{R_{sphere} - R_{GC}}{R_o} \tag{8}$$

Where V_o, k_o and R_o are constants allowing to adjust the velocity profile.

C. Control Module

A trajectory control module is implemented to guide the MRbot along the desired path. The module takes in two error signals: the first one is the difference between the desired pose vector and the current pose vector, while the second error signal is the difference between the current velocity vector and the desired velocity vector. The two error signals are combined and sent to a proportional controller which generates a proportional control signal to force the particle to follow the desired path.

$$G_{prop} = K_p * (e_p + e_v) \tag{9}$$

To compensate for the drag effect, an additional control signal is necessary to complement the proportional control signal. This signal is provided by a parallel feedforward controller, which includes an inverse model for the drag component of the force, as depicted in Figure 3. By doing so, the feedforward controller can predict and compensate for the drag force in advance, and the proportional control signal can focus on regulating the magnetic force.

$$G = G_{prop} + G_{compensation} \tag{10}$$

Where $G_{compensation}$ is the resulting control action coming from the feedforward controller.

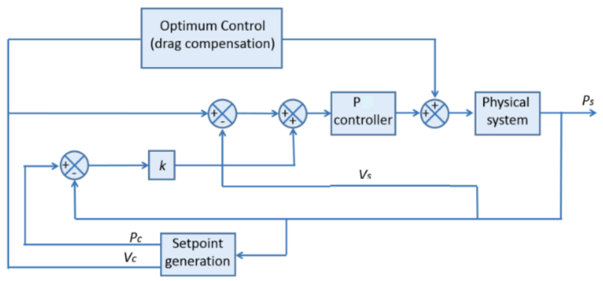

Fig.3 Automatic control (Figure adapted from [6])

III. Results

A MATLAB simulation was conducted to replicate the semi-circular trajectory motion scenario. The simulation employed the parameters outlined in Table I.

TABLE I. SIMULATION PARAMETERS

Parameter	**Value**
Sphere radius	2 μm
Magnetization constant	1.274 A/m
Number of voxels	1000
Guidance corridor radius	10 μm
Sampling time	0.01 sec.

The simulation was run for almost 16 seconds and the actual trajectory taken by the robot was compared against the desired trajectory as shown in Figures 4 and 5.

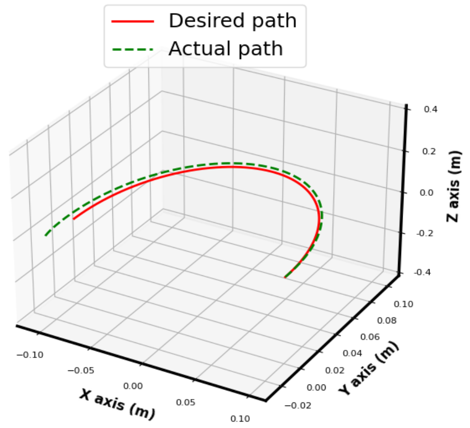

Fig.4 Desired path vs. actual path

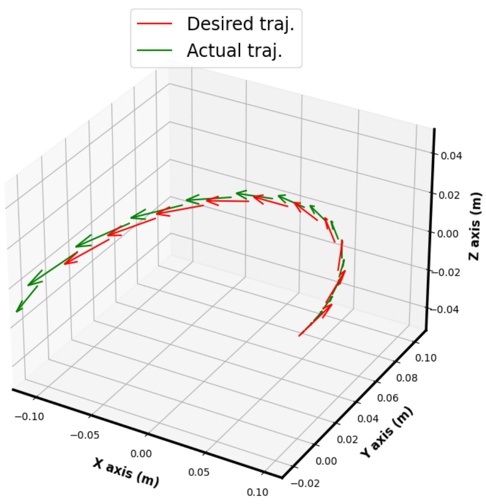

Fig.5 Desired trajectory vs. actual trajectory

IV. Conclusion

This study focuses on investigating the dynamic model of an MRbot and converting it into a programmable numerical format for validation purposes. The navigation algorithm of the robot was divided into two modules, namely path planning and control. The path planning module determines the desired path for the MRbot, considering safety and accuracy rules. On the other hand, the control module generates the gradient control action while also accounting for resistive drag. To verify the efficacy of the algorithms, they were implemented and evaluated using MATLAB.

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