Electromagnetic Actuation Scheme for Steering MNPs with Aggregations in Multi-Channel Vessels

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In this paper, for the first time, a novel steering scheme for multi-channel vessels using electromagnetic actuation (EMA) is introduced. The presented scheme aims to guide MNPs and improve targeting efficiency in multi-channel guidance for the aggregated nanoparticles steering. The particles are simulated to reflect the aggregation behavior and the concept of transient field function is introduced for the steering strategy. Finally, high success rate for guidance can be achieved using the proposed actuation scheme. This promising simulation results encouraged us for further studies.

***Index Terms*—Electromagnetic Actuation (EMA), Multi-channel vessels, Magnetic Nanoparticles (MNP), Steering, Aggregates.**

I. Introduction

MAGNETIC micro-nano carriers as a noninvasive and efficient targeted drug delivery approach, have been emerged as a promising method. To guide these nano agents within a vascular system, we have developed an electromagnetic actuation (EMA) scheme in this paper.

The need for precise particles' steering in the vascular system leads to the development of micro-nanorobotic systems. Multicoil-magnetic systems were proposed as a solution for precise particle steering [1], [2]. The idea of using a field function (FF) to steer MNPs and solve particle-vessel sticking issue was first introduced in [3]. Furthermore, the field function concept was improved to include the aggregated particle steering [4]. The magnetic particle imaging (MPI) system is developed for a real-time feedback of the system [5]. The FF was used for the MNPs in the Y-shape bifurcations. However, the FF with only a safe zone for high steering performance in multi-channels is not feasible since there is no guidance strategy for the second bifurcation.

In our novel electromagnetic steering scheme, the MNPs move in the same direction with the flow and an electromagnetic actuator adjusts their position. Applying the concept of the safe zone and the field function enables us to keep the particles within the safe zone. In this paper a transient field function (TFF) is suggested to steer the particles between the safe zones and guide them toward the desired outlet in multi-channels. The T_{tran} is designed to change the MNPs between the safe zones. The schematic of the system is illustrated in Fig. 1.

II. Governing dynamic in MNPs steering

The nanoparticles are considered big enough (bigger than 500 nm) to exclude the Brownian motion and the Newtonian dynamic is used for particle steering (Eq. 1).

$$m_i \frac{dv_i}{dt} = F_{MF} + F_{drag} + F_m \tag{1}$$

where the index i indicates particle I, m_i is the particle mass, v_i is the particle velocity, F_{MF} is the magnetic force, F_{drag} is the hydrodynamic drag force, and F_m is the gravitational force.

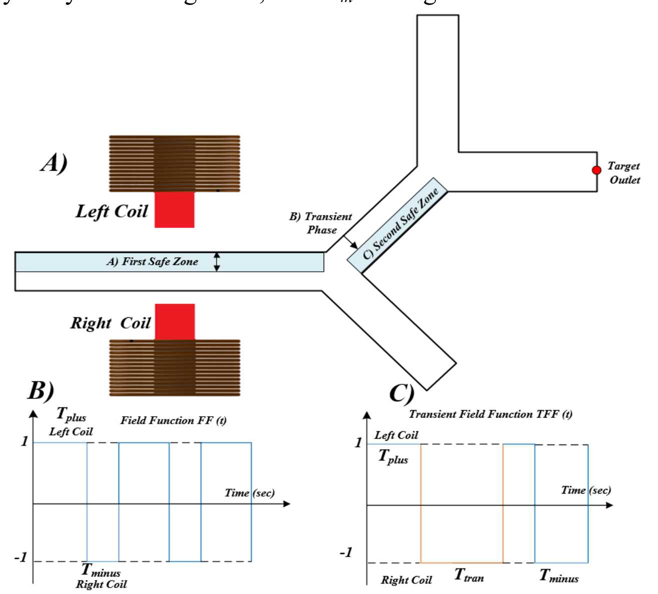

Fig. 1. A) the safe zones are designed to guide the particles toward the desired outlet B) The field function (T_{plus}, T_{minus}) designed to keep the particles within the safe zone C) the Transient Field Function is designed to steer particles between safe zones (T_{plus}, T_{tran}, T_{minus}), (the orange color is showing the TFF (t)).

The MNPs are subjected to a magnetic force in a magnetic field. This magnetic force is used for MNPs steering and introduced as:

$$F_{MF} = V \mu_1 M_{sat} \nabla H_f \tag{2}$$

where M_{sat} is the magnetic polarization, ∇H_f is the gradient of magnetic intensity, μ_1 is the permeability of the free space and the particles are considered uniform with the V as their volume.

The field function and the transient field function are combined in the steering magnetic field function (*SMFF(t)*).

The SMFF*(t)* can guide the MNPs by changing the magnetic field MNPs and keep them within the safe zones:

$$\nabla H_f = SMFF(t).\nabla H \quad (3)$$

III. Particle Tracking Simulation for Multi-Channel Steering

We imported the multi-channel model into the COMSOL software (COMSOL Inc., Palo Alto, CA, USA) and used the particle tracking module to study the proposed EMA actuation scheme for multi-channel guidance. A multi-channel vessel with one inlet and four outlets (all with the diameter of 1 mm) and the length of 5 mm (for all branches), is modeled. The blood velocity is considered to be 0.1 mm (for capillaries) and the particles are of 800 nm diameters.

A. Simulation results for steering MNPs in multi-channel

Initially the aggregates are considered to be a chain of 4 to 8 particles. Due to the simulation platform limitation, the properties of the aggregates are given to the particles to resemble more realistic steering simulation.

The field function is designed to keep the particles within the safe zone and the (TFF(t)) is designed to guide them in between the safe zones. Since the field function (FF(t)) alone cannot achieve high steering performance in multi-branches [3], the transient field function (TFF(t)) is suggested based on the aggregates characteristics to move MNPs between safe zones and guide them toward the desired outlet. The T_{tran} is designed based on the aggregates motion dynamics (introduced in [4]) to move them between the safe zones.

The Fig. 2 A illustrates the aggregates of six particles which are guided with the proposed scheme. As it is illustrated the particles initially remain in the safe zone and pass the first bifurcation. In the appropriate activation time (measured based on previously developed MPI feedback [5]), the transient field function can change the safe zone and particles can reach to the second safe zone and continue toward the correct outlet. The transient field function is obtained using the COMSOL simulations (Fig. 2).

To study a more realistic simulation platform, the particles are considered to be aggregated [4]. The Fig. 2B demonstrates the behaviors of these aggregates under the introduced scheme (in Fig. 2b, the aggregates of 4 green, 6 blue and 8 red). Finally, Fig 2c shows that the aggregates of the similar size can be guided in the multi-channel.

B. Discussion and conclusion

The initial result in the Fig. 2 A shows that using the correct feedback (the time for start of the transient field function (TFF) can be provided by the previously developed magnetic particle imaging (MPI) system [5]), it is possible to successfully guide the nanoparticles between the safe zones and steer them toward the desired outlet. This scheme, for the first time provides a feasible approach for the multi-channel guidance.

Moreover, the simulations are further developed with multi-aggregates (green a chain of 4 particles, red a chain of 6 particles, and blue a chain of 8 particles). The different behaviors of the aggregates during the steering indicated that an optimization approach should be used alongside with the proposed scheme to elevate the chance of successful guidance.

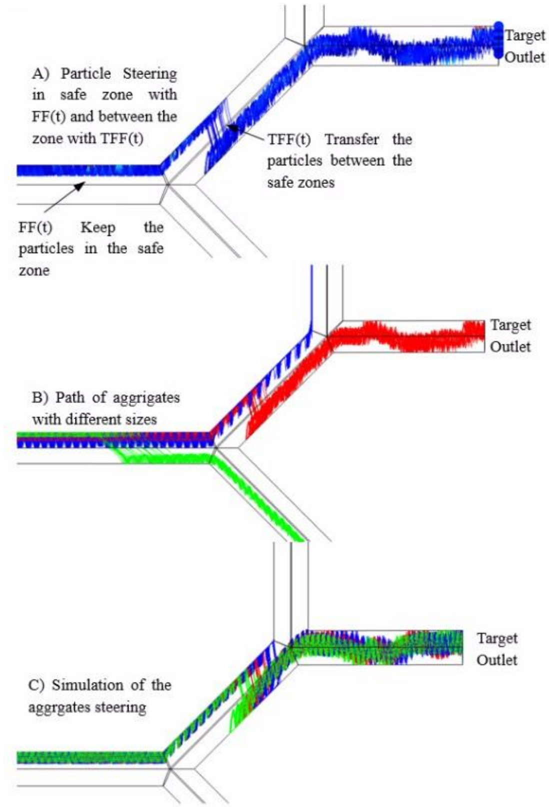

Fig. 2. A) Particle tracking simulation of MNPs under the designed electromagnetic actuation reach the correct outlet B) particles with different aggregates properties C) the designed TFF(t) can guide the particles to the desired outlet.

Finally, considering these behavior patterns and using the MPI feedback to find the proper time for steering, the designed scheme could guide the majorities of the particles toward the desired outlet in the vascular.

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