Control Based Navigation of Non-ferromagnetic Particles in Ferrofluids

A Novel Idea
Particle navigation can be achieved without the presence of carriers.

Derivation and Simplification of Equations

$$F_m = -\mu_0 M H \frac{dM}{dt}$$

Mathematic Modeling and General Equations

Navier Stokes

$$\frac{DV}{dt} + \nabla \cdot \mathbf{V} = -\nabla \mathbf{p} + \mu \nabla^2 \mathbf{V}$$

Maxwell Equations

$$\mathbf{E} = \nabla \phi + \frac{1}{c^2} \frac{\partial \mathbf{B}}{\partial t}$$

Determine Geometry for Specification of Quantities

• A suitable magnet configuration is shown in figure 4.
• The iron-based carrier (either a bead or a capsule) is the only component that encounters forces to gain motion.

Information on Current Techniques

• While tagging techniques are very useful and serve many applications well, they may not be preferred in some instances for the following reasons:

Targeted Opportunities

Current

Magnetic Field

Figure 2-Current Open-Loop Control

Open-Loop Control

- All navigation/targeting attempts thus far have been open-loop.
- The position of the target or the progression of navigation was not controlled via a closed loop implementation.
- Such open-loop processes comprise particle sorting/counting, targeting micro-robots or drugs.
- With open-loop operation only, success of the mission will be difficult to assure under disturbances and uncertainties.
- Implementation of closed-loop feedback control can make particle transport with magnetic fields a much more powerful tool.

A Possible Application

- The technology this project will lead to has impacts in efficiency improvement of intra-cytoplasmatic sperm injection (ICSI).
- One of the reasons ICSI has as low as 50% efficiency is because irreversible damage is incurred when a pipette pierces the extremely flexible oocyte (female germ cell).
- Using ferrofluid technology, it may be possible to precisely (a) navigate the oocyte toward a stationary pipette and (b) apply necessary forces to balance the contact force between the pipette and the oocyte.

Future Work

1. Build and perform tests with the prototype
2. Begin work on a second prototype with four coil pairs
3. Introduce the force formulation into the N-S equations for a complete solution for the particle
4. Begin control phase of research
5. Compare particle dynamics information obtained with phase II open-loop control with mathematical model
6. Design and implement closed-loop control

Phase I Prototype

A first prototype has been designed and is based on one dimensional particle motion.
- Permanent magnets are used for simplicity.
- Lead screw driven system provides separation distances of 0°-10°.
- Radial distances of 0°-6° can be tested.

Figure 11-Phase I Prototype

Ferrofluids

- Ferrofluids are stable suspensions of small, magnetic particles in some continuous medium such as water or oil.
- The particle sizes are in the range of 3nm to 15nm.
- Although a concentration gradient of particles can occur, the particles are generally evenly dispersed. They are coated with a molecular layer of dispersant to prevent them from sticking to one another.
- Similar to other fluids, controllable and inaccessible ferrofluids is preserved under certain conditions, therefore they comply with Navier Stokes Equations coupled with Maxwell Equations when a magnetic field is present.
- Ferrofluids respond to magnetic fields allowing for the application of controllable body forces.

Figure 12-ICSI

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Special Thanks to:
Northeastern Department of Mechanical and Industrial Engineering & Alper Ozturk

Background

- The ability to control forces on ferromagnetic materials allows for transport and manipulation of non-ferromagnetic monodisperse scale particles (non-Fe-P, in short).
- In principle, the material to be transported is physically connected to a ferromagnetic particle.
- The iron-based carrier (either a bead or a capsule) is the only component that encounters forces to gain motion.
- The presence of the carrier is required to gain motion.

Information on Current Techniques

While tagging techniques are very useful and serve many applications well, they may not be preferred in some instances for the following reasons:

- The process to attach the carrier to the particle is very involved and requires extensive chemical engineering.
- Often the particles to be transported are cells which are alive and can grow around the carrier.
- Once the transport mission is complete, the carrier presence is not desired and becomes a foreign body attached to the particle.
- Navigation within the human body using these techniques requires extremely high magnetic field gradients which exceed those produced by a typical MRI machine.

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