Directed Self-Assembly of Selectively-Buoyant Capsules with a Clinical MRI scanner

Ouajdi Felfoul, Aaron Becker, Alina Eqtami, and Pierre Dupont

***Abstract*— Clinical MRI systems have three magnetic coil pairs that can create a 3D linearly-varying gradient field. These gradient fields are relatively weak compared to the static magnetic field, so the magnetic field orientation remains constant. We engineer a range of selectively buoyant capsules. By manipulating the vertical magnetic gradient, we can transition these capsules between floating and sunken states. In this paper we present a control method to steer multiple capsules in optimum time.**

I. Introduction

This project addresses the need for ultra-minimally invasive robots to perform diagnostic and therapeutic tasks deep inside the body while simultaneously addressing the need for integrated real-time imaging. In contrast, most existing approaches employ large robots and consequently require relatively large incisions. In consequence, substantial healthy tissue can be damages en route to the diseased tissue. Because of this collateral damage, treatment is often delayed or alternative less-effective techniques are employed. For example, in brain surgery, it is often necessary to sacrifice functioning brain tissue to reach an underlying tumor. In heart disease, less-effective catheterization procedures may be performed to avoid the risks and trauma of open-heart surgery.

ref?

At the millimeter and sub millimeter scale, groups of MRI-powered swimming robots could perform targeted therapies inside fluid-filled regions of the body, such as the ventricular system of the brain.

figure from NRI?

Because the ventricles provide access to a substantial portion of the brain, the proposed millirobots, injected into the spine and steered to the brain, could significantly reduce the morbidity of current procedures whiles also enabling a broad range of new procedures. These millirobots could be capable of performing localized therapies such as drug and cell delivery for the treatment of cancer, epilepsy and other diseases. They could also be capable of forming sensor networks to monitor such quantities as pressure. As delivery vehicles(of drugs, for example), they would be superior to systemic delivery since they would enable high concentrations to be delivered to very specific locations while bypassing the blood-brain barrier and without exposing the rest of the body.

Math about swimmer bouyancy

Math about dipoles in a very strong magnetic field [1]

Simulation of many dipoles in a strong magnetic field – 4 dipoles in field, start at random positions, see what shapes are formed. Do experiment 1000s of times and get shape formation probabilities. We derive inspiration from simulations by Alink et al. on self-assembly of 3 to 4 permanent magnets [2], and simulations of aggregation with nanoparticles in [3].

Experiments – place 2-5 magnets in water, record ending configurations. Show this matches simulation (?)

Controlled buoyancy experiments – show we can make configurations that are unlikely by chance

Show we can make a desired configuration

Steer the assembly around.

A. Why MRI?

Our paper is organized as follows. After a discussion of related work in Section II, we describe our model and control law in Section III. Section IV examines how to optimize system design. We report the results of our experiments in Section V, and end with concluding remarks in Section VI.

II. Related Work

A. MRI actuators

a) Motors:

b) Milli-robots: Zykov et al. [4] built actuated centimeter-cale modules equipped with electromagnets that could selectively control the morphology of the robotic assembly.

Nap et. al [5] built populations of magnetic modules with tunable stochastic properties. By modifying the breaking probabilities they could change the expected proportion of robots in the set of possible configurations.

Vartholomeos [6] introduced MRI control of multiple magnetic capsules by varying their inertial properties.

Diller et al. [7] designed magnetic modules less than 1mm in every dimension that could be steered in 2D with an external magnetic field. Individual modules could be held in place with a specialized electro-static substrate. In recent work Diller et al. [8] designed neutrally buoyant particles constructed of soft-magnetic material that could be demagnetized, allowing new modules to be docked to the assembly,

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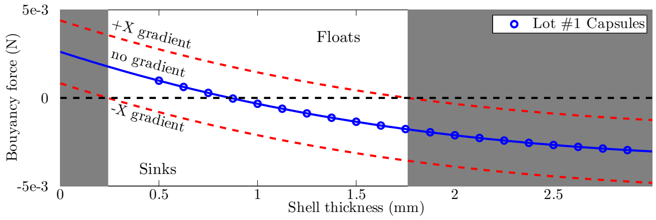

Fig. 1. The first lot of capsules were 5× scale. Each was a 10mm capsule containing a 2mm-diameter ferrous ball-bearing. Varying the shell thickness varied the buoyancy. Capsules in the white region could be selectively changed from floating to sinking by varying the x-gradient (vertical).

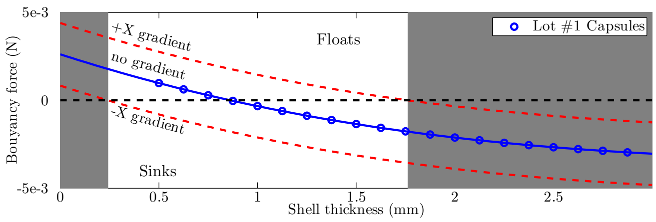

Fig. 2. Capsules used in these experiments. A 4 mm steel bead is enclosed by a water-tight capsule of ABS plastic. Capsules are shown in the unassembled and assembled state.

and then welded with hot-melt adhesive. The assembly could then be re-magnetized and steered to a desired position.

Alink et al. [9] studied the interactions of spherical magnetic dipoles and modeled the energy landscape for arrangements of 2,3, and 4 modules.

B. Controlling many robots with uniform inputs

III. Capsule Design and Control

IV. Analysis

V. Experiment

VI. Conclusion and Future Work

VII. Acknowledgements

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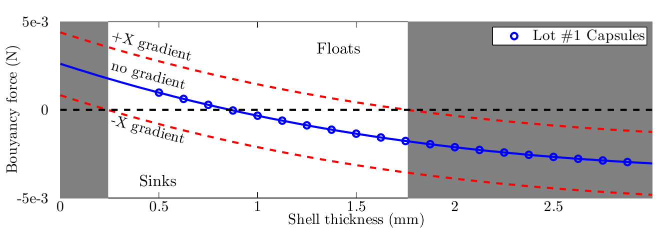

Fig. 3. (Left) container vessel. A molded plastic grid lines the container bottom. (Right) experimental setup with the vessel and capsules inside a 600mm bore Siemens 3T MR-scanner.

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