**Toward Tissue Penetration by MRI-powered Millirobots Using a Self-assembled Gauss Gun**

Abstract—

MRI-based navigation and propulsion of millirobots is a new and promising approach for minimally invasive therapies. The strong central field inside the scanner, however, precludes torque-based control. Consequently, prior propulsion techniques have been limited to gradient-based pulling through fluid-filled body lumens. This paper introduces a technique for generating large impulsive forces that can be used to penetrate tissue. The approach is based on navigating multiple robots to a desired location and using self assembly to trigger the conversion of magnetic potential energy into sufficient kinetic energy to achieve penetration. The approach is illustrated through analytical modeling and experiments in a clinical MRI scanner.

I. INTRODUCTION

Millimeter-scale robots have the potential to provide highly localized therapies with minimal trauma by navigating through the natural fluid-filled passageways of the body.

While navigation through, e.g., the circulatory system or cerebrospinal fluid spaces is sufficient for some applications, it can also be necessary to penetrate into the surrounding tissue. Examples include puncturing a membrane to release trapped fluid, opening a blocked passageway or delivering a drug to a tissue location several centimeters from a fluid-filled space. The forces required for tissue penetration, however, are substantially higher than those needed to propel a millirobot through a bodily fluid and, consequently, can be difficult to achieve. Prior tetherless systems for moving through tissue have relied on magnetic forces and torques produced by large external magnets to either pull magnetic spheres through brain tissue (cite Video Tumor fighter) or to rotate threaded magnetic cylinders through muscle tissue (Japanese guy).

Alternatively, methods for tetherless robot propulsion and control have been developed that employ the magnetic gradients of clinical MRI scanners [1-4]. MRI also provides the capability to image both the robot and surrounding tissue to guide navigation. MRI-based millirobot navigation in the vasculature was first demonstrated in [Martel – put this ref first in list]. Recently, algorithms enabling the simultaneous MRI-based control of multiple millirobots [Panagiotis, Alina] and macro-scale rotary actuators [Panagiotis, Aaron] have also been developed.

To date, however, the motion of MRI-powered millirobots has been constrained to fluid-filled spaces since the magnetic gradients produced by the scanner are relatively weak. The maximum gradient produced by most clinical scanners is in the range of 20-40mT/m producing a force on a magnetized steel particle equal to 36-71% of its gravitational force. While it is possible to install custom high-strength gradient coils, such as the 80mT/m coil reported in [3] **(see our IJRR paper – the Martinez? lab at MGH has published abstracts with much higher gradients)**, this approach is costly and reduces the size of the MRI bore. While to facilitate motion within a fluid, a millirobot can be designed to be neutrally buoyant, the force magnitude produced by magnetic gradient is not capable of producing tissue penetration.

Consider, for example, that a standard 18 gauge needle requires 0.59+-0.11N of force to

penetrate 10mm into muscle tissue [6]. Bioinspired design can somewhat reduce these forces, e.g., the backward-tipped barbs of the North American porcupine quill exhibit forces of 0.33+-0.08N for 10mm of muscle penetration [6]. Nevertheless, to reproduce even these forces using an MRI with a steel needle would require a 3.3m long shaft – longer than the bore of the scanner. While the size of macro-scale MRI-based actuators permits the use of gear transmissions to trade off velocity and force [Panagiotis, Aaron], this approach is not feasible at the millimeter scale. Therefore, to address the challenge of MRI-based tissue penetration, an alternative to gradient-based force production is needed.

The observation that tissue penetration force is inversely related to penetration velocity [Mahvash] motivates the concept of using energy storage and sudden release to perform penetration. Furthermore, while the maximum gradient forces produced on a steel particle are low, the magnetic attraction forces between particles inside the scanner is, by comparison, quite high. Thus, the approach proposed here involves navigating individual millirobots to a target location and allowing them to self-assemble in a manner that focuses the stored magnetic potential energy as kinetic energy for tissue penetration.

The concept, illustrated in Fig. 1, corresponds to a Gauss gun or accelerator [11,12]. Comprised of one or more stages, each stage is composed of a strong magnet, followed by two or more steel ball bearings. By colliding a single ball bearing with the first magnet, a chain reaction is initiated, greatly amplifying the speed of the first ball bearing.

In an MRI scanner, there is no need for permanent magnets, since steel is highly magnetized by the 3T magnetic field of an MRI. Each stage, containing two magnetized spheres separated by a nonmagnetic spacer, is individually stable. Using existing control approaches [x,y], they can be navigated through fluid-filled spaces and self-assembled at a desired penetration location. The assembly can then be fired by a special trigger module consisting of two ball bearings separated by a spacer longer than that used in the individual stages. After firing, the assembly can be navigated out of the body.

The remainder of the paper is arranged as follows. The mathematical model of the MRI Gauss gun is derived in the next section. Section III details the design of experimental prototypes. Experiments evaluating self assembly and penetration are provided in Section IV. Conclusions appear in Section V.

Fig. 1. Operation of a Gauss gun. (a) Standard design for use outside an MRI scanner shown before and after triggering. Magnetized spheres are red and green. Non-magnetized spheres are gray. (b) Design for use inside an MRI scanner shown before and after triggering. All spheres are magnetized when inside scanner.