RF-Selective-Excitation for State Estimation of an MRI-Powered Motor

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Introduction

Magnetic Resonance Imaging (MRI) is increasingly attractive for intraoperative guidance of surgical interventions, and MRI-compatible robotic systems can enable clinicians to operate with high dexterity from outside the scanner bore. Existing MRI-compatible robots, however, rely on traditional actuation principles, implying high costs and tethered connections to a console exterior to the scanner room. Medical devices that are powered, imaged, and controlled by MRI can be inexpensive tetherless alternatives. The principal component of such MRI-powered robotic systems is the MRI-powered motor [1]. This abstract presents an RF-selective-excitation-based methodology to estimate the state (angular position) of the MRI-powered motor in real-time, thus preventing it from slipping [1] and ensuring maximum torque generation.

Materials and Methods

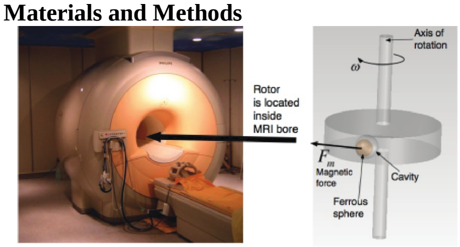

Fig. 1: MRI-powered actuator concept.

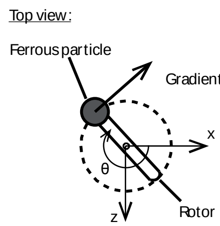

Fig. 3: Orthogonal gradients supply max torque.

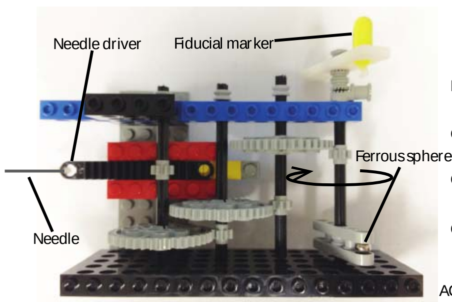

Fig. 2: The MRI-powered actuator on a needle driving robot.

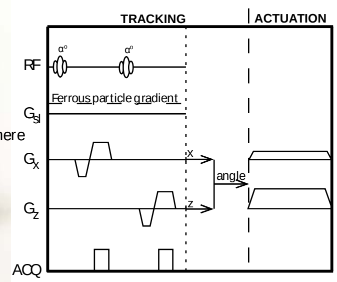

Fig. 4: Pulse sequence for tracking and optimal gradient generation.

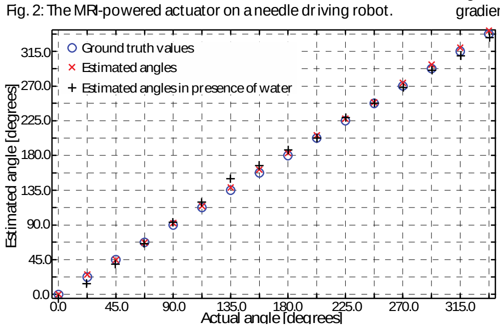

Fig. 5: Rotor angle estimation in the in the absence and presence of water.

By analogy to electric motors, an MRI-powered motor consists of a rotor, which can be a chrome steel bead attached on a rotating arm, and the stator, which is the MRI scanner (see Fig. 1). By rotating the MRI gradients, useful mechanical energy is created through lever rotation. Subsequently, a set of gears transforms this rotating motion into, for example, linear needle motion (see Fig. 2).

Maximum mechanical energy generation occurs when the MRI gradients are applied perpendicularly to the lever arm (see Fig. 3). To achieve this, the lever angle needs to be known in real time. Since the actuator is MRI-invisible, an MR-SPOTS marker (Beekly Medical, CT) was positioned above the rotating ferromagnetic bead (see Fig. 2). The magnetic field B_P generated by the bead, however, distorted B_0 and complicated marker tracking by dephasing its water molecules.

To overcome this, RF-selective pulses that account for the $B_0 + B_P$ field at the marker location were utilized [2]. After estimating B_P by modeling the ferrous particle as a point dipole, the frequency of the RF pulse was selected.

A single dimensional gradient echo (TR = 13ms, FOV = 300mm, $\alpha = 80^o$, matrix = 256 pixels) followed by peak detection provided the coordinates of the particle along the x and z directions. Subsequently, rotor angle was calculated trigonometrically. No slice selection gradient was necessary since encoding was possible due to the gradient caused by the ferrous particle.

Results

Experiments were performed in a 1.5T Signa GE scanner with the MRI-powered motor mounted on a needle-insertion robot constructed from LEGO® components (see Fig. 2). The selected frequency and bandwidth of the RF pulse were 1200Hz below the Larmor frequency corresponding to B_0, and 3.2 KHz, respectively. Signal processing was performed on a workstation that communicated with the scanner via RTHawk [3]. The full tracking cycle, including signal acquisition and processing, was completed in approximately 30ms, satisfying the real-time constraint. For various angle configurations, tracking was possible with less than 5^o average error (see Fig. 5). Due to the RF frequency shift, tissue (simulated by water) positioned at the needle-driver side did not affect angle estimation. Based on the estimated rotor angle, the MRI gradients that generate maximum torque can be applied to the rotating lever.

Conclusions

This paper presents a methodology to supply maximum torque to an MRI-powered actuator by real-time rotor-angle estimation. The actuator and tracking methodology are the building blocks for more advanced wireless medical robots that are powered, imaged, and controlled by MRI scanners.

References

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