Closed-loop Position Control of an MRI-powered Biopsy Robot

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INTRODUCTION

Clinical MRI scanners can provide large amounts of electromagnetic energy that potentially could be used for actuation as well as imaging and so provide a complete environment for robotic interventions. The idea of using MR scanner magnetic gradients for actuating and tracking millimeter or micrometer size ferromagnetic particles was initially proposed and performed by Martel *et al.* [1] for drug-delivery applications. In parallel, many groups have developed MRI compatible robots for interventional applications (see reviews in [2,3]).

Inspired by this existing body of work, our group developed an MRI-powered robotic actuator, which was introduced in [4]. Our design leverages the force generation principles studied in [1] to perform the interventional procedures described in [2,3]. In this paper, we introduce closed-loop position control in the context of driving a biopsy needle into tissue. The approach utilizes interleaved actuation and imaging pulse sequences to drive a needle a specified displacement using image-based feedback of a fiducial marker that moves with the needle.

MATERIALS AND METHODS

Principle of operation and prototype: The proposed MRI powered actuator is comparable to an electric motor. It consists of a stator, which comprises the MRI scanner together with the fixed supports of the actuator, and a rotor, which is the rotating portion of the actuator and contains a ferromagnetic sphere. The actuator is rotated through the application of rotating magnetic field gradients that induce a force on the ferromagnetic sphere. A prototype actuator was constructed using LEGO components as shown in . LEGOs offer a fast, convenient and reliable way to build MRI-compatible mechanisms. The small ferrous sphere is located outside the imaging field of view and so does not affect imaging quality.

The actuator itself is wireless and compact. Its principle of operation, its dynamics and capabilities are described in [4]. For the experiments described here, the actuator is placed near the isocenter of the scanner with the plane of the rotor aligned with the X-Z plane of the scanner reference frame. Using the maximum gradient of a clinical MRI, 40 mT/m, the actuation pulse sequence shown in Fig. 3 produces a force on the rotating ferrous sphere (Fig. 1) on the order of 10mN, which is amplified using a gear train and converted to linear coordinates using a rack and pinion. Our open-loop experiments with this prototype have demonstrated needle forces up to 1.2 N.

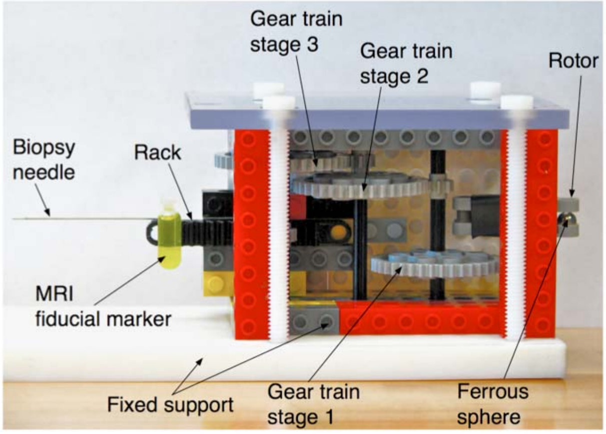

Fig. 1. LEGO prototype. The rotor contains a ferrous sphere and its rotational motion is converted into linear motion using a rack and pinion configuration. The marker on the rack serves as a fiducial for localization of the needle attached on the rack.

Closed-loop position control: The closed loop control architecture and its components are depicted in Fig. 2. Experiments were conducted in a 1.5T clinical MRI scanner. To track the relative displacement of the needle tip, an 8 mm-wide MR-SPOTS fiducial marker (Beekley Medical, CT) was attached to the rack component holding the needle as shown in Fig. 1. While it is also possible to track the needle tip, the use of a passive fiducial marker simplifies the image processing requirements. Since, in our approach, the MR scanner alternates between driving the actuator and tracking its state, reducing the tracking overhead facilitates a higher controller rate.

As shown in Fig. 3, the tracking algorithm employs a gradient echo pulse sequence to generate single-dimensional projections of the field of view. The advantage of this pulse sequence is that it does not contribute to the net motion of the ferrous sphere. Following a background suppression filter to remove the influence of the tissue, the marker is localized using the mean value of a Gaussian function fit to the signal values whose magnitudes are in the top 45%.

Position control experiments were conducted inserting an MRI-compatible needle (MReye, Cook Medical) into chicken breast. The needle was first driven into the tissue to an arbitrary initial location. A gradient echo imaging sequence was then used to image the needle and to determine the distance in the image coordinate frame that the needle must travel to reach a target selected in the image. This displacement command (set point in Fig. 2) was then sent to the external computer for closed-loop execution.

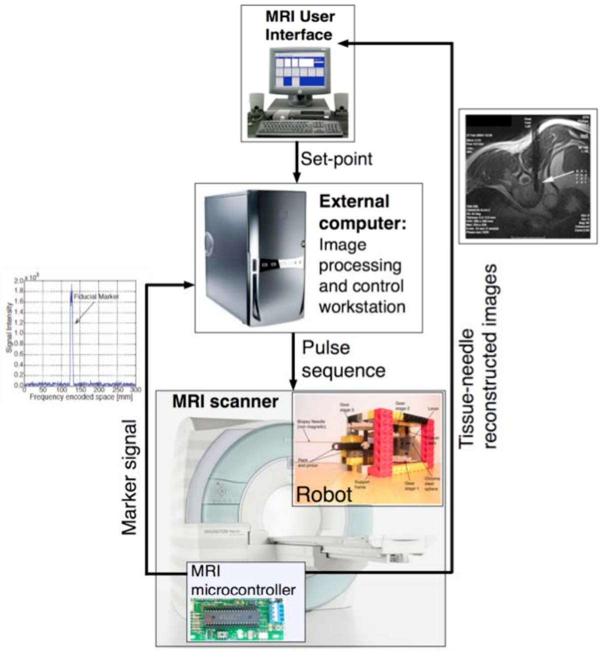

Fig. 2. Closed loop architecture of the MRI-powered robot.

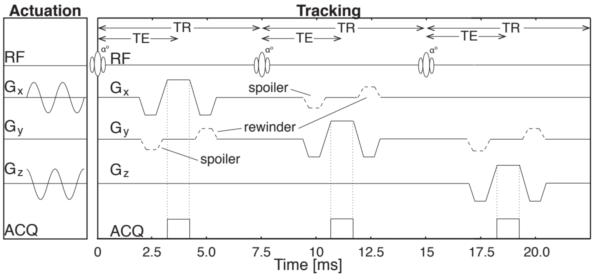

Fig. 3. Actuation and tracking pulse sequences.

RESULTS

Each actuation cycle consists of a single sinusoidal cycle of magnetic gradients which equates to a needle displacement of 250µm. With a field of view in each coordinate direction of 300mm corresponding to 512 voxels, the maximum imaging resolution is 580µm/voxel. Consequently, needle displacements that correspond to less than three actuation cycles (750µm) are not observable. Preliminary localization experiments demonstrated that tracking precision was ± 1.2mm, due to noise in the imaging signal. Therefore, the imaging pulse was set to follow a sequence of five successive actuation pulses, which correspond to 1.25mm of needle motion. This value is within the tracking capabilities, and indicates the worst-case experimental precision.

An example trial is shown in Fig. 4. Figure 4(a) shows an MR image acquired using gradient-echo imaging, wherein a 10 mm desired needle displacement is selected. This distance corresponds to 8x5 actuation cycles. The displacement was monitored by the tracking algorithm, which terminated the motion when the estimated distance travelled was 9.95mm.

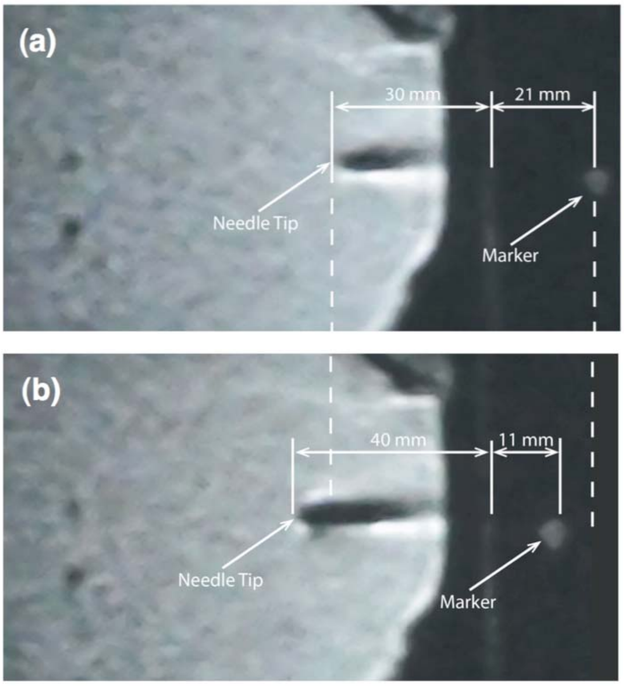

Fig. 4. Illustration of an automated biopsy procedure using gradient-echo imaging, MRI-powering and marker tracking.

DISCUSSION

This paper has presented the effective use of a passive fiducial marker for implementing closed-loop position control of MRI-powered needle displacement in a clinical scanner. These successful experiments provide direction for our future work which will focus on implementing rotor commutation control in order to maximize output force as well as increase actuator output resolution. In addition, we plan to develop techniques for implementing independent position control of multiple degrees of freedom.

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