A Closed-loop MRI-powered Actuator for Robotic Interventions

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Introduction

Robotically-assisted MR-guided interventions are becoming increasingly important in the clinical community. Surgical robots offer precision, accuracy, speed, and the potential for remote operation, while the MRI offers superior soft tissue contrast and a well-defined 3D coordinate system. The synergy of both systems results in robotically assisted MR-guided interventional procedures that can target lesions more accurately and more efficiently. Recently, an MR-powered and controlled actuator technology has been proposed for needle guidance of biopsies or interventional therapies. The principle of operation is based on one or more small ferromagnetic bodies embedded in the actuator that serves to convert the electromagnetic energy of the MR gradients into mechanical energy [1]. A prototype was constructed to show that the actuator can drive a needle and successfully puncture a swine heart under open-loop control. In order to improve actuator performance as well as to automate the puncturing procedure, a closed-loop MRI-controlled actuator is developed.

Method and Material

The actuator consists of the stator, which, in this case, is comprised of the MRI scanner together with the stationary components of the actuator, and a rotor, which is the rotating portion of the actuator that contains the ferromagnetic object enclosed in a cavity (Fig. 1a). When sinusoidal gradients (Fig. 1b) are applied in the x-z plane, the magnetic force acting on the ferromagnetic body rotates the lever around the y axis. An actuator prototype was constructed using Lego components (Fig. 1c), which are MR-compatible. Rotation of the lever drives a gear transmission that in turn drives a rack to which the needle is mounted. The direction of rack motion depends on the phase difference between the two sinusoidal gradients, Gx and Gz.

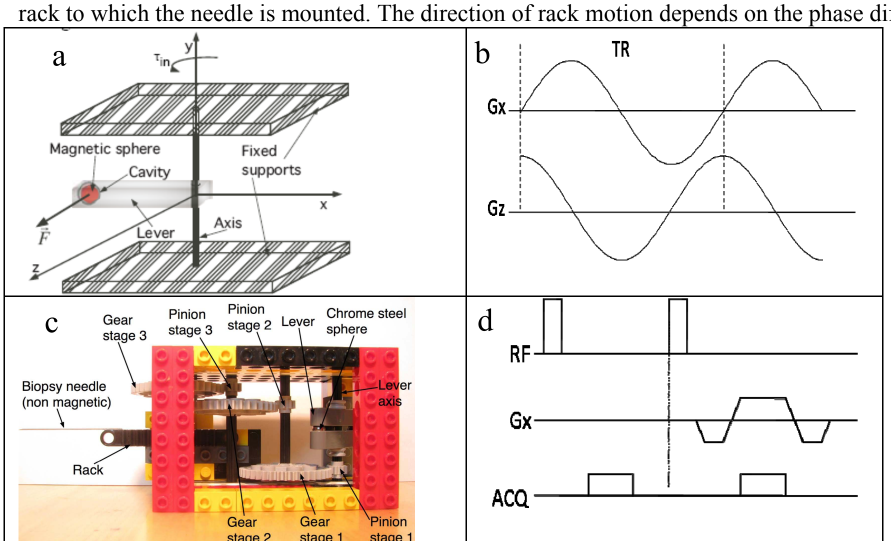

Figure 1. (a) Actuator schematic. (b) Sinusoidal gradients to power the actuator. (c) Actuator prototype. (d) Tracking sequence.

For closed-loop control, it is necessary to track needle position during motion so that it can be stopped at a preset distance. To fulfill this requirement, an MR-SPOTS (Beekley Medical, CT) marker was attached to the rack. Its location was detected with a tracking sequence (Fig.1d). To correct for local B0 in-homogeneities, one excitation was performed without a spatial encoding gradient to provide a reference frequency-offset. The subsequent excitation included a nonselective RF pulse followed by a gradient readout along the axis of motion. The reference frequency was then subtracted from the peak location of the Fourier-transformed signal of the directionally-encoded profile, providing the marker location. This tracking sequence was interleaved with the sinusoidal (actuation) sequence so that the position of the rack was estimated after every five cycles of actuation. The MR tracking parameters were: TR/TE/θ = 7.5ms/3ms/5°, 300 mm FOV, ±32 KHz bandwidth, 256 matrix. Tracking readouts were processed in real-time through RT-HAWK [2] on an external computer. The procedure terminates when the tracking distance equates to the preset distance.

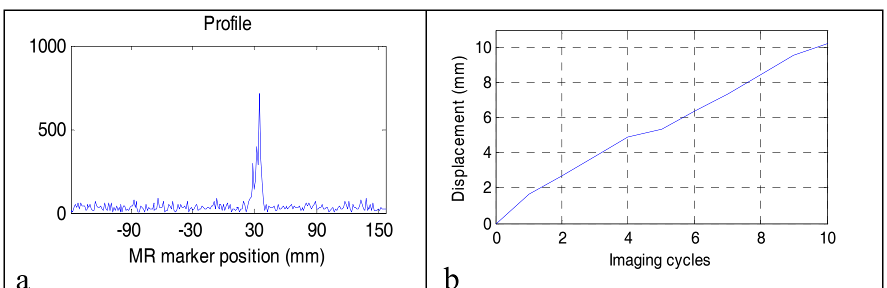

Figure. 2 (a) Profile readout with the MR tracking sequence. (b) Position of the needle under the closed-loop control of the actuator.

Results

Experiments were performed in a clinical GE 1.5T MRI scanner (Milwaukee, WI). Sinusoidal gradients of 40mT/m and 1Hz were applied to rotate the lever. A 5-inch surface coil was used as the receive coil to track the MR-SPOTS marker. One profile of the MR-SPOTS is shown in Fig. 2a, whose peak location indicates the needle position. The preset distance was set to 10mm. After 10 tracking readouts (50 actuation cycles), the needle had moved 10mm, and the external computer sent a signal to the MRI control computer to terminate the procedure (Fig. 2b). The linearity of the curve suggested that the actuator moved at relatively constant speed during the experiment. The position error of the needle with respect the desired displacement was 200 μm.

Conclusion

This paper presents a novel MR-powered and controlled closed-loop actuator technology for robotically-assisted MR-guided interventions.

References

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