Published in final edited form as:

J Eng Sci Med Diagn Ther. 2020 February ; 3(1): . doi:10.1115/1.4044609.

Demonstration and Experimental Validation of Plastic-Encased Resonant Ultrasonic Piezoelectric Actuator for Magnetic Resonance Imaging-Guided Surgical Robots

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Abstract

Intra-operative medical imaging based on magnetic resonance imaging (MRI) coupled with robotic manipulation of surgical instruments enables precise feedback-driven procedures. Electrically powered nonferromagnetic motors based on piezoelectric elements have shown to be well suited for MRI robots. However, even avoiding ferrous materials, the high metal content on commercially available motors still cause distortions to the magnetic fields. We construct semicustom piezoelectric actuators wherein the quantity of conductive material is minimized and demonstrate that the distortion issues can be partly addressed through substituting several of these components for plastic equivalents, while maintaining motor functionality. Distortion was measured by assessing the root-mean-squared (RMS) change in position of 49 centroid points in a 12.5 mm square grid of a gelatin-filled phantom. The metal motor caused a distortion of up to 4.91 mm versus 0.55 mm for the plastic motor. An additional signal-to-noise-ratio (SNR) drop between motor off and motor spinning of approximately 20% was not statistically different for metal versus plastic ($p = 0.36$).

Introduction

Brachytherapy [1], a localized radiation-based cancer treatment, biopsies, and tumor ablation [2] are examples of routinely performed medical procedures that require accurate positioning of a needle inside the patient. In all cases, improved three-dimensional location of the needle and structures of interest during the procedure can lead to better results. Today, several imaging modalities are used for guidance including ultrasound, computed tomography, and magnetic resonance imaging (MRI) [3]. Recently, MRI is becoming a stronger candidate for imaging due to its superior soft tissue contrast which yields higher

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sensitivity for detecting malignancies [4,5]. The MRI is also able to perform multiparametric scans including flow diffusion, real-time temperature mapping, and oxygenation measurements. However, the confined space of the MRI bore, strong magnetic fields and susceptibility to electrical noise pose challenges, ones that can be addressed by the use of MRI compatible robots [6].

Several MRI compatible robots are available in the literature and demonstrate unique ways to deal with the challenges posed by the environment in the MRI [7]. In all cases, no ferromagnetic components are used due to projectile risks and an attempt is made to minimize or properly locate conductive components. In efforts to best achieve this, various groups have employed a variety of actuators to move these robots.

Pneumatically actuated MRI compatible robots have been demonstrated and the technology has been developed greatly since its first appearance. Stoianovici et al. created the PneuStep motor, a pneumatic stepper motor that, having no electrical or conductive components, does not affect image signal-to-noise-ratio (SNR) [8,9]. Fischer et al. developed a robot for intraprostatic needle placement that achieved 0.94 mm RMS accuracy inside an MRI using custom made glass/graphite cylinders [10]. Comber et al. presented a five degrees-of-freedom active cannula robot for lower brain interventions that builds upon Fischer et al.'s fail-safe rod lock to improve robot safety during procedure. Yakar et al. also demonstrated the feasibility of pneumatically actuated robots in the MRI through a ten patient human trial [11]. These motors can offer high torque and be constructed from all plastic parts to achieve MRI safe classification. However, they are limited by the slow reaction times of the valves and long air lines. This is partly addressed by the controller design of Yang et al. that includes a model of the transmission lines [12].

Hydraulic actuation addresses some of the latency limitation of pneumatic actuation. Kokes et al. demonstrated the feasibility of using hydraulic cylinders in the MRI for breast cancer-related intervention [13]. Lee et al. make use of hydraulic rolling diaphragm motors in their multi-axis cardiac cauterization robot [14]. Similar to pneumatic motors, the long hydraulic lines affect the response time of these actuators and leakage of the hydraulic fluid during a procedure can compromise the sterile field.

Electrical actuation in the form of piezoelectric motors has also been demonstrated in MRI compatible robots. Masamune et al. built one of the first such robots in 1995 [15]. Patel et al. demonstrated the use of nonresonant piezoelectric motors in a three degrees-of-freedom needle steering robot [16]. Nycz et al. characterized a stereotactic frame replacement robot with seven degrees-of-freedom powered by resonant piezoelectric motors [17]. The pneumatic powered positioning stage of Seifabadi et al. for prostate biopsy [18] was later converted to work with resonant piezoelectric motors [19]. Piezoelectric motors pose some challenges for MRI compatibility due to their primarily metallic construction. Although nonferromagnetic, the generation of eddy currents due to the MRI's gradient fields can lead to magnetic field distortions causing image artifacts. Motor vibrations due to interactions between the MRI's magnetic fields and those generated by the eddy currents can further degrade image quality by causing image artifacts. However, piezoelectric motors have fast

reaction times and robots that use them may have reduced setup time as compared to other modes of actuation.

In this paper, we demonstrate that image distortion related issues can be partly addressed by replacing metallic nonactive motor components from a resonant ultrasonic motor for nonmetallic equivalents. Furthermore, the replacement can be done with no detriment to the SNR as compared to its metallic counterpart.

Motor Construction

Piezoelectric ultrasonic motors are designed around two components: A stator with a ceramic ring coupled to it and a rotor that is frictionally coupled to the stator surface by applied pressure. The piezoelectric element, usually composed of lead zirconium titanate, is patterned with conductive electrodes to which drive signals are connected. The excitation of the ceramic at a particular frequency by two properly shifted sinusoidal waves induces a vibrational mode with a traveling wave that rotates around the shaft. This traveling wave pushes the rotor generating torque [20].

A nonferromagnetic USR-60 motor (Shinsei, Japan) shown in Fig. 1(a) was modified to reduce its metal content. The USR-60 is excited by 40–45 kHz sine waves to achieve a maximum speed of 150 revolutions per minute. Only the aluminum rotor and the copper stator with attached ceramic were incorporated into the new motor. A new enclosure was machined out of ULTEM™1000, a drive shaft was machined from Delrin™stock and nylon screws were used in place of brass. A shim or metal spring is typically used to maintain a preload between the rotor and the stator in metal motors; however, our design uses a polyurethane disk to accomplish the same function. The final assembly can be observed in Fig. 1(b).

Methodology

The motors under study, a standard USR-60 and our semicustom motor, were analyzed inside a Philips Achieva 3 T scanner. The USR-60 and the semicustom motor will hereto be referred to as the metal motor and plastic motor, respectively. A three-dimensional printed phantom 90 mm × 90 mm × 60 mm with a 45 mm homogeneous region and a 15 mm tall grid composed of 12.5 mm × 12.5 mm squares in the lower portion were used as the object being imaged similar to Refs. [17] and [21]. The phantom was filled with a low concentration gelatin and care was taken to purge all bubbles.

The phantom was elevated approximately 5 cm above the MRI table using a foam block and two Philips Flex Sense M imaging coils were placed on either side of the phantom. A wooden support structure was positioned above the phantom so that the motor under test could be located on it. The setup can be observed in Fig. 2.

Motors were powered from the controller box used by the robot in Ref. [17]. The controller box is fully shielded and is placed inside the MRI room. It was shown in Ref. [17] that it does not affect SNR when powered on. A fully shielded cable connects the controller box to a breakout board inside the scanner. The same motor driving card was used for both motors

to reduce experimental uncertainty and contains a DS6060 (Shinsei, Japan) turned on and off via a control signal modulated at a frequency of approximately 300 Hz on the clockwise direction line at 50% duty cycle. Pulse width modulation is commonly used in electrically powered MRI robots to control motor speed, and for this reason, we decided to perform tests under PWM. However, PWM with a piezoelectric motor can generate mechanical vibrations which can cause a signal drop in the MRI.

A T2 spin double echo sequence was used for imaging the phantom. The repetition time was set to 2000 ms, echo time 20/80 ms with 30 256 mm × 256 mm × 5 mm slices. Voxels were 1 mm × 1 mm × 5 mm. Slice overlap was set to 2.5 mm. The sequence had a bandwidth of 16.6 kHz and lasted approximately 17 min per run. This sequence is representative of those used during intra-operative imaging with MRI robots.

Two repetitions of the T2-weighted scan were acquired in each of the six conditions shown in Table 1. The two conditions with a position of *side* were collected with the plastic and metal motor each positioned alongside the phantom instead of on the support structure. These conditions were used exclusively for distortion calculation since changing the position of the motor within the scanner should not change the scanner's pickup of its radiative emissions, whereas MRI image distortion can be affected by orientation. Figure 3 shows the positions of the plastic and metal motor both on top and alongside the phantom.

Signal-to-noise-ratio was calculated based on the image difference method presented in Ref. [22] as “method 1.” In this method, the second image is subtracted from the first for each image pair to create a difference image. A region of interest (ROI) containing most of the phantom is chosen and kept constant for all image sequences. The average signal intensity μ is calculated as the average of voxel intensities in the ROI. The noise is calculated as the standard deviation σ of the pixel intensities in the ROI of the difference image divided by $\sqrt{2}$. The SNR is defined as in Eq. (1). SNR results between different test conditions were compared using IBM SPSS software based paired *T*-test. Statistical analysis is based on 14 slices through the homogeneous region of the phantom for each test condition.

$$\text{SNR} = \frac{\mu}{\sigma} \quad (1)$$

The image distortion was calculated following the same procedure as in Ref. [17]. A slice in the center of the phantom's grid was chosen for each imaging sequence. The centroid of each square was computed using an OpenCV-based script and then the difference between the location of each centroid between the image of interest and the baseline was computed through an iterative closest point algorithm in MATLAB. The results were converted to mm. The distortion represents the distance between the centroid locations in the baseline image and those in the comparison image.

Results

The SNR for each motor was compared to baseline for each of two test conditions: Motor off and motor spinning. Figure 4(b) shows the results. There was no statistical difference

between baseline and the plastic motor inside the MRI ($p = 0.714$) when powered off. The metal motor when inside the MRI and powered off causes a reduction in SNR of 23% ($p < 0.001$). The drop in SNR for the metal motor powered off may have occurred due to distortion in the magnetic field near the imaging location causing a signal drop. Both motors when spinning caused an additional drop in SNR of approximately 20% as compared to their powered off state. The additional drop in signal was not statistically different for both motors ($p = 0.36$). The SNR drop was not significant enough to be apparent upon visual inspection of the images as can be observed in Fig. 5. The larger spread in SNR for the motors in the moving state are related to the SNR of different slices varying depending on their distance from the motor. This may be related to motor vibrations propagating through the phantom.

The plastic motor outperformed the metal motor in the distortion experiments. Table 2 shows the results. No difference was observed between the motor powered off and motor spinning. The larger difference between the motors was observed in the side configuration which is along the MRI's primary magnetic field and in close proximity to the region of the phantom that contains the grid. In this configuration, the metal motor had over ten times the maximum distortion of the plastic motor.

The raw MRI scans are shown in Fig. 5 using the same windowing. The distortion caused by the metal motor in the side configuration can be seen in Fig. 5(g) and quantified in Fig. 4(a). The surface plot shows a peak distortion of 4.91 mm in the top left corner which is stretched upward. The metal motor creates a darkened region with an 80% drop in signal in the first grid square which only returns to nominal approximately 45 mm into the phantom. The plastic motor shows no visible difference, see Fig. 5(f), to baseline when in the same configuration.

Conclusion and Future Work

Results have shown that the plastic motor causes less distortion while maintaining an equivalent or better SNR. The maximum observed distortion decreased from 4.91 mm to 0.34 mm for the plastic motor versus the metal motor when positioned on the side of the phantom. The lower distortion allows for higher flexibility in motor placement since it can be located closer to the ROI. Results have shown that the SNR for the plastic motor was better than its metal counterpart, despite it being often implied that a metal enclosure is required for a piezoelectric motor to shield the MRI from electrical noise. These are promising results for the field of piezoelectric powered MRI compatible robots since these modifications can be done to commercially available motors or used as a guidance for new motor development.

The demonstration that removing the metal enclosure of a piezoelectric motor that is driven by clean signals that do not contain harmonics near the Larmor frequency for the scanner decreases distortion without causing an SNR decrease paves the way for fully plastic motors. Replacing the stator and the rotor's friction disk for plastic equivalents will lead to even lower distortion since only the wires and copper plating on the ceramic crystal will remain as conductive parts.

Funding Data

• National Institutes of Health (NIH) under the National Cancer Insitutiton (NCI) (Grant No. R01 CA166379; Funder ID: 10.13039/1000000009).

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Fig. 1.

(a) Construction of a standard nonmagnetic Shinsei USR-60 motor and (b) of the plastic-encased piezoelectric motor. In the plastic motor, the aluminum rotor, copper stator, and piezoelectric ceramic are taken directly from a Shinsei USR-60. The aluminum housing, bronze drive-shaft, shims, and screws have been replaced with nonmetallic substitutes.

Fig. 2.
Full experimental assembly in MRI scanner with bed moved to extremity

Fig. 3.

(a) Metal motor positioned on top of the phantom, (b) metal motor positioned on the side of the phantom, (c) plastic motor positioned on top of the phantom, and (d) plastic motor positioned on the side of the phantom. In all cases, the motor was approximately 10 mm from the start of the gelatin.

Fig. 4.

(a) Distortion magnitude with the metal motor positioned on the side of the phantom. This is the test condition shown in Fig. 3(b) and calculated from the change between Figs. 5(a) and 5(g). In all other test conditions, the maximum distortion is less than 0.7 mm. (b) SNR results of the five different testing conditions. For each condition, SNR was calculated on 14 slices through the homogeneous region of the phantom. Results are normalized with respect to the baseline scan.

Fig. 5. MRI slice through phantom grid for each test condition: (a) baseline, (b) plastic off, (c) metal off, (d) plastic spinning, (e) metal spinning, (f) plastic off, on side, and (g) metal off, on side

Table 1

Motor conditions used during MRI image acquisition

Motor material	Position	State
Metal	Top	Stopped
Plastic	Top	Stopped
Metal	Top	Spinning
Plastic	Top	Spinning
Metal	Side	Stopped
Plastic	Side	Stopped

Table 2

Maximum distortion for 49 centroids in phantom grid

Test condition	Plastic	Metal
On top and power off	0.54 mm	0.62 mm
On top and power on	0.55 mm	0.68 mm
Side and power off	0.34 mm	4.91 mm

Note: Three test conditions for each of plastic and metal motor.