

Manipulation in MRI Devices using Electrostrictive Polymer Actuators: With an Application to Reconfigurable Imaging Coils

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Abstract - MRI (Magnetic Resonance Imaging) is a powerful medical diagnostic tool. Its value would be greatly increased if it was possible to physically manipulate objects within the MRI during imaging. However, the extraordinarily strong magnetic fields used by the MRI make conventional electromagnetic components, such as actuators and sensors, unusable. In this paper, it is shown that devices constructed using binary polymer based actuators, called Electrostrictive Polymer Actuators (EPAM) are able to function effectively within the MRI without degrading its imaging performance. These actuators eliminate the need for conventional electromagnetic actuators and their associated electronics. The binary nature of the actuators eliminates the need for feedback sensors to control the devices motion. The basic concept called Digital Mechatronics is briefly summarized in this paper. Its application to a reconfigurable MRI surface-imaging coil (RMIC) is also presented. Experimental results are presented that show the EPAM RMIC is completely compatible in the MRI and can be used to enhance the diagnostic capabilities of MRI. The paper also suggests other applications of binary EPAM based actuators for use in MRI systems.

Keywords – *polymer actuation; magnetic resonance imaging; manipulators; medical devices*

I. INTRODUCTION

A. Motivation

MRI (Magnetic Resonance Imaging) is a powerful and effective medical diagnostic tool. It has been well recognized that its value would be greatly increased if it were possible to physically manipulate objects within the MRI machine during imaging. An example would be performing endoscopic surgical procedures while observing

the procedure inside the patient in real time. However, the limited workspace within a typical MRI machine makes manipulation of objects difficult. Robotic systems provide potential solutions to this problem [1]. However, because of the extraordinarily strong magnetic fields used for MRI, conventional electromagnetic components such as actuators and sensors are unusable. Robotic systems using alternative components, such as piezoelectric actuators, have been developed [2,3]. These systems tend to be complex and expensive.

In this paper it is shown that devices constructed using binary polymer based actuators are able to function effectively within the MRI and do not degrade its imaging performance. EPAM's eliminate the need for conventional electromagnetic actuators and their associated electronics. The binary nature of the actuators eliminates the need for feedback sensors for motion control. Their construction is fundamentally inexpensive and simple. They can be constructed essentially from plastic, making their potential cost low enough to be disposable. The basic concept called "Digital Mechatronics"[4] is briefly summarized in this paper.

A practical design concept for an EPAM actuated MRI device is presented. This device is a reconfigurable MRI surface-imaging coil (RMIC). Experimental results show the EPAM RMIC is completely compatible with MRI and can be used to enhance the diagnostic capabilities of MRI.

In MRI, individual coils are placed directly on the patient to enhance the image quality and resolution in a local region of interest. Optimal image quality results when the sensitivity profile of the coil is matched to the volume of the region of interest within the patient. The function of a conventional surface coil is limited because it has a fixed size and shape. Therefore, during an imaging session a coil may be moved or replaced with a different sized coil to improve image quality. This usually requires that the

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patient be removed from the machine. This is time consuming, leading to increased expenses and patient discomfort. This paper presents a new method for remotely changing the size and location of the coil with EPAM actuators while the patient remains in the MRI. The experimental results show both EPAM-MRI compatibility and the promise for enhancing treatment capabilities of MRI. The manipulation of an imaging coil demonstrates the feasibility of EPAM actuated robotic manipulators. There are number of possible applications for robotic manipulators for MRI[5,6,7]. The compatibility of EPAM actuators suggests that a new class of MRI compatible manipulation devices, such as MRI-guided EPAM manipulators, are possible.

B. Background

The criteria for MRI compatibility of devices and robots have been discussed in detail[8, 9]. To be MRI compatible, a device must function safely and correctly in the high magnetic fields of the MRI environment without causing damage to the system or injury to the patient. Also, it must not affect the imaging quality. The strong magnetic fields prevent devices constructed of common engineering components from being MRI compatible. Ferromagnetic materials are dangerous when placed in close proximity to an MRI machine. Electronically driven motors and sensors can cause electromagnetic interference, thus disturbing the MRI image.

The EPAM actuators developed in this study are fundamentally MRI compatible. They consist of a dielectric polymer film with compliant electrodes on either side. The electrodes consist of conducting particles, such as carbon or silver, suspended in grease. Polymer film is stretched in a plastic frame that forms the actuator body and maintains the pre-stretch required for the actuator performance [10]. Built into the frame are compliant elements that tune the force characteristics of the actuator. When a voltage difference is applied across the dielectric, the polymer film is subjected to compressive force, and the film expands in area. This area expansion can be utilized for the development of mechanical actuators. The operation does not require any metallic parts or sensors that might affect image quality. The binary character of the actuator forces the device into clearly defined positions, eliminating the need for internal feedback sensors to achieve precision or disturbance rejection.

EPAM actuators are well suited for MRI environments because they are lightweight and can be fabricated in a large variety of shapes and sizes. Thus the design can be customized to fit in the limited workspace of MRI environments. Work has been done in designing all-plastic manipulation systems using EPAM actuators - called Binary Robotic Articulated Intelligent Devices (BRAID)[11]. A conceptual model of a BRAID from this study is shown in Fig. 1. Fig. 2 shows a two stage BRAID prototype used as an articulated mirror mount.

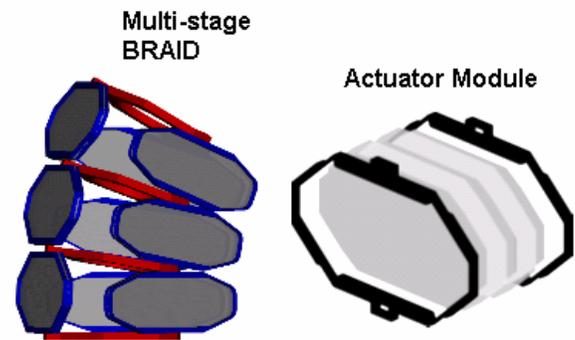


Figure 1. BRAID (Binary Articulated Device) Conceptual Design.



Figure 2. A Two Stage Functional BRAID Prototype

These devices use the control scheme known as “Digital Mechatronics.” Such systems consist of a large number of binary actuators, each with two distinct states. Control is achieved by actuating the appropriate actuators to achieve desired position. As the number of discrete actuators increases, the performance approaches that of a continuous system. Using this control method, feedback and sensors are not necessary.

II. OPERATING PRINCIPLES

A. The EPAM

A simple single layer EPAM actuator is made of a layer of dielectric elastomeric film surrounded by layers of compliant electrodes, see Fig. 3. The actuator used for this study has two states, ON and OFF. In the OFF position there is zero voltage difference between the electrodes. In the ON position the electrodes are charged like a capacitor to a high DC voltage difference and draw negligible current. Since the actuator works in only two states, each corresponding to a known mechanical position, no feedback is necessary for operation. Therefore issues regarding MRI compatibility of sensors necessary for feedback are not necessary. The EPAM actuators have no metallic parts, which might affect the homogeneity of the magnetic field of the MRI scanner or be affected by the magnetic field.

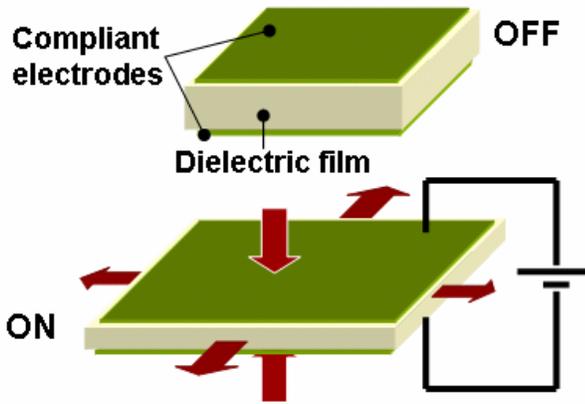


Figure 3. The EPAM actuation pressure is generated by simple electrostatic effects

The pressure generated across the film is a combination of the attractive stresses acting across the film between the oppositely charged electrodes and the repulsive stresses acting on both surfaces. Derivation of the electrostatic model yields the following expression for describing actuation pressure [12]:

$$\sigma_z = \epsilon \epsilon_0 E^2 = \epsilon \epsilon_0 \left(\frac{V}{z} \right)^2 \quad (1)$$

Where ϵ_0 is the permittivity of free space, ϵ is the dielectric constant of the polymer film, E is the electric field present in the film, V is the voltage difference across the film, and z is the film thickness. The compressive forces that result cause the film, which is ideally a very soft polymer, to decrease in thickness. The film laterally expands in area due to the constant volume property of polymers. The strain values that result can exceed 200%.

The EPAM actuator must be under some initial planar tension in the OFF state to prevent buckling in the ON state. When compressive stress is applied to a film already in planar tension, there will be a significant reduction in the tension of the film. This change in tension provides the force necessary to achieve movement in the film. The external tension can be applied by constraining the film in either a rigid or flexible frame.

Fig. 4 shows an EPAM actuator constrained in a round, rigid frame. In this case the clear acrylic film is stretched and fixed within the circular frame. The electrodes in this case are silver grease. The constrained film provides the tension. When actuated, the light colored region in the center expands because its planar stiffness is effectively decreased and the tension outside of that region remains constant. The magnitude of the expansion is a function of the amount of initial tension and the relative size of the active region compared to the size of the fixed frame.

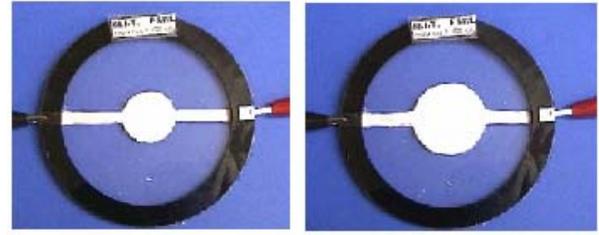


Figure 4. EPAM Radial Expansion.

When the film is placed in a movable frame, mechanical energy can be obtained from the system. For this study, a planar linear actuator was fabricated using a flexible diamond shaped frame, which changes shape upon actuation, see Fig. 5).



Figure 5. A Linear EPAM Actuator Shown in its ON (left) and OFF (right) Configurations

The elastomeric film and electrodes collectively behave like a spring in tension with variable stiffness. When actuated, the electrostatic compressive force across the film causes a relative relaxation in the planar directions of the film, and the stiffness profile of the film shifts. The frame acts as a compressive element or pre-load spring. It provides a force in the opposite direction of the film and maintains tension in the film. A simple illustration of the force-displacement characteristics of the system is represented in Fig. 6.

The pre-load spring force-displacement curve is actually a negative force, but is shown as positive to better illustrate the intersection points of the curves. When the force-displacement curves intersect, the sum of the forces within the system is zero and the EPAM is in equilibrium. Therefore, S_1 indicates the position when the actuation is OFF (film spring is stiff) and S_2 indicates the position when the actuator is ON (relative relaxation in film). The area enclosed by the arrows represents the energy obtained from the system. Typically, to optimize the performance of a single actuator, the difference between the two equilibrium points should be maximized, thus maximizing the stroke and energy output of the actuator. The stiffness of the film is generally a function of the thickness and shape (provided by the frame) of the film. The stiffness of the frame can be tuned by designing flexures into the plastic retaining frame or by attaching external elements, such as metal or rubber springs, to the frame. For the actuators used in this study, elastic elements were attached to the frame in order to provide a non-linear restoring force, which increased with displacement. This restoring force allows for large displacements.

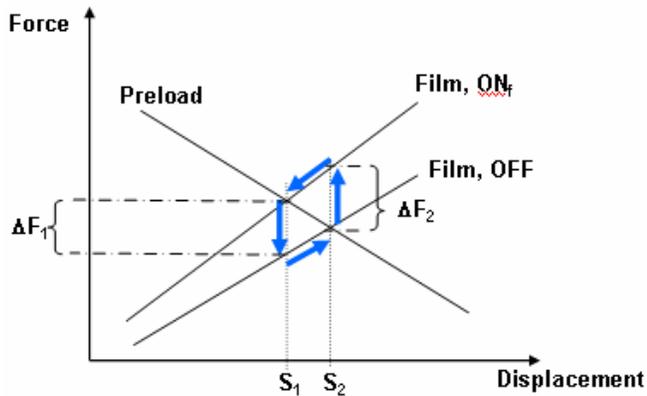


Figure 6. Mechanical model of a linear EPAM actuator

B. The MRI Imaging Coil

The imaging coil was selected as a relatively simple, yet practical demonstration of the EPAM actuated MRI manipulation. The MRI coil is a tuned resonating circuit operated in receive only mode. It behaves like a radio frequency antenna to pick up the weak magnetic field emitted as protons in the sample return to equilibrium state after excitation. The magnetic field induces a current in the coil. A series of such signals are collected and used to reconstruct the MR image. The conductive path of the coil is typically copper tubing, tape, wire, or an etched trace.

A trade-off in image quality exists between depth of penetration of a surface imaging coil and peak signal to noise ratio (SNR) as a function of coil dimensions. To optimize image quality at a given distance from the coil, the appropriate coil dimensions should be selected. Smaller coils offer higher SNR for regions of interest close to the skin; where as larger coils are better suited for imaging of deeper regions of interest [13,14,15].

To improve image quality with a conventional surface coil, the coil may be moved or replaced with a coil of different dimensions, which requires the patient be removed from the bore of the MRI scanner [16]. This is time consuming, costly, and leads to patient discomfort. Phased array coil technology largely addresses this problem for human imaging by carpeting the sample with elements that can be turned on or off. However, the variability in patients suggests there exists an ideal phased coil for each patient, with element sizes matched to the depth of the anatomy of interest (e.g., the heart) [17,18]. Moreover, coil sensitivity profile is altered with changing the dimensions of the elements. Such a change would impact parallel imaging techniques, perhaps enabling optimized encoding for a given patient [19, 20, 21].

Further imaging capabilities that might arise from this work are left for future study. The objective here was to show that EPAM was MRI compatible actuator technology, and that it could resize or move the coil with respect to the patient while the patient remained in the MRI.

III. RECONFIGURABLE COIL DESIGN

Two coil design concepts were considered in this study. The first design, called the Single Actuator Integrated Coil, provides a simple method for resizing an imaging coil with a minimum of moving parts. This method uses fundamental EPAM concepts to provide simple shape changes, see Fig. 7. A second design, called the Multi-Actuator Modular Coil was developed, which yielded better results. This design employs linear EPAM actuators to actuate a movable frame.

The first concept involves printing a conducting trace onto a polymer film and then radially deforming the film (Fig. 7). The conducting trace, which is comprised of silver grease, forms a ring that acts as an imaging coil. Carbon grease electrodes are patterned in the interior of the circular trace. Referring to Figs, 4 and 7, when a voltage is applied to the carbon grease (black area), it expands, and the area contained within the Radio Frequency (RF) signal carrier coil (grey area) also changes. Note that the EPAM electrode (black) is separated from the RF signal carrier (grey).

The diametric change causes the field of view (FOV) of the surface coil to change.

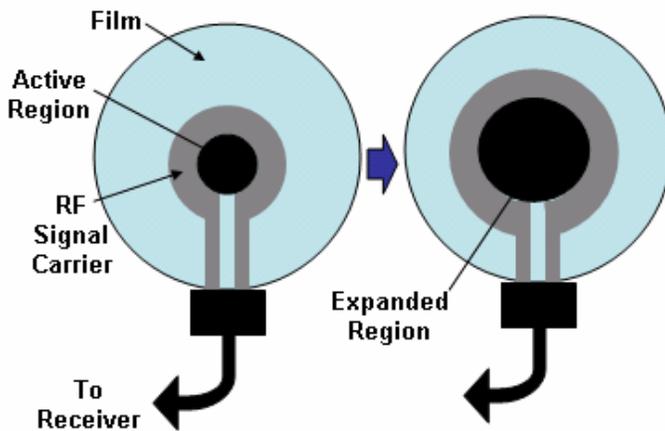


Figure 7. The Single Actuator Integrated Coil Design

This concept allows for only concentric shape changes. The shape or position cannot be modified. Different methods may be employed for patterning electrodes onto the film such that not only the shape, but also the position or orientation, of the RF coil changes.

In the second design an external EPAM actuator is used to manipulate a rectangular frame made of telescoping copper tubes (Fig. 8). The construction of the frame can be designed such that several actuators can be used to modify its shape. Each linear actuator can translate, causing the frame to change size. The system has a degree of freedom for each actuator, and for each distinct combination of activated actuators, there is a unique orientation for the frame.

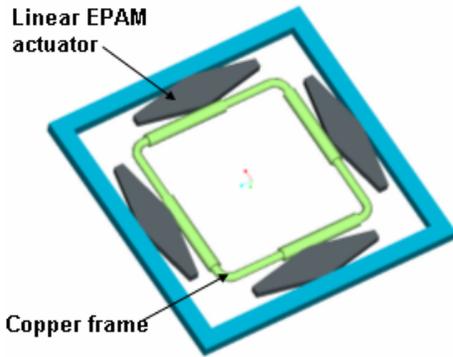


Figure 8. The Multi-Actuator Modular Coil Design

While the first design only allows for resizing of the circle while the central axis of the coil remains fixed, the second design allows for the coil's size, shape, and position to be changed. All four actuators can act independently. Each has two states, ON or OFF (corresponding to contracted or expanded), yielding 2^4 , or 16, possible configurations for the coil, see Fig. 9.

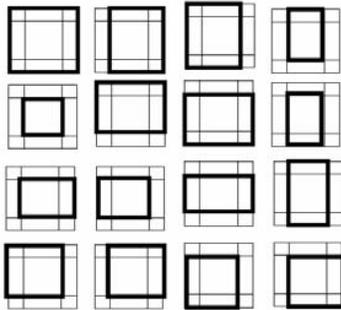


Figure 9. Possible configurations the Multi-Actuator Modular Coil Design.

For the Multi-Actuator Modular Coil Design, the FOV can be coarsely selected to provide the best imaging capability based on the depth and location of the target. In the normal configuration, when all actuators are off, the coil is at its largest and the potential imaging volume is at its maximum. If focusing on a smaller region within this volume is desired, then the appropriate configuration can be selected.

The first design was initially tested to show compatibility and proof of principle. Because of current limitations in materials and fabrication techniques, only preliminary images were produced. Extensive testing was done with the second implementation to show compatibility, image quality, and reconfigurability. Resizing of the coil is accompanied by a large change in resonant frequency. In this experiment, a variable capacitor was manually trimmed to retune the coil after transition from the ON to OFF state.

IV. RESULTS

For all MRI experiments, images were acquired of a homogeneous doped water phantom using a gradient echo imaging sequence on a 1.5T CV/i scanner (General Electric

Medical Systems, Milwaukee, WI). The power supply for the EPAM actuators was placed inside the MRI room.

The compatibility of EPAM actuators with MRI scanning was first verified. In the first set of tests, imaging was performed with a commercially available 3" diameter surface coil (General Electric Medical Systems, Milwaukee, WI). The test was repeated with a functional EPAM actuator placed directly beside the imaging coil. With the EPAM under actuation, there was no alteration to the image results.

A. The Single Actuator Integrated Coil Design

Given the compatibility, the capabilities of the first design were evaluated experimentally from two points of view: the resizing capability and the available image quality. The image quality was evaluated using an imaging coil fabricated from EPAM materials. The silver grease was patterned onto the polymer film in a ring (Fig. 10b), simulating the design concept (but without resizing capability). The grease was used as the RF conductor as opposed to the copper used for conventional coils (Fig. 10a). The appropriate tuning circuit was attached, and images were acquired. These images (Fig. 10c and 10d) were compared to those from a two turn copper wire coil of similar dimensions. Brighter images reflect regions with greater signal. Grainy results indicate noise.

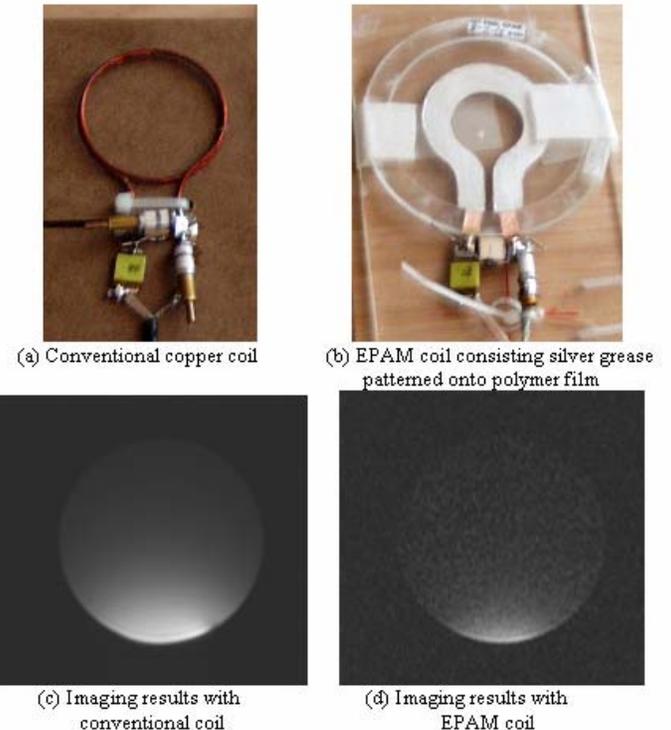


Figure 10. A conventional copper coil (a) and an EPAM based coil (b) of similar dimensions with their acquired images (c,d).

The comparably lower SNR can be seen in the EPAM coil image (shown by the darker image) is due to the high resistance in the silver grease. The grease deposition was thickened to decrease the resistance around the loop.

However, the best quality factor, which is the ratio of inductive energy to dissipated energy, achieved was on the order of 20, as compared to 250 for the copper coil. It is suspected that the contact resistance between the silver particles, which are immersed in a silicone oil, is the source of overall resistance.

Another empirically evaluated aspect of the initial design concept is its ability to change size. It is necessary to radically resize the imaging coil in order to significantly alter the FOV. The initial goal was to change the diameter of the imaging coil by a factor of 2. This requires an area expansion of four times for a circle. The maximum expansion of the polymer material when actuated (and under a constant tension) was tested experimentally. Fig. 11 shows a curve fit for an experimental plot of the maximum area expansion upon actuation. The peak expansion for the acrylic polymer being used is around 2.6 times the initial area. This expansion occurs when the material is pre-strained at around 200% in both axes. The material is pre-strained in order to raise the dielectric strength of the material as well provide tension in the film. The physics of expansion and modes of failure of the material have been analyzed in depth for this study, but are beyond the scope of this article.

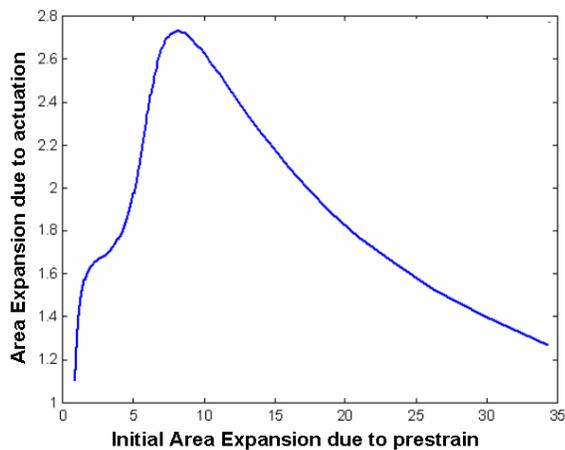


Figure 11. The Maximum Area Expansion of the Polymer as a Function of Initial Pre-Strain in both directions, with a peak of about 270.

This area expansion corresponds to a maximum diameter expansion of about 1.6, at the material failure point. The maximum area expansion is a function of the mechanical and dielectric properties of the specific material. This value is not a fundamental limitation of the technology, only of the specific polymer being used. The polymer used in these experiments is an acrylic film widely used for achieving large expansions [22].

Due to these limitations in the capability of the Single Actuator Integrated Coil Design tests were not performed in which the geometry was changed. The compatibility and proof of principle tests are enough to show the fundamental feasibility of the design. Due to the limited image quality and resizability, the visible change in imaging capability would be negligible.

B. Multi-Actuator Modular Coil Design Concept

To test the design concept shown in Fig. 8., a one-dimensional version was constructed. The resizable frame was built out of telescoping copper tubes (1/8" and 5/32" outer diameter) with soldered corner joints. A linear EPAM actuator was attached to one side. The experimental prototype is shown in Fig. 12. The actuator used here is capable of 1.25" of displacement (approximately 200% of the active area). Two EPAM elements were cascaded together in the final design.

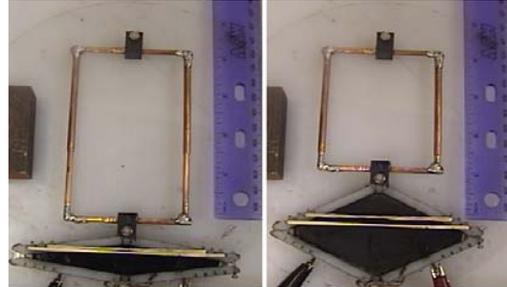


Figure 12. Resizable copper frame with the EPAM in both the OFF and ON position.

To evaluate the MRI compatibility of the design, images were acquired with a conventional 3" diameter surface coil while the EPAM coil was placed in the vicinity and activated, the imaging results from which are shown in Fig. 13a. No RF noise was noted in the results. Next, the EPAM coil shown in Fig. 12 was used to acquire an image in the actuator OFF (Fig. 13b) and actuator ON (Fig. 13c) states. The coil was manually retuned between acquisitions to compensate for the shift in resonant frequency. Image quality was comparable to that achieved with commercial coils. Analysis of the signal distribution for both the ON and OFF configurations confirms the expected difference in imaging capability, and the images of Fig. 13 illustrate these results. Depth of penetration was, as expected, greater with the coil in the larger configuration (Fig. 13b). This is indicated by a greater SNR deeper in the sample (bright portion covers larger area). Conversely, peak SNR was greater with the smaller diameter coil (Fig. 13c). This region is smaller but the signal is more intense (brighter) than for the larger diameter coil.

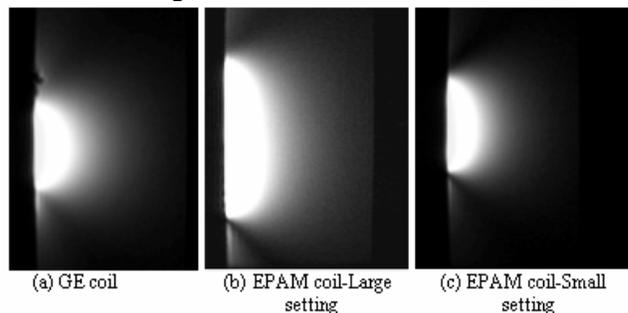


Figure 13. Imaging results of commercial coil (a) compared to those for Multi-Actuator Modular Coil Design (b,c).

V. DISCUSSION

The results of this experiment clearly demonstrate the compatibility of EPAM actuators and MRI technology. EPAM actuators can not only function directly within imaging zones, but they can also be used to manipulate the imaging capabilities. These actuators have the potential to provide robust and simple methods for adaptable imaging without complex electronic hardware. The initial concept provides an elegant method for manipulating imaging capabilities. The limitations are due of properties of the materials available for these experiments. The development of materials with more suitable properties (lower stiffness, higher dielectric strength, higher dielectric constant) could lead to greater strain capabilities. Alternatively, the concept could be coupled with a motion amplification mechanism that would provide for greater apparent expansions.

The inadequate image quality for the first concept should not be considered a fundamental limitation. The silver grease was the only flexible conductor used for the RF trace in this concept. Other methods of creating flexible conducting elements, such as coiled wires, could provide a substitute for the silver grease. The second design also shows room for improvement and for future implementation. For example, only a one-dimensional version of the design was used for experimentation in this study. The two dimensional case, with multiple configurations, would provide a much more illustrative example of the concept.

Since the EPAMS used here have only two states, the resonant frequency shifts are predictable. The retuning of the coil can easily be automated. Varactor diodes in the tuning circuit can be biased to change capacitance to the appropriate level[23,24]. The same switching circuit to activate the EPAMS can be used to bias the diodes.

Besides demonstrating a specific application for EPAM actuator technology to MRI imaging, this study suggests a broader class of EPAM MRI devices can be developed. The fundamental demonstration of compatibility lays the groundwork for future work. The actual demonstration of enhancing imaging capabilities shows that EPAM actuation can perform functional tasks within an MRI environment. Future developments could involve the use of all-plastic manipulators for surgical assist robots within the confines of open or closed MRI machines.

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