Approaches to Creating and Controlling Motion in MRI

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Abstract— **Magnetic Resonance Imaging (MRI) can provide three dimensional (3D) imaging with excellent resolution and sensitivity making it ideal for guiding and monitoring interventions. The development of MRI-compatible interventional devices is complicated by factors including: the high magnetic field strength, the requirement that such devices should not degrade image quality, and the confined physical space of the scanner bore. Numerous MRI guided actuated devices have been developed or are currently being developed utilizing piezoelectric actuators as their primary means of mechanical energy generation to enable better interventional procedure performance. While piezoelectric actuators are highly desirable for MRI guided actuation for their precision, high holding force, and non-magnetic operation they are often found to cause image degradation on a large enough to scale to render live imaging unusable. This paper describes a newly developed piezoelectric actuator driver and control system designed to drive a variety of both harmonic and non-harmonic motors that has been demonstrated to be capable of operating both harmonic and non-harmonic piezoelectric actuators with less than 5% SNR loss under closed loop control. The proposed system device allows for a single controller to control any supported actuator and feedback sensor without any physical hardware changes.**

I. INTRODUCTION

Magnetic resonance imaging is an ideal interventional guidance modality: it can provide real-time high-resolution 3D images or 2D images at arbitrary orientations, and is able to monitor therapeutic agents, surgical tools, tissue biomechanical properties, and physiological function. However, MRI poses formidable engineering challenges with limited access to the patient and a strong magnetic field that prevents the use of many conventional materials and electronics. This paper reports a modular control system that we have developed for controlling motion of piezoelectric actuators inside an MRI scanner with little to no image quality degradation.

In order for a system to be considered MRI-compatible, it must meet the following requirements [1]: 1) safety in the MRI environment, 2) preservation of image quality and 3) ability to operate unaffected by the scanner's electric and magnetic fields. Ferromagnetic materials must be avoided entirely because they cause image artifacts and distortion due to field inhomogeneities, and they pose a dangerous projectile risk. Non-ferromagnetic metals such as aluminum, brass, titanium, high strength plastic, and composite materials are permissible. however, the use of any conductive materials in the vicinity of the scanner's isocenter must be limited

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because of the potential for induced eddy currents to locally deform the magnetic field homogeneity. Electrical systems must be properly shielded and filtered, designed to limit noise emission. Care must also be taken to avoid resonance and heating.

While many have expounded upon the multitude of benefits to integrating the high resolution multidirectional live imaging of diagnostic MRI to image guided surgery [2], the ability to create and deploy a device capable of operating within the scanner bore is still frustrated by the high strength magnetic fields, and extreme sensitivity to electromagnetic interference (EMI) [3]. To date, there are a wide variety of non-magnetic motors that are MRI safe, but not necessarily MRI compatible [4]. Classically, the term MRI compatible has been utilized to describe an item that both poses no hazards to utilize in a scanner and does not cause imaging artifacts, however this term is now undefined [3]. Despite these difficulties, many devices have been designed to function within the MR environment have been constructed. Some examples include a liver ablation system [2], a prostate intervention system [5], and a neural intervention system [6]. There are many types and styles of actuators used for these devices including: pneumatic, hydraulic, harmonic piezoelectric and non-harmonic piezoelectric. [7]. Despite the fact that hydraulic and pneumatic actuation systems tend to be intrinsically MR compatible, precise control of their motion is very difficult to achieve and the equipment required to operate them tends to be bulky and expensive. Classically, electromechanical actuation systems have been relatively easy to develop with in a safe manner in an MRI environment, however, these systems can often cause unacceptable amounts of noise (upwards of 40% signal loss) in the image space [8], [9]. As can be seen in Fig. 1, many different kinds of actuators are used in MRI guided interventional devices, and it has been argued that a good solution for a given application often involves a combination of several actuation principles.

II. METHODS

We present the design, construction and validation of a generalized ceramic actuator driver and control system for use with MRI guided interventional systems. Each control system contains a plurality of actuation channels, each capable of driving and controlling multiple actuator styles. This would allow the system to be utilized with a number of different manipulators requiring only a software change to switch from one to the next, rather than expensive and time consuming hardware modifications. The system supports
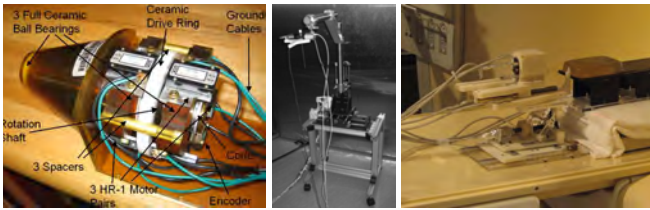
Fig. 1. Representative piezoelectrically actuated MRI-compatible robotic systems: a prostate intervention device [8] utilizing Nanomotion motors (left), a liver ablation utilizing Shinsei motors [2] (center), and a PiezoMotor PiezoLEGS driven prostate needle insertion device [10] (right) all developed by different groups
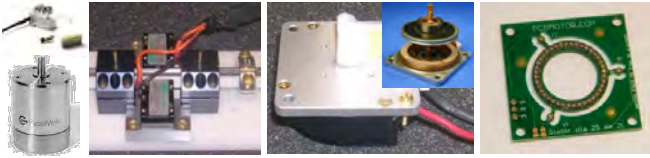

Fig. 2. PiezoLEGS non-harmonic rotary motor (left), Nanomotion HR-2 harmonic linear actuators driving a linear stage (left-center), Shinsei harmonic rotary actuator (right-center), and customizable harmonic PCB Motor (right).

Fig. 3. Driving waveforms from off the shelf nanomotion driver (left). Closeup view of a high frequency artifact (center). Scanner image taken of a motor being operated by this driver [8] showing a high degree of distortion and noise (right).
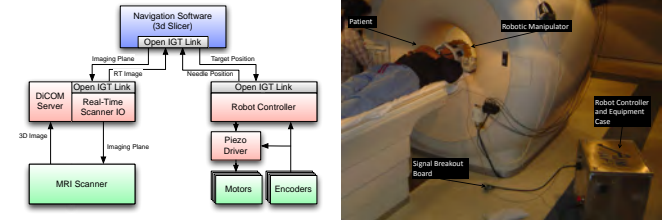

Fig. 4. Architecture of the modular MRI-compatible surgical system (top). Example configuration of the robotic system with the controller and other equipment within the scanner room (bottom).

all commonly used MRI-compatible piezoelectric actuators including: Nanomotion (www.nanomotion.com), Shinsei (www.shinsei-motor.com, Piezomotor (www.piezomotor.se) and PCB Motor (www.pcbmotor.com) products as shown in Fig. 2. Further, it can be configured to control other actuation system including pneumatics and hydraulics as well as to perform therapeutic procedures under real-time MRI guidance through powering interstitial ultrasonic ablation probes. In addition to this, the proposed system will be designed such that it will not cause noise within the scanner bore while operating these devices.

A. Piezoelectric Actuator Properties

Piezoelectrics are one of the most commonly utilized classes of actuators in MRI guided devices [11], and fall under two main categories: harmonic and non-harmonic, both of which have been demonstrated to cause interference within the scanner bore [12], [10], [13] as can be clearly seen in Fig. 3. It is the authors proposal that this noise is in fact not caused by the actuator itself, but by the driving signal utilized to operate the actuator. In Fig. 3, the driving signal produced by a Nanomotion controller to operate the actuator can be seen. The small section of said waveform is then enlarged to show a small, but repeated section of high frequency instability. This is an unintentional and undesired effect caused by the electrical structure used in the off-the-shelf driving circuitry; it does not cause side effects in mechanical operation, but the high frequency noise does have significant impact on MR image quality. These small sections of high frequency noise have been found in the output of all drivers for the Shinsei, Nanomotion, and PiezoMotor motors, and are postulated to be the cause of image degradation clearly visible in the image taken of a motor operated by that same driver. We have developed a ceramic motor driver system capable of operating several kinds of harmonic and non-harmonic piezoelectric actuators.

B. System Architecture

The high level architecture for this system is comprised of three pieces of equipment integrated with a diagnostic scanner: a user workstation, an in-room controller, and a manipulator as shown in Fig. 4. In addition to the driving system being presented below, the in-room controller contains linear voltage regulators, a fiber optic ethernet converter, and a small form factor computer, which allow the controller to operate in the scanner room without requiring any electrical signals or energy to be passed through the scanner room wall.

C. Piezoelectric Drivers

Two different styles of piezoelectric actuator are targeted to be supported by this system: harmonic and non-harmonic. While these motors operate on similar basic principles, signals required to effectively utilize and control them are very different. Harmonic motors such as the Nanomotion device found in Fig. 2 are generally driven with a fixed sine wave at 38-50kHz frequency. Velocity control of these motors is through modulation of the systems amplitude in a range of 80-300VRMS; Shinsei harmonic motors, however, are speed controlled through frequency modulation. Non-harmonic motors, such as the PiezoLEGS motor found in Fig. 2 and described in [14], operate at a much lower frequency than harmonic motors (750Hz to 3kHz). These actuators require a complex shaped waveform generated with high precision at a fixed amplitude to operated most effectively, such as those shown in Fig. 6. Speed is controlled through modulating the drive frequency.

The driver architecture depicted in Fig. 5 has been demonstrated to be capable of operating all of the motors shown in Fig. 2, and the ability to switch between operating each of these kinds of motors remotely through the operation of configuration software protocols. This ability fulfills the requirement that a single in-room controller can operate a
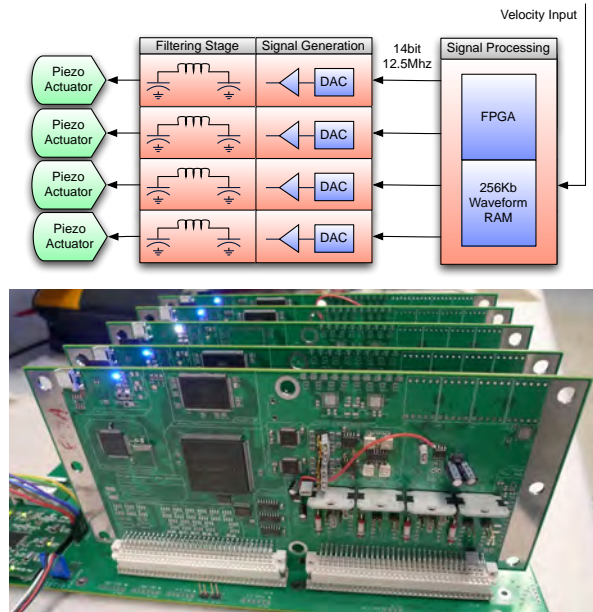
Fig. 5. System diagram of piezoelectric driver (top). Photograph of five motor driver modules mounted in a backplane (bottom).
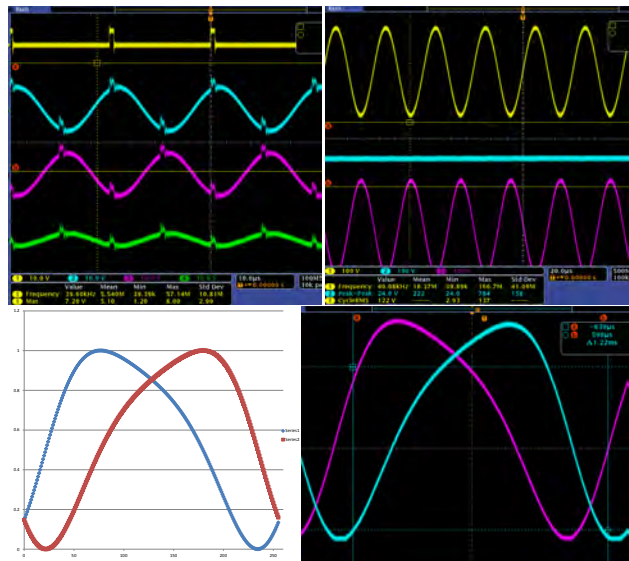

Fig. 6. Standard Nanomotion drive signals (top-left) and experimental Nanomotion waveforms with noise removed (top-right). Optimized non-harmonic ceramic motor driving waveforms for PiezoLEGS motor (bottom-left) and recorded output waves of same experimental system under load (bottom-right).

multitude of independently developed manipulators. Though this has not yet been tested, a single complete unit of the design presented would theoretically be able to operate each of the manipulators presented in Fig. 1 without any modification to either the controller, or the devices themselves, despite all three devices being independently created by different teams of people.

III. VALIDATION

A. Experimental Configuration

The first step validating the system effectiveness was to verify producing correct driving signals, tuned to support the operation of the motors but without the high frequency noise generally found in off the shelf drivers, as shown in Fig. 6. All motors can be driven with variable speed as well as an microstepping one period of the waveform at a time, thus allowing precised closed position loop control with a standard PID loop running at 1kHz. Dynamic tracking accuracy is not discussed in this paper, however, steady state error for all closed loop motion can be achieved at the level of the encoder or other measurement instrument used. For the closed loop experiments, a single encoder tick representing $0.07°$or 0.01mm – much higher accuracy is expected to be possible with a more precise position measurement system.

A liquid filled cylindrical imaging phantom with copper sulfate solution was utilized for compatibility analysis under T1 weighted Gradient Echo and T2 weighted Spin Echo imaging protocols. The scan protocols and configuration used mimicked those described by Fischer, *et al.* in [4]. Under each scanning protocol, a set of baseline images of the phantom is first recorded that all future images will be assessed against. After these baseline images are established, it is important to prevent the scanner from automatically self calibrating by ensuring the gains stay fixed, as this

will corrupt the ability to utilize these baseline images as valid comparators. After the baseline is established, a series of studies are conducted with the equipment placed in the scanner but not energized. After verifying the presence of the equipment has not caused either noise, or distortion artifacts detectable by visual inspection of the images, the controller is powered on, but does not supply driving waveforms to the motors. Again these images are visually inspected for noise and distortion, and if these appear clear, the final studies are performed with each motor under motion individually and collectively. Once the compatibility of the drive train is verified, precision control testing is performed to determine how accurately the motor-driver-encoder combination can self position.

B. MRI Compatibility Analysis

Signal to noise ratio (SNR) was used as the metric for compatibility analysis. SNR was calculated as the mean power of a section of the image taken about the centroid of the imaging phantom, divided by the RMS of the noise taken from a sample in the upper left corner of the image. Matlab was utilized to perform this task, including automatically identifying the centroid of each of phantoms in the center of the scanned images to prevent human error in noise value calculation. As can be seen from the quality of the images shown in Fig. 7, there was very little visibly detectable noise in any of the scanning protocols analyzed, however it should be noted that there was clearly some form of error in the baseline images for the T2 series. Normalized SNR change for all T1 images was consistently less than 3% and never exceeded 6%, and the variation of this data is statistically very similar to the variation of the baseline images of the scanner alone. Despite the clear error in the baseline images, normalized SNR change for the remaining studies under T2 imaging showed a less than 5% average SNR change, and a

maximum SNR change under 10%, a large improvement over the previously reported 40% SNR change under T1 imaging with similar protocol parameters [8].
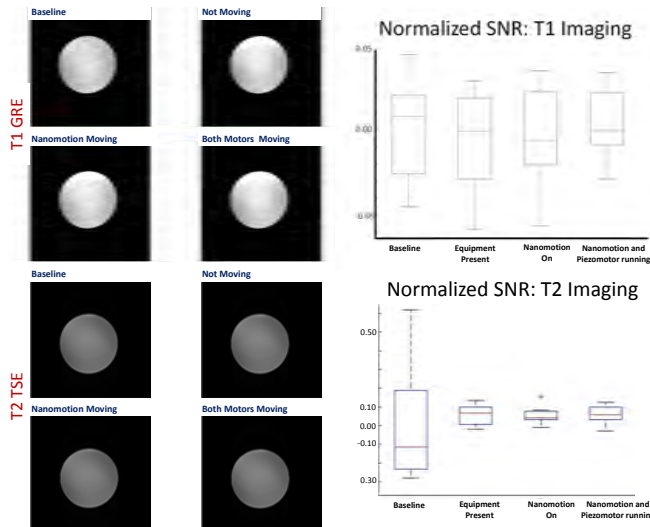

Fig. 7. Selected images from studies showing qualitatively the compatibility of the actuation system (left). Corresponding box plots of normalized change in SNR demonstrating quantitative the compatibility of the actuation system during synchronous imaging and robot motion (right). Note that variation in the T2 image set stems from a corrupted baseline images - it is apparent that enabling motion did not cause significant SNR loss.

IV. Discussion

It has been shown that this surgical system is both capable of creating and controlling motion in an MR scanner without causing image interference, and that the system can be adapted to a multitude of procedure specific mechanisms. This system was developed based on the theory that if piezo-electric actuators could be driven by a control system that could constrain undesirable high frequency subcomponents of drive waveforms from being transmitted to the motors from an in-room controller, reductions in image degradations could be achieved when compared to previously reported image quality analysis of the same actuators operated by off the shelf drivers. Compatibility analysis demonstrates that this theory show promising results for the Nanomotion and Piezomotor actuators reported upon, showing an average of 2% SNR for Nanomotion and Piezomotors driven under T1 imaging, and 5% SNR for the same actuators under T2 imaging, despite an uncharacteristically noisy baseline image set. Positioning accuracy for the actuators has been demonstrated to reach the level of the precision of the measurement device. In the future, similar compatibility and precision tests will be performed on other piezoelectric actuators being utilized in MR guided devices such that this system, once deployed, could support a wide variety of piezoelectric actuators without requiring any hardware changes. The next motors to be analyzed and tested will be Shinsei rotary motors, and PCB motors. In addition to performing similar studies as presented in this paper, mechanical properties such as torque, speed and holding power must be analyzed for all supported actuators. With the generalized control architecture presented, new MR-guided devices could be developed independent of possession of any of the control hardware, so long as supported hardware was utilized during construction, drastically reducing the financial and temporal costs involved in bringing a new system from concept to reality.

MRI is a highly effective soft tissue imaging system, and the ability to utilize this procedure in-vivo coupled with precision computer controlled motion will prove to be an invaluable asset in the future development of minimally invasive surgery. The authors hope the presented modular robot controller system will help to expedite the the development of clinically viable MR image-guided robotic surgery systems.

V. Acknowledgements

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