Towards Accurate and Automated TMS Coil Placement with a Robotic System in MRI: A preliminary study

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Synopsis

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Motivation: Precise TMS control within MRI is fundamental for clinical and neuroscience advancements. However, challenges remain in accurate targeting, variability in functional anatomy, and real-time brain dynamics.

Goal(s): We aim to develop a robotic system for accurate, automated TMS coil placement inside MRI.

Approach: We developed a 3DOF robotic system to place a mock TMS coil within the MRI environment. Wireless markers identify the end effector's position through fast projection acquisitions, enabling closed-loop adjustments for accurate positioning.

Results: We showcase our robotic and localization system working within the MRI environment, detailing the placement precision achieved during initial trials.

Impact: This system demonstrates capacity for precise, automated TMS coil positioning within the MRI, laying a foundation for fully integrated TMS-MRI setups. This approach will facilitate patient-specific, adaptive stimulation, enabling studies on dynamic brain-state-driven stimulation and improving clinical reproducibility.

Introduction

A system of concurrent Transcranial Magnetic Stimulation (TMS) and Magnetic Resonance Imaging (MRI) offers a powerful multimodal approach to understanding and modulating brain function in real-time[1]. This integrated system has the potential to advance neuroscience and clinical applications, particularly in personalized brain stimulation therapies. However, precise control of the TMS coil placement is critical yet challenging[2,3,4]. Traditionally, the optimal stimulation site, or "hotspot," is determined outside the MRI scanner or during a separate MRI session, which limits flexibility for real-time adjustments. Most existing TMS-MRI setups rely on suboptimal, off-the-shelf TMS apparatuses placed inside MRI coils, where precise engagement with specific brain regions remains difficult to achieve.

To overcome these challenges, we are developing a robotic system for accurate, automated TMS coil positioning within the MRI, enabling real-time adjustments (Figure 1). Here, we present our progress with a 3-degree-of-freedom (3DOF) robotic arm designed to position a TMS coil inside the MRI. By using wireless markers and rapid projection acquisitions, we effectively close the feedback loop on coil positioning, enhancing accuracy. This initial work lays the foundation for our future 7DOF system capable of precise positioning and orientation control, paving the way for a fully integrated system that allows for real-time adjustments based on fMRI and EEG responses.

Methods

Figure 2 depicts the overview of the TMS robot control. The robotic arm with the mock TMS coil and markers is positioned on the patient table. MR imaging localizes both the TMS coil and the subject's head (represented by a phantom here). A 3D-SPGR scan obtains the head's geometry, and a localization sequence determines the positions of wireless markers. A computer in the console room controls the robot and manages MRI scans directly through GE's External System Interface (ExSI). Additionally, we stream real-time localization data from the scanner computer to the robot control computer using GE's Raw Data Server (RDS) via TCP communication.

Figure 3 illustrates our 3DOF robotic arm, which utilizes three ultrasonic motors (WLG-75-R, Tekceleo, France). Two motors extend and retract a two-link arm, with each link at 250 mm. A third motor rotates the entire assembly, enabling the robot to position the end effector in 3D space. To reduce image artifacts, the robot is 3D printed using polylactic acid (PLA), and motors are positioned at the robot's backend. For low-level control, we employ a microcontroller (NUCLEO-F446RE, STMicroelectronics, Switzerland) programmed using Lingua Franca[5]. High-level control is managed through ROS2[6], with communication between high-level and low-level systems established via the UART protocol. MoveIt2[7] is used for motion planning, and RViz is employed to visualize the robot and its environment, also serving as an interface for target position selection. Upon selecting a target position, the robot is planned and moved to the specified location, automatically triggering the localization sequence through ExSI. Real-time scan data is streamed via RDS, enabling positional error computation and iterative adjustments to close the feedback loop effectively.

Following the work in [8], our markers (Figure 4) and localization sequence enable fast localization without requiring full 3D volume acquisitions. The wireless markers reduce additional hardware and cabling on the robot. The localization sequence includes a non-selective RF pulse, gradient echo readouts, and perpendicular gradients to dephase the magnetization of large volumes. This sequence was implemented using PulSeq[9] and interpreted with Toppe[10].

Experiment and Results

We conducted our experiments on a 3T GE-MR750w scanner. We began with a calibration phase where we moved the robot to several predefined locations and measured the position using the markers to establish the transformation between the Robot and MRI coordinate systems. Subsequently, we implemented our closed-loop positioning strategy, obtaining a mean position error of 0.88 cm after four iterations (Figure 5).

This error can largely be attributed to mechanical limitations of our 3DOF robot version: the ultrasonic motors have a minimum operating speed that causes vibration and restricts fine movement resolution, an effect amplified by the length of the robot's arms. Additionally, the current prototype, constructed from compliant plastic materials, deforms slightly under its own weight, reducing precision at various positions. Planned improvements, including a higher gear reduction ratio in a future 7DOF arm, are expected to significantly enhance positioning accuracy.

Conclusion

We demonstrated our 3DOF robotic system for TMS placement inside the MRI, showcasing an integrated setup that automates processes after selecting target locations. Our future work includes developing a 7DOF TMS system and closing the loop with real-time adjustments based on patient responses, incorporating fMRI and EEG data for enhanced precision in neuromodulation.

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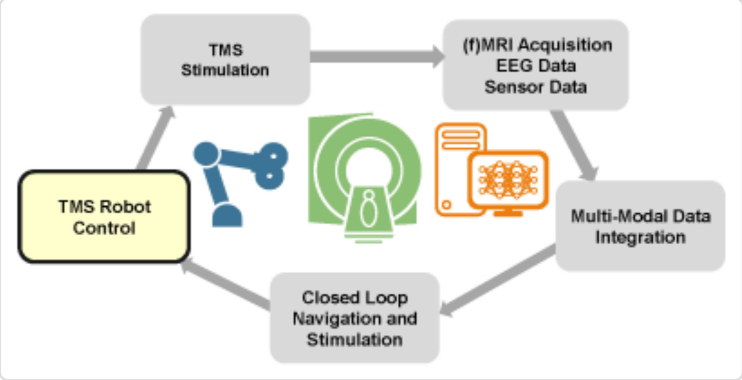
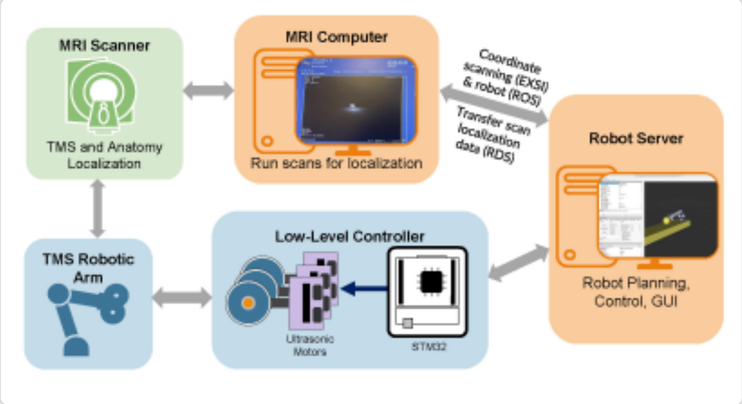
Figures



Overview of the future robotic system for automated TMS coil positioning within the MRI. The envisioned multimodal system will integrate TMS stimulation, (f)MRI, EEG, and external sensor data, for closed-loop navigation. The robot will then place the TMS coil accurately based on this data, enabling real-time, patient-specific adjustments. In this work, we focus on the robot control aspect, progressing towards this larger goal of automated and adaptive TMS stimulation.



Zoomed-in view of the robot control system. The MRI scanner is used to localize the TMS coil and anatomy. The MRI system is interfaced with an external robot server running ROS, which coordinates scanning via EXSI and RDS for real-time data streaming. The robot server then interfaces with the low-level controller, based on an STM32, to control the ultrasonic motors of the robot. The system enables closed-loop placement of the TMS coil at target locations.

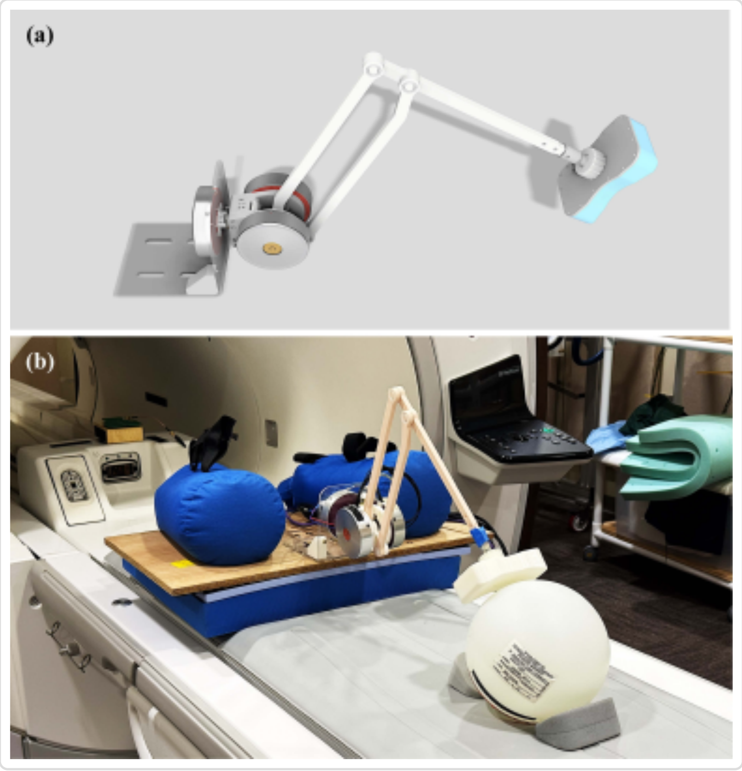
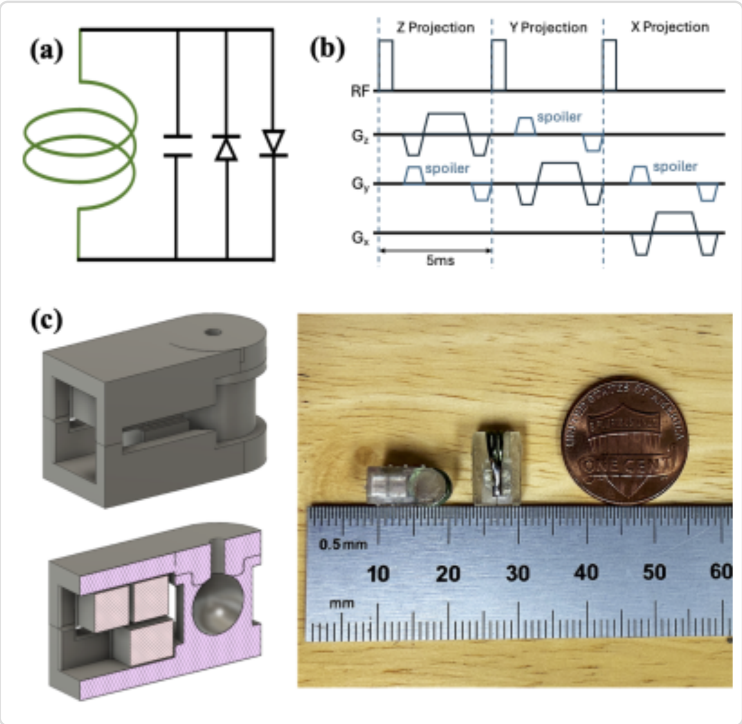
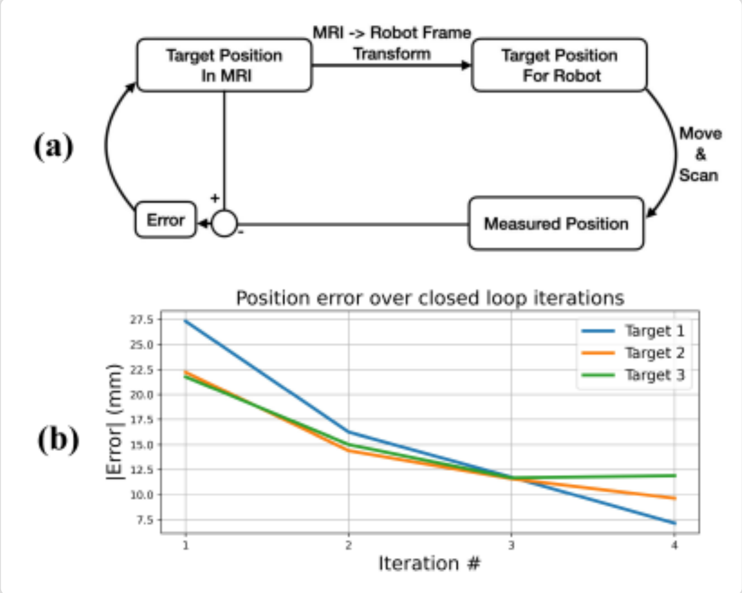


Illustration of the 3DOF robotic arm used for TMS coil positioning. The arm incorporates three ultrasonic motors: two motors control the extension and retraction of a two-link arm (250 mm each link), while a third motor rotates the entire assembly, allowing for 3D positioning of the end effector. The robot is 3D-printed using PLA, with the motors positioned towards the back to minimize image artifacts. A mock TMS coil is mounted on the end effector.



(a) Wireless marker circuit design[8], including an RF coil, capacitor, and diodes that passively detune the circuit during RF transmit. (b) Localization sequence comprising a non-selective RF pulse, gradient echo readouts, and perpendicular dephasing gradients to obtain XYZ projections in <20 ms. (c) CAD design and 3D-printed marker prototype (<11x7x6 mm), featuring a 3mm spherical cavity filled with Gd-doped solution as the tracking point.



(a) Diagram of the closed-loop positioning strategy to correct for measurement noise and transform between MRI and robot coordinates. (b) Plot showing the error over multiple iterations of the closed-loop process. The error decreases with iterations, but the accuracy is limited due to mechanical limitations of the 3DOF robot, including vibrations from minimum motor speeds and deformation from compliant materials. Planned improvements, including a 7DOF arm with a higher gear reduction ratio, are expected to enhance accuracy.

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