BRAIN Initiative: Transcranial Magnetic Stimulation Automation and Calibration

Garth D. Todd, Ahmed Abdellatif, and Abas Sabouni, *IEEE Member*

Abstract— **In this paper, we introduced an automated TMS system with robot control and optical sensor combined with neuronavigation software. By using the robot, the TMS coil can be accurately positioned over any preselected brain region. The neuronavigation system provides an accurate positioning of a magnetic coil in order to induce a specific cortical excitation. An infrared optical measurement device is also used in order to detect and compensate for head movements of the patient. This procedure was simulated using a PC based robotic simulation program. The proposed automated robot system is integrated with TMS numerical solver and allows users to actually see the depth, location, and shape of the induced eddy current on the computer monitor.**

I. Introduction

Transcranial Magnetic Stimulation (TMS) is a non-invasive brain treatment and diagnostic method that is currently approved by the Food and Drug Administration (FDA) for the treatment of depression for patients who have not had success with medication. This treatment involves positioning a coil above a patient's head and delivering a large number of electromagnetic pulses in various locations to stimulate neurons. Other uses of TMS are currently being researched [1]. Current TMS systems in use rely on manual or computer assisted coil positioning which is subject to low accuracy and repeatability. With manual positioning, a motor-evoked potential (MEP) location must be found by probing around the head while delivering single pulses until a location that causes a physical motor response is found. The coil is then manually positioned relative to the MEP location [2]. Head movements of patients are also not accounted for. Due to the duration of a TMS treatment session (30-45 minutes), it is likely that a patient's head will move, even if only slightly. In order to increase the accuracy of TMS and eliminate MEP probing, robotic automation is utilized. This involves using a 6 axis articulated robotic arm to position the coil and an infrared optical measurement system to compensate for head movements.

Current TMS systems do not provide any visual feedback regarding the effects of the treatment on the brain in real-time. Using electromagnetic simulation software to pre-process simulations of the treatment, visual feedback can be implemented by using a fast TMS solver for displaying simulation data relevant to the current coil position during a treatment session. Due to the limited knowledge of *in-vivo* dielectric properties of brain matter [3], a calibration experiment was performed in order to reduce numerical error in simulation of eddy currents in the brain due to TMS treatment.

Research supported by Wilkes University.

G. Todd is a Mechanical Engineering undergraduate with Wilkes University, Wilkes-Barre, PA 18702 USA. (garth.todd@wilkes.edu)

A. Abdellatif is an Electrical Engineering undergraduate at Wilkes University. (ahmed.abdellatif@wilkes.edu)

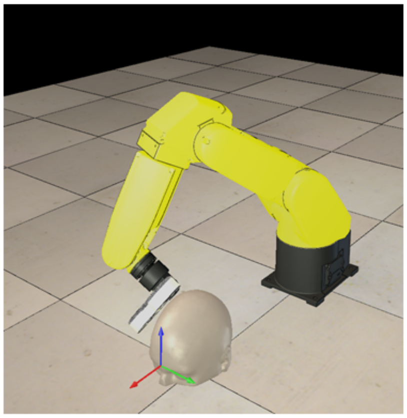
A. Sabouni, Ph.D is an Electrical Engineering faculty at Wilkes University. (abas.sabouni@wilkes.edu)

II. Methodology

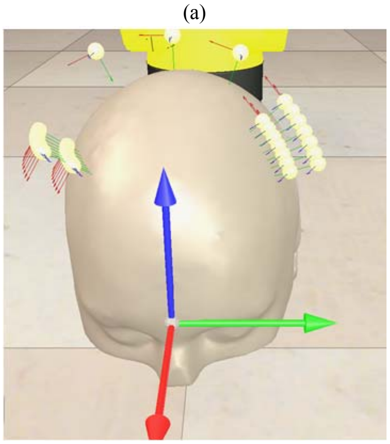
For a new patient, a full head Magnetic Resonance Imaging (MRI) scan is required before treatment can occur. This MRI data is then imported into neural navigation software, in this case BrainSight, which produces a 3D model of the brain, differentiating between different brain matters. A qualified medical professional will then use the software to target specific areas in the brain depending on the treatment goal. From these targeted areas, the software will output data for the desired coil position and orientation. This data is in the form of a 4×4 matrix consisting of a 3×3 direction cosine matrix and 3×1 spatial coordinates. This provides data for a 6 degree of freedom position and orientation in free space. A TMS treatment session typically consists of many target positions in order to sufficiently stimulate desired areas. Data from the neural navigation software is in the form of a text file. Data is extracted through a script and assembled into a CSV file, where each row of data corresponds to one position. Each position has a total of 12 components, 9 for orientation and 3 for spatial position.

A simulated version of the Fanuc LR Mate 200iC is used for automation using the robotic simulation environment software V-REP 3 Pro. A phantom head model as well as target coordinates in a CSV file are imported to the simulation program. Through the use of inverse kinematics and motion planning, a path is automatically developed to move the coil from point to point while avoiding contact with the patient's head. The simulated robot and imported head are shown in Fig. 1. A 3D head model derived from an MRI scan was also imported into V-Rep. To this head model, target points were added. These target points have one axis normal to the surface of the head to allow for proper coil positioning. Intermediate targets were also added 20mm away from the surface targets to aid in stability of positioning. The head model and targets are shown in Fig. 1(b). Along with the addition of a head model and targets, a model 8-figure TMS coil and mount were added to the end of the robot. The tip dummy was then positioned on the bottom center of the TMS coil. The coil then became the tip of the robot. The imported 8-figure coil model attached to the robot is shown in Fig. 2.

By using feedback from the Polaris Spectra, the head model and targets can be moved in real-time. Inverse kinematic solving in V-Rep is performed on the head/targets, allowing for compensation for movement. Inverse kinematics of the moving head/targets allows for real-time motion compensation, while motion planning allows for movement between targets while also considering head movements.



(a)



(b)

Figure 1. (a) Simulated Fanuc 200iC with TMS coil and head model, (b) imported head model and targets for the TMS coil. Intermediate targets are added 20mm away from the surface targets to aid in stability.

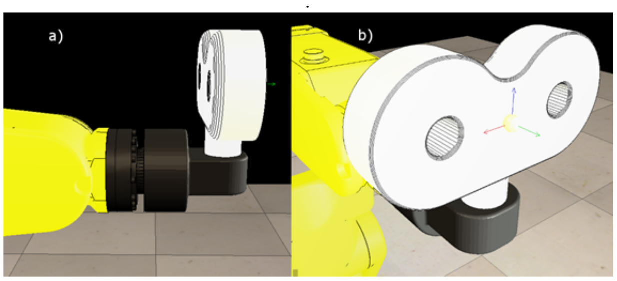


Figure 2. TMS coil and mount attached to the model robot. View a) shows detail in the connection to the robot. View b) shows the bottom of the coil and placement of the tip dummy.

A Polaris Spectra optical measurement system is used to collect full 6 degree of freedom position data regarding location of the patient's head (Fig. 3). A rigid body consisting of 4 reflective spheres is attached to the patient's head. The patient's head is then temporarily placed in a known, fixed position and the measurement system is initialized, where location data for the fixed position is recorded. The patient can then move their head to a natural location and the measurement system will output the difference between the initial and current position and orientation.

Figure 3. Northern Digital Instruments Polaris Spectra (left) and passive rigid body (right).

The difference from the Polaris Spectra is then communicated to V-Rep through a C++ data processing program. This data is used to move both the phantom head and target positions in V-Rep, allowing for the inverse kinematics and motion planning to account for head movements. Safety checks are performed in the C++ program, where the robot will be signaled to pull back to a safe location if erratic and/or excessive head movement is detected. In the implementation of a physical robot, the current draw of servos will be monitored. In the event of excessive current draw, which would be indicative of a collision, the robot will also pull back. The details of the safety feature for the proposed technique have been discussed in part III.

A robotics environment simulation program is used in order to allow robust development and testing in the absence of a robot. V-Rep also allows for a robotic program that can be exported to the robot controller to be developed. The simulation program allows for various parameters to be easily changed while maintaining the same control features. Adding different coils or robots is a matter of importing CAD files and changing the position of the robot relative to the head in an appropriate manner to allow for the coil to be positioned in all necessary locations. A block diagram of robotic control is shown in Fig. 4. This highlights the process of data acquisition from the Polaris Spectra for head movements of the patient, as well as data flow to the visual feedback program. The offset data from the Polaris, after processing, is used to move the model of the head, to which the target points are attached. Real-time inverse kinematics solving allows the robot model to compensate for head movements. A timing signal is generated in the C++ program, which is communicated to V-Rep and signals the robot to move to the next target position. The current location of the coil is then communicated to the TMS simulation program, which will display the simulation results at the current position.

Fig. 5 contains a visual block diagram of the overall system. Once a TMS coil and stimulator are added to the system, timing signals from the stimulator can be used in order to provide signals to the robotic control system to move to the next target point.

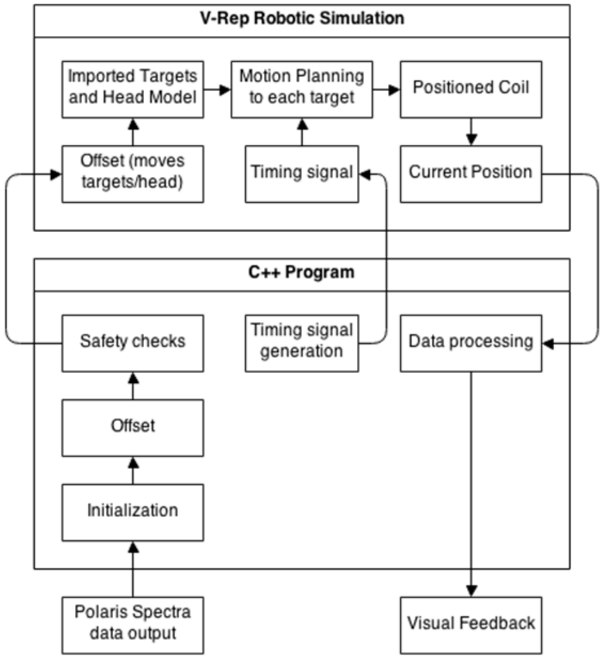


Figure 4. Block diagram of robotic control with motion compensation and visual feedback.

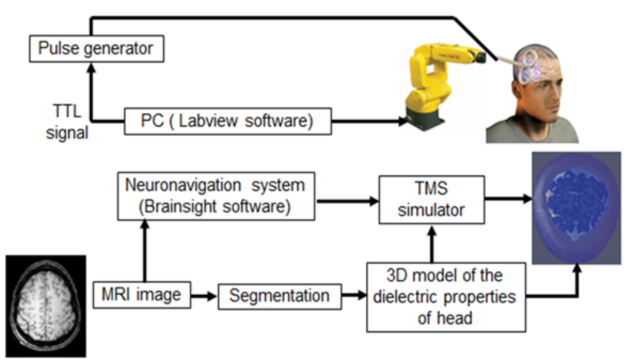


Figure 5. Block diagram of the automated system with visual feedback.

III. Safety Features

Due to the nature of this automated procedure, it is necessary to ensure that proper steps are taken to prevent the robot from colliding with a patient. In this simulation, there are two different safety features that attempt to avoid collisions.

Both the inverse kinematics and motion planning calculations modules in V-Rep have collision avoidance functionality built in. When either of these calculation modules are being used to position and move the robot, collisions with other objects in the scene, namely the head model, will be avoided. A second safety feature will move the robot to a safe position if excessive head movement is detected. This is accomplished by continuously checking the data values from the Polaris Spectra and comparing them with the previous value. If the difference between the two exceeds a certain value, a function is called that rapidly moves the robot to a safe position away from the patient's head. An example of the robot after moving to the safe position is shown in Fig. 6.

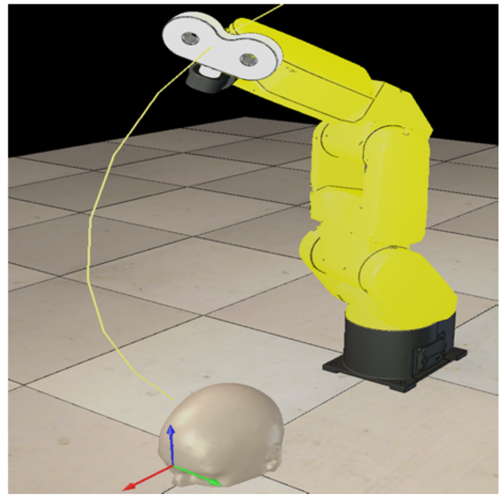


Fig. 6. Robot model after excessive motion was detected. The robot rapidly moves away from the head model.

IV. Calibration and Visual Feedback

In order to calculate the induced current during the TMS procedure, an in-house TMS solver is used [4]. For this to be accomplished, MRI data from a patient is segmented into a 3D brain model, where white matter, grey matter, cerebrospinal fluid, skull, and scalp are differentiated between. Then each of these types of matter is assigned with different dielectric properties according to the best available *in-vivo* data in order to be solved with TMS solver based on Finite Element Method (FEM) numerical technique. This process is shown in Figs. 7 and 8.

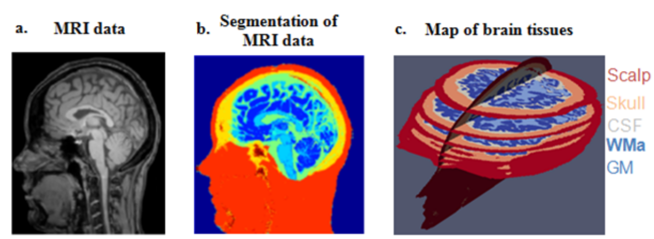


Figure 7. (a) Raw MRI data from a patient scan. This scan data is then segmented into discrete regions depending on the brain matter, as shown in (b). A 3D map of brain tissues is then developed as shown in (c).

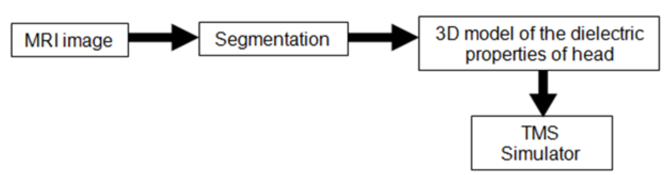


Figure 8. Block diagram of monitoring induced current during TMS procedure

In order to avoid numerical error in the TMS solver, a correction coefficient was calculated by comparing the simulation and measurement results of eddy currents. To develop the correction coefficient, measurement of induced current was performed and compared with simulated values. A hand-wound coil with 350 turns was created and connected to an AC power supply running at 3.3kHz. A jar containing a dielectric fluid was then placed perpendicular to the coil, as shown in Fig. 9.

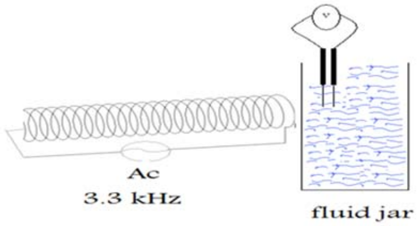


Figure 9. Diagram of measurement setup

Two probes at a known distance with known resistance were placed in the fluid. Voltage was measured from these probes and recorded. Then by knowing the impedance of the fluid material, the eddy current is calculated. The measured current can be the average of two conductive and displacement currents in a dielectric medium. The conductive current is given by (1), where σ is conductivity of the material and E is the electric field within the material. The displacement current is calculated by (2) where *ε* is the permittivity, *E* is the electric field in the material and *D* is the electric displacement vector.

$$J_c = \sigma E \tag{1}$$

$$J_d = \frac{\delta D}{\delta t} = \varepsilon \frac{\delta E}{\delta t} \tag{2}$$

Since the TMS frequency is low, therefore the displacement current can be neglected and the conductive current can be considered as eddy current [5]. In this simulation, the head tissue is considered as seawater, which is a very simple but reasonably accurate approximation for human tissue. The above mentioned measurement setup was simulated in order to calculate the calibration coefficient. The calibration coefficient is the ratio of the simulated eddy current over the measured eddy current (3).

$$\text{Calibration coefficient} = \frac{I_{simulation}}{I_{measurement}} \tag{3}$$

Results of experimentation are shown in Table I.

TABLE I. Experimental and simulated values, as well as a calculated coefficient resulting by dividing simulated and experimental current values.

Values	Seawater
Voltage (mV)	6.546
Resistance (Ω)	4.68E+06
Experimental current (A)	1.34E-09
Simulated current (A)	5.39E-09
Calibration coefficient	0.248

After applying the correction coefficient to the simulation result, the calibrated eddy current can be considered as an actual induced eddy current inside the brain. Fig. 10 shows the induced eddy current after calibration for 25 years old female subject. For these simulations, the circular coil is considered as TMS coil for excitation.

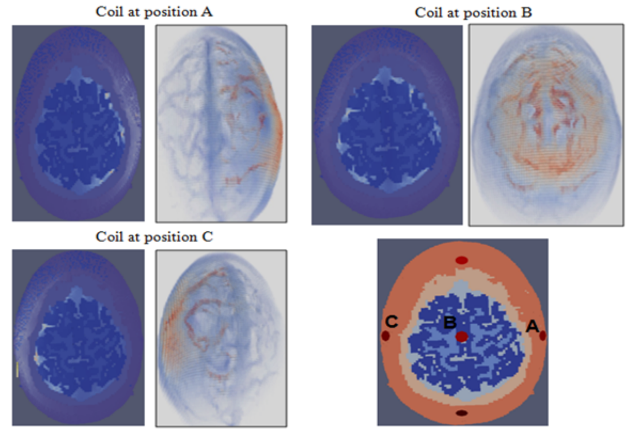


Figure10. Example of visual feedback for several different coil positions. Right figures represent the magnitude of eddy currents (the red coloration) and left figures indicate the eddy current registered into MRI date.

V. Conclusion

In this paper robotic automation of a transcranial magnetic stimulation treatment session was simulated on a PC. This was achieved through the construction of a robot model in V-Rep Pro and the use of motion planning and inverse kinematic calculations. By using the robot, the TMS coil can be accurately positioned over any preselected brain region. A Polaris Spectra optical measurement device was used to quantify head movements and allow for motion compensation by the robot model. Real-time motion compensation was implemented and several safety features were developed in order to avoid collision of the robot and head. The proposed automated TMS system allows users to actually see the depth, location, and shape of the induced eddy current on the computer monitor.

Acknowledgement

The authors would like to acknowledge the financial support of Wilkes University. The authors would like to thank Mr. Kevin Vanderhoof for programming the Polaris Spectra optical system. Also constructive discussions with Dr. David Carey and Dr. Rodney Ridley are greatly appreciated.

References

[1] S. Groppa, A. Oliviero, A. Eisen, A. Quartarone, L.G. Cohen, V. Mall, A. Kaelin-Lang, T. Mima, S. Rossi, G.W. Thickbroom, P.M. Rossini, U. Ziemann, J. Valls-Solé, and H.R. Siebner, "A practical guide to diagnostic transcranial magnetic stimulation: Report of an IFCN committee," *Clinical Neurophysiology,* vol. 123, pp. 858-882, 2012.

[2] P.M. Rossini, L. Rossini, and F. Ferreri, "Transcranial magnetic stimulation: A review," in *IEEE Engineering in Medicine and Biology Magazine,* vol. 29, no.1, pp. 84-96, 2010.

[3] E. Wassermann and T. Zimmermann, "Transcranial magnetic brain stimulation: therapeutic promises and scientific gaps," *Pharmacology and Therapeutics,* vol. 133, no. 1, pp. 98-107, 2012.

[4] A. Sabouni, P. Pouliot, A. Shmuel, and F. Lesage, "BRAIN Initiative: Fast and Parallel Solver for Real-Time Monitoring of the Eddy Current in the Brain for TMS Applications," in *IEEE Engineering in Medicine and Biology Conference*, 2014.

[5] X. L. Chen, S. Benkler, C.H. Li, N. Chavannes and N. Kuster, "Low frequency electromagnetic field exposure study with posable human body model," in *IEEE International Symposium on Electromagnetic Compatibility,* pp. 702-705, 2010.