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# Hot Spot Hound: a novel robot-assisted platform for enhancing TMS performance

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*Abstract*— **Transcranial Magnetic Stimulation (TMS) is a non-invasive technique that produces excitatory depolarization in the neurons located in the cerebral cortex. In order to proficiently stimulate a specific cerebral area it is of main importance the correct positioning and maintaining of the magnetic coil, while avoiding the mismatch due to subject head-coil relative movement.**

**Hot Spot Hound is a novel robot-assisted experimental platform for enhancing TMS stimulation performance. It integrates a commercial optoelectronic neuronavigation system (E.M.S. srl, Italy) for gathering data on the relative pose (position and orientation) of subject's scalp and TMS coil, and a service robotic arm designed for human interaction (LWR system by KUKA, Germany).**

**Besides integrating and synchronizing different platform sub-systems, we implement a control strategy to center the stimulation point and compensate for involuntary subject movements. Specifically, the proposed control maintains constant over time the homogeneous transformation matrix between the pose of the coil and of the head.**

**The value of position stiffness has been chosen in order to assure the better compromise between coil position and orientation error, and the safety of the experimental subject. In this paper we show that Hot Spot Hound can provide coil position and orientation errors well beyond the ones achieved by manual experimenter, while assuring safety in the physical interaction with the stimulated subject.**

## I. Introduction

This Transcranial Magnetic Stimulation (TMS) is a non-invasive method to cause, from outside, excitatory depolarization in the neurons located in the cerebral cortex just below the scalp. It is widely used in neuroscience, neurology and psychiatry, most for investigating cortical information processing, while have been proposed also for therapeutic application.

An electromagnetic coil, which sees a current of about 5000 A passing inside its solenoid, placed over the head, is able to produce a large but brief current pulse. The ensued changing magnetic field induces a current in the conductive tissue of the head including the underlying cerebral cortex [1][2][3]. Since magnetic field is inversely dependent on the distance, the cortical activity produced by TMS is critically influenced by the coil location and orientation, since the cortical response to the stimulation is the highest when the induced electromagnetic field is oriented parallel to the cortical columns[4], and by the relative coil-head movement.

Hence a correct use of TMS requires the knowledge of where on the cortex the magnetic stimulation has to be applied, and the control of where it has been really applied. Once the desired stimulation site has been chosen through several different modalities (i.e. functionally through the hotspot that produces peripheral motor twitch or topographically basing on Talairach or MNI coordinates) the coil is typically positioned and held in that position manually. Thus, the exact stimulation of a pre-defined site is difficult to achieve and even more difficult to be maintained, making this a major issue that affects efficiency of existing systems [5]. Small involuntary movements of the hand-held coil and subject's head must be compensated by manually adjusting position and orientation of the coil continuously, which results in a loss of accuracy. Fixation of the head cannot be considered in a clinical routine due to safety issue, subjects' comfort, and durability of the fixation.

Studies with the TMS face the general problem of positioning the magnetic coil above relevant cortical areas [6]. Most studies using TMS do not take the individual anatomy into account, thereby running the risk of not reaching the intended area exactly. A solution to the problem of the exact coil positioning is offered by neuronavigation devices that enable the precise location of the magnetic coil with respect to the scalp [7]. Neuronavigation has become a standard technique for navigated coil placement during TMS. An optical tracking device identifies the TMS coil and patient's head, thus allowing to set the coil based on subject-specific information (e.g. MRI head scans). In the neuronavigation procedures, once the target area of the cortex has been defined, the magnetic stimulation coil has to be manually moved upon the head of the patient by the experimenter, who has to follow an accurate trajectory in space. Even if visual feedback (a crosshair on the screen) is provided by a navigation system to facilitate the positioning

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of the coil, no precise motion can be practically achieved. Moreover, in case of long treatments (e.g. repetitive TMS), to manually maintain the coil in the correct position and orientation, compensating head movements, results very difficult and tiring.

In contrast to manual placement, robotized systems combine the benefits of neuronavigated TMS with automation.

Literature offers two different approaches for robotic TMS system development that exploit "ad hoc" designed custom system [8] or integrate pre-existing system [9][10][11].

The proposed robot-aided TMS system, named Hot Spot Hound, is an integrated system and provides automatic coil positioning with high accuracy, repeatability, and maintenance of the using motion compensation techniques.

## II. METHODS

### A. Integrated system for robot-aided TMS

The Hot Spot Hound setup for experimental robot-aided TMS (Fig. 1) is based on a LWR system (by KUKA, Germany) for positioning and maintaining the TMS coil and a commercial optoelectronic neuronavigation system SoftAxic (by E.M.S. srl, Italy) for gathering data on the relative pose (position and orientation) between subject's scalp and the TMS coil. The neuronavigation system is composed by an optical tracking system POLARIS VICRA (NDI, Canada), and the neuronavigation software.

Magnetic stimulation have been delivered through a MAGSTIM 200[2] (The MAGSTIM Company LTD, UK) with a figure-of-eight shaped coil.

A comparison of Hot Spot Hound with other integrate systems for enhancing TMS performance [9][10][11] show that system architecture presents similar components. However, for the first time it has been used a service robot which enables an impedance control without the use of additional force sensors. This allows to simplify both workflow of the system and control strategy.

### B. Workflow of the system

To control in real time the correct positioning of the magnetic coil during a TMS session, a closed loop feedback control has been implemented using the system architecture represented in fig.1:

- A headband with passive infrared-light reflecting POLARIS markers is attached to subject's head and worn throughout the whole session. The POLARIS VICRA camera identifies the spatial position of the passive markers and builds the head and coil systems of reference (SoR).
- The neuronavigation software collects these data from the camera and builds a virtual head model on the basis of a set of 3D MRI images of the cranium.
- A different software on the same PC extracts spatial information from the neuronavigation software and transmits them to the KUKA control software at a sampling frequency of 10 Hz.
- The KUKA control software converts data from the neuronavigation system in the robot SoR. By setting the KUKA Robot Controller in command mode, robot control places the coil properly on the subject's head and chases the hot spot in the case of involuntary head movements.

It is worth noting that, because the coil must be placed in contact with the target point of stimulation on the subject's skull, during head movements the consequent robot compensation can generate interaction forces, which should range from zero (ideally absent) up to 2.5 N.

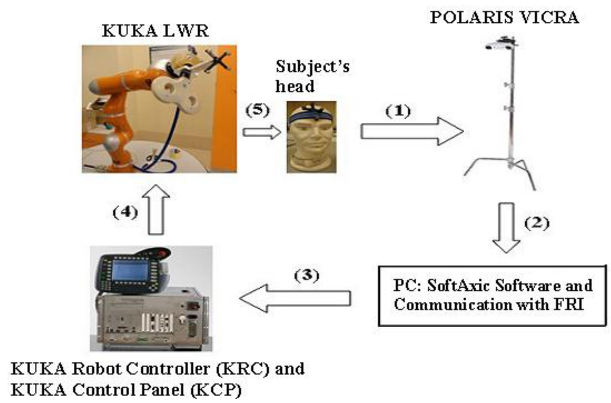


Figure 1. System architecture and workflow.

### C. Control strategy

In order to obtain a tracking of the target point of stimulation, the homogeneous transformation matrix between the pose of the coil and the pose of the head has been determined for each time step, and maintained constant over time. It means that the relative position and the orientation of the coil with respect to the hot spot are constant during the stimulation session since the robot compensates for head movements.

The aforementioned transformation matrix is formed by four blocks:

$$A_{coil}^{head} = \begin{bmatrix} R_{coil}^{head} & p_{coil}^{head} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} \tag{1}$$

where $R_{coil}^{head}$ is the rotation matrix of the coil SoR with respect to subject's head SoR, and $p_{coil}^{head}$ is the position vector of the origin of the coil SoR in the head SoR. Calculating the transformation matrices of the coil SoR with respect to the robot SoR (by KUKA LWR) and that of the coil relative to the head (using the neuronavigation system), it is possible to obtain the transformation matrix of the head relative to the robot:

$$A_{coil}^{head} = A_{coil}^{robot}\left(A_{coil}^{head}\right)^{-1} \tag{2}$$

The new state that the robot must reach at next time step, is determined of the following transformation matrix:

$$A_{coildes}^{robot} = A_{head}^{robot} A_{coildes}^{head} \quad (3)$$

The new state will be an input to the control strategy.

The robot FRI allows three main possible control strategies: position control, joint impedance control and Cartesian impedance control. For Hot Spot Hound we use the Cartesian impedance control, because it gives the possibility to directly control the interaction forces between the robot and the subject's head. The control parameters that can be set independently are the Cartesian stiffness k=[kx, ky, kz] (max 5000 N/m) and torque stiffness $k_t$ = [kφ, kθ, kψ] (max 300 Nm/rad), where φ, θ and ψ are the roll-pitch-yaw angles in the robot global SoR. It is also possible to set the damping factor (it has been set to 0.8).

### *D. Validation*

The performance of the proposed solution has been validated using a phantom head, in order to estimate, for different values of robot control parameters, the position and orientation errors.

The tests were carried out by moving the head of the phantom along generic trajectories. The head motion was then stopped on an arbitrary point of the space for a few seconds, in order to simulate the conditions of the steady state.

To determinate the better values for impedance control parameters, in particular the stiffness (damping factor is set to a constant value of 0.8, since the sampling time is high (0.1 s) it is preferable to have a slightly over-damped behavior), three test sessions have been carried out with the stiffness at 1000 (Fig. 2), 2500 (Fig. 3) and 5000 N/m (Fig. 4), respectively. Torsional stiffness has been set at 200 Nm/rad (Fig. 5). The norm of the error was used to assess control performance. In a second set of tests we move the head phantom along the single axes of the robot SoR, to verify the dependency of the error in steady state condition in the different directions of the workspace. This was done both with stiffness at 1000 N/m and at 2500 N/m. Lastly, to get preliminary indication about the performance of the system in real condition using optimized parameters, a test with a real subject simulating (without stimuli) a session of TMS was carried out. The position error of this experiment is shown in fig. 6.

## III. RESULTS

For generic trajectories optimal value for the stiffness has been found to be 2500 N/m. In fact, when control stiffness has been set to 1000 N/m (position stiffness) and 200 Nm/rad (orientation stiffness), mean position error was about 5 mm, while orientation error was 0.5° (Fig. 5). When the position stiffness has been changed towards values of 2500 N/m or 5000 N/m the system resulted more accurate and the recorded position error was about 1 mm in the steady state condition. Since there is inverse relation between position accuracy and interaction forces in the Cartesian space, value of 2500 N/m has been considered to be the best tradeoff for our application.

As regards the single axis trajectories, table 1 summarizes the static accuracy (mean ± standard error (SE)) for 2 different values of stiffness (1000 and 2500 N/m). For stiffness values of 2500 N/m the static error ranges between 1-2 mm.

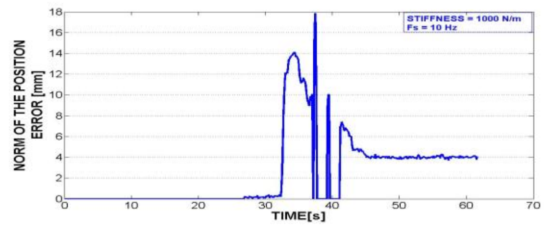


Figure 2. Evaluation of the position modulus error in steady state condition after generic trajectory for stiffness of 1000 N/m.

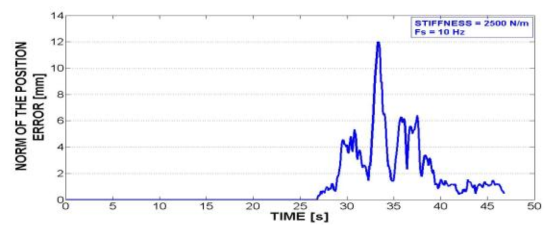


Figure 3. Evaluation of the position modulus error in steady state condition after generic trajectory for stiffness of 2500 N/m.

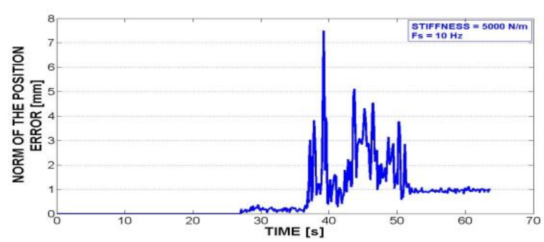


Figure 4. Evaluation of the position modulus error in steady state condition after generic trajectory for stiffness of 5000 N/m.

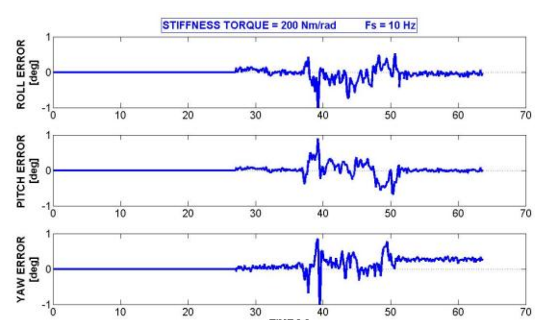


Figure 5. Evaluation of orientation error in steady state condition after generic trajectory for stiffness torque of 200 Nm/rad.

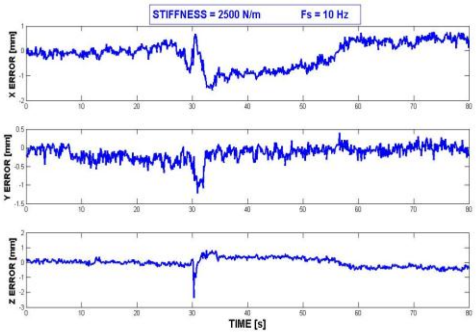


Figure 6. Evaluation of the position error with real subject for stiffness torque of 2500 N/m.

TABLE I Static error (mean ± SE) for different directions in single axis movements.

| Movement Direction | stiffness = 1000 N/m | | stiffness = 2500 N/m | |
|---|---|---|---|---|
| | mean [mm] | SE[mm] | Mean [mm] | SE[mm] |
| X | 5,6 | 0.0492 | 1,2 | 0.0411 |
| Y | 4,0 | 0.0540 | 2,0 | 0.0579 |
| Z | 5,5 | 0.0575 | 2,5 | 0.0636 |

## IV. Conclusion

The present paper describes the implementation of the Hot Spot Hound, a robot-aided experimental setup for neuronavigated TMS and presents the investigational procedure exploited to determine the best impedance control parameters.

HotSpotHound is an integrated system that, compared to the previous, has the main advantage of using a service robot rather than an industrial one. Given that a service robot is designed to interact with humans its control strategy mainly takes into account physical human-robot interaction. Hence, easier system architecture is achievable without the need of integrating additional force/torque sensors [13]. However, in choosing robot control parameters it has to be considered that low values of stiffness, even if produce an increase orientation and position errors, generate smaller interaction forces in Cartesian space, thus increasing subjects' safety. On the other hand, for higher stiffness values the accuracy of the robot increases together with the interaction forces, and therefore the risk for the subject during the TMS procedure. It has to be noted that the results obtained in this experimental procedure are related to wide movements (about 30 cm), well beyond the normal displacements of the subject's head during TMS treatment (usually of few centimeters). Even in this extreme experimental condition, the higher position error was lower than 2 mm. This is an encouraging result, considering that, through the use of the sole commercial neuronavigation system, experimenters are able to obtain an accuracy of about 2 mm [7][12], only with an unacceptable increase of the time-duration of stimulating session. Table I also show that the position accuracy is axis-dependent: for stiffness value of 2500N/m, translations along the x-axis exhibit higher accuracy (mean error = 1.2 mm), while it is lower for translations along the z-axis (mean error = 2.5 mm). Since in real trajectories the translation along z (vertical movements of subject's head) does not often occur, the previous result does not affect too much the system's performance. Moreover setting stiffness torque to 200 Nm/rad produced an excellent orientation error lower than 0.5°, unachievable by neuronavigated manual stimulation. Considerig the positive result of the test in real condition (Fig. 6), future works might aim at validating the proposed system during a real session of TMS, and at assessing a possible influence of the increase of precisionin evoking neurophysiological parameters.

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