A Robotic System for Automated Image-Guided Transcranial Magnetic Stimulation

Cyrille Lebossé, Pierre Renaud, Bernard Bayle, Michel de Mathelin, Olivier Piccin and Jack Foucher

***Abstract*— This paper presents a new robotic system for automated image-guided Transcranial Magnetic Stimulation, a non-invasive technique for the treatment of neurologic pathologies such as depression. This stimulation technique requires the accurate positioning of a magnetic coil in order to induce a specific cortical excitation. The neurologist currently positions the coil manually by means of a navigation system, which does not allow the precise clinical evaluation of the procedure. In this paper, a novel robotic system is proposed to assist the neurologist during a TMS session. The proposed system and its control are designed to satisfy simultaneously safety and accuracy requirements.**

I. Introduction

Transcranial Magnetic Stimulation (TMS) is a new non-invasive method allowing to deliver an electric stimulation to the cortex. With this technique, a cortical excitation is created using a train of magnetic impulses emitted by an external stimulation coil. Its efficiency has been demonstrated in the case of depression [1], [2], and studies are currently being conducted for other pathologies like post-traumatic anxiety, compulsive obsessive disorders, schizophrenia and epileptic disorders [3]. Even if this technique is very promising, it is not yet widely accepted because of the observed variability of efficiency between patients. It is essentially due to the difficulty of the gesture with the available stimulation systems which leads to a poor repeatability. Indeed, in the current procedures, the magnetic stimulation coil has to be manually moved on the head of the patient by the neurologist to follow accurately the preplanned trajectory in space. Even if a visual feedback is provided to the neurologist by a navigation system to facilitate the coil positioning [4], no precise motion can be practically achieved. Furthermore, a manual treatment cannot be considered in a clinical routine because of the duration of stimulation sessions, in the order of 30 minutes.

The assistance of the TMS procedure by a robotic system should therefore naturally lead to a better evaluation and development of this treatment. The workflow of a robotized TMS procedure is composed of several tasks before the autonomous execution of the stimulation procedure: MRI images recording, 3D head model building, target cortical regions specification, coil trajectory computation, patient installation and registration of his head with respect to the 3D model and the robot. To our knowledge, very little work exists on robotized transcranial magnetic stimulation. Fox *et al.* [5] has initiated a research project on an image-guided robotically positioned TMS system to demonstrate the achievable high level of accuracy of planned TMS. Similarly, Matthäus *et al.* [6] proposed a robotized system with a realtime vision-based control to take into account head movements. However, in both projects, industrial-like robots have been used which are not well adapted to move a probe always in contact with the head of a patient, especially without any contact force evaluation. Lebossé *et al.* proposed in [7] a new robotic design dedicated to the execution of a safe TMS procedure.

In this paper, we present a whole robotic system whose design fulfils the constraints associated with a safe autonomous TMS procedure. The focus on safety and accuracy requirements is emphasized. A brief review of the dedicated robotic design is given and the associated software for the planning of the TMS procedure and for the robot control are presented. This is the last step before the building of a prototype to clinically validate the therapeutic effects of TMS.

II. The Medical Constraints

As introduced previously, the robotic device aims at replacing the arm, the hand and the eye of the neurologist during the complete stimulation session. The medical gesture consists in positioning the magnetic stimulation coil on the head of the patient. A typical design of a coil is a figure-of-eight shape with a planar surface of contact with the patient's head. Different models of the electrical field induced in the brain have been proposed [8], [9], [10]. They consistently demonstrate that the electrical excitation of the brain tissue is maximal along the line that is orthogonal to the contact plane and goes through the coil center with a decrease function of the distance to the coil center. Since a thin layer of air between the coil and the head induces a significant loss of effectiveness, the positioning is consequently considered to be composed of three tasks: i) the contact has to be ensured between the stimulation coil and the head of the patient; ii) the coil plane needs to be tangent to the head; iii) the orientation of the coil has to be precisely controlled since the cortical response to the stimulation is the highest when the induced electric field is oriented parallel to the cortical columns [9].

The center of the coil can be placed during a treatment in the area covered by the hair as well as the forehead and the temples, with a required accuracy in the order of

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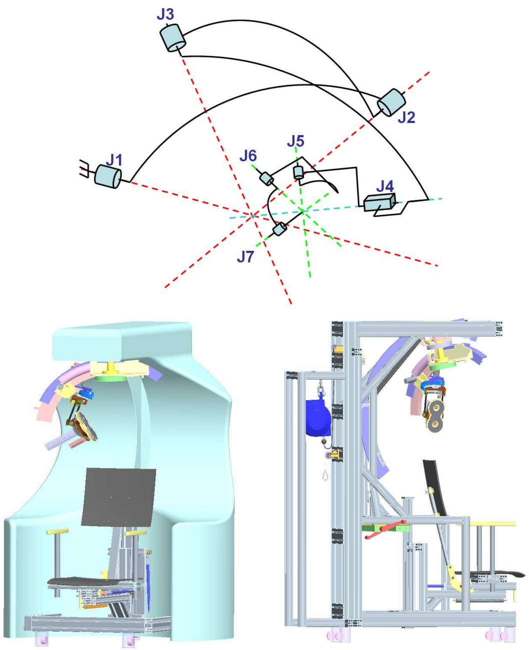

Fig. 1. The kinematics scheme and the CAD model of the robot.

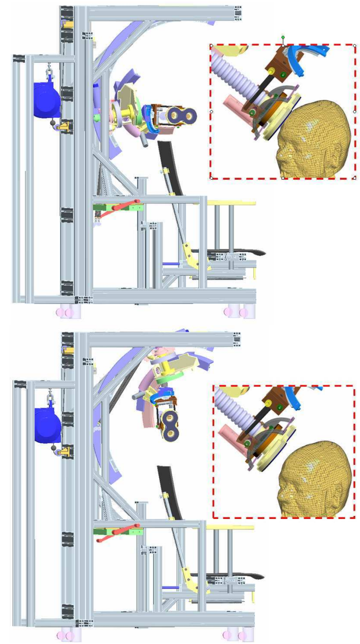

Fig. 2. Robot configuration before and after power failure. In dotted squares, the coil movement is represented with respect to the head.

1 mm. The safety and the comfort of the patient imply a maximum threshold for the force applied on the skull in the order of 2.5 N. In addition to that, since the patient is not anesthetized, he is susceptible to move his head during the TMS session. Consequently, the system has to be able to take such movements into account. Finally, it may be noticed that the kinematics and dynamics constraints are weak since the probe velocity during the stimulation is about 0.05 mm/s, with a coil weight of approximately 1.5 kg.

In order to fulfil the previous medical constraints, we propose a robotic system whose architecture is intrinsically safe and which enables to execute the workflow presented in [7]. It is mainly composed of a dedicated redundant robot, a reference path computation module, a safe motion planning method and a module for head movements tracking.

III. The Proposed Robotic System

A. *The Robotic Device*

The proposed robotic device is a redundant serial structure with seven active degrees-of-freedom (DOF). It is based on three subsystems, following the decomposition of the medical task.

The first subsystem is a spherical mechanism, with a 3-DOF serial structure (J1-J2-J3 in Fig. 1), because of the spherical shape of the workspace. The positioning of the coil center can therefore be achieved around a sphere centered on the head of the patient. The use of a redundant mechanism allows us to get a satisfactory kinematic behavior, with an average isotropy factor of 0.8 over the workspace and without any singularity, which is impossible with only 2-DOF. This affects positively the positioning accuracy and the control safety. The proposed structure is obtained using an original arrangement of circular guides (Fig. 1), so that no interference can occur between the robot and the patient, while the stiffness of the structure is optimized to handle the weight of the coil. The behavior of the mechanism remains safe even in case of power failure. The first rotation axis is controlled by a constant-force spring system, so that the mechanism configuration is in a few seconds compatible with the exit of the patient (Fig. 2), without any interference during the movement. The second joint axis is stopped by a power-off brake, and the third axis mechanically blocked, so that no other movement of the first subsystem can occur.

The second subsystem is simply composed of an actuated prismatic joint (J4 in Fig. 1). Two elements are placed on the same joint axis, so that the control of the contact force between the coil and the patient is obtained using a compliant element between the actuator and the coil. Even if the first subsystem remains safe in case of power failure, a mechanical system is inserted to automatically move the coil outwards (Fig. 2).

The third subsystem is composed of a spherical serial wrist (J5-J6-J7 in Fig. 1). It allows rotation around a fixed point which is the contact point between the coil casing and the head. Two DOF guarantee the tangency of the coil with the skull without changing its centre position. The last DOF is controlled to follow the cortical columns direction. The angular variations (+/-45°, +/-45° and +/-180°) of the wrist have been defined using reconstructed patient heads from MRI images, to evaluate the angles needed to ensure the tangency of the coil plane with respect to the head. Since the center of rotation of the first subsystem can be slightly

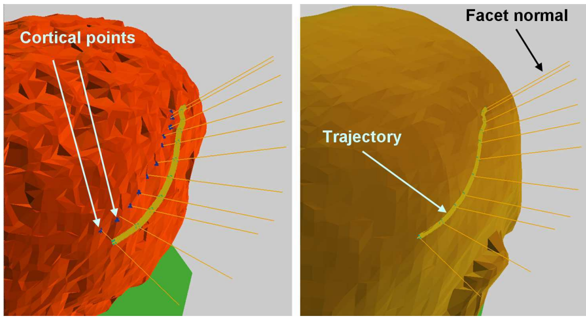

Fig. 3. On the left: the brain with the cortical points. On the right: the 3D skull model with the corresponding closest facet normals and the computed trajectory.

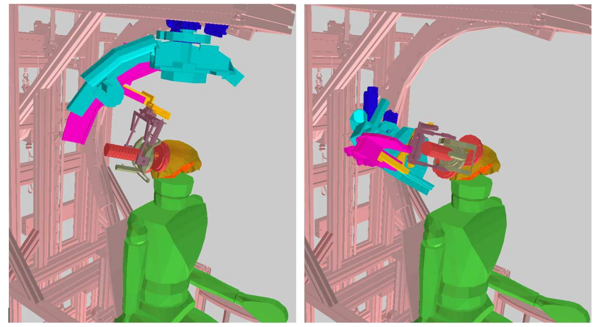

Fig. 4. Two robot configurations obtained during the motion execution. These configurations are far away from each other due to a joint limit avoidance made possible thanks to the motion planning algorithm.

different from the geometrical center of the head, possible deviations have been taken into account. It must be outlined that the coil case directly integrates the force sensor, so that the contact force is explicitly measured. This simplifies the force control, and improves the safety of the device.

B. Reference Path Computation

According to the workflow, once the cortical regions to be stimulated have been specified by the neurologist, the coil center trajectory that best stimulates these regions is computed. The medical constraints indicate that the best stimulation of a given cortical point occurs when the line that is normal to the coil plane and going through the coil center also goes through the cortical point and when the distance between that point and the coil center is minimal. Thus, for each cortical point, the facet of the reconstructed head whose normal and center are the closest to the point among all the facets of the 3D skull model, is searched for. To avoid useless calculations, only the part of the 3D skull model corresponding to the treatment area is considered for the search. Eventually, a classical cubic spline-based interpolation is performed between the obtained points on the head in order to get a smoother trajectory. The overall generated error which depends on the 3D skull model quality is around 0.5 mm.

A corresponding motion is computed to specify at each sample time the position and orientation of the coil according to the desired stimulation. It must be noticed that the orientation of the coil is imposed by the interpolated normals and the local tangent to the computed curve. Indeed, cortical points usually correspond to a cortical column which has to be stimulated and thus, the tangency to the curve ensures an induced electromagnetic field parallel to the cortical column. The required velocity of the probe is derived from the stimulation frequency and the imposed number of pulses per stimulation point defined by the neurologist. Finally, a specified end-effector (EE) motion is obtained which has to be executed by the robot.

C. Motion Planning Algorithm

In order to execute specified motions of the probe with a prescribed velocity and a redundant mechanism, a generic probabilistic motion planning algorithm has been developed. It enables to find a trajectory for the robot joints compatible with the specified EE motion, while satisfying constraints such as joint limits, joint velocity limits and while avoiding potential collisions.

A planning based algorithm has been preferred over a control based one because of the guarantee to find a solution. It is based on sampling-based methods derived from Probabilistic Roadmaps [11]. The method builds a graph of randomly generated robot configurations, called roadmap, where each configuration corresponds to a pose of the EE on the reference path. The EE motion is sampled in Np evenly distributed milestone points. For each point, Nc collision-free configurations satisfying the joint limits are generated. A new configuration becomes a new node in the roadmap if and only if it can be linked to at least one node of the previous point. This link is possible if the robot can execute the specified EE motion between the corresponding milestone points with the prescribed velocity. A pseudo-inverse velocity control technique is used in order to execute the prescribed probe motion [12]. It is associated to an optimization term that allows to reach the intermediate target configuration. During the motion, joint limits are checked, as well as velocity limits and collisions using effective collision detection algorithms. If none of the Nc configurations can be linked, the building of the roadmap has failed. The building of a new roadmap is then tried after incrementing Np and Nc. Once the roadmap building has succeeded, an optimal path in the graph is searched by applying the $A^\star$ algorithm. This motion planning algorithm is illustrated in Fig. 4, where robot configurations obtained during the motion execution are displayed. These configurations are far away from each other due to a joint limit avoidance made possible by the algorithm efficiency.

It must be noticed that the reference path computation and the motion planning can both be done off-line without requiring the presence of the patient.

D. The Stimulation Process with Head Tracking

The TMS session begins with the installation of the patient in the robotic system. A registration of his head with respect to the robot and the 3D head model is carried out.

The registration of the head and its tracking are performed using the POLARIS optical tracking system (NDI Inc., Canada). To track the head, a headband with passive markers is worn by the patient. The registration of the head with respect to the 3D head model is achieved via a landmark matching method. The POLARIS optical tracking system is used with a pointer to acquire three landmark points on the head, e.g. the left and right tragus of the ear and the bridge of the nose. The user marks the landmarks on the 3D head model. Then a registration via point-to-point correspondence is performed. The head of the patient is also registered with the robot using the POLARIS and the pointer to designate predefined landmarks placed on the mechanism.

The planned motion cannot be directly executed due to the possible head movements which lead to modifications of the reference path of the probe. For this reason a module is added that acts like a feedback controller and compensates for head motions. The position of the head is continuously monitored and changes are translated into robot motions added to the planned ones so that the coil follows the exact specified trajectory relative to the head. An example of motion compensation is simulated in Fig. 5. It illustrates the tracking of an imposed single head movement defined by steps of [+1 cm, -1 cm, +0.5 cm] along the x, y, and z directions, during the motion execution.

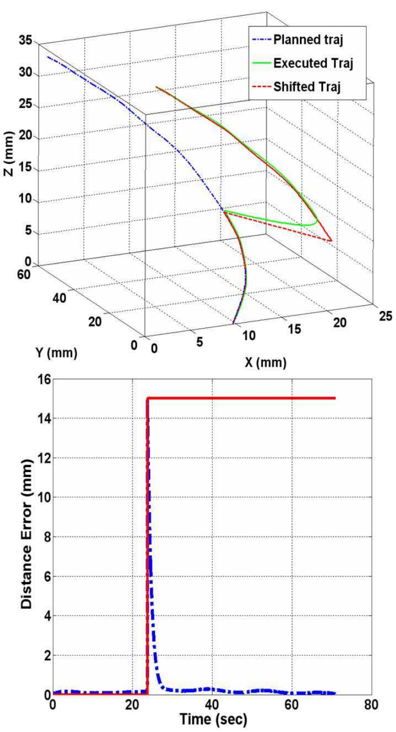

Fig. 5. Head tracking example. Planned trajectory (dashed-dot line in blue), same trajectory with a shift due to a head movement (dashed line in red) and coil trajectory obtained with the motion compensation module (solid line in green). Below: distance error.

Another module is added to ensure the contact between the coil and the head with an applied force smaller than 2.5 N using the actuated prismatic joint combined with a force sensor. The use of a sensor which is not sensitive to the magnetic field enables us to place it inside the coil casing, as close as possible to the contact area and therefore to directly measure the force exerted on the skull. Eventually, the stimulation procedure is executed autonomously allowing for head movements, while recording the actual position and orientation of the coil for a post-procedure analysis.

IV. Conclusion

In this article, a novel robotic system and an associated workflow are proposed for transcranial magnetic stimulation. They enable to move automatically a magnetic stimulation coil on the head of the patient while the design satisfies the safety constraints. Algorithms for 3D head reconstruction from pre-operative MRI images, motion planning and head movements compensation enable to simulate a stimulation procedure. A prototype of the robotic TMS system is currently being built. We plan to use it to clinically validate the therapeutic effects of TMS on different pathologies such as depression and so to precisely define the indications of TMS.

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