Design of a New fMRI Compatible Haptic Interface

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ABSTRACT
In this paper, we present the design of a new fMRI compatible haptic interface with 3DOFs, based on electrical DC actuation, for the study of brain mechanisms of human motor control. In order to evaluate the validity of the proposed solution, we performed some preliminary experiments with a single degree of freedom device to test the compatibility with the fMRI environment. The 1DOF design was extended to the implementation of a 3DOF parallel manipulator with 3UPU kinematics. Due to the dimensional constraints imposed by the fMRI environment, the choice of the dimensions and of the adopted mechanical solution was a result of an optimization process, that is presented in this work. Reachable workspace, kinematic isotropy, end-point stiffness, minimum force and translational clearance were studied in different configurations to select the stroke of the prismatic joint and the radius difference between the moving platform and the base. A further optimization of the mechanical design was then conducted in order to reduce the torque requested to the actuators for gravity compensation and consequently improve the performance of the manipulator. The final design resulted in a system capable of satisfying all the environment and user requirements.

Index Terms: fMRI, haptic, compatible interface, mechanical design

1 INTRODUCTION
Over the past few years, functional Magnetic Resonance Imaging (fMRI) has been proved effective for the research of human brain mechanism of motor control and cognition [9]. fMRI has been used to investigate the adaptation of human motor control in controllable dynamic environments when performing a sensorimotor task. So fMRI compatible haptic interfaces which can measure position precisely and deliver forces smoothly and fast during the scanner images the brain, are becoming an essential tool in neuroscience and rehabilitation [6].

However, in order to operate in an fMRI scanner, a robotic interface should meet the high safety and electromagnetic compatibility standards, because of the strong intensity of the magnetic field, with greater attention to the security issues beyond the standard requirements of medical robots. Most importantly, the interface should not introduce disturbances or electromagnetic side effects during imaging.

There have been some successful interfaces developed to overcome such constraints. Some research groups have developed MRI-compatible robots actuated by ultrasonic motors which are well compatible with MR scanners because they do not use any magnetic materials [6] [14] [5]. But the limit of ultrasonic motors is that they are not well suited for force control, and it is difficult to achieve a high fidelity force response because of friction, non-linearity and non-backdrivability [11]. Hydraulic or pneumatic actuators have been also employed, which are flexible and can be easily adapted to the environment and placed around obstacles [2] [10] [3]. There are, however, still some problems to be resolved, such as the limited range, noisy, leakage and time delay which brings difficulties to realize the precise force and position control. Electrical DC motors, which are widely used and excellent for force and position control, are also possible to be used within the MR room, but when well shielded and keep at a safe distance from the center of the scanner [11].

The motivation of this study was to design an fMRI compatible robot, based on electrical DC actuation, with a spatial parallel kinematics to allow the execution of hand movements during neuroscience experiments. In order to evaluate the validity of the proposed solution, we performed some preliminary experiments with a single degree of freedom device to test the compatibility with the fMRI environment. The 1DOF design was extended to the implementation of a 3DOF parallel manipulator with 3UPU kinematics. Due to the dimensional constraints imposed by the fMRI environment, the choice of the dimensions and of the adopted mechanical solution was a result of an optimization process, that is presented in this study. Reachable workspace, kinematic isotropy, end-point stiffness, minimum force and translational clearance were studied in different configurations to select the stroke of the prismatic joint and the radius difference between the moving platform and the base. A further optimization of the mechanical design was then conducted in order to reduce the torque requested to the actuators for gravity compensation and consequently improve the performance of the manipulator. The final design resulted in a system capable of satisfying the environment and user requirements.

The rest of this paper is organized as follows. Section 2 discusses the design of the serial 1DOF haptic system and the results of the validation experiments. The kinematic analysis and optimization of the 3UPU manipulator is described in section 3 and section 4 respectively, and its mechanical optimization in section 5. The performances of the mechanism are given in section 6, and finally the conclusions of the study are drawn in section 7.

2 DESIGN OF 1DOF fMRI COMPATIBLE HAPTIC INTERFACE
In this section the design of the 1DOF fMRI compatible haptic interface is presented, including preliminary compatibility test, the mechanism design, control system, virtual application and validation experiments.

2.1 Preliminary Compatibility Experiment
In order to validate the assumptions that DC motors can be used in the fMRI environment and to assess the distance necessary between DC motor and our fMRI scanner (3T Siemens Allegra head scanner, Erlangen, Germany), we conducted an experiment with a single motor (Maxon RE 40, Graphite Brushes, 150 Watt). From the MR compatibility specification of the scanner used in this experiment, the magnetic intensity at the magnet isocenter is 3 T, but only 3 mT at a distance of 2 m from the center [15].

Fig.1 shows the implementation of this experiment, which includes two main parts in the test equipment, a shielded aluminum box (a DC motor insides) and a power supply. In the fMRI room the two BNC cables from the shielded box connect to the BNC filter...
2.2 Mechanism Design

The preliminary compatibility experiments validated our assumption to choose shielded DC motors as the actuators when there was a distance above 1.8 m between the shielded box and the scanner. Taking into account the dimensional constraint due to the safety distance, a specific solution was developed for the actuation, consisting in a actuation unit, made by one rigid rod connecting through a universal joint to the end-effector (shown in Fig. 2). Forces are transmitted through a cable transmission by a rotational DC motor.

Figure 2: The mechanical design of the 1DOF haptic interface attached to a supporting frame.

Considering the high magnetic application environment, polymers with excellent mechanical and machining capability were mainly used. Parts exposed to high stress were manufactured from non-ferromagnetic metals, such as aluminum and brass [16]. Carbon fiber beams with high stiffness were applied as links of the mechanism, which also guarantee magnetic compatibility in the MR room. Braid yarn cable was chosen as the transmission form to acquire precise position and force control.

2.3 System Control and Application

The control of the interface was realized by a consideration of the magnetic compatibility of electronic components. The device with the shielded motor and encoders was placed inside the fMRI room, which was interfaced to the fMRI scanner and subjects. The device communicated through BNC panel with the control electronics embedded in a target PC dedicated to the real-time control of the system, outside the fMRI room.

A stereoscopic tracking application was also designed through the XVR development suite to test the device with subjects and shown to the subjects through a special visual projection equipment. The application consisted in a virtual tracking board which traces the position of the end-effector and random virtual spheres moving in a straight line (shown in Fig. 3). Subjects hold and move the end-effector which corresponds to the movement of the pad in VE to catch the marked sphere. When the collision was tested by the system between the pad and the sphere, force feedback was outputted to subjects through the end-effector.

Figure 3: The scenario of stereoscopic tracking application of the haptic interaction system.

2.4 Compatibility Experiments

The fMRI compatibility is critical for both the safety of the human subjects and the imaging quality. To ensure that the haptic device did not introduce any degradation in the MR images and to guarantee the possible artifacts after the introduction of the device in the magnetic field, a series of fMRI compatibility tests with a phantom and human subjects were conducted on the system using a gradient echo planar imaging sequence (TR = 2 sec; TE = 30 ms, 192 mm FoV; 35 slices; 64x64 in plane resolution) commonly used in functional imaging (shown in Fig. 4).

Figure 4: The experimental scene of the haptic interface with the subject performing.

2.4.1 Phantom Tests

The compatibility of the system was first examined by computing the variation of signal to noise ratio (SNR) in a phantom, placed inside the fMRI scanner. The SNR was calculated as a ratio of the mean value of an ROI (region of interest) at the center of the phantom image and the width of the noise computed by choosing an
ROI near the image edge outside the phantom [4]. Four fMRI conditions were carried out in order as follows: (1) no device present inside the fMRI room, (2) device present, but turned off, (3) device present and turned on, and (4) device present and turned on with subjects operating the device. Table 1 shows the value of SNR in the four conditions, although suggesting that there is only a small drop on the value of SNR in the last three conditions, the phantom images in all four conditions (shown in Fig.5) are clear without any deformations or dark spots, which means the interface does not interfere the fMRI scanner.

Table 1: The SNR of the fMRI Compatibility Experiments on Phantom.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>no device present</td>
<td>54.7</td>
</tr>
<tr>
<td>device present, but turned off</td>
<td>53.9</td>
</tr>
<tr>
<td>device present and turned on</td>
<td>53.5</td>
</tr>
<tr>
<td>device present and turned on with</td>
<td>53.4</td>
</tr>
<tr>
<td>subjects operating the device</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: Effect of the haptic prototype on the phantom images, (a) no device present, (b) device present, but turned off, (c) device present and turned on, (d) device present and turned on with subjects operating the device; (e - g) show the subtractions of the baseline (a) from (b - d).

2.4.2 Human Tests

Although the phantom tests proved that there was no decline on the quality of images in the condition of subjects operating the device, human tests was still necessary to validate the usability of the system on the research of human motor control. The human tests were conducted with subjects lying in the normal position of the fMRI scanner, whose heads were immobilized by a support frame inside the bore of the scanner. The images under two conditions were compared: brain activities whether subjects operated the interface or not when imaging. As shown in Fig.6, there was no statistically significant distortion on the image when subjects performed with the interface compared with the images when subjects performed without the interface. After both the phantom and human tests, the compatibility of the interface has been validated and the system can be applied in the fMRI environment when imaging.

Figure 6: Effect of the haptic prototype on the human brain images, (a) brain activity when subjects performing without the interface inside the fMRI scanner, (b) brain activity when subjects operated the interface, (c) the difference of (b) minus (a).

For further analysis the functional images were preprocessed and statistically analyzed using SPM5 (Functional Imaging Laboratory, London, UK). The resulting statistical parametric maps were initially thresholded with p<0.001 (uncorrected for multiple comparisons). Resulting clusters surpassing a threshold of p<0.05 (corrected for multiple comparisons) were considered as significantly activated. Results are depicted in PALS space using Caret [21][20]. Fig.7 shows the human motor activation maps obtained during the moving sphere application experiment. The left panel (a) was acquired without the subject performing on the haptic device but just watching the optic flow, and the right panel (b) with the subject watching the optic flow and tracking objects using the haptic device. We found activation in the primary visual system (a and b), in areas typically processing optic flow (e.g. hMT+ in b) and motor commands (parietal reach region and somatosensory cortices along the central sulcus in b). Both the maps showed expected and plausible results patterns for optic flow and haptic stimulation and point towards the fMRI compatibility of the manipulator introduced above.

3 KINEMATIC ANALYSIS OF 3UPU fMRI COMPATIBLE HAPTIC INTERFACE

After the successful validation of the 1DOF solution, we exploited the single actuator design to implement a multiple degrees of freedom mechanism with parallel kinematics to improve the dynamic property of the manipulator with long slender actuation links, with each leg based on the adopted 1DOF solution. Due to the dimension constraints and the implementation of the 1DOF solution, the natural solution was to employ a 3UPU parallel mechanism, as shown in figure 8. There are two universal joints and one prismatic joint on each link, and the resultant motion of the moving platform is controlled by extending or retracting the prismatic joints [18] and restricted to be only fully translational [7].

Due to the design constraints described above, the only two free parameters to define the kinematic design were the stroke of the prismatic joint and the radius difference of the moving platform and the base, denoted by $s$ and $D$ respectively, (shown in Fig.8), being the distance between shielded DC motors and fMRI scanner and the radius of the moving platform fixed for the fMRI compatibility requirement and under the assumption of a symmetrical disposition of actuators. In order to choose these two kinematic dimensions in an optimal way, five indicators of performance were computed for different kinematic configurations of the manipulator: workspace size, kinematic isotropy in the workspace, end-point stiffness, end-point force, position accuracy induced by joint clearances. The reachable workspace was computed numerically, but for sake of brevity we report below only the adopted numerical procedure used to compute the other four performance indicators.

3.1 Kinematic Isotropy Analysis

The kinematic isotropy was evaluated as the product of the sum of the inverse condition number with the workspace volume divided...
Figure 8: The schematic of the 3-UPU parallel manipulator, where is the stroke of the prismatic joint whose value is equal to the length of transmission cable of each link, and is the radius difference between the fixed base and the moving platform, denoted by and .

by the number of points in the workspace [1], shown as Eq.1,

\[ \eta = \frac{\int_{W} \frac{1}{x} dW}{\int_{W} dW} \]  

where is a differential workspace of the manipulator and is the condition number defined by the specific value of the maximum and minimum singular values of the Jacobian respectively [17]. Acceptable configurations were defined as the ones with the kinematic isotropy value not exceeding the target value.

3.2 Stiffness Analysis

The mechanical stiffness perceived at the point provides the capability of the device to perform a given task. The accuracy of the endpoint position has a direct relationship with the stiffness of the manipulator. As links become longer and slender, link compliance become the major source of deflection [19]. In this manipulator, however, long transmission cables with much lower stiffness than the carbon beam are the main source of compliance. According to the dual relation between force mapping and movement mapping, the relationship between the Cartesian stiffness matrix, , and the joint stiffness matrix, , is determined by Eq.2.

\[ K_p = K_q + J^{-T} K_q J^{-1} \]  

where

\[ K_q = \begin{bmatrix} \frac{\partial J^{-T}}{\partial x_1} \tau & \frac{\partial J^{-T}}{\partial x_2} \tau & \frac{\partial J^{-T}}{\partial x_3} \tau \end{bmatrix} \]  

is a 3x3 diagonal matrix in which each non-zero diagonal element, , represents the stiffness of each link and point (x1, x2, x3) is the location of the moving platform. So is a 3 x 3, symmetric and configuration dependent matrix and can be mapped as a function of the moving platform location. A more detailed discussion is given in [13]. Here the minimum stiffness of the manipulator at each point within the workspace can be calculated as the minimum eigenvalue of the Stiffness matrix at the corresponding eigenvector direction.

3.3 Minimum Force at Endpoint

The minimum force acceptable at the endpoint of a manipulator is an essential performance in the simulation environment. For each choice of the parameters of the manipulator, the minimum force at point directed along an arbitrary direction within the whole workspace for each prismatic joint to exert a force, , can be calculated. Using the Jacobian, we can get

\[ f(P) = J^{-T} F_p = J^{-T} \frac{\tau}{r} \]  

where is the torque exerted by the actuators, is the radius of the pulley. When the forces applied by joints are constrained to lie on a sphere of unit diameter, the force exerted by the endpoint at point span the surface of an ellipsoid. The minimum force at point is calculated as the value of the minor axes of the ellipsoid.

3.4 Estimation of Position Accuracy

An estimation method based on screw theory proposed by A. Frisoli et al. [8] is applied for the calculation of the generic motion of the end-effector which is expressed as a quadratic function of the end-effector displacement. In this method the maximum displacement of the end-effector can be estimated on condition that the kinetics of the mechanism and the values of the tolerances in the joints of the mechanism are given. The detailed computational process can be found in the reference [8]. The characteristic dimensions of the joints in each leg of the manipulator are shown in Table 2, where is the radial play of the tolerance and the semi-length of the joint (shown in Fig.9).

<table>
<thead>
<tr>
<th>Joint</th>
<th>Radial Play ((r_i)) (mm)</th>
<th>Semi-length ((L_i)) (mm)</th>
</tr>
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<tbody>
<tr>
<td>J1</td>
<td>0.022</td>
<td>60</td>
</tr>
<tr>
<td>J2</td>
<td>0.022</td>
<td>30</td>
</tr>
<tr>
<td>J3</td>
<td>0.03</td>
<td>18</td>
</tr>
<tr>
<td>J4</td>
<td>0.022</td>
<td>18</td>
</tr>
<tr>
<td>J5</td>
<td>0.022</td>
<td>18</td>
</tr>
</tbody>
</table>

Figure 9: Indication of clearances of the joints, (a) the rotational joint, (b) the prismatic joint.

4 KINEMATIC OPTIMIZATION OF 3UPU fMRI COMPATIBLE HAPTIC INTERFACE

Due to the limited reachable workspace inside the fMRI scanner and the future experimental requirements, such as lower output force but higher position accuracy, the kinematic optimization was carried out on the set of points \([S, D]\) to identify the optimal configuration satisfying the following functional requirements: (1) the volume of reachable workspace between \(6 \times 10^5 cm^3\) and \(8 \times 10^5 cm^3\); (2) the average value of kinematic isotropy larger than the target value of 0.1; (3) the minimum stiffness in the whole workspace greater than 10 N/mm; (4) the minimum force at the end-effector over 10 N; (5) the average value of maximum translational clearance in the central part of the workspace lower than 2 mm.
The optimization procedure was based on an interval search process and consisted of the following steps: (1) The set of \([S, D]\) satisfying the workspace constraint were fixed firstly, and the low-boundary, high-boundary and average value of these target points were found (shown as iso-curves in Fig.10); (2) The four performance indices are calculated and analyzed with the different sets of \([S, D]\) on the three curves drawn in the first step.

Fig.10 shows the volume of the reachable workspace as a function of \([S, D]\). From this plot, it is obvious that the volume of the workspace increases with larger stroke of the prismatic joint and lower value of the radius difference.

Figure 10: The workspace volume analysis of the manipulator, in the left figure the part on the 3D surface between two black planes is the object volume range of the workspace, the target set of \([S, D]\) is plotted by 'X' in the right figure, and also the low-boundary, high-boundary and average value of these target points by red, black and cyan lines respectively.

Fig.11 exhibits the relationship between the performance analysis items and the radius difference with the comparison of the low-boundary, high-boundary and average value of target sets. From Fig.11 (a) regular increases of \(S\) worsen the performance of the mechanism stiffness because of the transmission cable, while the radius difference advances the property markedly. As for the analysis of the kinematic isotropy and the minimum force shown in Fig.11 (b) and (c), larger values of \(D\) improve the performance linearly, without apparent impacts from the stroke of the prismatic joint. Fig.11 (d) shows that increasing of \(D\) decreases the average value of maximum translational clearance in a non linear way: in particular the slope of the curves decreases with increasing \(D\), with a comparable performance of points with high \(D\).

The selection of the set of \([S, D]\) followed the process of the analysis above: the stroke of prismatic joint \(S\) was firstly decided to achieve all the functional requirements, and then the radius difference \(D\) was chosen based on a fixed radius of the moving platform to limit the bulk of the base. The following parameters are chosen for the final configuration: (1) the length of each link is 2000mm, (2) the stroke of prismatic joint is 500mm, (3) the radius of the base is 530mm, (4) the radius of the moving platform is 30mm.

5 MECHANICAL OPTIMIZATION OF 3UPU fMRI COMPATIBLE HAPTIC INTERFACE

After the definition of the kinematics, the overall mechanical design was revised in order to optimize the motor torques required to each actuator for the gravity compensation of the mechanism, which are greatly influences by the position of mass center of each link. The mass properties of links were derived by the CAD software Pro/Engineer.

According to the definition of the lagrangian formulation, the motor torques for the gravity compensation can be expressed as

\[
\tau_G = J^T f_G = J^T \left[ \frac{\partial U}{\partial F_x} \frac{\partial U}{\partial P_x} \frac{\partial U}{\partial P_y} \right]
\]

Figure 11: The optimization item plots of the 3UPU haptic interface in the desired workspace, (a) the minimum stiffness analysis, (b) the kinematic isotropy analysis, (c) the minimum force analysis, (d) the maximum translational clearance, with the selected set of \([S, D]\) outlined by a red square in plots.

where \(U\) is the potential energy and \(P = [P_x, P_y, P_z]\) is the position of the end-effector in the base coordinate system.

Figure 12: The gravity compensation comparison of three legs of the manipulator (the definition of legs shown in Fig.14) between the unmodified and modified mechanism on the Z axis.

In order to decrease the percentage of torque needed for the gravity compensation, a modification of the mechanical design of the link holding the motor - shown in Fig.13 - was made, to change the mass center from a changeable position according to the movement of the end-effector to a fixed position at the center of the universal joint. This modification led to an effective reduction of the torque output of motors of about 25%, as shown in figure 12.

6 PERFORMANCES

Fig.14 shows the structure of the 3 degree-of-freedoms haptic interface with parallel mechanism placed in the fMRI room at the experimental position. The following performance is achieved at the level of the end-effector, which are well beyond the design requirements: (1) the volume of the reachable workspace is 63300m\(^3\) (shown in Fig.14); (2) the average value of kinematic isotropy index is 0.19, larger than 0.1; (3) the minimum value of mechanical stiffness of the whole workspace in the worst case is 18N/mm; (4) the minimum force at the end-effector is 11.3N with the maximum force of 48.2N at the continues output torque 300Nmm of actuators; (5) the average value of maximum translational clearance in the
central workspace with a cubic of $200 \times 200 \times 100 \text{mm}^3$ is $1.8 \text{mm}$; (6) the percentage for gravity compensation of torque output of actuators is down from 50% to 25%.

Figure 14: A design module of 3DOF parallel haptic device placed in its experimental position inside the fMRI scanner, with its reachable workspace expressed in blue shadow.

7 Conclusions

In this paper we have presented the overall kinematic design and mechanical study of a 3UPU fMRI compatible haptic interface. After the confirmation, through a preliminary compatibility experiment conducted with one single motor, that shielded DC motors can be used in the fMRI environment with a safe distance between the motor and fMRI scanner, we manufactured a new prototype of 1DOF manipulator to assess the compatibility of the proposed solution both through phantom and human tests. This result was assumed as the ground to carry out the design of a spatial haptic interface. Taking into account the geometric constraints from the fMRI environment, that restricted the range of some kinematic dimensions, the other dimensions were selected through an analytical characterization of the performance of the manipulator in terms of workspace size, kinematic isotropy analysis, stiffness, output force and translational clearance. The parameters were selected after a multi-objective optimization and further a mechanical revision of the design was made to reduce the torque requested at the actuators for the gravity compensation. The results of this paper have led to the full definition and mechanical design of prototype of a fMRI compatible haptic interface with 3DOFs and pure translational motion. The device is actually under construction and will be afterwards tested in a series of experiments to be conducted in the fMRI scanner.

References