Robot assisted needle interventions for brain surgery

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Abstract

Brain diseases affect a sizable amount of people worldwide, being the brain surgery an attractive but challenging therapeutic procedure for treatment. The fast evolution in the robotics field can provide more precise and less invasive tools to overcome certain limitations of the conventional brain surgeries. In this work, a new robotic solution involving the KUKA LWR 4+ was proposed and fully implemented in order to perform brain surgeries involving any kind of targeting within the brain. The robot’s positioning task is assisted by a co-manipulation setup between the surgeon and a virtual impedance environment. A simulation of a brain biopsy to the red nucleus was performed using the developed robotic system. A Needle Path Planning software was also designed to choose the desired target point along with the planning of the needle’s trajectory. Our findings revealed that this procedure has a total positioning error of 6.3 mm. In this work a user-friendly and intuitive robotic system was successfully created providing a new alternative tool for the brain robotic surgery.

Keywords: Brain Surgery, Robotic Brain Biopsy, Co-manipulation, Virtual Impedance Control, KUKA LWR 4+ Kinematics

1. Introduction

Brain cancer statistics demonstrate that, throughout both sexes and a standardized age, in Europe this disease affects 6.6 people per 100,000 population (total of 57099 people) and have a mortality rate of 4.9 people per 100,000 population (total of 44979 people), occupying the sixteenth position in the most common cancer ranking. The statistics also show that in Portugal 7.1 people per 100,000 population (total of 932 people) suffer from brain cancer and it has a mortality rate of 5.0 people per 100,000 population (total of 718 people)[1, 2].

Diagnosis of this disease strongly relies on neuroimaging techniques like magnetic resonance imaging (MRI) and computed tomography scans (CT-scan). Although these methods are good surveying for brain tumors, to obtain a definitive diagnosis, an histopathological examination of the tumor tissue is essential. In order to obtain a sample of this tissue a brain biopsy must be performed [3]. Currently, there are two standard procedures for performing this surgery, the stereotactic brain biopsy and the neuronavigation assisted brain biopsy.

Neuronavigation is a method that allows the surgeon to observe the various brain structures that are not visible otherwise, thus making it possible to "navigate" through the brain. This method offers, not only, a way of locating tumors within the brain, but also the possibility to plan the best needle trajectory to reach them [4]. This surgery relies on two optical digitizer cameras and a light-emitting diodes (LEDs) setup that allows the tracking of the patient’s head as well as the biopsy needle during the entire procedure. For this, LEDs must be attached to the needle and the Mayfield frame, which is a tool that holds the head in place in these surgeries [5].

Another type of procedure that makes possible the biopsy of lesions/tumors deeply embedded in the brain is the stereotactic brain biopsy. The surgery consists in defining a working space around the patient’s head by setting up a cartesian coordinate system [6]. This can be achieved by attaching a light-weight frame to the skull [7]. The stereotactic brain biopsy is a technique largely used worldwide, since the stereotactic apparatus provides a safe and static environment for this type of surgery and can achieve errors around 0.5 mm.

With the advancements in the robotics field, today, more precise and user friendly robots exist. The state of art technology in the field of neurosurgery comprises 3 major commercialized robots, the ROSA™, the Neuromate® and the neuroArm. ROSA™ is a versatile instrument that can assist neurosurgeons in a wide range of surgical procedures to the brain, including the brain biopsy. This robot can behave in two different ways during
the surgery. It can position the surgical instrument automatically according to the pre-planned trajectory, or it can be co-manipulated. This last feature allows the surgeon to move the robot manually, but constraining, at the same time, the movement to the preprogrammed trajectory. The safety mechanisms are further enhanced by the security zone feature, available on ROSA™. This functionality confines all the robot’s motions to a preoperatively planned cone defined along the trajectory. All these ROSA™’s characteristics ensure that the surgical instrument stays aligned with the planned trajectory and that the entire procedure achieves the minimum invasion possible[8, 9, 10, 11].

The Neuromate® robot is another state of the art equipment, specifically developed for stereotactic brain surgeries, whether frame based or frameless. It offers different options in terms of the surgery itself. If the surgical procedure is a biopsy, for example, the surgeon can command the robot to position the biopsy needle in two distinct ways. One approach is to use the endoscopic navigation option to insert the needle. In this case the surgeon can control the insertion with a remote control (tele-manipulation) while observing the inside of the brain [12, 13]. Another approach is to command the robot to position the needle automatically. In either method, a burr hole in the skull’s bone must be opened, before inserting the biopsy needle. A laser pointer mounted on the robot’s arm is used to correctly position the burr hole.

The neuroArm robot was developed by Garnette Sutherland and Associates and, currently, it is the most sophisticated master-slave system used in brain surgery [13]. This robotic system comprises two seven degrees of freedom (DOF) robotic arms, a main system controller and a workstation (human-machine interface), where the surgeon is capable of controlling the robot in an extremely interactive way [14, 15]. The neuroArm allows both stereotactic and microsurgical procedures and it is characterized by being fully MRI compatible and be teleoperated from a workstation situated outside the operating room. Fully MRI compatible means that it can operate while an MRI scanner is acquiring images of the brain [16]. This feature allows procedures to be performed in an environment with real-time update of the brain’s position, which enables the correction of the deformation/displacement of the brain during surgical procedures (Brain Shift). This workstation includes one high-definition medical monitor and two six-DOF haptic devices that provide, respectively, visual and tactile feedback of the robot’s work environment [17]. The medical monitor receives images from two high-definition cameras present inside the operating block, which enable the surgeon to have full-depth perception and spatial orientation, thus granting plain 3D display capabilities. The use of six-DOF haptic devices adds many functionalities to the robot including the filtration of the surgeon’s hand tremor, the scaling of the surgeon’s motions and the force-feedback. The later tries to mimic the tactile feel that the surgeon would get as if he was performing the surgery in the conventional way[15].

The objective of this work is to develop a complete robotic solution that can improve and replace the conventional brain surgeries that are performed nowadays. In this line of thinking, the robot should perform the surgical procedure with the help of the surgeon, in a cooperative way. The proposed robotic solution to improve brain surgery is to use a robotic arm, the KUKA LWR 4+, to do the positioning of the needle during the surgery. In any kind of surgery it is very important that the surgical environment be as safe as possible. For this purpose a virtual impedance environment was implemented. This consists in an impedance cone that constrains the robot’s movement to a safety zone. Although the robot is manipulated by the surgeon, the robot also constrains the surgeons movement to the cone-shaped zone. This relation between robot and surgeon is called co-manipulation. The impedance cone is aligned with the orientation of a preoperatively planned needle’s trajectory and the cone vertex is positioned at a safe distance from the patient’s head. As the needle’s tip passes the cone vertex the robot locks its orientation and only allows the needle to move along the predefined trajectory. When the needle’s tip reaches the target point the robot stops and forbids any movement further down the planned trajectory. While this whole process is in course, the surgeon can observe the robot’s virtual environment in a 3D simulator. This includes the virtual cone defined as the safe working zone. In order to offer the surgeon a training instrument and a way to exploit the features and capabilities of the robot, the 3D simulator can also be used in offline mode.

2. Materials

2.1. KUKA LWR 4+

The KUKA lightweight robot (LWR) 4+ is the product of a research collaboration between the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR) and the KUKA Roboter GmbH. The KUKA’s key features are its 1:1 power-to-weight ratio and its kinematic redundancy that makes it resemble the human arm. These properties along with its flexibility to execute tasks, give the KUKA the position of one of the most advanced robot in the human-robot interaction field. The KUKA can be commanded in two different ways, by
means of the KUKA Fast Research Interface (FRI) or by directly controller console via KUKA Robot Language (KRL). Both of these languages use standard functions of KUKA industrial robots which offer three types of control methodologies, the Joint Impedance control, Cartesian Impedance Control and the Joint Position Control.

2.2. Brain Phantom

In this work, a human brain inside an acrylic box was provided by Dr. Herculano Carvalho from Hospital Santa Maria. An MRI of the phantom was performed so as to grant knowledge of the deep anatomical structures of brain. The purpose of the phantom’s box is to play the role of the human skull allowing the creation of a reference frame for the brain.

3. Developed Software

3.1. Needle Path Planning Software

The preoperative planning is a very important step of the surgical procedure. At this stage, the surgeon must plan and define the trajectory that the needle will travel to reach the desired target point. This trajectory must be carefully delineated since it must avoid relevant areas of the brain. In order to make this process as simple and intuitive as possible a user interface was developed under Matlab® R2014a (The MathWorks, Inc.; Natick, Massachusetts, United States) (Figure 1). The development of some features available on this software were based on the work of Teodoro et al. [18]. The working principle behind this interface is very straightforward and follows a logical sequence of steps: Load an MRI file and its 3D reconstruction file; Choose the desired target point and Choose a needle’s entry point.

First, to setup the GUI the surgeon must load the MRI file, as well as its 3D reconstruction file. To do this, the surgeon just needs to press the menu File -> Open and File -> Load 3D Model buttons present in the menu bar and choose the correct files. Right after the program finishes loading both files, the various brain slices are displayed in three windows on the left side of the GUI, whereas the 3D model of the brain can be observed in the right side window. The brain slices are displayed in three views that correspond to the axial, the sagittal and the coronal planes. There are also slide bars on the windows’ sides that can be used to scroll through the brain slices. When the slide bar is used the slice number is updated and displayed in the Section Views panel. At this point the surgeon can use the Colormap, Contrast and Brightness buttons in the menu bar to improve the image quality.

Usually, for the surgeon’s better understanding of the brain’s anatomy by looking at the MRI images, he needs the planes where the images are displayed to be orthogonal to a plane that intersects the anterior (AC) and posterior (PC) commissures of the brain (AC-PC line). This is another functionality that the software provides. To rearrange the displayed brain slices according to the AC-PC line, the surgeon can use the small slide bar present at the right-top side of the coronal and sagittal planes. The images should be rotated till the AC-PC line becomes horizontal. This process is usually performed in the sagittal view since it is the most intuitive view to perform this task. When an image is rotated, the images in the other planes are also updated to match that same rotation. The next step consists in selecting the desired target point. To do this the surgeon should use the Choose Target Point button present in the Selection Tools panel. When the button is clicked the mouse gains a cross shape form, then the surgeon only needs to click the desired target point in the view that is most intuitive to him. Every time that a point is chosen in one of the views, the projection of that same point in the other views is also displayed. The desired target point appears in the three views as a red dot.

After defining the target point the user can choose the needle’s entry point. Once again the user should go to the Selection Tools panel and click the Define Needle Trajectory button. When that button is clicked the program allows the surgeon to choose an entry point at the brain’s surface. This can be done in the right window where the 3D model of the brain is displayed. To select this point the surgeon just needs to click the brain’s surface and a green line representing the needle’s trajectory will be displayed. The user can hold down the left mouse button to re-position the entry point. After defining the needle trajectory the user can click in the Show Needle Trajectory button to display the path in the three plane views. This tool exhibits the intersection of the chosen slice with the trajectory line, thus producing an intersection point (displayed as a green point in the section views). This tool enables the surgeon to check if the chosen trajectory passes through some important area of the brain, thus allowing him to correct the specified needle path. Apart from the buttons already mentioned, the Selection Tools panel also displays the select target and entry points.

There is one more panel that also contains useful functionalities, which is the 3D View panel. In it the surgeon can change the transparency of the 3D brain model, display the target point in the 3D view (appears in red) and observe a given brain slice. To use this last feature, the check boxes named after each section view can be clicked to show or hide the respective slice. If the check box is active the
surgeon can then use the slide bar to scroll through the brain slices. This feature is very useful since it provides the surgeon an intuitive way of avoiding important brain structures when defining the needle trajectory.

3.2. CHAI3D Virtual Environment

In order to have a tool that can represent accurately the robot working environment and a virtual impedance control, a 3D simulator was developed. This software was developed in Microsoft Visual Studio® 2010 (Microsoft Corporation; Redmond, Washington, United States) with the CHAI3D C++ libraries [19], and uses the KUKA FRI communication protocol as an interface between the PC and the KUKA robot (Figure 2). Two haptic devices were integrated with the CHAI3D, the Omega.6 haptic device (Force Dimension; Switzerland) [20], which is six-DOF pointer (three for the position and three for the orientation), and the KUKA LWR 4+. Both haptic devices were attached to the 3D model of the biopsy needle used in this work, since it is the needle’s tip position and orientation that we want to track and control. The virtual environment also contains a 3D model of the robot and a model of the needle’s holder. This surgical virtual environment has two main goals:

- It is intended to be a tool for the surgeon to have a feel of the brain biopsy procedure (offline mode).
- A tool for the surgeon to use in a co-manipulation procedure. The software creates an impedance environment that, with the help of the surgeon, will guide the robot to the preplanned needle’s orientation and the target position within the brain. The robot will be the haptic tool which will interact with the virtual and real environments.

3.2.1. Surgical Co-Manipulation Mode

This mode allows the surgeon to perform the surgical procedure. It uses the FRI API to make the connection between the computer and the KUKA controller. This mode is automatically set at the start up of the program if the robot is connected to the PC. Before the program launches the visual interface, it will send the robot to a pre-programmed position, in cartesian impedance control, where the robot can work safely. After this, the visual interface window opens and the program is ready to use. In this mode the robot is the haptic device used. If the surgeon moves the robot the 3D model of the robot with the needle holder and needle will move accordingly in the virtual environment, to fully mimic the real robot’s movements. This was achieved by implementing the direct kinematics of the KUKA [21].

After the program has successfully opened and the robot is in its starting position, the surgical procedure can begin. This process can be summarized in two steps, the registration of the phantom and the positioning of the needle in the target point via an impedance environment. One thing to have in mind is that the preoperative planning of the surgery, i.e., define the target point and the needle’s trajectory in the needle path planning soft-
ware, must be performed before the surgical procedure starts.

Figure 2: Image of the developed CHAI3D virtual environment.

**Registration Procedure**

The registration procedure is very simple and straightforward. To start it the surgeon should press the J button in the keyboard and a message in command window will show that the program is ready to start the registration procedure. After the button is pressed the surgeon must not move the robot since it takes approximately five seconds for the robot to change from the cartesian impedance control to the joint impedance control mode. In this mode all the joint’s stiffness are set to zero, and the robot is now in gravity compensation. This means that the robot is completely maneuverable and only applies the necessary force to maintain its pose. To perform a successful registration the surgeon must acquire points that belong to five faces of the phantom. To do this he must use the needle’s holder tool spherical part. The methodology for acquiring the points is quite simple. The surgeon must first lightly press the tool’s spherical part against the cube’s face, and then press the Space Bar so that the program starts recording the tool’s position. During the acquisition the surgeon must perform slow movements and go through all the face’s area, in order to minimize the error inherent to the registration process. When these conditions are met, the surgeon must press the Space Bar to stop the program from acquiring more points. The sequence of planes to be acquired is left, front, right, back and bottom.

After finishing the point acquisition, the program performs all the necessary calculations to find the geometric transformation between the MRI’s phantom and registered phantom [22]. Afterwards, the brain model along with a representation of the box appear in the virtual environment. The impedance cone also appears together with a sphere representing the desired target, chosen with the Needle’s Path Planning interface. The cone is aligned with the needle’s trajectory and its vertex is set 20 cm from the chosen brain’s entry point along that same trajectory. At this point, the surgical setup is ready to perform the surgery.

When the registration is over the robot changes the controls again from joint impedance control to cartesian impedance control to get ready for the co-manipulation surgical procedure. To activate the virtual impedance environment mechanism the surgeon should click the 3 button on the keyboard.

**Virtual Impedance Positioning**

The impedance environment implementation was based on the Doctoral Thesis of Pedro Pires [23]. The virtual impedance positioning control, which is illustrated in Figure 3, can be split in three parts:

- While the tool center point (TCP) is in the safety zone and it has not passed the cone vertex (A).
- While the TCP is between the cone vertex and the target position, along the needle trajectory (B).
- When the TCP reaches the target point (C).

For the purpose of implementation, a virtual impedance environment between the robot tool and the pre-planned needle trajectory axis, \( Z_{Brain} \), was created. This system attracts the tool to correctly align it with the needle trajectory. The distance between the target point and the needle’s tip is expressed in the brain reference frame (which has its origin at the desired target point), along the needle’s trajectory and can be defined as follows:

\[
P_{\text{Brain}}^{\text{Tool}} = R_{\text{Brain}}^{-1}(p_{\text{Tool}}^0 - p_{\text{Brain}}^0)
\]  

(1)

Since the \( X_{\text{Tool}} \) axis represents the orientation of the needle in the tool reference frame, the distance between the TCP and the target point, along the needle trajectory corresponds to the \( x \) component of \( p_{\text{Tool}}^{\text{Brain}} \) \( (p_{\text{Brain}}^{\text{Tool}})_x \). The other two elements of \( p_{\text{Brain}}^{\text{Tool}} \) represent the directions where the stiffness values will vary.

The impedance control law applied in this work consists in changing the spring stiffness values as a function of \( (p_{\text{Tool}}^{\text{Brain}})_x \). The equation that defines this control is as follows:

\[
K_{\text{StiffVal}} = K_{\text{StiffMax}} - K_{\text{StiffMax}} \cdot \frac{\sqrt{(p_{\text{Brain}}^{\text{Tool}})_x}}{\sqrt{l_{\text{Imp}}}}
\]  

(2)

where \( (p_{\text{Tool}}^{\text{Brain}})_x \leq l_{\text{Imp}} \land (p_{\text{Tool}}^{\text{Brain}})_x > 0 \). As can be deducted from eq. 2, when \( (p_{\text{Tool}}^{\text{Brain}})_x \) is
greater than a predefined distance, \( l_{imp} \) the value of \( K_{CStiffVal} \) is set to zero, making the robot enter the gravity compensation mode. To calculate the applied force that the virtual spring exerts in the TCP, eq. 3 was used.

\[
F_{K_{CStiffVal}} = R^p_0 \ Brain \begin{bmatrix} \{ p_{Brain} \}_y & \{ p_{Brain} \}_z \end{bmatrix} \cdots \ K_{CStiffVal} \sqrt{\{ p_{Brain} \}_y^2 + \{ p_{Brain} \}_z^2} \]

(3)

To this last equation, a dissipative force function with damping coefficient factor \( \xi \) was added, thus obtaining

\[
F_{Imp} = F_{K_{CStiffVal}} + D(\xi)
\]

(4)

Figure 3: Two dimensional illustration of the virtual impedance environment.

The fact that the \( X_{Tool} \) axis of the tool reference frame is aligned with the needle orientation, allows the simplification of the \( k_{CStiff} \) vector calculations, making the diagonal stiffness matrix become

\[
K_{CStiffImp} = \text{diag}(\begin{bmatrix} 0 & K_{CStiffMax} & K_{CStiffMax} & \cdots & K_{CStiffMax} & K_{CStiffMax} \end{bmatrix})
\]

(5)

According to eq. 6 the robot is constrained from performing any rotation at it can only move along the needle’s trajectory. Finally, when the robot reaches the desired target all entries of \( K_{CStiffImp} \) are set to the maximum stiffness values thus preventing the robot from moving further. At this point the surgeon can perform the biopsy from the desired anatomical structure.

One more functionality that this system provides is the ability to change the robot configuration while it maintains the needle position and orientation (robot’s null space). This is a very useful feature that allows the surgeon to modify and optimize the work space.

3.2.2. Training Mode

Another goal of this software is to offer the surgeon a way to practice the surgery and test the capabilities not only of the co-manipulation procedure as well as the virtual environment itself. When this program is started it checks if any haptic device is plugged to the computer. If the robot is not detected then the program automatically starts the offline mode. In this mode only the omega.6 haptic is available to the surgeon. With this haptic device the surgeon can control the needle’s orientation and its tip position. When the needle’s tip moves the 3D robot model also moves mimicking the robot’s real movements. This was achieved by implementing the forward and inverse kinematics of the KUKA [21]. Each time the surgeon moves the joystick of the omega.6 its position and orientation are retrieved and the inverse kinematics are calculated to discover the set of angle joints that produces that same needle’s pose. After finding the set of angles, the program uses the forward kinematics to update the position and orientation of each of the robot’s joints, giving the sensation of the real robot’s movements.

This mode also allows the surgeon to feel the force exerted on the robot when it enters in contact with some virtual structure or when the impedance mode is turned on. For this, the model of the brain and the cone used in the impedance mode are also loaded on the program start up. Since this is just a test mode, the brain is placed in a predefined position and a default target and needle trajectory are chosen so as to set the impedance cone accordingly.
The virtual impedance system setup is exactly the same as the one from the co-manipulation surgical mode.

### 4. Results

The developed robotic solution was applied to the brain biopsy surgery. For this, the phantom with a human brain inside was used. The procedure was performed by the surgeon in order to fully validate the robotic solution.

To obtain the results that will be presented a sequence of steps from the Surgical Co-Manipulation Mode were followed. In a preliminary step the Needle Path Planning software was used to set the desired target along with the trajectory that the needle must follow. The chosen target was the red nucleus, which is a 6 mm size anatomical structure situated in the midbrain next to the substantia nigra and it is involved in motor coordination.

To perform the surgical procedure, the robot was connected to the computer to serve as an haptic device. After the robot reached its starting position the registration procedure was started. This process had to be performed by two persons, one that clicked the Space Bar button and another that maneuvered the robot while the program was acquiring the points from the phantom’s faces. The order for the planes’ point retrieval was the following, left plane → front plane → right plane → back plane → bottom plane. An illustration of this process is shown in Figure 4. Since the bottom face of the box can not be reached, the table’s surface was used for the same purpose. This can be done since the acquired points are fitted to planes. The top plane is not acquired since the box can be opened during the registration procedure. The top plane was discovered with the knowledge of the box’s dimensions.

After all point were acquired, it took about ten seconds for the program to load the MRI data and perform all the calculations required to discover the transformation between the acquired physical box and the virtual MRI box. In order to calculate the errors inherent to the registration procedure, the difference between correspondent box vertexes were calculated and the results are presented in Table 1. These errors were measured in the reference frame of the physical box so that a meaningful geometric evaluation could be performed.

![Figure 4: Illustration of the registration procedure. The sequence of the process is from the image a) to image e).](image)

<table>
<thead>
<tr>
<th>Vertex</th>
<th>$x_i$</th>
<th>$y_i$</th>
<th>$z_i$</th>
<th>RMSE$_i$</th>
</tr>
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<tbody>
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<td>0.1326</td>
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<td>0.7560</td>
<td>0.5725</td>
<td>0.3683</td>
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</tbody>
</table>

In the table 1 it can be observed that the mean errors in the $x$, $y$, and $z$ directions were, respectively, 0.7530 mm, 0.5725 mm and 0.3683 mm. The mean value of the root mean square errors (RMSE) was 1.1066 mm.

Right after the program finishes all the necessary calculations associated to the registration, the virtual impedance environment was created in the 3D simulator. Before clicking the $3$ keyboard button, the robot was set in the safe working space and was roughly aligned to the pre-planned needle trajectory. This intermediate step can be seen as a safety procedure and it is done to certify that the robot does not start in a no-go zone.

Following the previous safety check, the positioning of the needle was performed via the co-manipulation virtual impedance environment. In this step the surgeon pulled the robot towards the the desired target point and the virtual impedance environment correctly guided the robot to the desired position. When the robot reached the target position it stopped in the target point with an offset.
of no more that 0.5 mm. This offset is the distance between the needle’s tip and the target point measured in the virtual environment. During this whole process the 3D virtual environment was frequently checked for a better understanding of the needle’s location inside the brain.

Figure 5: Photograph of the robot correctly positioning the needle in the desired target.

After the needle was correctly positioned the surgeon removed two pieces of brain tissue from the target and injected a contrast mixture made of barium sulfate, which provides contrast in the CT scan, and magnesium sulfate, which provides contrast in the MRI. This contrast was also injected every 2 cm while the needle was being removed. Such process was performed so that the needle trajectory can be easily detected in the postoperative images. One important thing that must be noted is that during this process the robot managed to keep a constant position and the effects of tremor inherent to the surgeon’s hand were significantly attenuated with nothing more than the virtual impedance control that was implemented. The postoperative images from the brain can be observed in the figure that follows.

Figure 6: Postoperative images from the biopsied brain.

After carefully analyzing the postoperative MRI it was concluded that there was no significant changes in the brain position nor any distortion of its structures. The error in the biopsy needle’s positioning was then calculated and the results are shown in Table 2.

| $|x|$ | $|y|$ | $|z|$ | $RMSE$ |
|---|---|---|---|
| $1.7 \pm 0.5$ | $4.9 \pm 0.5$ | $3.6 \pm 0.5$ | $6.3$ |

The errors shown in the table 2 were also calculated in the reference frame of the physical box and the total positioning error obtained for the robotic system was 6.3 mm. The axial deviation from the chosen target (center of the right red nucleus) has a magnitude of 1.7 mm in the $x$ direction and 4.9 mm in the $y$ direction and the depth error has a value of 3.6 mm. These results where somehow expected, and are justified by accumulation of errors starting with the robot kinematic calibration. The enhancement of this robotic solution must now be done in future work. For the robot to biopsy the red nucleus, an accuracy of approximately 2 mm should have been obtained. In a real surgery, a poorer accuracy than 2 mm to biopsy a structure of 6 mm size is far too risky to even consider performing it.

The three main sources of error in the performed surgical procedure lie in the tool calibration (1.7 mm), the registration method (1.1 mm) and the needle’s positioning (0.5 mm). Another source of error can be due to some deviation of the biopsy needle, that might have occurred when it perforated the brain, since it was significantly stiffer than a living one. The knowledge of these errors can provide a good guess where the robotic solution can be improved.

5. Conclusions

The presented work focused on developing a complete robotic solution that can effectively position a needle in a desired target inside the brain. Using a robotic system in this type of surgeries brings many advantages when compared to the conventional brain surgeries, namely, it is capable of removing the tremor of the human hand, it can achieve a higher level of accuracy and it allows the decrease of the burr hole size. A secondary but also important objective of this work was to test the capabilities of the KUKA LWR 4$^+$ in a co-manipulative surgery. Although the robotic system presented was tested on a brain biopsy surgery it can also be used in similar procedures that involve some kind of positioning, like the placement of an electrode in DBS.

As a first product of this work, a software for choosing the desired target, along with the definition of the trajectory that the needle should travel
to reach that same target was developed. This user interface has a wide range of functionalities, which goes from improving of image quality to the redefinition of the planes in which the MRI images are displayed.

The ultimate product of this work is the robotic system developed for brain surgeries. This system comprises a 3D virtual environment that can be used, not only as a surgical tool but also as a training tool for surgeons. For this last part the omega.6 haptic was used to serve as a substitute for the robot.

The developed virtual impedance control solution is a smart, safe, and helpful way for the surgeon to guide the robot to the desired target position. This solution provides a safe environment to be used in surgery, since a security zone was implemented that stops the robot to enter the no-go zone even if the surgeon forces it. The robotic solution was tested in a procedure that tried to simulate a brain biopsy as realistic as possible. For this, the phantom with a human brain inside was used as a patient. This procedure consisted in three main steps. First, the choosing of the desired target position and needle trajectory via the Needle Path Planning Software; second, the registration of the phantom; and third, the guidance of the needle to the target point.

The total error of the entire procedure has a value of 6.3 mm, while the errors obtained in the x, y and z directions are, respectively, 1.7 mm, 4.9 mm and 3.6 mm. These are positive results, since the main objective of this work was to develop a good and robust foundation for a robotic solution and not a perfect one. The three main sources of error that influenced the final needle position were the registration method, the needle’s positioning and the tool calibration. The RMSE from the registration process was of 1.1 mm, which can be explained by displacement of the table and/or the phantom during the procedure. The needle’s positioning error measured in the virtual environment was of approximately 0.5 mm and the tool calibration error was of 1.7 mm. From these, one can extrapolate that the main source of error is in fact the last one. This is a good sign for this project, since it is the easiest to correct. To do this an optical tracking system could be employed to reduce this error as much as possible. In order to reduce the error inherent to the registration procedure a force control could be implemented. Since this means that the robot would keep a constant force applied in the box’s faces, the oscillations that occur while the registration procedure is being performed would be greatly reduced.

In sum, the final outcome of this work is very positive and it constitutes a good foundation for further development and enhancement of this robotic surgical system. The advantages of using the developed system can be resumed to the fact that it is a very slender and compact solution that can provide a fast and easy way to perform brain surgeries. One other advantage that this robotic solution has in respect to the other surgical robots presented in the state of the art is that the registration procedure is done with the robot itself, no other tools are needed, thus making it a more cost effective product.

6. Future work

My suggestions and recommendations for the continuity of this project so as to improve the developed robotic solution are:

- Integrate an optical tracking system to improve the robot’s tool calibration error.
- Implement a force control to decrease the error associated to the registration procedure.
- Implement a tele-manipulation functionality that would allow the scaling of the surgeon’s hand movements.
- Implement a brain shift correction module that would update the brain volume in real time and detect if any of the brain’s structures moved from its original position.
- Implement a registration algorithm that can perform the registration of a real patient, via a 3D reconstruction of the head and a contour of the patient’s face.

References


