NEURONAV: A Tool for Image-Guided Surgery - Application to Parkinson's Disease

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Abstract. Deep Brain Stimulation (DBS) is a surgical procedure used to treat symptoms associated with Parkinson's Disease (PD). The success of DBS depends on the correct location of a microelectrode over the subthalamic area. This paper presents the software NEURONAV for image-guided surgery. This software serves as a support for the medical specialist in DBS. NEURONAV has two principal modules. Firstly, it allows to plan the DBS. The application contains options such as 3D image viewer, image registration, slice viewers, landmark medical planning and visualization of 3D brain structures. Secondly, NEURONAV includes an interactive application to perform the tracking of the microelectrode during the DBS. NEURONAV has been tested in procedures performed at a specialized medical center in Colombia. Results show an adequate tracking of the microelectrode implanting process and it is possible to achieve better therapeutic outcomes, and more robustness to the side effects generated by DBS in PD patients.

1 Introduction

Deep Brain Stimulation (DBS) is a surgical option for patients with Parkinson's disease that do not respond efficiently to a drug therapy. During DBS, a microelectrode is implanted over the subthalamic region. This device stimulates electrically a target brain structure, specially the Subthalamic nucleus (STN). Controlled stimulation with the DBS electrode achieves a reduction in all symptoms of PD and improves the quality of life of patients [1].

Image-guided surgery (IGS) systems are often used in complex surgical procedures. IGS systems have the ability to track surgical devices in spatial coordinates during intraoperative procedures. Since the IGS tools have been established as clinical support for specialists during surgical procedures demanding high precision, the scientific community has increased the interest in the development of these systems [2,3].

G. Bebis et al. (Eds.): ISVC 2015, Part I, LNCS 9474, pp. 349–358, 2015.
DOI: 10.1007/978-3-319-27857-5_32

Currently, research teams are developing IGS software for functional localization of brain structures in DBS. For example, [4] proposed an automatic pattern recognition system based on Spikes analysis and frequential transform methods to identify microelectrode recordings (MER) signals from specific subcortical nuclei (i.e. Subthalamic Nucleus-STN) [5]. Similarly in [6], the authors presented a query software to estimate the electrical potential generated by the DBS electrode in the nervous system, and they conducted an analysis of the relationship with clinical outcomes in several patients. These systems proved the profits of automated softwares as a decision support for the medical team during DBS.

Accurate preoperative systems applied to surgical procedures are necessary. A priority of IGS must be the protection of patients against any potential mistake [7]. For this reason, the medical image processing and their applications to the neurosciences field must be explored [8,9]. Image-guided surgery gives new advantages in critical surgical procedures like DBS. For example, Integration of computed tomography (CT) and magnetic resonance imaging (MRI) allow an accurate mapping of the brain in 3D models. Also, it is possible to acquire spatial coordinates for tracking of microelectrode devices during DBS [10].

In this paper, we present a tool for image guide surgery called NEURONAV. NEURONAV is an open-source application that allows interactive neurosurgical planning, volume rendering, rigid and nonrigid registration, 3D image viewer, flexible layouts and slice viewers, atlas registration, and on-line tracking of microelectrode devices during DBS. The goal is to provide a support tool for the DBS surgery in which the neurosurgeons can accurately identify the real location of the microelectrode device over the subthalamic area in a 3D environment. Moreover the main purpose of this system is to reduce the adverse side effects that may occur because of inadequate identification of the target brain areas. Currently, NEURONAV has been tested in DBS's performed in the institute of epilepsy and Parkinson of the Eje Cafetero, located in Pereira, Colombia. Results obtained are promising and satisfactory.

The rest of the paper is arranged as follows. Section 2 provides a detailed discussion of materials and methods. Section 3 presents the experimental results and discussion respectively. The paper concludes in Sect. 4, with a summary and some ideas for future research.

2 Materials and Methods

2.1 Database

The database of Universidad Tecnológica de Pereira (DB-UTP) contains recordings of MRI studies from four patients with Parkinson's disease and it was labeled (brain structures) by neurosurgery specialist from the Institute of Parkinson and Epilepsy of the Eje Cafetero, Pereira, Colombia. This database contains $T1$ and $T2$ sequences with $1\,\text{mm} \times 1\,\text{mm} \times 1\,\text{mm}$ voxel size and slices of 512×512 pixels.

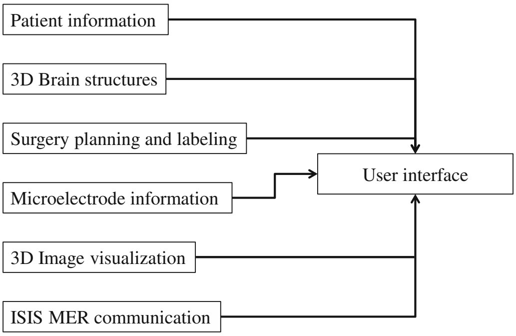

Fig. 1. NEURONAV pipeline.

2.2 Microelectrode Device

The neurosurgical equipment ISIS MER[1] (Inomed Medical GmbH), is used to collect data for derivation of potentials from the trajectory of microelectrodes in deep brain stimulation surgery applied to patients with Parkinson disease. The sampling frequency of the ISIS MER system is 25 KHz and 8 bit-resolution.

2.3 Software Development

NEURONAV is composed of a main interface and two independent modules, which are loaded dynamically during the program initialization. These modules are related by functions and controls defined in the main program. Software modules include:

1. Patient information module
2. 3D Brain structures module
3. Surgery planning and labeling module
4. Microelectrode information module
5. 3D Image visualization module
6. ISIS MER communication module

Figure 1 shows the outline of the NEURONAV system.

Patient Information Module. The patient information module contains the name, age, sex, and neurological and surgery planning information of the medical diagnosis. This information is relevant for purposes of medical history of patients.

3D Brain Structures Module. In this module the user can edit and refine the brain structures segmentation using a geometric transformation panel with translation, rotation and scale options. In addition, this tool allows the selection of a particular brain structure (3D mesh), color change, opacity and visibility.

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[1] http://www.inomed.com/products/functional-neurosurgery/isis-mer-system/.

Deformable Registration. We use deformable medical image registration based on B-spline transform to perform the atlas reconstruction [11]. To perform the registration task, we took as system parameters: (1) *Moving Image:* we denote this parameter as Atlas Intensity and it contains the MRI $T1$ volume data from SPL-PNL atlas.[2] (2) *Fixed Image:* Here we used the MRI $T1$ data volume from the DB-UTP, because the main goal of our approach is deform the MRI volume that contains the Atlas labels (SPL-PNL) to match them with the MRI volume from a given patient. (3) *Metric:* To assess the quality of the registration process, we have calculated the mean and variance of the mean squared sum of intensity differences (MSE) for similarity measure (error) as well as normalized mutual information (4) *Interpolator:* we proved the performance of the registration process using nearest neighbor. (5) *Optimizer:* for data processing, we used regular step gradient descent and versor rigid 3D transform optimizer to measure the computational cost of the procedure.

Brain Atlas Reconstruction. After performing the registration process, we obtain the registered moving image that matches with the MRI volume data, the next step is to perform a transformation over the labels that describe the brain structures. The 3D brain structure reconstruction process is accomplished by transforming the labels maps of a given atlas using the B-spline method. Finally we used the marching cubes algorithm to build the 3D models of the brain structures. For the marching cubes algorithm we use the available implementation in the visualization toolkit (VTK) [8]. Figure 2 shows the brain atlas reconstruction framework.

Surgery Planning and Labeling Module. This module allows the planning of deep brain stimulation surgery. Here, it is possible to make interactive marks on each of the MRI slices (axial, coronal and sagittal) such as entry location and target location of the microelectrode device (stereo-tactic coordinates). In addition, this module allows the visualization of the AC-PC coordinates. Finally, the user can add another fiducial points[3] in order to perform an atlas registration for a new study of neurosurgery.

Microelectrode Information Module. The microelectrode information module, indicates the real position of the DBS device. But, the most important function of this module is the tracking of the neurostimulator inside the brain during a surgery. This position is indicated in millimeters and it is taken from the depth sensor of ISIS MER.

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[2] Brain Atlas developed by the Surgical Planning Laboratory in collaboration with the Harvard Neuroscience Laboratory at Brockton VA Medical Center. http://www.spl.harvard.edu/publications/item/view/1265.

[3] A fiducial point is a key mark over the MRI volume used to plan the entry and the target point in the DBS surgery.

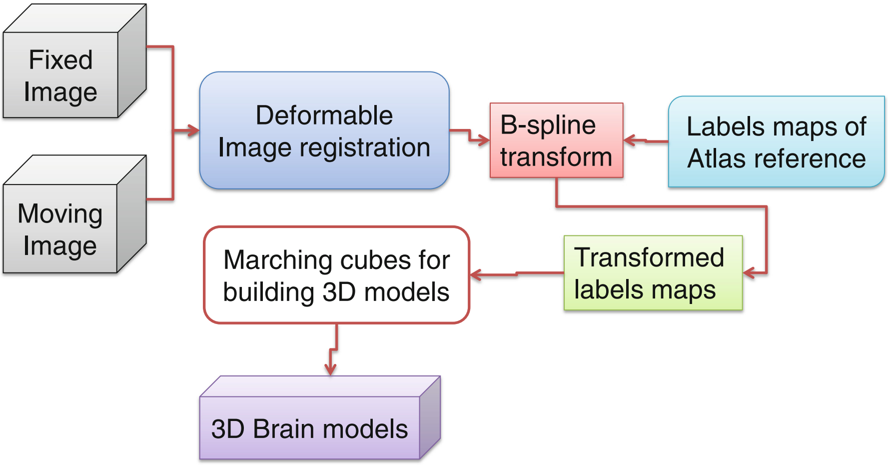

Fig. 2. 3D brain atlas reconstruction scheme

3D Image Visualization Module. This module has an interactive way to analyze medical images by scrolling the MRI and CT slices in three axis (axial, coronal and sagittal). Also, this module has a 3D view for mesh and volume visualization. Some of the tools of this module are zoom, contrast, illumination and slices scrolling.

ISIS MER Communication Module. Within this module, NEURONAV establishes a communication with ISIS MER via the IP port. This module receives the real location of the microelectrode device using IP communication, whereby the neurosurgical device sends the current state of the depth information (microelectrode implant process) at a 25 KHz frequency.

2.4 Toolboxes

To build this system we use powerful open-source toolboxes. First, the Visualization Toolkit (VTK[4]) was used for image processing and visualization. Second, Insight Segmentation and Registration Toolkit (ITK[5]) was used to atlas register and landmark manipulation. ITK is an open-source cross-platform system that provides developers with an extensive suite of software tools for image analysis. Thirdly, the Image-Guided Surgery Toolkit (IGSTK[6]) was used to perform the microelectrode tracking. IGSTK is a high-level, component-based framework which provides a common functionality for image-guided surgery applications. Finally, FLTK[7] toolkit was used to build the graphic user interface. FLTK is a

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[4] http://www.vtk.org/.
[5] http://www.itk.org/.
[6] http://www.igstk.org/.
[7] http://www.fltk.org/.

cross-platform C++ GUI toolkit multi-platform. FLTK provides modern GUI functionality without the bloat and supports 3D graphics via OpenGL and its built-in GLUT emulation.

3 Experimental Results and Discussion

3.1 Deformable Registration Results

Table 1 summarizes the results of the registration quality of the MRI DB-UTP database in terms of sum of the squared differences between intensity values (MS) and normalized correlation coefficient (NC) for the different metrics, optimizers and interpolator configurations. The results clearly show that the registrations which are based on nearest neighbour interpolator improve the correlation between the images before and after the registration process. The results also show that the computational cost is higher when the mean square metric is used. This is due to the search for similarities values on intensity values.

Table 1. Deformable registration accuracy results. **N**: Nearest Neighbor Interpolator, **NC**: Normalized Correlation, **MS**: Mean Squares, **V**: Versor Rigid Optimizer, **R**: Regular Step Gradient Descent

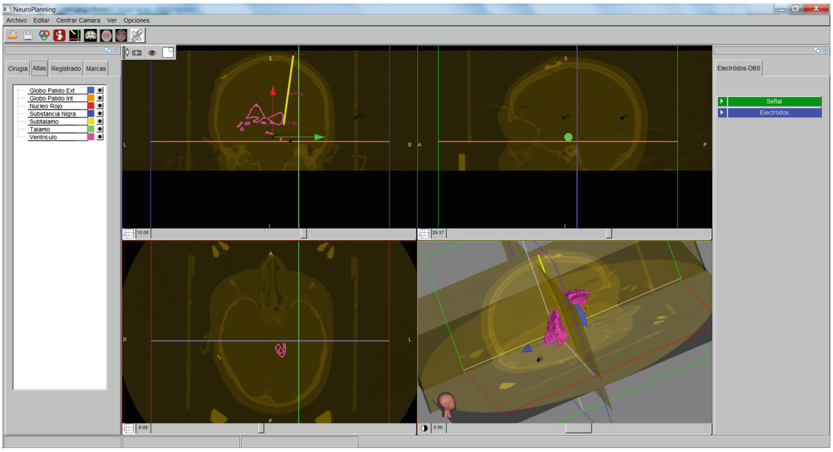
Interpolator	Metric	Optimizer	Time (s)	Error
N	NC	R	218.852 ± 3.2	0.72 ± 0.023
N	NC	V	229.024 ± 4.1	0.83 ± 0.015
N	MS	R	627.68 ± 8.3	279.2 ± 0.21
N	MS	V	663.67 ± 5.4	279.6 ± 0.16

3.2 NEURONAV System

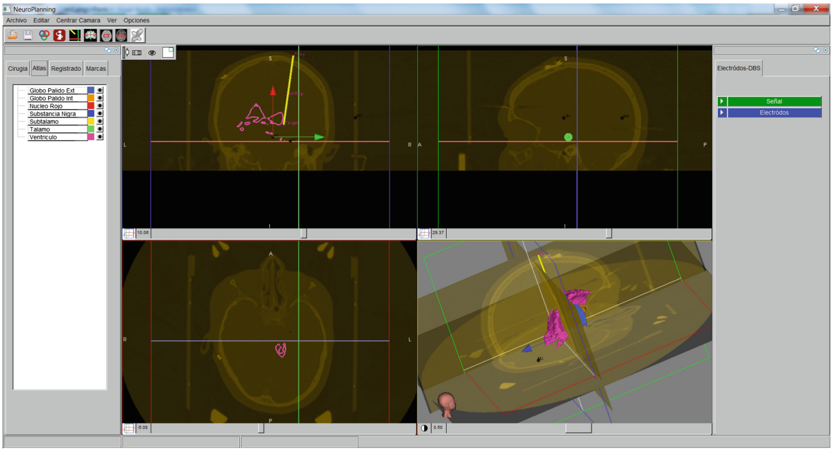
This is an application in which a specialist can perform the planning and execution of a deep brain stimulation surgery. NEURONAV allows an interactive management and analysis of MRI data volumes, compute an atlas registration and perform real-time tracking of microelectrode devices. Figure 3 shows the interface of the application and the 3D transformation module on brain structures. The system includes functions for translation, rotation, scale, opacity, and color visualization.

3.3 Results Obtained in the Operating Room

Currently, NEURONAV has been tested in Deep Brain Stimulation Surgeries performed at the Institute of Epilepsy and Parkinson of the Eje Cafetero, in Pereira-Colombia. The results show a useful and interactive tool for the medical



(a) Transformation module



(b) Registration module

Fig. 3. NEURONAV 3D mesh transformation and registration modules. We implement rigid and nonrigid registration methods that deform accurately a given atlas into a new MRI volume [9].

specialist, which allows to identify the real location of the microelectrode device during DBS surgery. The results show that NEURONAV fulfill the medical protocols for planing an image-guided surgery. Figure 4 shows the operating room interface. The results shows the 3D environment in which the neurosurgeon can control the depth of the microelectrode device to perform the stimulation.

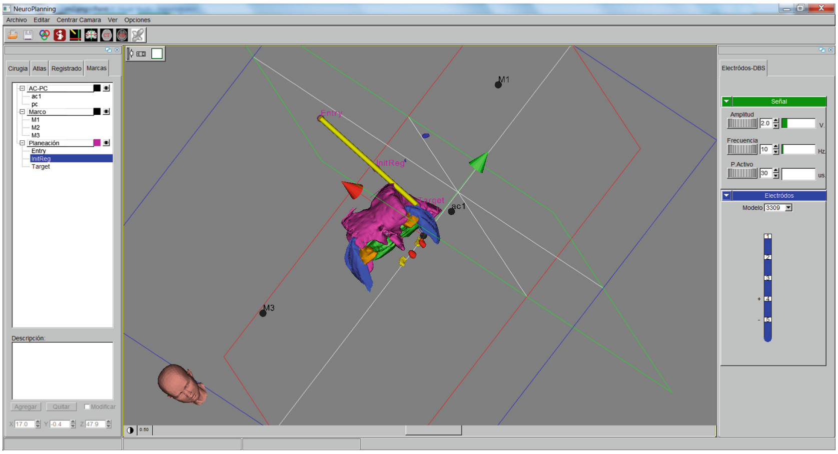


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Fig. 4. Operating room interface and microelectrode information modules.

3.4 Discussion

We give some comments about results:

- NEURONAV is an application developed with open-source platforms for neuronavigation applied to Parkinson's disease surgery. The user can perform planning of deep brain stimulation, where it is defined the boarding path and the target point (Subthalamic Nucleus). Moreover, during surgery the software is linked to the medical equipment ISIS MER for tracking the location of the electrode during the insertion process. For this purpose, we use the IP port and the depth sensor information is transmitted online to NEURONAV. Moreover, the user has the possibility of analyzing MRI data volumes and performing Atlas registration for automatic segmentation of key brain structures in DBS.
- Another attribute that this software has is the transformation and registration models of 3D brain structures. For this purpose we developed functions of translation, rotation, scaling, opacity and color display as well as rigid and nonrigid image registration methods [9]. These tools provide a significant contribution to medical specialists due to the ability of tuning certain 3D structures according to their convenience.
- Figure 4 shows the operating room interface and the microelectrode tracking device. The figure shows the fiducial points related to entry and target marks and manual landmarks. The 3D environment shows an illustrative way to visualize a brain structure while the surgical procedure is accomplished. Right GUI panel, shows the real location of the depth information of the microelectrode. The results show high robustness in the IP communication between the ISIS MER device and NEURONAV tool.

4 Conclusions and Future Work

In this paper, a tool for image-guided surgery called NEURONAV was presented. NEURONAV is a open-source application that allows interactive neurosurgical planning, volume rendering, rigid and nonrigid registration, 3D image viewer, flexible layouts and slice viewers, atlas registration, and real-time tracking of surgical instruments (microelectrode device).

The results show a medical support tool for the DBS surgery in which the neurosurgeons can accurately identify the correct location of the microelectrode device in the thalamus area whereby the success of surgical procedures increases. The developed application has great potential for planning and execution in surgeries resulting from neurosurgical procedures.

Three main tasks are let as future work: Firstly, the proposed scheme can be used to reconstruct 3D brain structures from 2D MRI slices. Secondly, NEURONAV tool pretends to be available for free access to the academic and medical community. Thirdly, NEURONAV should be continued using in DBS surgeries in order to collect some data tests which can improve the performance of the developed application. Furthermore from this tool, we are developing a Volume Tissue Activation module to control the stimulation parameters in Parkinson's treatment.

Acknowledgments. H.F García and H.D. Vargas Cardona are funded by Colciencias under the program: *formación de alto nivel para la ciencia, la tecnología y la innovación - Convocatoria 617 de 2013*. This research has been developed under the project: *Estimación de los parámetros de neuro modulación con terapia de estimulación cerebral profunda en pacientes con enfermedad de Parkinson a partir del volumen de tejido activo planeado*, financed by Colciencias with code 1110-657-40687.

References

1. Benabid, A.: Deep brain stimulation for Parkinson's disease. Curr. Opin. Neurobiol. **13**, 696–706 (2003)
2. Metson, R., Cosenza, J., Cunningham, M.: Physician experience with an optical image guidance system for sinus surgery. Laryngoscope **110**, 972–976 (2000)
3. Eliashar, R., Sichel, J.Y., Gross, M.: Image guided navigation system: a new technology for complex endoscopic endonasal surgery. Postgrad. Med. J. **79**, 686–690 (2003)
4. Vargas Cardona, H., Padilla, J., Arango, R., Carmona, H., Alvarez, M., Guijarro Estelles, E., Orozco, A.: Neurozone: on-line recognition of brain structures in stereotactic surgery - application to parkinson's disease. In: 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 2219–2222 (2012)
5. García, H.F., Álvarez, M.A., Orozco, A.: Bayesian shape models with shape priors for MRI brain segmentation. In: Bebis, G., et al. (eds.) ISVC 2014, Part II. LNCS, vol. 8888, pp. 851–860. Springer, Heidelberg (2014)

6. Miocinovic, S., Noecker, A., Butson, C., McIntyre, C.: Cicerone: stereotactic neurophysiological recording and deep brain stimulation electrode placement software system. In: Sakas, D.E., Simpson, B.A. (eds.) Operative Neuromodulation: Neural Networks Surgery, vol. 97/2, pp. 561–567. Springer, Heidelberg (2007)
7. Wise, S., DelGaudio, J.: Computer-aided surgery of the paranasal sinuses and skull base. Expert Rev. Med. Devices **2**, 395–408 (2005)
8. Cosa, A., Canals, S., Valles-Lluch, A., Moratal, D.: Unsupervised segmentation of brain regions with similar microstructural properties: application to alcoholism. In: 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC 2013), pp. 1053–1056 (2013)
9. Cabezas, M., Olive, A., Llado, X., Freixenet, J., Cuadra, M.: A review of atlas-based segmentation for magnetic resonance brain images. Comput. Methods Programs Biomed. **104**, e158–e177 (2011)
10. Schmelzeisen, R., Nils-Claudius, G., Schramm, A., Schon, R., Otten, J.: Navigation-guided resection of temporomandibular joint ankylosis promotes safety in skull base surgery. Int. J. Oral Maxillofac. Surg. **60**, 1275–1283 (2002)
11. Rueckert, D., Sonoda, L.I., Hayes, C., Hill, D.L.G., Leach, M.O., Hawkes, D.J.: Nonrigid registration using free-form deformations: application to breast MR images. IEEE Trans. Med. Imaging **18**, 712–721 (1999)