Supporting Deep Brain Stimulation Electrode Placement through Multimodal Uncertainty Fusion

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Abstract

Deep Brain Stimulation (DBS) is a surgical intervention that is known to reduce or eliminate the symptoms of common movement disorders, such as Parkinson's disease, dystonia, or tremor. During a DBS intervention, stimulating electrodes are implanted into specific brain regions, whereby correct placement is crucial. As the electrode placement is based on multiple modalities, visualization can help the surgeon to mentally fuse these modalities, take into account their uncertainties and finally place the electrodes. We present a system that combines the currently unconnected information channels, derives uncertainty margins based on these modalities and communicates this information in a way which reduces the cognitive overload involved in mental registration. Thus, the presented system gives the surgical team immediate fused access to preoperative imaging data, Microelectrode Recordings, and patient feedback, which reduces the time in the operating room and increases the precision of the placed electrode. Finally, it will allow the surgeon to perform post-operation analyses to improve heuristics frequently employed during DBS interventions.

1. Introduction

Due to advances in medicine, society is now facing the problems of an aging population suffering from an increasing occurrence of age-related diseases like *movement disorders* such as Parkinson's Disease (PD), dystonia, or tremors that greatly affect the patients' quality of life. As both symptoms affecting motor skills, and the psychological consequences of these diseases have a great impact on everyday life, successful treatment strategies are of increasing importance.

Deep Brain Stimulation (DBS) is a procedure for reducing the symptoms of these diseases [BCMP09], and it is capable of improving the overall quality of life in cases where medication is not a viable option. To conduct a DBS, electrodes are implanted into specific regions of the brain and then emit electrical signals to stimulate these regions. In the case of PD, the most effective target areas for electrode placement are the subthalamic nuclei (STN) with sizes of a few millimeters. As misplaced stimulation electrodes can have severe side effects, including speech difficulties, increased tremor, or long term memory problems, accurate electrode placement is crucial. Nowadays the access path to the target region is planned using a combination of magnetic resonance imaging (MRI) and an atlas-based heuristic to locate the STN. Depending on the location of the electrode, a different region of the brain may be stimulated, which results in measurable responses from the patient. These responses can be cognitive, e. g., memory impairment, or motor-related, e. g., increased tremor or speech impairment. Therefore, to further verify the electrode placement, the patient performs simple tasks during the intervention that are monitored by the surgical staff. To further reduce the uncertainty of the electrode placement intra-operative x-ray scans can be performed to confirm the electrode placement. In recent years, Microelectrode Recording (MER) has emerged as an additional technique allowing the surgeon to better locate the target region for DBS intra-operatively [LDK*88]. MER measures the electrical field of the brain during the surgery by inserting electrodes into the access path. The measured information is presented to the surgical staff by showing the amplitude in the time domain for each electrode, from which the expert can differentiate functional regions of the brain.

In order to allow for an intuitive and accurate placement of the electrodes, it is important that the surgeon has access to all these modalities in a unified manner. Our interactive visualization system supports the surgical team in two ways. First, by integrating the different modalities into a unified system, we enable faster and more reliable access to the necessary information. This increases the accuracy and precision of the placement and reduces the time spent during the operation. The latter is an essential aspect, since the patient is awake during the procedure and under a lot of physical stress, which puts a natural limit on operation time. Second, by storing all the data acquired during the operation and being able to review past operations, it becomes possible to do a visual post-analysis in order to improve the patient-neutral heuristics, which are applied to locate the STN.

In the next section will give a brief overview of the DBS procedure and then present the important views and techniques that were developed to create the system. Section 3 will elaborate on the medical benefits of these techniques, relate them to the current systems, while Section 4 will show the results of an evaluation we have performed with the help of 5 neurosurgeons. We will conclude in Section 5.

2. System Overview

A DBS intervention can be divided into three subsequent phases (see Figure 1): *planning*, in which the intended target region is selected based on pre-operative scans; *recording*, in which the MER signal as well as intra-operative x-ray scans are obtained (see Figure 3) to gain information about the actual position of the target region; and *placement*, in which the emitting electrodes are inserted, patient checks are performed, and the placement is evaluated. Based on our experience in conducting DBS interventions, as well as in the area of medical visualization, we have developed an interactive surgery system, which support these operations. We propose a visualization system that fuses the different modalities: imaging data, MER and patient checks, as well as the associated uncertainties. The system is based on multiple views as described below, and a more detailed description of the various parts can be found in [BLE*12] and [BLE*13].

Contextual View This view, visible in the top left corner of Figure 3, is used in all phases and provides the spatial registration for the surgeon. It shows the pre-operative scans, together with the intra-operative x-ray images and the analyzed MER signal.

MER Visualization This view, shown in Figure 3, provides simultaneous access to the recorded MER signal and the relative position of the measuring electrodes. The measured signal is shown as discs behind each electrode. As the frequency of the spikes is of primary interest, all values below user-defined threshold are removed.

Electrode Closeup In this view, shown in Figure 4, the area immediately around the target region is shown with all gathered information. It combines the inter-operational x-ray scans (blurred grayscale electrode), MER recording (red/green coloring on the back face), and patient checks (colored transparent spheres).

Uncertainty View Each data source provides information about the actual location of the target region, along with an uncertainty. In this view, shown in Figure 5, these probabilities and uncertainties are presented to the surgeon which enables him to access this information at one glance.

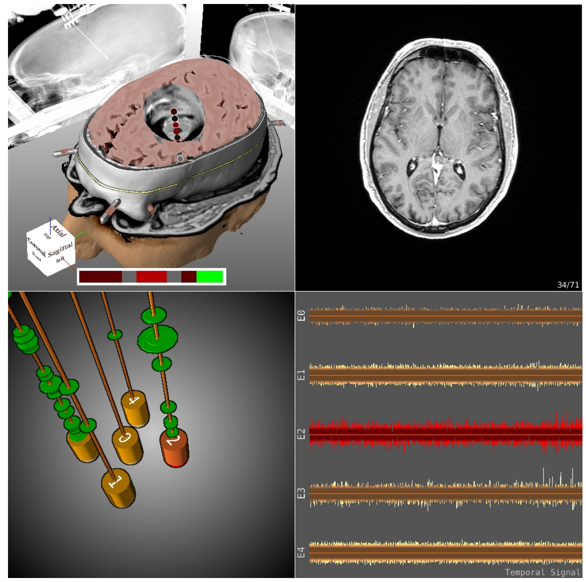

Figure 2: Screenshots of our system during the recording phase. The top two views show the same view as visible during the planning phase and provide spatial context. The lower two views show the MER signal in the spatio-temporal and in the 2D temporal view.

Modality-based derivation and presentation of the potential target region uncertainties is one of the key features of our system. By having a fused uncertainty view, the surgeon can easily assess the optimal target region. Hereby, the *Electrode Closeup* enables the surgeon to qualitatively inspect possible target regions embedded in the spatial context, while the *Uncertainty View* presents the quantitative aspect of the recorded data and enables the data-driven decision making.

3. Medical Benefits

The main goal of the designed system is to support the surgeon during the DBS procedure. We achieve this by reducing the cognitive load through fusing the available modalities and thus facilitating mental registration. The current situation in the operating room is that the methods for inspecting the structural modalities, such as MRI, CT, and biplanar x-ray scans, are fairly advanced and widely used. However, the systems for recording and analyzing the MER signals and patient checks are decoupled from the other modalities. This forces the operating team to perform tasks serially, which prolongs the tiring procedure for the patient. By correlating the temporal data of the recording with the spatial orientation

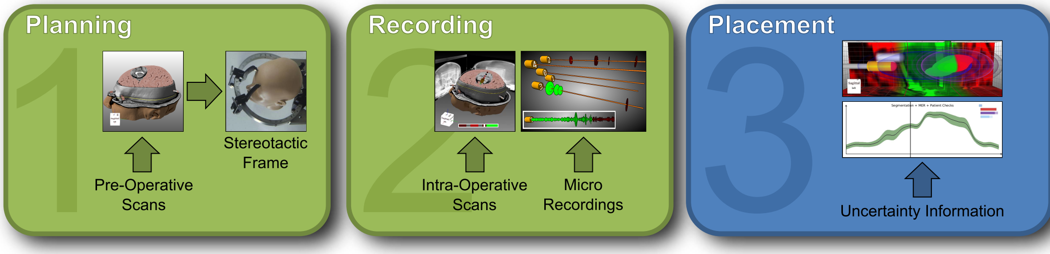

Figure 1: The workflow of the proposed DBS intervention system can be divided into three phases: planning, recording and placement. To support each of these phases, we employ dedicated views that are arranged in a multiple view setup as shows in Figure 3. External components interacting with our visualization system are shown for each phase.

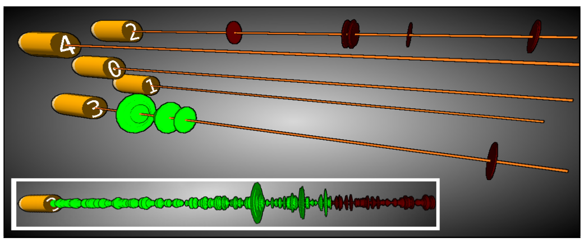

Figure 3: Combining the spatial orientation and layout of the recording electrodes with the temporal signal relieves the surgeon of the burden to keep this association in mind. To enhance the perception of the spikes, only the values above a certain threshold are shown in this view so that they are visible pre-attentively. The inset shows the result for one electrode without thresholding.

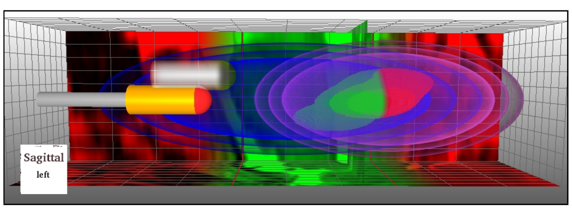

Figure 4: The target closeup visualization shows the potential target regions (speech tests=blue, movement tests=purple). The spatial context provided by the MRI signal is color coded using the red-green MER region mapping. The stimulation electrode changes its color when entering the intersection of the potential target area. This view gives qualitative access to all uncertainty data fused with structural data in one glance. In addition, the x-ray scan based reconstruction of the electrode's position is shown in grayscale.

of the scans (see Figure and Figure 3), the surgeon is relieved of the distracting task of maintaining the position for each trajectory (for example anterior, posterior lateral central or medial) in his head. This reduces the burden of mental registration and can perform the operation faster and with greater confidence; a direct clinical benefit.

The second method through which we support the electrode placement is to derive potential target regions based

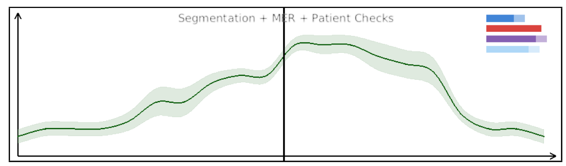

Figure 5: The placement guide gives a quantitative overview of measured data for potential target regions. The top figure is a combination of all data values, where as the lower figures present detailed information by showing either all values or pairwise combinations. These combinations enable the surgeon to gain further insight into the measurements in certain situations, for example, when a measurement proves unreliable during the procedure.

on the acquired modalities, and present these together with their uncertainty boundaries in such a way that the optimal placement location is immediately visible for the surgeon (see Figures 4 and 5). The optimal target region is the intersection between the target regions derived from the image-based planning, the MER recordings, as well as the patient checks. The respective uncertainties are derived by considering the spatial variance of each of these information sources. Nowadays, all this information is available in separate systems and the surgeon has to perform a mental registration before deriving the uncertainty margins mentally. By combining all of the information about the potential, and most likely, target regions, we can support a more efficient and effective intervention by reducing the cognitive load related to these mental tasks.

Another, orthogonal, medical benefit of our system is, that it enables a long-term, horizontal study of the relationship between placement accuracy and the success of the operation. By storing all relevant information about the operation (e. g., pre-operative and intra-operative x-ray scans, the acquired MER signal, and the results of the patient checks), it becomes possible to review the full progress of past operations. This, in turn, will enable medical researchers, to improve the patient-neutral heuristics for finding the STN in the many cases where it is not visible on the pre-operative scans. This will hopefully lead to a direct overall increase in the operation's success rates.

4. System Evaluation

We have based the development of the proposed system with respect to the experience gathered by conducting DBS interventions for several years. As a key problem, we have addressed the fusion of different information sources, which is always a problematic issue during operations. In addition, post-analysis of operations is of great clinical interest as it would lead to methods to quantify the error introduced by the heuristics, and ultimately allows us to improve electrode placement accuracy.

To evaluate the practicability of the proposed system we have conducted a user-study with five neurosurgeons, all of whom have extensive experience in the field and perform DBS interventions on a regular basis. As medical certification procedures make it difficult to apply the system in the operating room, the neurosurgeons were presented with a showcase demonstration of the system going through all three phases (planning, recording, and placement). Based on the demonstration the neurosurgeons had to answer a questionnaire consisting of eight statements and questions, as well as a text field for arbitrary comments. Each of these statements and questions had a positive and a negative reply with no opportunity to abstain. The following table shows all statements and questions together with the number of positive answers:

The user is not disturbed by images, colors, or animation while interacting with the system	4
The result of any action done by the user is clearly and immediately visualized	4
The tools provided by the system are easy to use	3
System data is understandable and clearly visualized	4
The actions' succession proposed by the system is logical from the user's point of view	5
The system's features are compatible with all the user's expectations	4
Would you like to use this system during an intervention in addition to the old system?	5
Is the fusion of MER signals with image data useful for increasing the accuracy?	3

Overall, the feedback from the neurosurgeons was very positive. The least satisfied expert agreed with only five statements whereas the most satisfied expert agreed to all. On average the experts agreed to 6.5 of 8 statements if we assume an equal weighting of the statements. The relatively bad score of only three positive answers to the last question seems to be the strongest drawback to the method, but considering that all of the experts would like to use our system in the operation room makes it a good result. In the comments, one expert emphasized especially the ”correlations between target region and the neurophysiological data” as an important aspect of the system. Only two neurosurgeons did not see the benefits of incorporating the fused views, while they still liked the overlapping view of the different probable target regions.

While we cannot perform a full evaluation in the operating room at this point, since we would need an approval according to the EC directive or the FDA, the feedback of the five neurosurgeons suggest that it might be worth to go ahead, and prepare for a real study in the operating room.

5. Conclusions

We have presented and evaluated a visualization system that has been designed to support neurosurgeons during DBS interventions by fusing measurement data, along with their uncertainties, with structural modalities to facilitate mental registration. This multimodal information is presented to the surgeon during the intervention both in the context of the rendered imaging data, as well as a separate view showing the combination of these measurements. As the MER and patient checks are performed during DBS interventions to improve the localization of the stimulation electrode, we feed back the results of these checks into our system. When displaying and intersecting the potential target regions we take into account the different degrees of uncertainty that result from their acquisition process. This uncertainty-aware information fusion in image space, as well as in a profile plot, enables the surgeon to better assess the electrode placement and detect the optimal electrode placement. To estimate the clinical impact of the presented system we performed an evaluation with five neurosurgeons who regularly perform DBS interventions. The results indicate that the presented visualization approaches have strong medical benefits, as they are of great interest and seem to have the potential to improve DBS interventions.

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