AUGMENTED INLINE-BASED NAVIGATION FOR STEREOTACTIC IMAGE GUIDED NEUROSURGERY

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ABSTRACT

Image-guided neurosurgery requires navigation in 3D using a computer-assisted surgery system that tracks surgical tools in realtime and displays their positions with respect to the preoperatively acquired images (e.g. CT, MRI, fMRI etc.) A key problem in image guided procedures is the need to navigate to specific locations highlighted in the images, such as image-derived functional areas, that have no obvious corresponding anatomical landmarks – we refer to such locations as virtual landmarks. To address these issues, we contribute a novel interactive visualization technique to provide improved feedback to surgeons - *Augmented inline visualization*. Based on the results of an expert evaluation, we found neurosurgeons to be 30% more accurate when using our augmented inline representation.

Index Terms— Image-guided surgery, Visualization, Neurosurgery, Image Guided Navigation

1. INTRODUCTION

Image-guided surgery systems (IGS) have revolutionized surgical practice, especially in neurosurgery. Such systems, now commercially available, bring preoperatively acquired images (CT, MRI, fMRI) into the operating room that are registered to the patient and provide "GPS"-like functionality for the surgeons by identifying the location of their instruments with respect to the preoperatively acquired images. A good review of IGS can be found in DiMaio et al. [1].

Epilepsy surgery is a particularly challenging form of neurosurgery. This often involves a set of two surgeries, where in the first surgery intracranial electrodes are implanted to identify seizures. The electrical activity of the brain is then generally recorded for 7-10 days using these electrodes. From this data, it may be possible to identify the regions of the brains that are the source of seizures which are subsequently removed in a second procedure. However, this second surgery is often performed weeks later at which point the actual electrodes are no longer present. During the second surgery, the surgeons need to navigate back to the original positions of the electrodes. In order to do this effectively, the surgeons must navigate using the IGS, which guides them to the original positions using the "virtual" electrode locations displayed on the screen.

In this paper, we present work that uses multiple 3D views in which the camera locations are automatically set based on the current position and location of the surgical pointer (a tool the surgeons use to navigate with) to improve the navigation accuracy. Our approach builds on a commonly used method called *inline* visualization where the camera position is controlled by the surgical instrument. Our *Augmented inline* visualization augments the standard inline view with two other views obtained by rotating the camera about the axis formed by the surgical instrument. We augmented the inline view with inline+45° and inline-45° views as shown in Figure 1D.

We evaluated the effectiveness of our approach by assessing surgeon performance in a simulated navigation task. Figure 1 shows the four visualizations that were evaluated in the user study. We found that subjects were significantly (30% fewer errors, $p<0.001$) more accurate using our augmented inline visualization as compared to the currently used single 3D visualization.

2. APPROACH

We used a BrainLAB VectorVision Cranial (VVCranial) System [2] for stereotactic navigation. An attached infrared stereo camera based system (NDI Polaris) tracks the spheres attached to the surgical instruments. The position of the instrument is then interactively displayed on the screen in front of the surgeons for integrating research software with commercial IGS. In addition to the clinical system, we have previously developed a research workstation that can interface with the VVCranial software allowing for unobtrusive experimentation with novel visualization techniques [3].

2.1. Visualization Methods

Single 3D Visualization: The user sees a single 3D visualization of the anatomical data and some virtual landmark locations as shown in Figure 1(A). Surgeons use a combination of 2D views and a single 3D representations during surgery.

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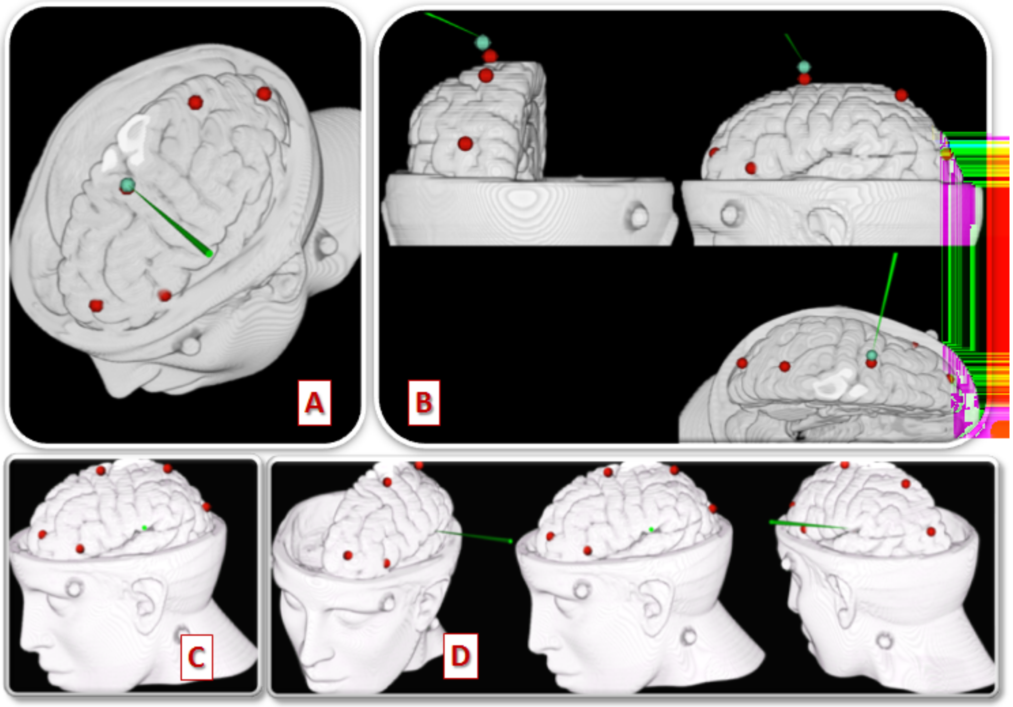

Fig. 1. Virtual landmarks are shown as red spheres and the surgical instrument is represented as a green cone. (A) shows a single three-dimensional view, (B) shows a multiple view system consisting of 3D axial, coronal and sagittal views of the same virtual locations, (C) shows a typical inline view, where the camera is always perpendicular to the data. Figure (D) shows our augmented inline setup, in which we augment the inline view with two other camera views (inline+45° and inline-45°).

These virtual landmarks are particularly hard to find in 2D views since they are visible as circular cross-sections in two or three slices. Therefore, we decided to pick only the 3D visualization. The major constraint in this case is that an expert with the visualization software is required in the operating room to interact with the data.

Multi-viewport based Visualization: This visualization was inspired by multi-viewport based setups that can be found in CAD and modeling software. Figure 1(B) shows the multi-viewport based setup where we provide 3D axial, coronal and sagittal views. They provide more visual feedback but navigating to regions of the brain using the three views can be difficult and requires significant practice.

Inline Visualization: Inline visualization (also known as *probe's eye view*) is a visualization that allows surgeons to control the position of the camera interactively. The camera position and orientation is now controlled by the position and orientation of the surgical instrument. This causes the virtual representation of the surgical instrument (shown as a cone) to become a green circle, as can be seen in Fig 1(C). While one can establish the horizontal accuracy of the probe's location, it is hard to ascertain the vertical distance from the landmark.

Augmented Inline Visualization - Our Method: We found that neurosurgeons liked the inline view but had trouble establishing how far the probe was from the surface of the virtual landmark. To improve on this, we developed augmented inline visualization, where we augment the inline visualization with two other visualizations of the data. These views are obtained by rotating the camera about the vector defined by the surgical instrument (the 3D location of the instrument tip and midpoint of the surgical instrument are known). The two views are obtained by rotating the camera 45° in either direction around the view up vector. Figure 1(D) shows the three views (inline+45°, inline, inline-45°). This visualization provides visual feedback regarding the distance of the instrument tip from the landmark and helps surgeons navigate to those landmarks on their own (without the need of a technician rotating the anatomical data).

3. EXPERT EVALUATION

The aim of our user study was to evaluate the efficacy of the augmented inline visualization in comparison with the currently used visualizations. For the single viewport-based visualization (Figure 1A), we picked a view commonly used for surgeries involving the temporal-parietal areas. For the multi viewport-based visualization, we showed three dimensional representations of the axial, coronal and sagittal views of the data that are coordinated. For the inline visualization, a full screen visualization of the data was shown to the subject. For our augmented inline visualization, three synchronized visualizations (as shown in Figure 1(D)) were shown to the subject.

To model navigating to specific locations (identified by

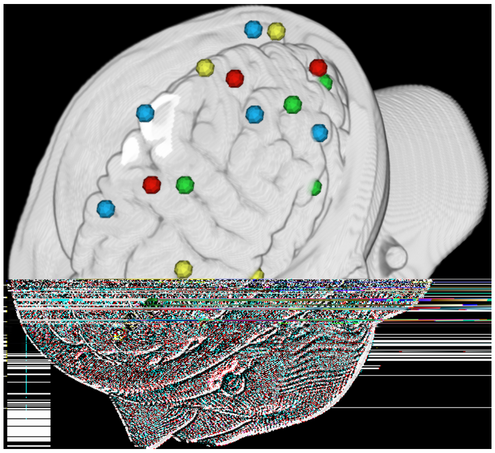

Fig. 2. This figure shows all the landmark datasets overlaid on the template CT. Dataset A is shown is red, dataset B is shown in yellow, dataset C is shown in green, and dataset D is shown is blue.

image-derived functional areas or electrode locations), we designed our task to test the effect of the visualization on the navigation capabilities of the surgeons. The task was to navigate to specific virtual landmarks on the surface of the brain in front to back order and specify their confidence for each landmark. Once the surgeon specified their confidence, the 3D location of the instrument tip was acquired and recorded. The subjects were timed per set of landmarks and their accuracy was calculated. Surgeons used the same tools/setup (i.e. the BrainLAB VVCranial system navigational pointer and cameras) that they use regularly.

Our testable *hypothesis* is that augmented inline visualization is more effective at providing visual cues for stereotactic navigation as compared to the currently used single 3D visualization. Here we define "effectiveness" as improved accuracy (fewer errors) and improved confidence as opposed to completing the task faster. Even though a majority of the focus during surgery is on accuracy, time required to localize is also a consideration and we report that as well. The *independent variable* in our case is the visualization system that is shown to the subjects. We randomized the ordering of the visualizations to compensate for any ordering effects. We evaluated our visualizations with *six neurosurgeons and neurosurgery residents* who were familiar with using the BrainLAB IGS [2] and our research system.

We used four different virtual landmark datasets (A,B,C,D), each of which had five virtual landmarks which were located on the surface of the brain. Figure 2 shows all the landmarks on the model CT image. We used a rubber head phantom, the anatomical CT data for which was used in the 3D volume rendering for Figure 2.

To test learning effects, subjects were asked to navigate to landmark dataset A a total of three times (A1, A2, A3). Next we asked the subject to navigate to datasets B, C, and D once each. The results from these three datasets along with the results of the third navigation on dataset A (A3) were used to make accuracy comparisons between the groups. For the single 3D view based visualization, subjects were asked to pick two views of their choice and navigate again on dataset A (A4 and A5). These final two trials were used to ensure no bias existed in the our default view used for the single viewport based 3D visualization. This simulates the operating room paradigm where surgeons request the IGS expert to change views to get a better understanding of the landmark locations. After the study was completed, qualitative feedback was obtained in the form of a questionnaire.

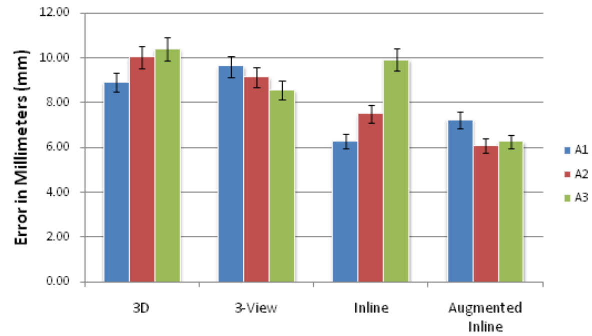

Fig. 3. Learning Effect Accuracy - Graph shows an improvement in accuracy when using the multi-viewport vs single 3D. Subjects get worse with inline visualization whereas when using augmented inline visualization their accuracy is consistently high. Error bars = 95% confidence intervals.

4. RESULTS

4.1. Analyzing the Learning Effect

Figure 3 shows the error per dataset for each visualization. The accuracy seems to decrease in the case of single 3D visualization over time, whereas the accuracy improves in the case of multi-viewport based visualization. In the case of Inline visualization, the accuracy decreases over time whereas in the case of Augmented Inline visualization, the accuracy is high (errors are low) almost consistently throughout the three iterations.

4.2. Performance Analysis

To compare the four visualizations, trials A3, B, C, and D were used. Overall, the subjects were *most accurate when using the augmented inline visualization* but slightly less confident than just inline visualization. Figure 4 shows a plot of the mean error for each technique with the error bars showing the variability in error. Subjects performed best when using the augmented inline visualization and the worst when using the inline visualization. Table 1 shows the results. The improvement in accuracy when using Augmented inline proved to be statistically significant at a 99% confidence level (p=0.00068) when analyzed using the ANOVA test. Overall we saw 30%

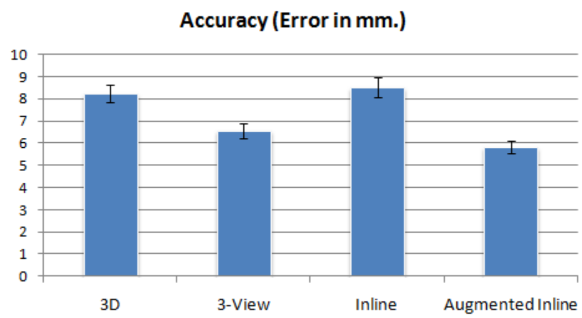

Fig. 4. This graph shows the average accuracy per visualization. Augmented inline showed the best accuracy (least error) while the inline view had the worst accuracy (most error). The result of performing the analysis of variance (ANOVA) on the accuracy data resulted in a p-value of 0.012 with $F(3, 796) = 3.659$. Error bars indicate 95% confidence intervals.

	3D	3-view	Inline	**Aug. Inline**
Acc. (Error in mm.)	8.23	6.57	8.515	5.832
Time (in secs)	102	147	85	96
Confidence	3.6	3.335	4.45	4.25

Table 1. The table shows the results of the expert evaluation. Based on the higher emphasis on accuracy, Augmented Inline has the least error (highest accuracy), takes the second least time and second highest confidence as compared to the other techniques.

improvement in accuracy when the surgeons used our augmented inline display over single 3D view.

Surgeons were most confident when using inline visualization (mean=4.45), followed by our augmented inline (mean=4.25). However, the confidence results were not significant. Subjects were probably less confident of their ability to accurately navigate to the landmarks using our augmented inline visualization due to the fact that this is a new visualization technique as compared to the somewhat familiar inline visualization (available in widely used IGS [2]). Even though they required slightly more time (Table 1, their increase in accuracy and confidence is more important. Based on discussions with neurosurgeons, we found that for a surgery that takes around 12 hours, a slight increase in time required was acceptable for a significant improvement in accuracy.

4.3. Analyzing user-defined views

When evaluating the single 3D visualization, subjects were asked to rotate the camera and pick two additional viewpoints of their choice (A4, A5) to use to navigate to the landmarks. In both A4 and A5, subjects were less accurate than A3. The mean accuracy for A3 was 10.39 mm, the mean accuracy for A4 was 14.34 mm, and the mean accuracy for A5 was 10.71 mm. Despite the decrease in accuracy (increase in error) in both A4 and A5, subjects were more confident in their choices with the mean confidence increasing from 4.15 for A3 to 4.375 for both A4 and A5. Subjects were also faster, by an average of 15 seconds (for A4) and 17 seconds (for A5) respectively.

5. DISCUSSION

Based on analyzing the subjects' answers to the questionnaire, subjects thought that it was extremely easy when using inline and very easy when using augmented inline. As regards the confidence per technique, subjects were most confident when using the 3D visualization and inline visualization, even though they were less accurate.

We found that our augmented inline visualization was the most "effective" in terms of accuracy and confidence. The improvement in accuracy is probably due to the fact that the depth cues missing from the inline view are provided by the +45° and -45° views. When evaluating the single viewport system, subjects were given the option of picking their own views. On analyzing the performance of subjects, we found that accuracy of the subjects was lower for the views they picked even though they were more confident of their answers. Surgeons have expressed considerable interest in using such a setup for training and accuracy evaluation purposes. Generally, surgeons use such a setup only during surgery and were of the opinion that tests of this nature might be helpful to them in terms of assessing how accurate they would be in localizing/avoiding critical structures.

6. CONCLUSION

In this paper, we have presented and evaluated our novel visualization to improve the accuracy of navigating to virtual landmark locations during stereotactic neurosurgery. Using augmented inline-based visualization during stereotactic navigation can increase the accuracy of navigating to critical regions for surgery with increased confidence. We feel that the augmented inline visualization can be widely used in stereotactic neurosurgery in both a clinical and training setting.

7. REFERENCES

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