Skull Base Surgery Navigation System Based on Updating Preoperative Images Using Positional Information of Surgical Tools

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Abstract

In this paper, we introduce a new concept of surgical navigation which processes information interactively between the real and virtual spaces, namely, updating preoperative images using the positional information of surgical tools. Although the organs are deformed by operative procedures during surgery, surgical navigation systems usually do not change the reference images that are taken prior to surgery. It is useful to generate deformed reference images during surgery while it progresses. We develop a skull base surgery navigation system that updates the preoperative images during surgery. To estimate the resected regions, our proposed system utilizes the positional information of the surgical tools that can be tracked by a surgical navigation system. Our proposed system reflects the bone removal on preoperative images by changing the voxel values of the preoperative images using the positional information of the tracked tools. The updated reference images are generated by visualizing the updated preoperative images using a volume rendering method. We evaluated the proposed system on a skull phantom created from CT images by a 3D printer. The experimental results showed that the proposed system updated the reference images in real time based on the surgical tasks including bone removal process. The accuracy of our proposed method was about 1 mm. It is very useful for surgeons to drill into such complex bone structure as the skull base.

Contents

1 Introduction

Based on a surgical navigation system, image-guided surgery has been widely performed in neurosurgery. A surgical navigation system dynamically presents the positions of the surgical tools on reference images (or preoperative images), which are usually generated from CT or MRI images taken before the surgery [1, 2, 3, 4]. Although the organs are deformed by the operative procedures during the surgery, the reference images in the surgical navigation system cannot represent the organ deformation caused by the operative procedures during surgery. Therefore, the reliability of the reference images in the navigation system decreases as the surgical procedure progresses. To solve this problem, several institutes have introduced intraoperative imaging scanners, such as MRI or CT, to operating rooms [5, 6]. Intraoperative imaging scanners enable surgeons to acquire intraoperative images during surgery. The reference images in the surgical navigation system are updated by replacing the preoperative images with the newly acquired intraoperative images. Since the intraoperative images reflect the organ deformation caused in the surgery, these images improve the reliability of the surgical navigation. However, if the surgery continues after taking the intraoperative images, the organs are deformed again and the reliability of the reference images used for the navigation is again decreased. Therefore, it is useful to update the reference images synchronized with the tissue changes caused in the operative procedure during surgery. Here, we introduce a new navigation system which processes information interactively between the real space and the virtual space. It captures the positional information in the real space. Then preoperative images are updated based on the accumulated positional information to obtain the updated images. The system provides surgeons 3D virtual images closer to the real surgical field. This helps surgeons to understand 3D surgical anatomy in real-time.

In many operative procedures, a surgeon utilizes several surgical tools, such as scalpels. Since organs are deformed by these tools, their positions are very useful information to estimate the deformed regions in the organs. Therefore, the reference images are updated using the tracking information of the surgical tools to reflect the organ deformation to the surgical navigation. In this paper, we focus on bone resection procedures in skull base surgery and present a method for updating the reference images using the tracking information of surgical tools. Also this paper shows a navigation system that updates the reference images in synchronization with a bone resection procedure using a drill. A drilling procedure is very common in neurosurgery.

Several research groups have also studied the generation of appropriate surgical assistance information using the positional information of surgical tools [2, 3, 7]. Hong et al. proposed a method for estimating tumor remnants using an electrocautery trace log [2]. Nakamura et al. proposed surgical workflow analysis using the information acquired from a surgical navigation system [7]. In [3], virtual intraoperative CT images have been generated using the positional information of surgical tools. Our proposed navigation system

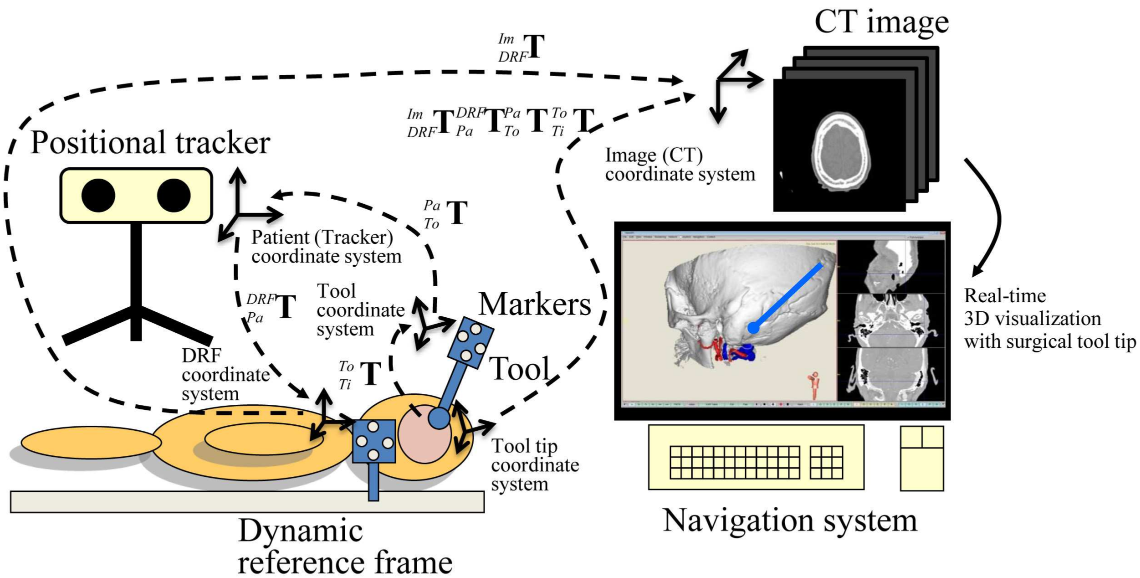


Figure 1: System configuration of proposed system and relationships among coordinate systems.

also uses the positional information of surgical tools to update the preoperative images. One characteristic of our proposed system is that it displays 3D volume rendered images of updated images in real time. 3D visualization of updated images allows surgeons to intuitively understand the removed and unremoved regions. We describe the details of our proposed system and show experimental results with discussion in the following sections.

2 Update navigation system

2.1 Overview

The configuration of our proposed system is shown in Fig. 1. It consists of a 3D positional tracker and a computer, as in conventional surgical navigation systems. Our proposed navigation system updates the reference images in synchronization with bone resection procedures during surgery. Since skull base surgery usually utilizes a surgical drill to resect the bone, we determine the resected bone areas by continuously tracking the drill tip. The proposed method updates the preoperative reference images using the drill's positional information, which is acquired from a 3D positional tracker. We attach the markers of the positional tracker on the drill to obtain the positional information. Patient-to-image registration is performed before the surgery to align the coordinate systems between the physical and image space. Using the registration result, we can acquire the position of the drill tip in the image coordinate system. The proposed method updates the reference images using the positional information of the drill as follows.

2.2 Update of reference images

The reference images are updated in synchronization with the resection of the bone using the positional information of the drill. We assume that the drill resects the bone as a set of spherical regions. The center

(a) (b) (c)

Figure 2: Skull phantom: (a) 3D visualization of an original CT image. Black lines show area of created phantom. (b) Skull phantom is created by 3D printer. (c) Sinus is located behind the skull phantom.

of each spherical region is the position of the drill tip obtained from the positional tracker. The radius of the spherical region is determined based on the size of the drill tip.

We represent the position of the drill tip in the tool tip coordinate system and in the image coordinate system as $\boldsymbol{p}_{Ti}$ and $\boldsymbol{p}_{Im}$. The drill tip position in image coordinate system $\boldsymbol{p}_{Im}$ is computed from $\boldsymbol{p}_{Ti}$ using the relationships among the coordinates (Fig. 1):

$$\boldsymbol{p}_{Im} = {}^{Im}_{DRF}\mathbf{T}\,{}^{DRF}_{Pa}\mathbf{T}\,{}^{Pa}_{To}\mathbf{T}\,{}^{To}_{Ti}\mathbf{T}\boldsymbol{p}_{Ti}, \tag{1}$$

where ${}^{Im}_{DRF}\mathbf{T}$, ${}^{DRF}_{Pa}\mathbf{T}$, ${}^{Pa}_{To}\mathbf{T}$, and ${}^{To}_{Ti}\mathbf{T}$ are a transformation matrix from the DRF (Dynamic Reference Frame) coordinate system to the image coordinate system, from the patient coordinate system to the DRF coordinate system, from the tool coordinate system to the patient coordinate system, and from the tool tip coordinate system to the tool coordinate system, respectively. ${}^{To}_{Ti}\mathbf{T}$ is calculated using a pivot calibration method. We can obtain the position of the drill tip in the DRF coordinate system using a 3D positional tracker. Eq. 1 is rewritten by 3D positional sensor output $\boldsymbol{p}_{DRF}$:

$$\boldsymbol{p}_{Im} = {}^{Im}_{DRF}\mathbf{T}\boldsymbol{p}_{DRF}. \tag{2}$$

To obtain $\boldsymbol{p}_{Im}$, we must calculate transformation matrix ${}^{Im}_{DRF}\mathbf{T}$, which we compute using a conventional point pair matching method [8].

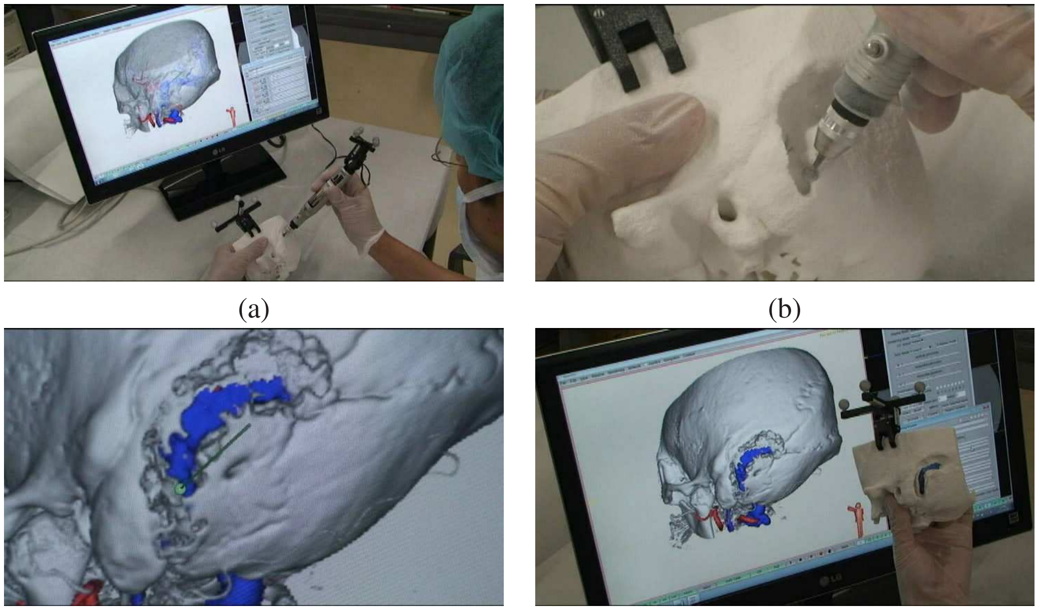
Next we write the position of the drill tip acquired from the positional tracker at time t as $\boldsymbol{p}^{(t)}_{DRF}$ and the predefined radius of the drill tip as r. The position of the drill tip in image coordinate system $\boldsymbol{p}^{(t)}_{Im}$ is obtained by Eq. 2. Resected regions $R^{(t)}$ at time t are defined as a set of voxel $\boldsymbol{v}^{(t)}$ that satisfies

$$|\boldsymbol{p}^{(t)}_{Im} - \boldsymbol{v}^{(t)}|^2 \leq r^2. \tag{3}$$

Our proposed method dynamically updates the preoperative image by changing the voxel value in resected region $R^{(t)}$ into a value corresponding to the air region. Our proposed system displays not only the updated 2D slice images but also the updated 3D virtual images as reference images. The updated 3D virtual reference images are generated by visualizing the updated preoperative images using the fast volume rendering method [9]. The above resection process is performed at regular intervals. After the drilling procedure, the resected regions in image R are set $R = R^{(0)} \cup, \ldots, \cup R^{(n)}$, where n is the number of the process.

3 Experiments

We evaluated our proposed system by utilizing phantoms created from CT images using two 3D printers, zPrinter 310 Plus (3D Systems Corporation, Rock Hill, SC, USA) and uPrint (Stratasys Inc, Eden Prairie,



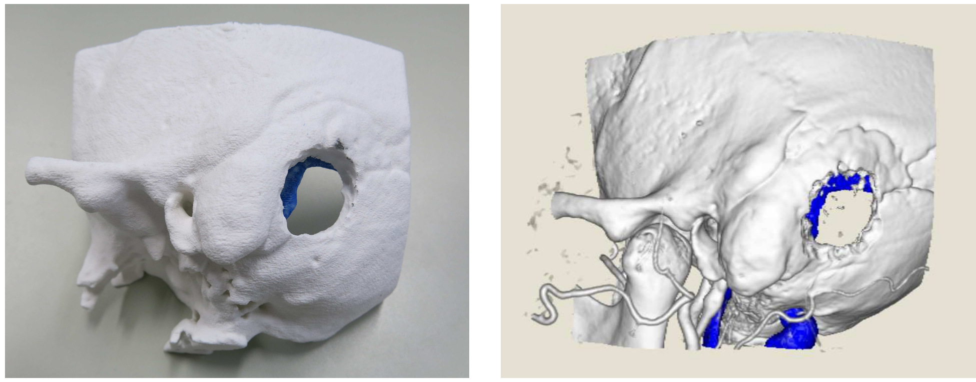
(a) (b) (c) (d)

Figure 3: Phantom experiment: (a) Experiment scene. Skull phantom is drilled using proposed navigation system. (b) Scene of drilling phantom. (c) Magnified view of navigation monitor. (d) Skull phantom and navigation image after experiment.

MN, USA). The size of the CT image was 512 × 512 × 521 voxels, and the voxel size of the CT image was $0.429 \times 0.429 \times 0.5\ mm^3$. Fig. 2 shows the created skull phantom. Fig. 2 (a) shows the area of the phantom created by a 3D printer. This phantom consists of part of the skull (created by zPrinter) and part of the sinus (created by uPrint). The skull part is made from calcium sulfate using zPrinter for easy drilling. The sinus is located behind the skull (Figs. 2 (b) and (c)).

In our experiment, a neurosurgeon resected the bone area and exposed the sinus using a drill (Fig. 3). We used a Polaris Vicra optical tracker (NDI, Waterloo, Ontario) to obtain the positional information of the drill. The positional and dynamic reference markers are attached to the drill and the skull phantom, respectively (Fig. 3 (a)). A surgeon resected the bone of the phantom while watching the navigation monitor (Figs. 3 (b) and (c)). In Fig. 3 (c), the blue region and a green probe show the sinus and the drill, respectively. The proposed system updated the preoperative images synchronized with drilling the skull of the phantom in real time. The processing time of the update of the reference images, including the 3D visualization, was about 0.2 seconds with a conventional laptop PC (Dell Precision M4600, CPU: Core i7-2860QM 2.5 GHz). The updated reference images at the end of the experiment resembled the drilled phantom (Fig. 3 (d)).

We also evaluated the accuracy of our proposed method. The same phantom described above was used in this experiment. We resected a circular region under the sinus using the drill and the proposed navigation system and compared the resected regions between the skull phantom and the updated 3D images after the operation. Fig. 4 shows the phantoms and the updated images. In visual assessment, the updated 3D image closely resembled the drilled phantom. The diameters of the resected circle regions were measured on both the phantom and the 3D image. In the phantom, we measured the diameter using a ruler. We measured the diameter to specify two points on the updated 3D image by a mouse. The diameters were measured in three different parts. The average difference of their distances was about 1 mm.



(a) (b)

Figure 4: Comparison between drilled skull phantom and updated 3D image after experiment: (a) Drilled skull phantom and (b) Updated 3D image.

4 Discussion

Our proposed system can handle information of both the real and the virtual spaces. It updates not only 2D slice images but also the 3D virtual images in real time based on the positional information of the drill. The updated 3D images were very similar to the shape of the drilled phantom (Figs. 3 and 4). The main advantage of our proposed system is that it can update the preoperative images and generate updated 3D virtual images in real time. In our experiment, the processing time of the generation of the updated 3D images was about 0.2 seconds using a conventional PC. This processing speed is adequate because surgeons move the surgical drill slowly during bone drilling procedures. They can intuitively understand the resected and unresected regions by observing the updated 3D images during surgery with such interactions as rotation or zooming up of the 3D rendered views. This helps them perform the surgery as planned. The proposed system is very useful when surgeons perform difficult operations that are required to resect complex bone structures in skull base surgery. It also provides useful information when they resect the complex regions surrounding vessels and nerves.

Our proposed interactive navigation system only reflects the tissue changes caused by the bone resection to the preoperative images. However, since many operative procedures cause soft tissue deformation during surgery, we must update the reference images by considering soft tissue deformation in surgical navigation systems. In the future, we will develop an advanced version of the interactive navigation system in synchronization with various kinds of soft tissue deformation by introducing a volume deformation method such as [10].

5 Conclusion

This paper proposed a method for updating preoperative images during surgery based on the positional information of surgical tools. We developed a skull base surgery navigation system based on dynamic updates of reference images. We applied our proposed navigation system to skull phantoms. Experimental results showed that it generated the updated 3D reference images in 0.2 seconds. Our proposed system is very useful for assisting complex bone resection in skull base surgery. Future work will introduce a volume deformation method for soft tissue deformation and applications of various kinds of surgical procedures.

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