

Skull registration for prone patient position using tracked ultrasound

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ABSTRACT

PURPOSE: Tracked navigation has become prevalent in neurosurgery. Problems with registration of a patient and a pre-operative image arise when the patient is in a prone position. Surfaces accessible to optical tracking on the back of the head are unreliable for registration. We investigated the accuracy of surface-based registration using points accessible through tracked ultrasound. Using ultrasound allows access to bone surfaces that are not available through optical tracking. Tracked ultrasound could eliminate the need to work (i) under the table for registration and (ii) adjust the tracker between surgery and registration. In addition, tracked ultrasound could provide a non-invasive method in comparison to an alternative method of registration involving screw implantation.

METHODS: A phantom study was performed to test the feasibility of tracked ultrasound for registration. An initial registration was performed to partially align the pre-operative computer tomography data and skull phantom. The initial registration was performed by an anatomical landmark registration. Surface points accessible by tracked ultrasound were collected and used to perform an Iterative Closest Point Algorithm.

RESULTS: When the surface registration was compared to a ground truth landmark registration, the average TRE was found to be 1.6 ± 0.1 mm and the average distance of points off the skull surface was 0.6 ± 0.1 mm.

CONCLUSION: The use of tracked ultrasound is feasible for registration of patients in prone position and eliminates the need to perform registration under the table. The translational component of error found was minimal. Therefore, the amount of TRE in registration is due to a rotational component of error.

1. INTRODUCTION

Tracked navigation is becoming prevalent in neurosurgery, guiding surgeons towards targets that are challenging to locate and visualize. It provides real-time tracking of surgical tools which are visualized in relation to patient anatomy and medical images. This process allows for image guided surgery (IGS) and is made possible through the process of registration. Registration is the transformation of data and images to the same coordinate system, allowing for the visual integration of different data sets. In IGS, registration is the integration of surgical tool movement, patient anatomy and a pre-operative scan. IGS gives surgeons the ability to know real time patient anatomy and tool position, providing them with the capability to pre-plan and perform, quick, safe and efficient, minimally invasive procedures.

In ISG the two most commonly used registration methods are landmark-based and surface-based. Landmark-based registration will use a rigid transformation to match fiducial points on the patient to where they are located in the image, through the use of a tracked pointer (Mirota 2013). Surface-based registration analyzes the contours of a surface through the collection of point clouds, which can be performed through the use of tracked ultrasound (Maurer 1999).

For IGS to be possible, registration requires that surgical tools and the patient be tracked in real time. There are two predominant methods of tracking; i) optical tracking and ii) electromagnetic tracking. Optical tracking is the predominant form of tracking and relies on having a constant line of sight between the camera and optical references placed on the patient and surgical tools. It is both an accurate and reliable form of tracking in surgical procedures. However, the constant line of sight requirement can be limiting (Kral 2013). Through the use of reflecting spheres or light emitting diodes, infrared tracking cameras are able to determine the spatial location of the patient and surgical tools. The spheres or diodes are placed on markers, of which are securely fastened to the patient and tools. For tracking to operate, a line of sight is mandatory, and the markers on the tools must be placed in locations and orientations that are assumed to be rigid and

within the camera's accepting range (Kral 2011). In multiple studies, of which analyzed the accuracy of tracking systems, optical tracking outperformed EM tracking, as EM tracking is vulnerable to distortions by metal objects within the workspace (Kral 2011, Mascott 2005, Harish 2016).

IGS a prevalent system in neurosurgical procedures giving surgeons have the ability to navigate around crucial vasculature and locate internal targets. However, the quality of applications using IGS in neurosurgical procedures varies depending on the patient's orientation. A prone patient orientation proves difficult for registration of a head in neurosurgery as it presents specific problems. Optical tracking and registration have issues when the patient is in a prone position, due to complications with maintaining line of sight and lack of anatomical landmarks. Using optical tracking, there are not enough identifiable and accessible landmarks on the posterior of the skull for landmark registration, and commonly used landmarks around the orbitals and along the nose bridge are only accessible when working under the table. Using facial surfaces results in moving the location of the optical tracker between registration and surgical procedure. In an alternative method, solving the problem of moving the camera and working under the table, involves the insertion of screws into the skull for landmark registration. However, this is an invasive method of registration resulting in more patient discomfort. Current methods of prone patient registration, result in increased registration error, inefficient workflow, or require invasive procedures.

We propose a method of registration that will; (i) eliminate the need for screws, resulting in a non-invasive approach, (ii) eliminate the need to work under the table, and (iii) eliminate the need to adjust the camera. Through tracked ultrasound, bone surface points around the skull are collected to perform a non-invasive surface-based registration. Our goal was to add bone surface points on both the mastoid processes and the posterior base that are not accessible through skin surfaces, for surface-based registration. We used tracked ultrasound images to access these bone surfaces. By only having to set up the optical tracker in one position, this could reduce inefficient procedural setups caused by movement of the optical tracker between registration and surgical views.

2. METHODS

2.1 Experimental Setup and Hardware

This experiment was performed using an open source platform, 3D Slicer (www.slicer.org), the PlusServer application (www.plustoolkit.org), a phantom skull (Sawbones, WA, USA), Polaris Optical Tracker (Northern Digital Inc., ON, Canada), and Teledyne MicrUs ultrasound (Teledyne Ultrasound Medical Systems, Vilnius, Lithuania) (Figure 1). The optical tracker and ultrasound devices were connected to a computer running 3D Slicer and the PlusServer application (Lasso 2014). The PlusServer application was used to relay tracking data from the optical tracker to 3D Slicer through the OpenIGTLink module (Tokuda 2009). The hardware used in the experiment, the tracked stylus and ultrasound probe, are calibrated through a series of transforms, of which are all placed under the reference coordinate system (Figure 2).

A computer tomography (CT) scan was taken of the phantom skull. Using 3D Slicer, a three dimensional model of the phantom skull was generated through segmentation of CT scans. This experiment required an optically tracked stylus, static reference body (SRB) and tracked ultrasound probe. A plastisol skin was made to simulate skin over the phantom skull. Plastisol was used because the velocity of sound is 1490 m/s, matching the velocity in water, which was used for ultrasound calibration (Maggie 2013). This allowed for bone surface points to be accurately localized in the ultrasound image.

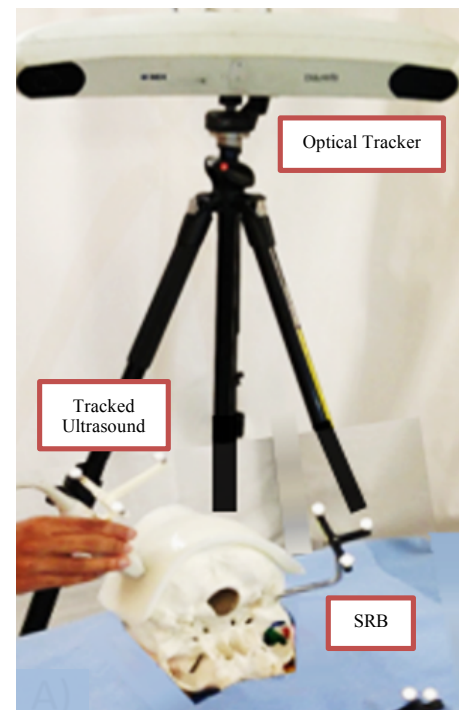


Figure 1. Experimental setup using optical tracker, tracked ultrasound, and phantom skull.

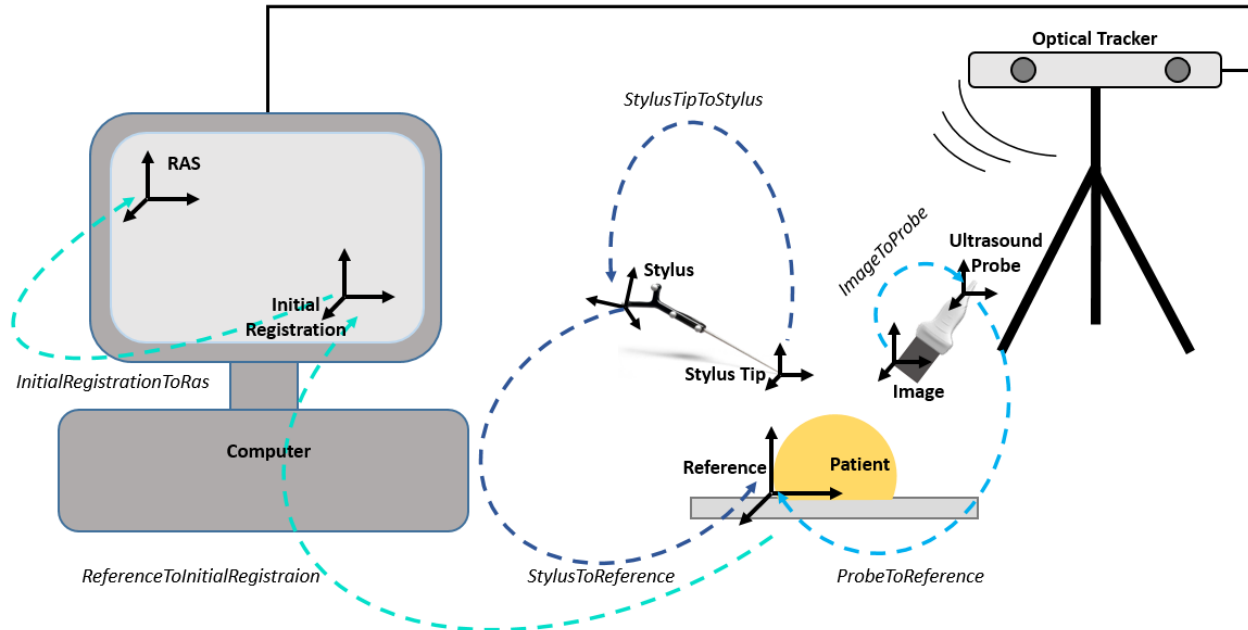


Figure 1. Experimental Transform Setup between system hardware

2.2 Segmentation Process

Once the CT scans of the patient skull had been obtained, they underwent the process of segmentation to highlight the bony surface of the skull. Through threshold segmentation it was possible to partition the image into regions sharing the same intensity in the CT images (Pham 2000). A threshold image was set to distinguish between desired classes. The evaluation of a threshold approach is based on visual assessments by the user (Pham 2000). The CT scans of the phantom skull had clearly visible bone surfaces and no internal structures which eased the segmentation process. The segmentation of the CT scans was implemented in 3D Slicer using the Segmentation module. The final segmented images were used to make a three dimensional model of the skull (Figure 3). The model generated was then be used to perform both landmark-based and surface-based registration.

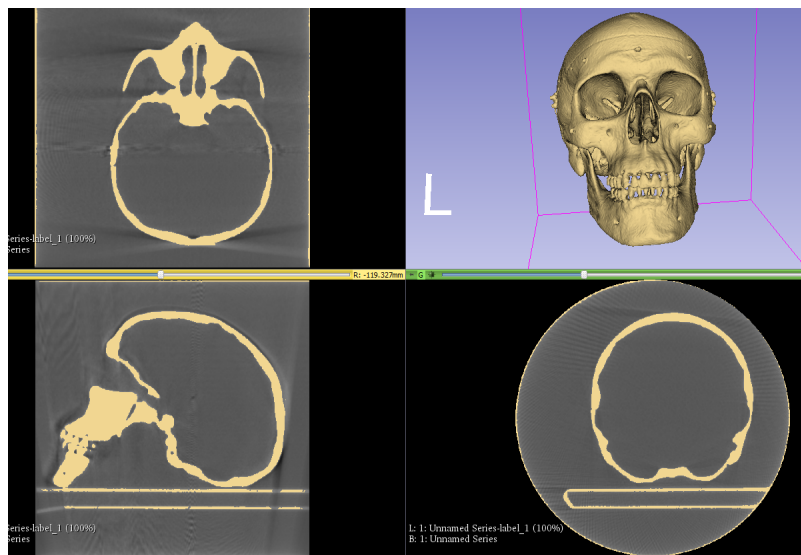


Figure 3. Segmentation of CT scans in 3D Slicer using threshold segmentation, and the resulting three-dimensional model.

2.3 Registration Process

A combination of both landmark-based and surface-based registration was used. Registration takes place in a two-step process, beginning with an approximated landmark-based registration and followed by a surface-based registration performed using tracked ultrasound. By combining both registrations, a final ReferenceToRas transform can be obtained and compared against a ground truth ReferenceToRas transform.

The initial landmark-based registration was performed using a tracked stylus and anatomical landmarks accessible as skin surface points. Three different skin surface points were selected on the posterior of the skull, the left and right mastoid processes, and the external occipital protuberance (Figure 4.A). These regions for registration were approximated, as there were no exact and marked locations for the placement of fiducials on the patient and on the three dimensional model. This process of landmark-based registration minimizes the average distances between identifiable points on the patient and their respective point on the three dimensional skull model generated, through the use of point-to-point registration (Lübbers 2011). This registration method ensured that the optical tools and skull model were within the capture range to perform surface-based registration. Ensuring that the skull model and optical tools lie within the capture range is important as the iterative closest point algorithm (ICP) does not find the globally optimized solution. The resulting transformation was a ReferenceToInitialRegistration transformation matrix.

After the application of the landmark-registration the tracked Telemed MicrUs ultrasound was used to collect bone surface points in the ultrasound image. As ultrasound is not effective in penetrating bone, this allowed for non-invasive visualization of the bony surfaces of the skull. Through the use of B-mode ultrasound, the phantom skull appeared as the brightest pixels in the ultrasound image. Using 3D Slicer and the Markups module, bone surface points were manually placed in the ultrasound image along the brightest visible contours (Figure 4.B). When scanning, points were placed around the left and right mastoid processes, the posterior base of the skull, the external occipital protuberance, and the skull cap, 100 points, randomly dispersed, were placed to cover the green area shown in Figure 4.A. The collected points were used in the Fiducial-Model Registration module of the SlicerIGT extension (www.SlicerIGT.org) for 3D Slicer (Ungi 2016). Through the use of ICP, a surface-based registration was performed. The output, an InitialRegistrationToRas transformation matrix, was calculated, along with the average surface registration distance.

By combining the two transforms, ReferenceToInitialRegistration and InitialRegistrationToRas, a resultant ReferenceToRas transform. That can then be compared to the ground truth.

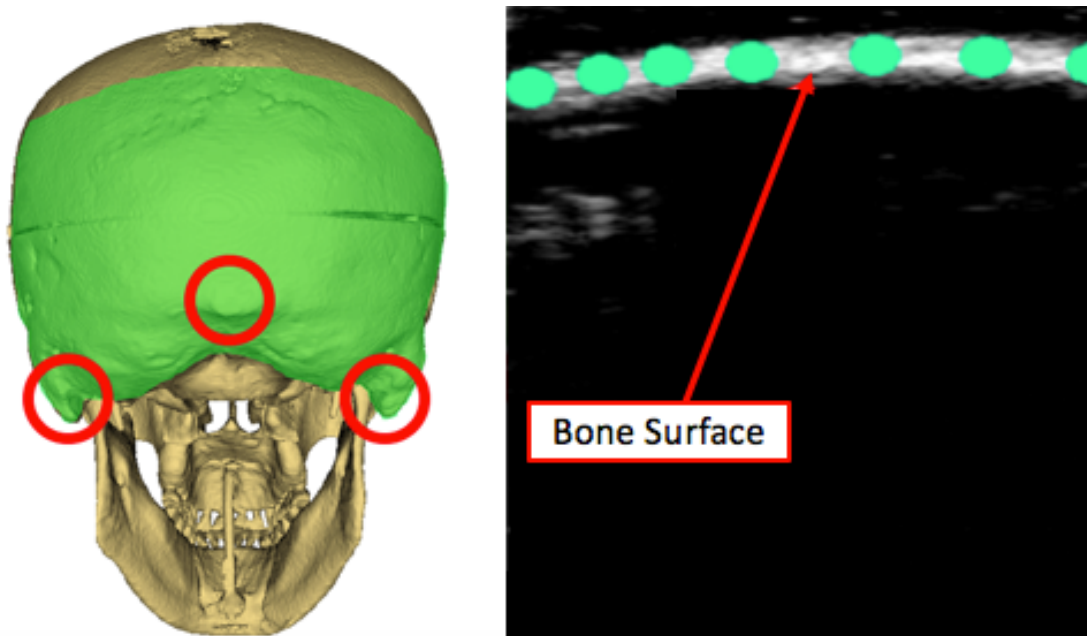


Figure 4. A) The red circles indicate areas used for point collection in initial registration and the green area represents surfaces accessible with ultrasound for surface registration; B) points marked on tracked ultrasound image for surface registration.

2.4 Accuracy Measurement

To assess the accuracy of the registration, it was compared against a ground truth landmark-based registration. The ground truth registration was implemented using 7 defined anatomical points that were visible on both the phantom skull and the three dimensional model and developed using point-to-point landmark-based registration. The phantom skull being used had several small divots that were able to be seen directly on the phantom skull's surface and were locatable on the three dimensional model generated. However, these points would not be locatable on the phantom skull in an ultrasound image or through skin surfaces.

A target point was defined within the skull and transformed by the ground truth ReferenceToRas transform and the experimental ReferenceToRas transform, a combination of initial and surface-based registrations transforms. The Euclidean distance between the two transformed points represented the target registration error (TRE) (Figure 5.A). The performance of the surface registration can also be seen when the model is intersected with the ultrasound image as shown in Figure 5.B.

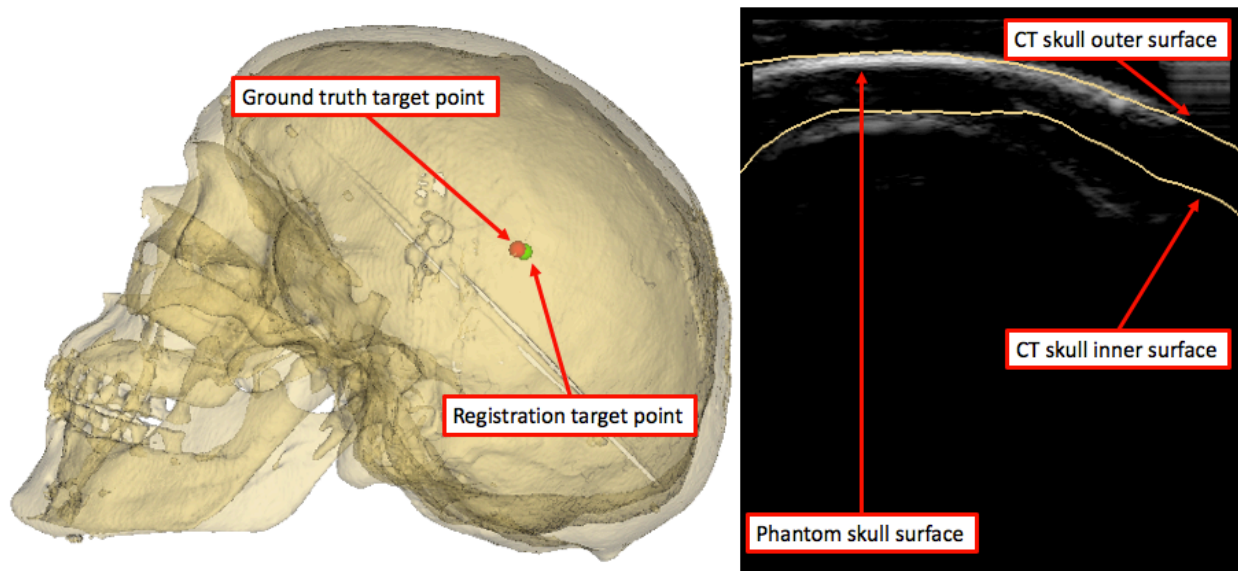


Figure 5. A) The location of transformed target point and ground truth target point in the skull. B) Qualitative display of the accuracy of the surface registration, showing intersection of the phantom and CT segmented model.

3. RESULTS

The phantom study explored the feasibility of using tracked ultrasound to perform surface-based registration on the posterior skull. This method of registration was performed five times ($n=5$). Three different values were recorded to correspond to each step in the registration: (i) registration error after the initial landmark registration, represented as initial registration TRE, (ii) average distance of surface points from the skull model for the final registration, represented as surface registration distance, and (iii) TRE of the final registration by comparing with the ground truth registration, represented as final TRE (Table 1). For all five trials, the surface registration reduced the error after the initial registration. The final registration error was found to be 1.6 ± 0.1 mm. The average initial registration error was found to be 2.5 ± 0.5 mm. The average surface registration distance was found to be 0.6 ± 0.1 mm.

Table 1. Phantom study results by surface-based registration.

Trial Number	Initial Registration TRE (mm)	Surface Registration Distance (mm)	Final TRE (mm)
1	2.1	0.6	1.8
2	2.4	0.5	1.6
3	2.4	0.5	1.5
4	2.4	0.7	1.5
5	3.4	0.6	1.7
Avg ± std	2.5 ± 0.5	0.6 ± 0.1	1.6 ± 0.1

4. DISCUSSION

The registration process designed did succeed in (i) eliminating the need for screws, resulting in a non-invasive approach, (ii) eliminating the need to work under the table, and (iii) eliminating the need to adjust the camera. The registration process presented performed with an average final TRE, 1.6 ± 0.1 mm improving upon the average initial registration, 2.5 ± 0.5 mm. The average surface registration distance was 0.6 ± 0.1 mm and therefore the surface registration does succeed in pulling the ultrasound bone surface points to the three-dimensional model surface, below 1mm. The average surface registration distance signifies that there is minimal translational error in the registration. However, the discrepancy between the surface registration distance and the final TRE, signifies that there is a problem with the rotational error in the registration. There are a set of limitations that could explain the rotational error in the process.

One limitation pertains to the experimental set up and surrounds the inability to evenly place surface points around the skull. This inability could be due to the location of the SRB on the phantom skull and the manual placement of markers in the ultrasound images. The SRB, attached to the right side of the skull, limiting access to certain areas along the right side of the skull, such as the right mastoid process. The right mastoid process one of the anatomically important landmarks on the posterior of the skull. By limiting access to this region of the posterior skull, there is one less uniquely contoured area to minimize rotational error. In addition to lack of access to an important anatomical landmark, the lack of full access to the right area of the skull means there is no even placement of bony surface points around the full skull.

Aside from the location of the SRB, another limitation was the manual placement of bony surface points in the ultrasound image. This could have contributed to the error discrepancies as manual selection is subjective and prone to error and extremely time consuming (Foroughi 2007, Foroughi 2008). The placement of surface points in the ultrasound image is not consistent, in terms of both the threshold being chosen for placement and the spacing between points within the image. Since all bone surface point placement is done by the user the process is very subjective. The error prone and subjective surface point selection could have played a role in the registration error.

The registration process proposed was able to eliminate the inefficient process of moving the camera between registration and surgical views, but the manual surface point placement was an inefficient process. To avoid additional error, once the ultrasound probe was in place the OpenIGTLink connection was paused to freeze the spatial location of the ultrasound image. This allowed for a more accurate placement of fiducials, however, the persistent turning on and off of the OpenIGTLink connection is time consuming.

Future exploration in this registration process would benefit from looking into limiting rotational error and improving time constraints. The use of tracked ultrasound as a method of registration could be enhanced by investigation into the optimal locations of the SRB and optimal scanning protocols to locate important and information heavy regions of the posterior skull. The investigating different regions for SRB location could increase access to all regions on the skull promoting a more even placement of surface points accessible by ultrasound.

To explore limiting the amount of time required per registration, it would be beneficial to explore automated bone surface point placement. The implementation of automated bone surface point placement could decrease the time required per registration, but it could also allow for the ability to set a minimum distance between bone surface points, and a consistent placement of bone surface points at a specified threshold level. The automated bone surface point placement would eliminate the subjective nature of the bone surface point placement and eliminate the need to control the OpenIGTLink connection.

5. CONCLUSION

The use of tracked ultrasound was proposed to solve problems that arise when the patient is in prone position. Some of the current problems in prone position registration are: (i) going under the table to collect surface points, (ii) adjusting the tracker between registration and surgical procedure, and (iii) invasive registration through the use of fiducial screws. The tracked ultrasound method of surface-based registration addressed the problems above. All points required for registration were collected above the table. Since all points were collected above the table, this allowed the optical tracker to be placed in an optimal location for procedure and registration. The demonstrated registration method using tracked ultrasound was non-invasive, eliminating the need for screw implantation. The average TRE of surface-based registration was 1.6 ± 0.1 mm. This registration method displayed rotational error which could be improved upon by analyzing different locations for the SRB and implementing automated placement of points in the ultrasound image.

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