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Technical Accuracy of an O-Arm Registered Surgical Navigator

Tapani Koivukangas, *Student Member, IEEE EMBS,* Jani P.A. Katisko, John P. Koivukangas

Abstract— **The objective of this study was to assess the accuracy of a commercial surgical navigator using optical tracking modality with automated registration between O-arm images and the scanned object. Automated registration was enabled by using the spine navigation software of the navigator.**

The used phantom was designed by the authors of this paper. The surgical navigators and the O-arm are routinely used at Oulu University Hospital, Oulu, Finland. The distances measured with the surgical navigator from the fixed origin of the phantom were compared to the known phantom accuracy assessment coordinates. The error of the surgical navigator was the difference between measured and true values. The mean displacement error was 0.20 mm with a standard deviation of 0.14 mm.

The results show that automated registration is very reliable for image guided surgery (IGS) and that the present accuracy assessment method can be used to periodically check surgical navigator accuracy using O-arm data.

Index Terms — **Image guided surgery, navigator, phantom, accuracy, automated registration, O-arm**

I. Introduction

SEVERAL procedures in neurosurgery and spine and trauma surgery currently utilize image-guided surgery (IGS) techniques. IGS is based on high resolution three dimensional (3D) images that have been taken prior to surgery or even during surgery. The benefits of image guidance have been demonstrated especially in cranial procedures where the use of images and visualization of the region of surgical interest help to assure successful and relatively safe operations. Computed tomography (CT) has been used in accuracy assessment protocols using phantoms for a variety of devices used in the medical field.

This paper compares in a hospital setting the working accuracy of a surgical navigator that is in routine use at Oulu University Hospital (Oulu, Finland). To evaluate the accuracy of an O-arm image guided surgical navigator, this study was divided into two main steps. First, the used phantom was scanned in the O-arm with the navigator's patient tracker attached, the image data was transferred to the navigator and the phantom was automatically registered. Second, the phantom accuracy assessment points were touched by the surgical navigator pointing tool and the results were compared to the true values.

The present phantom has earlier been used for accuracy assessment of a surgical navigator that has both optical tracking modality and tracking based on electromagnetic tracking system [1].

II. Materials and Methods

A. Materials

Materials used in this study consisted of a phantom that was designed by the authors of this paper [2], and an O-arm and StealthStation Treon+ navigator (Medtronic Inc., Louisville, CO, USA). The accuracy of the phantom was industrially verified to be ±0.015 mm for the accuracy assessment point displacement.

The shape of the phantom was a modified cube consisting of three identical levels and 6 mm beveled accuracy assessment points on each level. The beveled points were machined 20 mm apart. The data was analyzed using the 49 points on each level forming a rectangular shape with 160mm x 160mm x 100mm volume. The designed phantom and accuracy assessment protocol have earlier been published [2]. Figure 1 illustrates the used phantom.

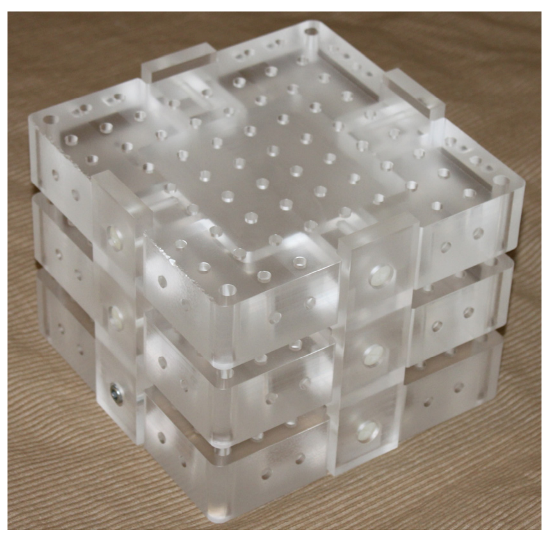

Fig. 1. The present accuracy assessment phantom.

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T. Koivukangas (M.Sc.) is researcher at the Department of Mechanical Engineering, University of Oulu, Oulu, Finland. (telephone: +358-41-502-7337, e-mail: tapani.koivukangas@gmail.com).

J. P. A. Katisko (Phil.Lic.) is Hospital Physicist at Oulu University Hospital, Department of Neurosurgery, Oulu, Finland. (e-mail: jani.katisko@oulu.fi).

J. Koivukangas (M.D., Ph.D.) is Professor and the Head of the Department of Neurosurgery, University of Oulu, and Chief of the Neurosurgery Research Unit at Oulu University Hospital, Oulu, Finland. (e-mail: john.koivukangas@oulu.fi).

The O-arm is a mobile 2D/3D intraoperative computed tomography (iCT) imaging system optimized for bony structures in spinal and orthopedic surgery. Scanning is based on cone-beam technology and a flat panel detector producing 196 slices in 13 seconds in the standard mode. Pixel size is 0.415 × 0.415 mm within a slice thickness of 0.833 mm. The size of the scanned cylindrical 3D volume is 21 cm × 16 cm (diameter × length).

The O-arm was taken into routine use at Oulu University Hospital, Oulu, Finland, in 2009. Figure 2 illustrates the phantom in the O-arm gantry. The patient tracker can also be seen attached to the phantom.

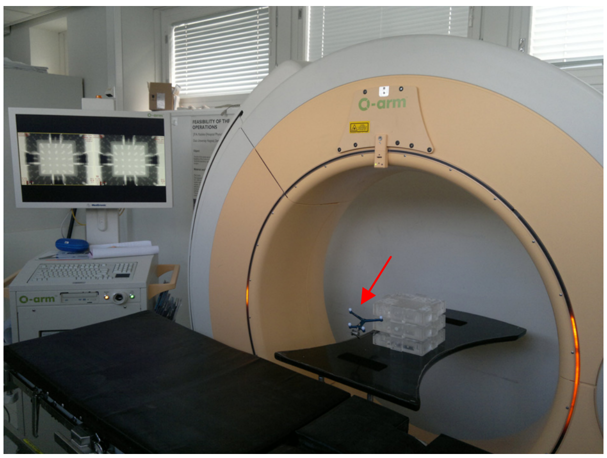

Fig. 2. O-arm setup with phantom in gantry (arrow points to the patient tracker).

A StealthStation Treon+ surgical navigator with spine software was utilized for navigation. Spine software enables automated registration between images and the scanned object when the O-arm is used. Automated registration requires a line of sight from the optical camera to the active O-arm tracker and the passive patient tracker in the scanner. Figure 3 illustrates the test setup for the image scanning. The StealthStation Treon+ navigator optical camera is seen in the middle of the picture with the surgeon monitor on the left and the O-arm on the right.

Fig. 3. The image scanning test setup.

B. Methods

The phantom was first scanned using the O-arm. For scanning, the phantom was placed in the O-arm's isocenter. Correct positioning was verified in lateral and vertical 2D fluoroimages. The 3D images were obtained utilizing the standard mode for a M-size patient in the thoracic region. Scanning parameters were adjusted to be 80 kVp, 40 mA and 156 mAs. The attenuation factor of the plastic phantom is less than that of bones, so the voltage was adjusted to be less than in conventional clinical use to obtain better contrast. The 3D-dataset was transported automatically to the navigation system. The surgical navigator's patient tracker was attached to the phantom prior to scanning, so automated registration was achieved.

After imaging, the phantom was fixed on the measurement platform and the error analysis was conducted according to the accuracy assessment protocol as earlier presented by the authors of this paper [1], [3].

The error analysis used in this study was based on the displacement error between the known phantom accuracy assessment point coordinates and the coordinates obtained from the navigator as shown in Equation (1): [4]

$$\text{Error} = (\text{measured value}) - (\text{true value}) \qquad (1)$$

where measured value was the navigator output coordinates and true value the corresponding points on the phantom.

Standard deviation of the error for each level was calculated using Equation (2): [5]

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \qquad (2)$$

The variance of the error was calculated using Equation (3): [5]

$$\mu = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 \qquad (3)$$

For standard deviation (σ) and variance (μ):

n = number of samples

x_i = sample

$\bar{x}$ = sample mean

The result gave the error for each accuracy assessment point and the mean accuracy over the whole volume. The method for assessing the accuracy was done in the following manner.

The obtained center point from the navigator in X-, Y-, and Z- coordinates of each level was marked as an origin and the distance from each point to it was measured. This was also done for the phantom.

The top level was measured first and the lower two in the corresponding order. Figure 4 shows the accuracy assessment protocol with the shape of each phantom level. The numbers correspond to the order the accuracy assessment points were touched.

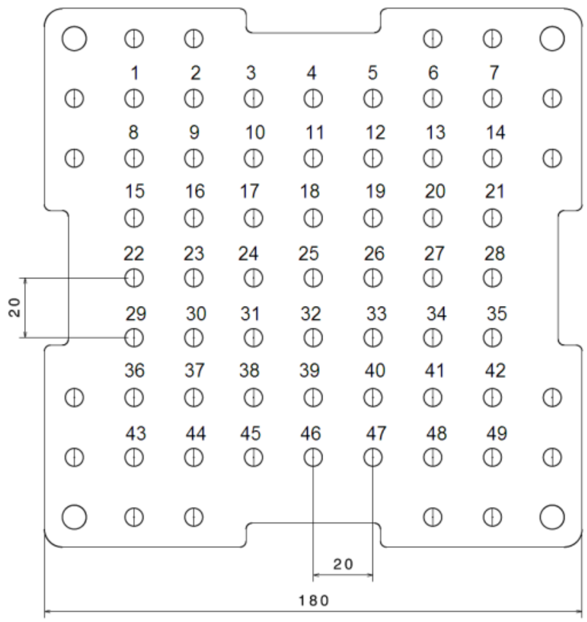

Figure 4. Accuracy assessment protocol.

III. Results and Discussion

The image data was collected using the O-arm. The optical tracking modality accuracy was assessed as presented in the materials and methods section. The displacement error analysis is shown in Figures 5 and 6. Table 1 shows the error statistics for the optical tracking modality. Figure 5 contains the distribution of the position error for each accuracy assessment point. Number 1 represents the first touched point and 147 the last one. Figure 6 illustrates the histogram of the position error.

TABLE 1
SUMMARY OF THE POSITION ERROR (MM)

	E, Optical Tracking (mm)
Mean Position Error, E	0.20
Standard Deviation, σ	0.14
Variance, μ	0.08
Min	0.00
Max	0.60

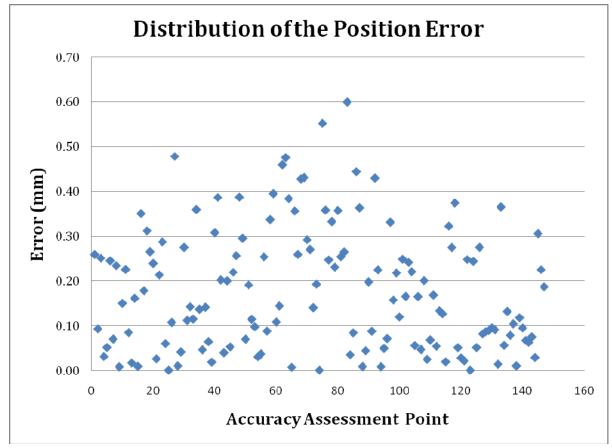

Figure 5. Distribution plot of the position error.

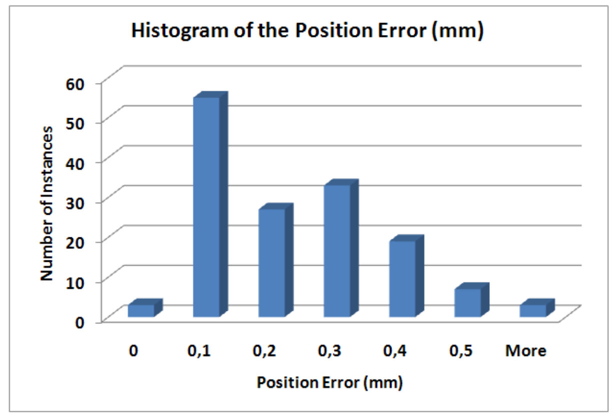

Figure 6. Histogram of the position error analysis

The phantom had a total of 147 accuracy assessment points that were localized and measured by the surgical navigator according to the accuracy assessment protocol. Mathematical analysis in this study was based on de Silva's [4] measurement error equation: error = (measured value) – (true value), where measured value was the navigator output coordinates and true value the corresponding accuracy assessment points on the phantom.

The overall results indicate a position error of 0.20 mm with a standard deviation of ±0.07 mm and variance of 0.08 mm. This error is within the manufacturer's specifications of 1.00 mm [6].

The distribution figure shows the scattered point plot, where each point corresponds to the displacement error of the navigator on the corresponding accuracy assessment point. As can be seen in the figure, there are only a few points where the error is measured to be over 0.50 mm.

The histogram also shows that the accuracy of the navigator is very high as mostly the error is within 0.30 mm.

Figure 7 illustrates the error analysis on a 3D surface. The error surface is shown on the coordinate system in such a way that the center of each phantom level, point number 25 of the accuracy assessment protocol (Fig. 2), is at the center of the grid. The error surface shows the mean error obtained for each corresponding point in the three levels, each having 49 accuracy assessment points.

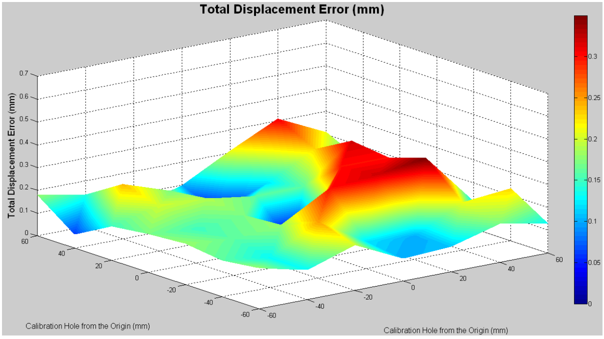

Figure 7. A 3D surface representation of the mean optical tracking modality accuracy errors.

As a comparison, Figure 8 illustrates a histogram of the position error of the same navigator using a phantom that was scanned with a high-field (1.5T) MR-scanner and registered point-to-point. These results have earlier been published by the authors of this paper in 2009 at the IEEE EMBS –conference in Minneapolis, MN, USA [3].

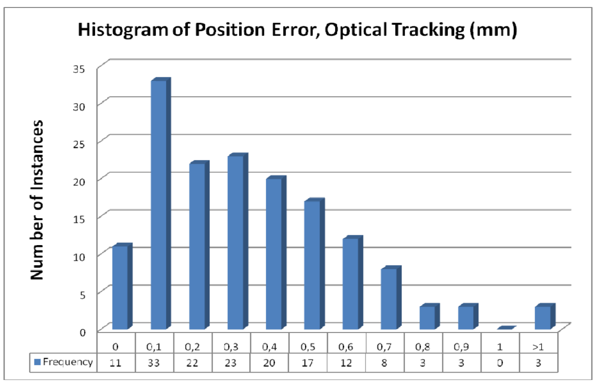

Figure 8. Histogram of the position error as obtained earlier [2].

As can be seen when comparing the histograms of the present study (Fig. 6) and the earlier study based on MRI data (Fig. 8), the trend of the position errors is similar. The histograms also reveal that using automated registration instead of the point-to-point method, the navigator accuracy is higher. Using automated registration, the error range is within 0.50 mm while with point-to-point registration, the error range is more scattered.

Quite similar test results have also been published by Wiles et.al. [7], for the optical tracking modality. They obtained a mean positional error of 0.193 mm with a standard deviation of 0.167 mm.

IV. Conclusions

The overall purpose of our work has been to design an accuracy assessment phantom and protocol that can be used in the hospital environment to periodically check routinely used surgical navigators. The navigator evaluated in the study was the Medtronic StealthStation Treon+ used at the university hospital for the last four years.

The use of surgical navigators has become routine in especially orthopedics and neurosurgery. Two localization techniques, optical and electromagnetic tracking, have become the methods of choice.

Even though the navigators are as accurate as the medical device companies describe, their accuracy can also be periodically evaluated during routine use. A variety of accuracy assessment phantoms has been developed for a wide range of medical devices, but there are no commercial phantoms for on-site study of the accuracy of surgical navigators used in hospitals.

The present study concentrated on the use of the O-arm for obtaining image data that can be automatically registered to assess the accuracy of the surgical navigator in the hospital setting. Assessment of the accuracy of a surgical navigator required the development of a specially designed phantom for O-arm imaging and an accuracy assessment protocol. The study showed that the present navigator even after four years of use had retained accuracy well within the specified 1 mm error range. The results also showed that O-arm imaging with automatic registration is a suitable method for checking navigator accuracy. Thus, on the basis of the accuracy results the method is also suitable for IGS.

Possible errors due to image data and image registration were minimized by using optimal imaging parameters and automatic registration to an industrially verified accuracy assessment phantom.

This is a surgical navigator accuracy assessment work-in-progress. Our earlier studies have concentrated on the evaluation of the accuracies of different tracking modalities including the optical tracking system and tracking based on electromagnetic fields (EMTS). Our future work will contain more detailed evaluation of the error sources and trends, i.e. whether possible errors tend to increase or decrease in particular directions, and also how to take this into account to enable even safer surgical technique.

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