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Development of an Accuracy Assessment Phantom for Surgical Navigators

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***Abstract*—The objective of this study was to design a calibration phantom for a surgical navigator used in a hospital environment. It addresses two major issues: the design of an accuracy phantom and the accuracy analysis of the surgical navigator in a hospital setting.**

The designed phantom was used to assess the accuracy of the optical tracking modality of the surgical navigator used at Oulu University Hospital, Oulu, Finland. The phantom functioned according to the design criteria, it was easy to use and it had enough calibration points that were localized by the navigator according to the accuracy assessment protocol to assess the accuracy error. The distances measured from a fixed origin with the surgical navigator were compared to the known phantom calibration point coordinates.

The mean error was within the manufacturer specifications of 1.00 mm. The analysis done using the designed phantom and accuracy assessment protocol showed that the error increased with the distance from the center of the phantom. The accuracy assessment protocol using the present phantom proved to be a suitable method for accuracy analysis of a surgical navigator in a hospital setting.

***Index Terms*—surgical, navigation, phantom, accuracy, protocol**

I. Introduction

IN neurosurgery, ENT and orthopedics, the development of computer aided new technologies has enhanced operations by providing more precise and accurate results. Minimally invasive techniques play an increasingly vital role in the operations. To achieve this goal, computers together with surgical tracking systems have been adapted to guide surgical tools. The main advantage reached with these navigational devices is that the surgeon can perform operations closer to sensitive structures in the patient. Also the incisions can be minimized and made closer to the operation zone. This has led to more error-free operations and to shorter recovery times. [2]–[5].

The accuracy of the surgical navigator during operations has to be reliably good. It is important for the surgeon to know if the navigator is still as accurate as when the device was built or how much the accuracy has decreased and in which direction, i.e. horizontal or vertical. This gives the surgeon a more comfortable state of mind and thus makes the operation even safer. To address this issue surgical navigator companies give a range of error in which the navigator operates. To make the understanding of the accuracy of the medical devices even better, accuracy assessment phantoms for special purposes have been developed. [6]–[9].

The objective of this study was to design and develop a phantom and an accuracy assessment protocol for a surgical navigator used at Oulu University Hospital. A new navigator was taken into use in January 2008. This surgical navigator has both optical tracking and EMTS (electromagnetic tracking system) modalities. For this study, we only concentrated on the optical tracking modality. The surgeon can use which ever tracking gives a better result for the operation. The device used is the Stealth Station Treon+ by Medtronic Inc. (Minneapolis, MN, USA).

The main criteria for this phantom were that it needed to be manufactured with sub–millimetric error between the calibration points, easy to use, long lasting and dimensionally suitable and compatible for MR scanners in a hospital setting.

II. Materials and Methods

A. Materials

To assess the accuracy of the Medtronic StealthStation Treon+, two main issues were discussed and solved: an accuracy assessment protocol and a reference system with accurate calibration markers to test the system. As a reference system, an acrylic plastic (PMMA - polymethylmethacrylate) phantom was designed with a displacement error of ± 0.02 mm for the calibration holes. This phantom was scanned with a high-field (1.5 T) MR-scanner (General Electric, Fairfield, CT, USA) and the T1-weighted image data was registered to the navigator's database using the landmark based technique.

The phantom was designed so that it has three separate

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levels that can be easily taken apart. The shape of each level is identical.

On the three levels the 6 mm diameter calibration pegs with holes on the top (Figure 1) placed 22 mm apart (Figure 1). This gave the phantom a total of 255 measurement points. With the used NC machine (Yasda Precision, Japan) at the University of Oulu Mechanics Laboratory, the error for the distance horizontally and vertically was within ±0.02 mm. [10].

The design of the calibration levels together with the key design placements of the calibration pegs and holes is illustrated in Figure 1. These levels are combined (Figure 2) to make the phantom and it is placed inside a cylindrical container so the base design had to be circular. The corners on the main circle and the holes marked were precisely machined to give the fluid free flow through the construction (Figures 1 and 2). This made it easier to fill the phantom with liquid and remove the air.

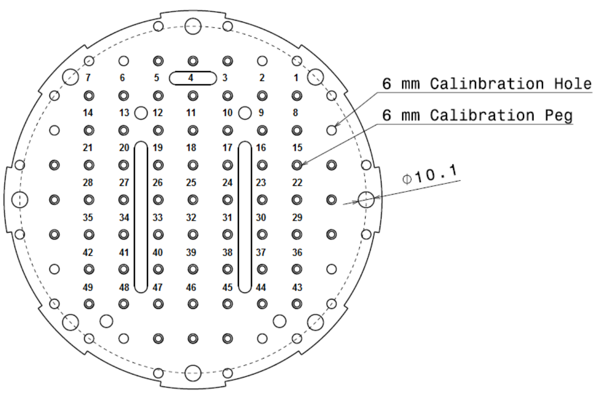

Fig. 1. Top view draft of the phantom levels. [1].

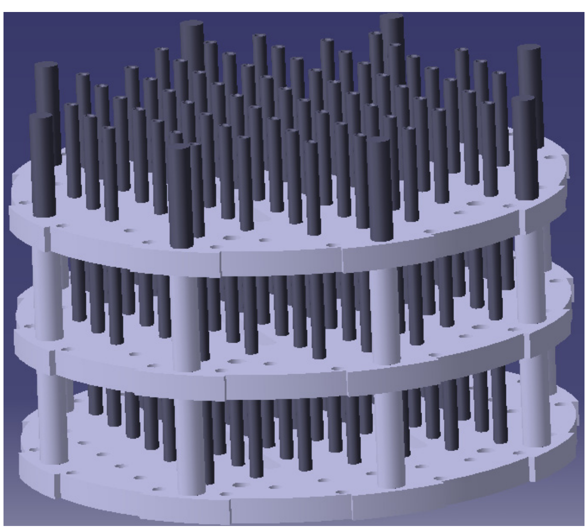

Fig. 2. 3D model of the accuracy assessment phantom. [1].

B. Methods

The protocol for accuracy assessment is illustrated in Figure 1. Numbers from 1 to 49 are the 6 mm pegs that were localized in successive order and the coordinates of each point were collected. The basic error analysis used in this study was that the error calculated is the displacement error between the known phantom calibration point distances and the calculated distances explained in this section. The result gives the error for each calibration point and the mean accuracy of each calibration level. Thus the results using the combined phantom can be calculated.

As the navigator gives the location of the instrument tip in the X, Y and Z coordinates, the mathematics used in this study to measure the total displacement error for optical tracking was based on the basic Pythagorean Theorem, $D = \sqrt{X^2 + Y^2 + Z^2}$ [11] where the squared sums of the calibration hole spots between the phantom ($X_{P,i}$, $Y_{P,i}$, $Z_{P,i}$) and the navigator's measurements ($X_{M,i}$, $Y_{M,i}$, $Z_{M,i}$) are compared to get the total error. The calculation was divided into four steps as explained with Equations 1 to 7. The same method was used for each calibration hole.

First the midpoint of each level was marked as the origin and the distance from each point to it was calculated. This was also done for the known phantom points. The origin of each level was assigned the coordinate point (X_{0M}, Y_{0M}, Z_{0M}) for the measurement results and (X_{0P}, Y_{0P}, Z_{0P}) for the corresponding phantom calibration points. The calculation was done using Equation (1) for the measured points and Equation (2) for the phantom points.

$$\begin{aligned} D_{XM,i}^{\;2} &= \left(X_{M,i} - X_{0M}\right)^2 \\ D_{YM,i}^{\;2} &= \left(Y_{M,i} - Y_{0M}\right)^2 \\ D_{ZM,i}^{\;2} &= \left(Z_{M,i} - Z_{0M}\right)^2, \end{aligned} \tag{1}$$

where iM is the calibration point number from the measurements.

$$\begin{aligned} D_{XP,i}^{\;2} &= \left(X_{P,i} - X_{0P}\right)^2 \\ D_{XP,i}^{\;2} &= \left(Y_{iP,i} - Y_{0P}\right)^2 \\ D_{XP,i}^{\;2} &= \left(Z_{P,i} - Z_{0P}\right)^2, \end{aligned} \tag{2}$$

where iP is the calibration point number on the phantom.

Next the squared distances were summed using Equation (3) for the measured points and Equation (4) for the phantom points. Using Equation (5) for the measured points and Equation (6) for the phantom points, the square root was taken to calculate the distance of each point from the origin.

$$D_{M,i}^{\;2} = \sum_{i=1}^{n}\left(D_{XM,i}^{\;2} + D_{YM,i}^{\;2} + D_{ZM,i}^{\;2}\right) \tag{3}$$

$$D_{M,i}^{\;2} = \sum_{i=1}^{n}\left(D_{XP,i}^{\;2} + D_{YP,i}^{\;2} + D_{ZP,i}^{\;2}\right) \tag{4}$$

$$D_{M,i} = \sqrt{\sum_{i=1}^{n}\left(D_{XM,i}^{\;2} + D_{YM,i}^{\;2} + D_{ZM,i}^{\;2}\right)} \tag{5}$$

$$D_{P,i} = \sqrt{\sum_{i=1}^{n}\left(D_{XP,i}^{\;2} + D_{YP,i}^{\;2} + D_{ZP,i}^{\;2}\right)} \tag{6}$$

where i is the measured calibration point and n is the number of holes in the measurement data.

The displacement error, $D_{TOT,i}$, for each point was calculated as the difference between the known phantom distance (6) and the measured distance (5), using Equation (7).

$$D_{TOT,i} = D_{P,i} - D_{M,i} \qquad (7)$$

The mean distance error, E was calculated using Equation (8): [12]

$$E = \frac{\sum_{i=1}^{n} D_{TOT\,i}}{n} \qquad (8)$$

The variance of the error was calculated using Equation (9): [12]

$$\mu = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2 \qquad (9)$$

Standard deviation of the error for each level was calculated using Equation (10): [12]

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (10)$$

For variance (μ) and standard deviation (σ):
n = number of samples
x_i = sample
$\bar{x}$ = sample mean

The result analysis was done using Matlab V5 Release 12 for the 3D error surface plots and the numerical analysis was done using Microsoft Excel 2003.

The phantom was fixed on the measurement platform using screws and the patient tracker was attached on the same platform so the system was immobilized. The bottom level was measured first and the upper two in the corresponding order. Figure 3 shows the accuracy assessment protocol setup for optical tracking modality.

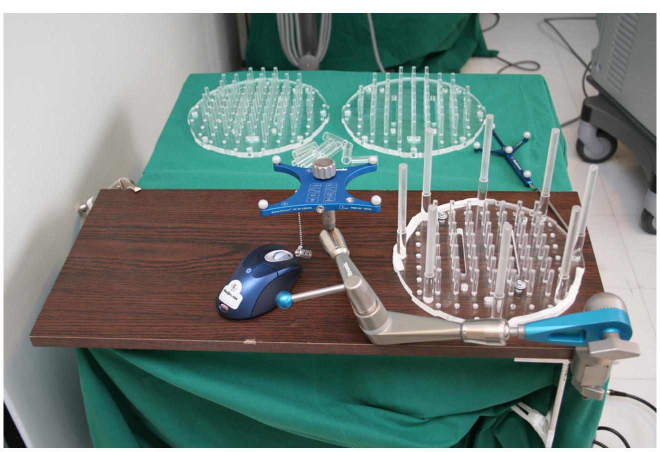

Fig. 3. Surgical navigator analysis setup. [1].

III. Results and Discussion

The main test data were collected from the three phantom calibration levels according to the test protocol using optical tracking. Accuracy results for the position error are provided in the following figures.

Figure 4 and Table 1 show the displacement error of the entire phantom in millimeters. Figure 4 shows the histogram of the measured position error. Table 1 gives the error statistics for the phantom. [1].

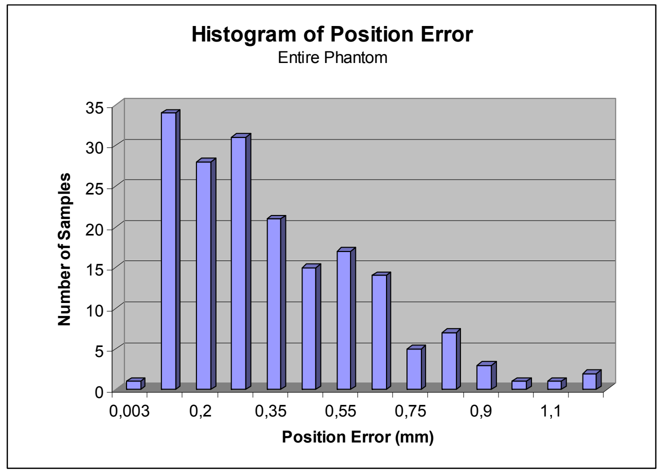

Fig. 4. Surgical navigator position error. [1].

TABLE I
Summary of Position Error

Phantom	Units, mm
Mean Position Error, E	0.32
Standard deviation, σ	0.25
Variance, μ	0.06
Min	0.003
Max	1.19

The phantom had a total of 255 calibration holes that were localized by the navigator according to the accuracy assessment protocol. The distances measured from a fixed origin with the surgical navigator were compared to the known phantom calibration distances. Mathematical analysis in this study was based on the basic Pythagorean Theorem. This method was used in the error analysis to transform the displacement in navigator's coordinates into the phantom coordinates. The error analysis part of this study gives a basic understanding of the trend of accuracy of the surgical navigator.

The analysis done using the designed phantom and accuracy assessment protocol showed that the error increased as the distance from the origin grew. This phenomenon can be seen in Figure 5 in which the x- and y-axes represent each calibration level and the intersection points represent the calibration pegs that are touched with the instrument. Z-axis represents the error in millimeters. The desired level at which there is no error lies on the Z=0 – level shaded with light blue color. The color bar includes the error map as the dark blue color on the bottom represents an error of -0.1 mm and the dark red color on top represents an error of 1.00 mm.

As Figure 5 illustrates, the greatest errors are on the edges of each calibration level. The Figure also shows that the error is mostly within 0.50 mm which is the mean position error with standard deviation as stated in Table I.

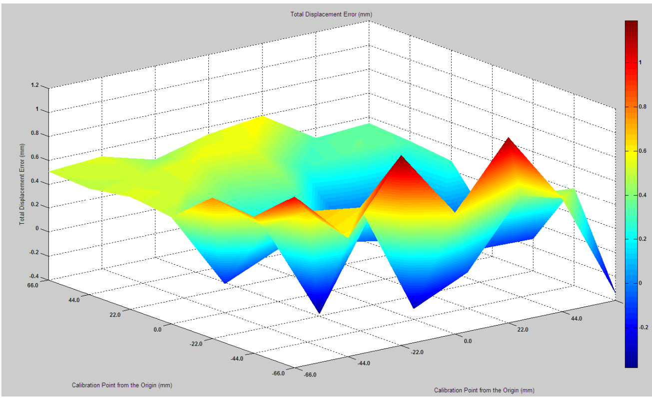

Fig. 5. A 3D representation of the displacement error.

Overall results for the entire phantom indicate a position error of 0.32 mm with a standard deviation of ± 0.125 mm and variance of 0.06 mm. The minimum error was 0.003 mm and the maximum error 1.19 mm for the displacement of the tip of the instrument. This error is within the manufacturer's specifications of 1.00 mm, when some larger outlier errors were rejected. The test shows that the phantom functioned well and also the Medtronic StealthStation Treon+ was proven to be as accurate as specified even after nearly one year of use.

IV. Conclusions

The purpose of this study was to design a calibration phantom for a surgical navigator for use in hospital environment. The evaluated navigator was the Medtronic StealthStation Treon+ routinely used at the hospital.

The use of surgical navigators has become a normal procedure in surgery especially in orthopedics and neurosurgery. Two main localization techniques have become the methods of choice. Especially navigation based on optical tracking is gaining an increasing number of users.

The navigators in use today are as accurate as the medical device companies describe, but as the navigators are used, the accuracy needs to be periodically evaluated. A variety of accuracy assessment phantoms has been developed for a wide range of medical devices, but there are no commercial phantoms for the hospital study of surgical navigators. To understand the accuracy of the StealthStation Treon+ navigator a phantom and an accuracy assessment protocol was designed.

This study reviewed analysis methods for accuracy assessment of surgical navigators in use in a hospital setting. Understanding the importance of the accuracy of a surgical navigator requires the use of a phantom for evaluating it. An accuracy assessment protocol and a phantom for this purpose were designed and analysis data on the accuracy of the system was collected and evaluated.

The tests for accuracy assessment of the used navigator were conducted in the Neurosurgery Research Unit at the Oulu University Hospital, Oulu, Finland. The designed phantom was used for testing the optical tracking modality. Some data was also collected using the EMTS, but this data was not analyzed in more detail for this study. Thus, it could be seen that this kind of phantom can function also for navigators using EMTS and mechatronic digitizers.

The results gained fulfill the requirements set for this study. It functioned well and it was easy to use. The phantom also had enough calibration holes to see the trend of the accuracy error. The present accuracy assessment protocol proved to be a practicable tool for accuracy analysis in the hospital.

Errors caused by the image data and image registration were minimized by using optimal imaging parameters and rigid registration with an industrially verified phantom.

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