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Design and accuracy evaluation of a new navigated drill system for computer assisted ENT-surgery

Thomas Wenger, Stephan Nowatschin, Wolfgang Wittmann, Florian Hurka, Gero Strauss and Tim C. Lueth, *Member IEEE*

Abstract— **In this article a new navigated drill system for computer assisted ear, nose and throat (ENT) surgery is presented. The navigated drill and the microscope probe are part of a surgical navigation system for ENT-surgery. In particular, the accuracy of the new navigated drill is compared to an existing navigated drill experimentally under conditions close to the surgical workflow. For the technical accuracy experiment, the new navigated drill in combination with the new microscope probe and a particular navigated measurement board have been integrated, together with the current navigated drill, in a navigation system by a special navigation software with measuring function, based on a standard ENT navigation software. The developed navigated measurement board provided the implementation of reproducible experiments and the direct accuracy comparison of the two navigated instruments under the same conditions.**

Thereby, N = 15 accuracy experiments are performed with both navigated drill systems with three possible tracker positions. The distance between the planned and the touched points were calculated and compared. The average distances from the planned points to the touched points with the new navigated drill is in the left tracker position 1.10 mm, in the middle tracker position 1.14 mm and in the right tracker position 1.59 mm. In comparison to the existing drill, the new navigated drill, measured with each tracker position, is 0.62 mm more accurate.

I. Introduction

Surgical assistant systems, especially image-guided surgical navigation systems, are increasingly deployed in connection with complex minimally-invasive procedures with a high risk potential. In surgical disciplines such as ear, nose and throat surgery, maxillofacial- and neurosurgery the proximity of the surgical instruments to sensitive anatomical structures involves a high risk of injury. In the surgical treatment of the temporal bone, where this new navigated drill system is evaluated, a considerable amount of time during the intervention is spent to protect and locate high-risk structures such as sigmoid sinus, facial nerve, cochlea, horizontal semicircular canals, dura and auditory ossicles [1]. According to the literature, the rate of complications involving damage to the aforementioned structures is specified between 2% and 6% [1]–[3].

In this article, a new navigated drill system for computer assisted ENT-surgery and an accuracy evaluation of this system using a particular measurement board is presented. The system is evaluated in combination with an already existing and clinically established surgical navigation system for ENT, the *Navigation Panel Unit (NPU)* [4]. In addition to the hardware approaches described below, there are also opportunities to correct automatically the registration errors by software at every location where an error has been detected, to keep the navigation accuracy as high as possible [5]. The accuracy of the already existing navigated drill is used as reference for the accuracy evaluation of the new navigated drill system. The existing navigated drill is already used for different studies together with Navigated Control® [1, 6–8].

II. Material And Method

In the subsequent sections the surgical navigation system and the navigated instruments that are used for the accuracy evaluation are presented. Furthermore, parameters, measurement and evaluation systems which are important for the devolution of the experiments are described. The chapter ends with a detailed description of the accuracy experiment with the navigated measurement board.

A. The navigation system

The navigation system which is used for these experiments is the *Navigation Panel Unit (NPU)* (KARL STORZ GmbH & CO. Kg, Tuttlingen, Germany). The system consists of a *Slimbook D220* Tablet PC (PaceBlade Technology Xcellent Mobility Solutions BV, Amersfoort, Netherlands) an optical measurement system *Polaris Vicra* (Northern Digital Inc., Waterloo, Canada) and an electronic adapter box. These components of the navigation system are mounted to a compact mobile stand. For the intraoperative navigation, the system includes a patient tracker, a navigated pointing instrument (probe) and three different navigated

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Thomas Wenger is with the ERGOSURG GmbH, Ismaning, Germany and the Institute for Micro Technology and Medical Device Technology at the Technische Universität München, Garching, Germany (corresponding author to provide phone: +49 89 322 094 62; fax: +49 89 322 094 66; e-mail: thomas.wenger@ergosurg.com).

Stephan Nowatschin is with the ERGOSURG GmbH, Ismaning, Germany (e-mail: stephan.nowatschin@ergosurg.com).

Wolfgang Wittmann and Florian Hurka are with the ERGOSURG GmbH, Ismaning, Germany and the Institute for Micro Technology and Medical Device Technology at the Technische Universität München, Garching, Germany (e-mail: wolfgang.wittmann@ergosurg.com, florian.hurka@ergosurg.com).

Gero Strauss is with the ENT Department, Universitätsklinikum Leipzig, Leipzig, Germany (e-mail: gero.strauss@medizin.uni-leipzig.de).

Tim C. Lueth is director of the Institute of Micro Technology and Medical Device Technology at the Technische Universität München, Garching, Germany (e-mail: tim.lueth@tum.de).

suctions. All of them have three reflective glass spheres, for localization. In this article this standard navigated instrument set was expanded with a navigated drill with two different tracker adapters and different reflector geometries, a navigated microscope probe, and a navigated measurement board. All instruments are implemented together in a special navigation software with measuring function, based on a standard ENT navigation software. During the navigation, the optical camera measures, in the measurement volume with an update rate of 20 Hz, the current position of the navigated instruments and sends these positions as transformation matrices to the Tablet PC. For each measurement, an additional indication of accuracy (*RMS*) is transmitted. The *RMS* varies depending on the orientation of the navigated instrument with respect to the optical measurement system and is an indication of the position of the tracker in the measuring volume. In the Tablet PC, the measured positions are processed and after a successful landmark registration the instruments are displayed in the CT, MRI or DVT data of the patient. The landmark registration is described in [9], [10] and is not part of this article.

B. The instruments

For the navigated drill a normal angled ENT INTRA-drill handpiece with a length of 12.5 cm from KARL STORZ was modified. With this modification it can be connected via an adapter with a tracker. In the first version [1, 6–8] three small slots were milled into the back of the handpiece (see Fig. 1).

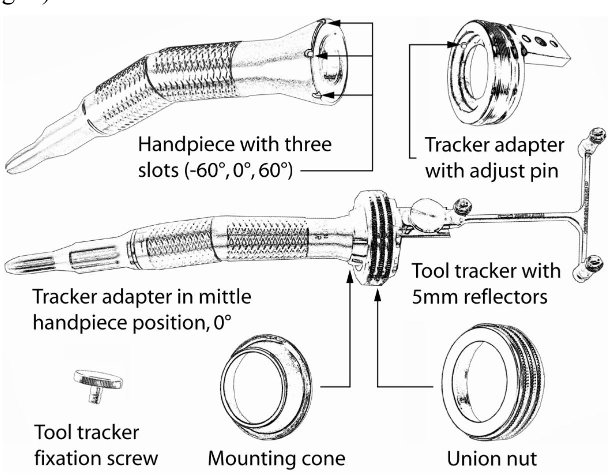

Fig. 1. Schematic representation of the present navigated drill consisting of the modified handpiece, the tracker adapter, the fixation screw, the mounting cone, the union nut and the tool tracker.

The adapter, which has an adjust pin and a bed for a tool tracker, can be fixed in three possible positions (-60°, 0°, 60°) on the handpiece by using the mounting cone and the union nut. The tool tracker with 5 mm glass reflectors is fixed to the adapter by the fixation screw.

In the new version of the navigated drill, instead of the three slots in the back of the handpiece the adapter is extended by two more mounting options to have the opportunity to fix the tool tracker without removing the tracker adapter. To increase the accuracy of the new navigated drill, a new drill tracker with a larger geometry than the previous tool tracker is developed. Due to its shape the new drill tracker is closer to the tool tip than the previous tool tracker. In addition, for this drill tracker 10 mm glass reflectors are used (see Fig. 2).

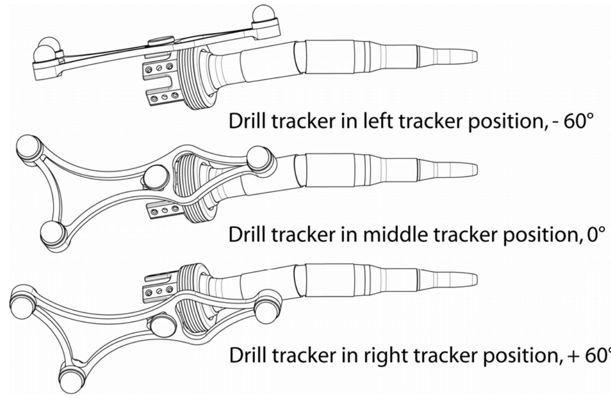

Fig. 2. Schematic representation of the navigated drill with the new drill tracker with 10 mm glass reflectors and optimized tracker adapter in all possible constellations (-60°, 0°, -60°) .

To calibrate the navigated drills, i.e. the calibration of the drill axis and the calibration of the bur length and radius, a specially developed navigated microscope probe is used. The short tip of this microscope probe has the diameter of a standard bur for KARL STORZ handpieces, so it can be inserted into the handpieces to calibrate the drill axis (see Fig. 3). In order to calculate the drill axis of the handpiece, the two nested instruments must be held in the measuring volume of the optical measurement system till the process is closed. The end of the process is signalized by a specific sound.

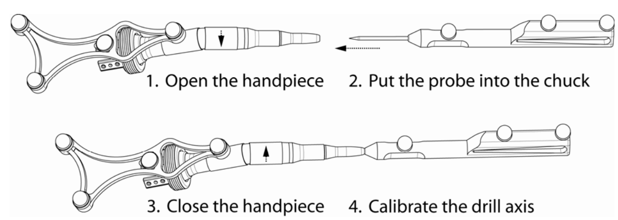

Fig. 3. Schematic representation of the drill axis calibration process of the new navigated drill with the new microscope probe.

After the calibration of the drill axis, the two instruments must be separated and a bur is plugged into the handpiece. Thus the length and radius of the bur can be calculated, the bur in the locked handpiece has to be put in the lateral slot of the microscope probe and pushed in the direction of the probe tip until it stops (see Fig. 4). The two instruments must be held together in the measuring volume of the optical measurement system. Then the length and the radius of the bur is calculated and visualized by the navigation software.

For the accuracy and design evaluation of the described navigated drill systems a navigated measurement board was developed.

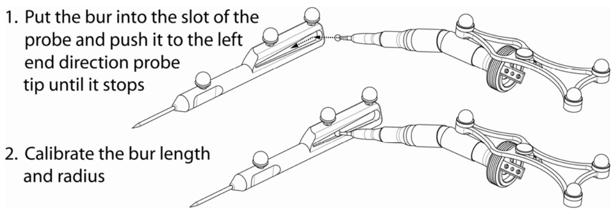

Fig. 4. Schematic representation of the bur length and radius calibration process of the new navigated drill with the new microscope probe.

The CNC milled measuring board (200 mm × 200 mm × 15 mm) is made of aluminum and the dimensions are tolerated to ±0.02 mm. The navigated measurement board has four screwed 10 mm glass reflectors and a separate adapter for the patient tracker on its surface. On the board surface are 46 indented measuring points and four predefined landmarks which can be touched by the navigated instruments. The measuring points are in a grid with 20 mm line interval within the four landmarks (see Fig 5). The precise and highly consistent data set from the navigated measurement board, directly out of the 3D CAD File, can be loaded and registered in the navigation software like the normal patient data sets.

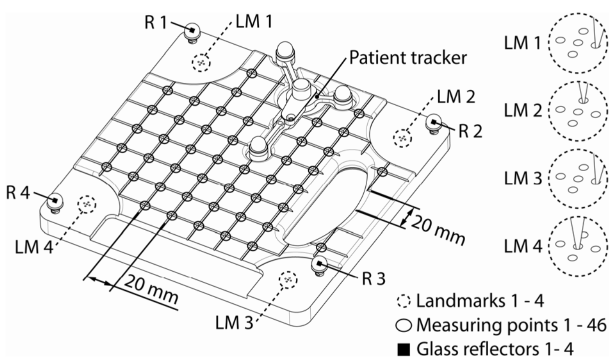

Fig. 5. Schematic representation of the navigated measurement board with four reflectors, four landmarks, a separate adapter for the patient tracker and 46 measuring points.

C. Evaluation of drill accuracy

1) Material: To evaluate the accuracy of the two different drill systems, the navigated measurement board is placed on a fixed frame with 30° angle to the horizontal table. The optical measurement system is aligned parallel to the navigated measurement board (60° between the vertical stand and the *Polaris Vicra*) in a distance of 80 cm (optimal position in the measurement volume of the *Polaris Vicra*). The patient tracker is fixed at the intended adapter on the navigated measurement board and except these two components and the navigated drill system (drill and microscope probe) there are no other navigated instruments in the measurement volume of the *Polaris Vicra*. The Tablet PC with the correct measurement software is started, and the data set of the navigated measurement board with the preset landmarks is loaded.

Two accuracy experiments with the different drill systems were performed: one with the existing drill system with three different tool tracker positions, and one with the new drill system with three different drill tracker positions. The two experiments were compared to each other.

2) Methods: Based on the CAD drawing of the navigated measurement board, the landmarks ${}^{mod}\mathbf{p}_{LM,i}$ and measuring points ${}^{mod}\mathbf{p}_{MP,i}$ are known. They are defined in the coordinate system of the navigated measurement board *mod*. The positions of the measuring points are entered into the file reference points in the data directory of the software, the positions of the landmarks are written in the planning data set of the measurement board.

After the successful landmark registration, the matrix ${}^{mod}\mathbf{T}_{pat}$ is calculated. The deviation between planned and touched anatomical landmarks is called the Fiducial Registration Error (*FRE*). The mean (eq. 1) and maximum (eq. 2) *FRE* is logged in the log file.

$$\overline{\mathrm{FRE}} = \frac{1}{4}\cdot\sum_{i=1}^{4}\left({}^{mod}\mathbf{p}_{LM,i} - {}^{mod}\mathbf{T}_{pat}\cdot{}^{pat}\mathbf{p}_{LM,i}\right) \quad (1)$$

$$\widehat{\mathrm{FRE}} = \max\left({}^{mod}\mathbf{p}_{LM,i} - {}^{mod}\mathbf{T}_{pat}\cdot{}^{pat}\mathbf{p}_{LM,i}\right) \quad (2)$$

The transformation ${}^{drill}\mathbf{T}_{loc}$ of the handpiece (position chuck of the handpiece to the drill tracker) is measured by the handpiece calibration. This is done in the drills coordinate system *drill*.

After successful length and radius calibration of the bur, the bur radius r_{mill} and length l_{mill} is logged in the log file.

To measure the accuracy of the navigated drill, measuring points on the top of the measurement board were touched with the tip of the bur. The touched position ${}^{mod}\mathbf{p}_{TCP}$ is compared with the known position ${}^{mod}\mathbf{p}_{MP}$ of the touched measuring point. The difference between the positions ${}^{mod}\mathbf{p}_{MP}$ and ${}^{mod}\mathbf{p}_{TCP}$ corresponds to the absolute position error of the bur tip (eq. 3). This is called the Target Registration Error (*TRE*). The *TRE* is influenced by the calibration of the mill (drill axis, bur length and diameter), the landmark registration, the production accuracy and tolerances of the tracker and instruments and the accuracy of the navigation camera.

$$TRE\left({}^{pat}\mathbf{p}_{TCP}\right) = {}^{mod}\mathbf{p}_{MP} - {}^{mod}\mathbf{p}_{TCP} \quad (3)$$

The position is stored in a ring buffer with 50 elements and during a measurement (when touching a measuring point) the average value from 50 consecutive measured values is calculated (eq. 4).

$${}^{mod}\mathbf{p}_{TCP} = \frac{1}{50}\cdot\sum_{i=1}^{50}\left(trans\left({}^{mod}\mathbf{T}_{pat}\cdot\left({}^{cam}\mathbf{T}_{pat,i}\right)^{-1}\cdot{}^{cam}\mathbf{T}_{probe,i}\cdot{}^{probe}\mathbf{T}_{TCP}\right)\right) \quad (4)$$

The measurement starts when the standard deviation (*sd*) of the bur tip is less than 0.3 mm (bur tip is held steady at a measuring point) (eq. 5). If σ increases during the measurement over 0.3 mm, the measurement is terminated automatically.

$$\sigma\left(trans\left({}^{cam}\mathbf{T}_{probe}\cdot{}^{probe}\mathbf{T}_{TCP}\right)\right) < 0.3\mathrm{mm} \quad (5)$$

After successful touching of a measuring point the navigation software calculates automatically the nearest

${}^{\text{mod}}\mathbf{p}_{\text{MP,closest}}$ from the touched measuring point ${}^{\text{mod}}\mathbf{p}_{\text{MP}}$ and creates an entry in the log file (eq. 6-8).

$$\text{Given} = {}^{\text{mod}}\mathbf{p}_{\text{MP,closest}} \tag{6}$$

$$\text{with} \left\| {}^{\text{mod}}\mathbf{p}_{\text{MP,closest}} - {}^{\text{mod}}\mathbf{p}_{\text{TCP}} \right\| = \min\left(\left\| {}^{\text{mod}}\mathbf{p}_{\text{MP,i}} - {}^{\text{mod}}\mathbf{p}_{\text{TCP}} \right\|, \forall {}^{\text{mod}}\mathbf{p}_{\text{MP}} \right) \tag{7}$$

$$\text{Transformed} = {}^{\text{mod}}\mathbf{p}_{\text{TCP}} \tag{8}$$

After the measurements the log file was transferred to a desktop computer and the results were evaluated as follows.

1.) The vector difference between the measured position of the bur tip when touching the measuring point *i* and the known position of the measurement point *i* (eq. 3). 2.) The amount of the *TRE* vector at each touched measuring point (eq. 9).

$$\left\| TRE\left({}^{\text{mod}}\mathbf{p}_{\text{TCP,i}} \right) \right\| \tag{9}$$

The average value of the position error over all *N* measuring points (eq. 10).

$$\overline{TRE} = \frac{1}{\text{N}} \cdot \sum_{\text{i}=1}^{\text{N}} TRE\left({}^{\text{mod}}\mathbf{p}_{\text{TCP,i}} \right) \tag{10}$$

The standard deviation of the position error over all measuring points (eq. 11).

$$\sigma(TRE) = \sqrt{\frac{1}{\text{N}-1} \cdot \sum_{\text{i}=1}^{\text{N}} \left(TRE\left({}^{\text{mod}}\mathbf{p}_{\text{TCP,i}} \right) - \overline{TRE} \right)^2} \tag{11}$$

III. Results

The experiment with the navigated measurement board was performed 15 times with both navigated drills and the three possible tracker positions. The four registration points were defined at the four landmarks (LM 1-4) in the corners of the measurement board (see Fig 5).

In all the 30 experiments the *FRE* has a mean value of 0.15 mm and a maximum value of 0.21 mm. With the existing drill system in the middle tracker position, an average *TRE* of 1.62 mm with a standard deviation (*sd*) of 0.33 mm was measured. With the new drill system in the middle tracker position, an average *TRE* of 1.14 mm (*sd* = 0.12 mm) was measured. Fig. 6 illustrates the results of the experiments using the navigated measurement board and both navigated drills with the tracker in the middle position.

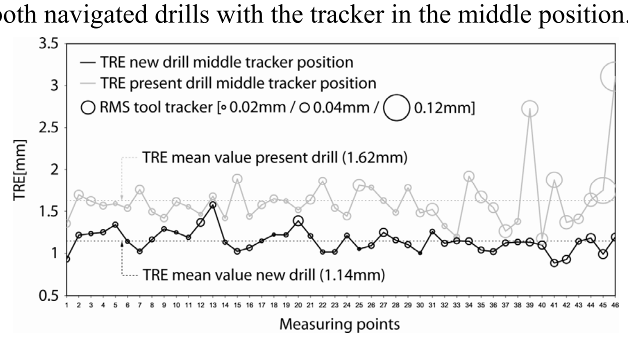

Fig. 6. *TRE* mean value, *RMS* and *TRE* for each of the 46 measuring points of the experiments with the new and the present drill system, both in the middle tracker position. The *FRE* was by mean 0.15 mm and max 0.21 mm.

With the existing drill system in the right tracker position, an average *TRE* of 1.76 mm (*sd* = 0.40 mm) was measured. With the new drill system in the right tracker position, an average *TRE* of 1.59 mm (*sd* = 0.14 mm) was measured. With the existing drill system in the left tracker position, an average *TRE* of 2.33 mm (*sd* = 0.54 mm) was measured. With the new drill system in the left tracker position, an average *TRE* of 1.10 mm (*sd* = 0.12 mm) was measured. It was measured that the new drill tracker has a consistently smaller *RMS* than the existing tool tracker. It was calculated that over the three tracker positions the new navigated drill is on average 0.62 mm more accurate.

IV. Conclusion

In this article a new navigated drill system for a navigation system for ENT-surgery was introduced and compared with an existing navigated drill system. Using a navigated measurement board and a surgical navigation system, the accuracy of both drill systems was measured.

Measurement errors can be caused by large *RMS* values of the smaller tool tracker. With the new tracker the *RMS* can be reduced and the accuracy of the navigated drill was increased. In the first clinical interventions the new drill showed many advantages in the clinical workflow.

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