Validation of custom active markers for use with a high accuracy tracking system

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***Abstract**:*
The success of an image-guided surgical procedure is dependent on a number of factors; foremost among these is the accuracy with which the positions of surgical tools can be determined relative to the patient. This information can be obtained using a variety of methods however in practice almost all available navigation systems utilize optical tracking. This work presents the validation of custom active tracking markers in combination with a high accuracy tracking system. Two evaluation methodologies are described; a relative positioning test in which the markers are moved in a known pattern throughout the camera workspace examining the positioning accuracy, and a rotation test designed to determine the effects of rotation on the tracked position of the locator. Position testing revealed a mean accuracy 0.019±0.019 mm, with a maximum error of 0.103 mm; rotation testing revealed a maximum deviation of 0.049 mm when rotating about a known axis, through a trackable range of approximately 80°. A maximum angular error 0.096° was noted when rotating about a known axis.

Key words: validation, optical tracking system, accuracy, robotics

1 Introduction

Computer assisted surgical (CAS) interventions often utilize optical tracking systems to increase accuracy and improve spatial positioning during surgeries. Depending on the type of surgery, the accuracy of such a system can be crucial for the success of the procedure. In particularly demanding applications, surgical robots can be combined with optical tracking to increase tool positioning accuracy and subsequently surgical outcomes.
Minimally invasive cochlear implantation is an example where exceptionally high tracking and tool placement accuracy, typically less than 0.5 mm [1], is required. Toward this end, a surgical robot system was developed at the University of Bern, which combines the high spatial accuracy of optical tracking with precise tool positioning available from robotic manipulation. This visual servoing technique, along with high precision patient to image registration, and customized tooling enables the system to achieve a high targeting accuracy of 0.15 ± 0.08 mm [2].
The integrated tracking system (CamBar B1, Axios3d, Germany) used in previous benchmarks has a specified accuracy of 0.05 mm [3]. The tracking system manufacturer recommends the use of printed paper markers, but problems associated with ambient lighting, aberrant reflections from the robot arm or other equipment, as well as low tracking frequency make this solution impractical for clinical use. The purpose of this work is to focus on the development of clinically relevant tracking hardware which overcomes the aforementioned limitations without compromising the tracking accuracy. The custom markers utilize active infra-red LEDs with a mask placed above as shown in Fig. 1. This allows the markers to be utilized without alteration of the existing image processing algorithms provided by the manufacturer. The goal of this work is to present an evaluation of the accuracy of the stereo camera in combination with the custom sterilizable active tracking markers.

2 Material and Methods

When considering the validation of tracking systems one must consider the difference between accuracy and precision; accuracy represents the ability of the system to closely identify the correct value of some parameter, while precision represents the ability of the system to reproducibly return the same value. There exist a variety of methods for testing the accuracy of tracking systems [4-7], this work focuses on validation methods which are directly applicable to the final application. Subsequently, three tests were defined: a static positioning test designed to evaluate the overall positioning accuracy of the tracking system within the complete workspace, and a second rotational test designed to ensure tracking accuracy at large angles as well as defining the trackable range. Finally, an angular test was defined in which the accuracy of the tracking when rotating the marker was examined.

Static Positioning Accuracy: A marker rigid body was attached to the X-Y table of a CNC machine (Picomax 20,

Figure 1: Developed sterilizable rigid body shield and robot tool (left). Set up for static positioning tests (right).

Fehlmann AG, Sion, Schweiz, accuracy <0.01 mm) and the camera positioned with the field of view approximately perpendicular to the rigid body face as in Figure 1. The camera was then rigidly fixed on a support connected to the ground. To eliminate problems with movement of the camera or vibration a second rigid body was attached within the camera workspace, stationary relative to the moving XY table of the CNC; all measured positions were taken relative to the reference rigid body. The CNC table was then moved in a plane with distances of 10mm between the points, covering the complete camera workspace. At each position 30 measurements were taken, resulting in a total of 1920 single points recorded in a grid of 64 known positions. A grid of the known positions was then generated in MATLAB (Mathworks, Natick, MA) and the ideal distances between the first point and each subsequent point calculated. The Euclidean distance of each measured point to the initial point was then calculated and compared to the ideal distance.
Rotational Positioning Accuracy: Rotational experiments were completed by fixing the marker rigid body to the spindle of a lathe, with the camera rigidly attached above. The spindle was then repeatedly rotated by hand until the rigid body was no longer visible by the camera. A circle was fit to the observed points; the radius of this circle was compared to the known (from CAD) radius of rotation. Errors were calculated based on the Euclidean distance between the fitted circle and observed rigid body positions.
Angular Accuracy: Testing of the angular accuracy of the developed locators was completed as follows: a single marker rigid body was attached to a turn table, with a reference rigid body fixed above. The marker was then rotated in known increments of 2.25° throughout the full range of visibility. Once the marker was no longer visible, the marker was rotated in the opposite direction with the same increment until no longer visible. At each 3.25° step a total of 30 points were taken; the angle observed between subsequent steps was then calculated and compared to the nominal value.

3 Results

The results of both the positioning and rotation experiments are shown in Table 1. Static tests reveal a mean positioning error of 0.019 mm with a standard deviation of 0.018 mm. The maximum observed positioning error was 0.103 mm. Rotational tests revealed an error of 0.021 mm from the observed radius to the known radius of rotation. A maximum deviation of 0.049 mm from the fitted circle was observed. Furthermore, the rigid body was trackable through an angular range of approximately 80°. A mean angular error of 0.003° was observed, with a standard deviation of 0.024° and maximum angular error of 0.096°. Fig. 2 shows the results of the positioning testing in the coordinate system of the CNC X-Y table, as well as the variation of the rigid body position from the fitted circle throughout the rotation. Note that for the rotation, the angle at which the rigid body was first visible was defined as 0°. A number of outliers were noted during the rotation testing, most of which occurred at approximately 12°; the reason for this is currently unknown, however further investigation is currently underway.

	Positioning (mm)	*Rotation (mm)*	*Angle (°)*
Radius	-	0.021	-
Mean	0.019	0.007	0.003
STD	0.018	0.005	0.024
Min	0.000	0.001	0.000
Max	0.103	0.049	0.096

Table 1: Results of positioning, rotation and angular tests; positioning results represent relative positioning errors throughout the camera workspace, rotation results describe the change in the position of the rigid body at different angles. Angle results describe the difference between the rotated angle and that calculated from the positions obtained from the tracking system.

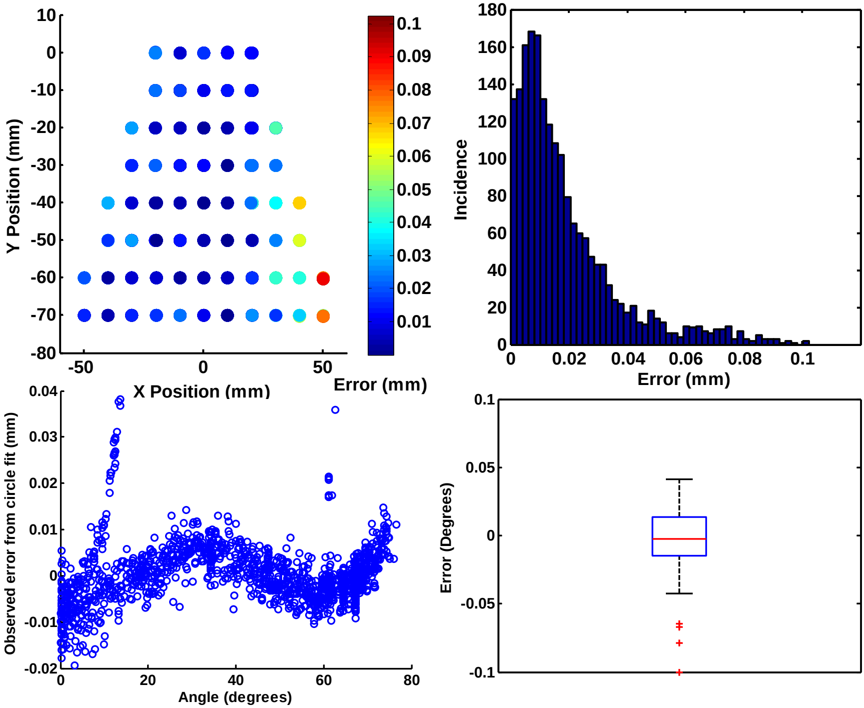

Figure 2: Results of relative positioning test; spatial distribution and histogram of observed positioning errors (top). Results of dynamic rotation and angular tests (bottom).

4 Discussion

This work has presented the validation of custom active tracking markers in combination with a high accuracy tracking system. The accuracy presented is similar to that described by the manufacturer; however the methodology is significantly different. The manufacturer defines testing of single points under a test protocol described by VDI/VDE 2634

[3]; while this information is interesting, it is not directly applicable to the case of intra-operative navigation in which at least 3 points are tracked in order create a coordinate system. While the accuracy of rigid body tracking is clearly dependent on the on the accuracy of single point tracking, the mathematical details of this relationship are described in [8], it is not always clear exactly how single point tracking accuracy affects rigid body definition and accuracy with a particular configuration of markers. The markers in question were designed with the recommendations found in [8] in mind; the tool axis is located along the major axis of the marker, the perpendicular distances from this axis were also maximized based on the size of the tool and the available camera workspace. Furthermore, [8] recommends increasing the distribution of points along the instrument axis in cases in which the trajectory error is important; this recommendation was also included in the design.

The positioning test defined within, in which the marker rigid body is tracked throughout the workspace, is designed to be directly applicable to the case of six-dimensional tracking of surgical tools. Although the marker rigid body is not moved throughout the full camera workspace, instead only on a plane within, the observed errors are dominated by those in the axial direction of the camera (approximately the Y-direction of the CNC X-Y table), suggesting that further movements throughout the workspace will lead to minimal changes in the results. The largest positioning errors occur at the rear and edges of the camera workspace; the largest observed error was 0.103 mm. Determination of positioning errors by comparison to the first observed point could potentially introduce additional errors (or lead to reduced errors) due to the noise in the camera system, however this relative positioning accuracy is of most interest in terms of the final application. As all tracking is completed relative to a reference marker, the relative movement i.e. relative distance moved by the marker is of most interest.

Tracking systems which utilize retro-reflective spheres as markers would be expected to be rotationally invariant, i.e. if the rigid body is rotated there should be no loss of accuracy, however the developed tracking markers utilize flat circular points which may be affected by changes in rotation. Additionally, there will be some maximum angle at which the flat points can be tracked. The rotation test described within is designed to examine the change in the position of the rigid body, defined as a point along the axis of the tool, if it is rotated about this axis. In terms of overall tracking accuracy, this means that the rotation of the tool relative to the camera will have little effect on the defined position of that tool. The results of this testing demonstrate that the change in the rigid body position is minimal through an angular range of 80°. Furthermore, angular accuracy testing reveals a maximum angular error of 0.096° when rotated throughout the full visible range. Rotation was completed around the major axis of the marker (i.e. the axis of the tool); due to the design of the markers and the relative inaccuracy in the axial direction of the camera, it can be expected that rotation about this axis would be the least accurate.

5 Conclusions

The accuracy observed after the completion of both static positioning, dynamic rotation and angular accuracy tests is sufficient for the defined application of minimally invasive cochlear access, and is similar to that observed in previous examinations of the tracking system accuracy as well as the manufacturer specifications.

7 References

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