

AN INTEGRATED CALIBRATOR AND VERIFICATION TOOL FOR ELECTROMAGNETIC NAVIGATION OF INTRAOPERATIVE COMPUTED TOMOGRAPHY

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INTRODUCTION

It is common for orthopaedic surgical navigation to be performed using optical tracking; however, this technology suffers from line-of-sight requirements and large tracker sizes. Electromagnetic (EM) tracking is an alternative tracking modality that provides highly accurate orientation measurements but less positioning measurement accuracy than optical tracking. EM systems have no line-of-sight requirement and can use small cylindrical sensors that are a few millimetres in diameter and 1cm long. These ergonomic factors are preferred for surgical navigation applications involving smaller anatomy, including the wrist and shoulder, for which optical targets are too large and bulky.

In surgical navigation, the transformation between the tracking system and any reference images must be accurately established. This calibration is often performed with a paired-point (Arun 1987) or iterative closest point (ICP) registration, both which requires collection of accurately known points in both the tracking and imaging systems.

In robotics, the inter-modality transform problem for two sensor systems is known as the 'hand-eye calibration problem' (Park 1994). These techniques require repeated pose measurements in each system, from which the registration is computed using orientation and position information collected from both systems. These methods have been applied in clinical settings (Malti 2010) and can be applied to characterize a fiducial visible in cone-beam computed tomography (CBCT) with an integrated EM tracker to build a calibrator for direct navigation. However, when applied to intraoperative imaging, the repeated pose measurements are time-intensive and calibration lacks any rapid verification check of registration validity.

This work describes the design and evaluation of a low-cost additively manufactured calibrator with an integrated verification tool, used to register an intraoperative CBCT image volume to an EM tracking system.

MATERIALS AND METHODS

In this study, an Aurora EM tracking system (Northern Digital Inc., Waterloo, CA) was used to track the calibrator and a 3mm diameter straight probe. Intraoperative CBCT imaging was performed with an Innova 4100 (GE Healthcare, Waukesha, US) isocentric C-arm.

The calibrator (Figure 1) was additively manufactured in ABS plastic. The base shape was a truncated cube tetradecahedron. The top face was instrumented with tantalum beads and each of the 4 side faces instrumented with a single bead. Through-holes of 3mm diameter perpendicularly connected opposing faces, producing 7 cylindrical paths that served as calibrator verification features. A dovetail joint, used to physically connect to other hardware, was clamped onto one face of the cube using nylon screws and also fixed a 6-degree-of-freedom (DOF) catheter-style EM sensor to the calibrator.

The calibrator was characterized using 10 different poses, captured in an operating room setting while raised 10cm above the carbon fibre patient table. Poses covered a wide range of positions and orientations within the CBCT volume. For each pose, a CBCT scan and 10 seconds of EM recordings were acquired.

In each scan, the calibrator beads were segmented, identified, and used to calculate the calibrator bead coordinate frame in CBCT. Each 10-second EM recording was simplified to an average pose. The transformation between the calibrator bead and calibrator EM frames was established using Park's hand-eye calibration method.

Target Registration Error (TRE) was established using an additively manufactured device with a central dovetail for calibrator fixation (Figure 1). This device had a planar surface with 14 fixed beads, arranged in an outwardly spiralled pattern, and six circularly distributed cubes with through-holes directed normally, radially, and tangentially to the plane. These features were segmented in CBCT and located relative to the calibrator with a 1s averaged 6-DOF EM probe pose recording. TRE was assessed as the residual between the CBCT-segmented bead positions and the probed measurements transformed into the CBCT frame using the calibrator transform. Axial TRE was calculated similarly, but with the CBCT axis directions based on the CAD and the measured bead locations.

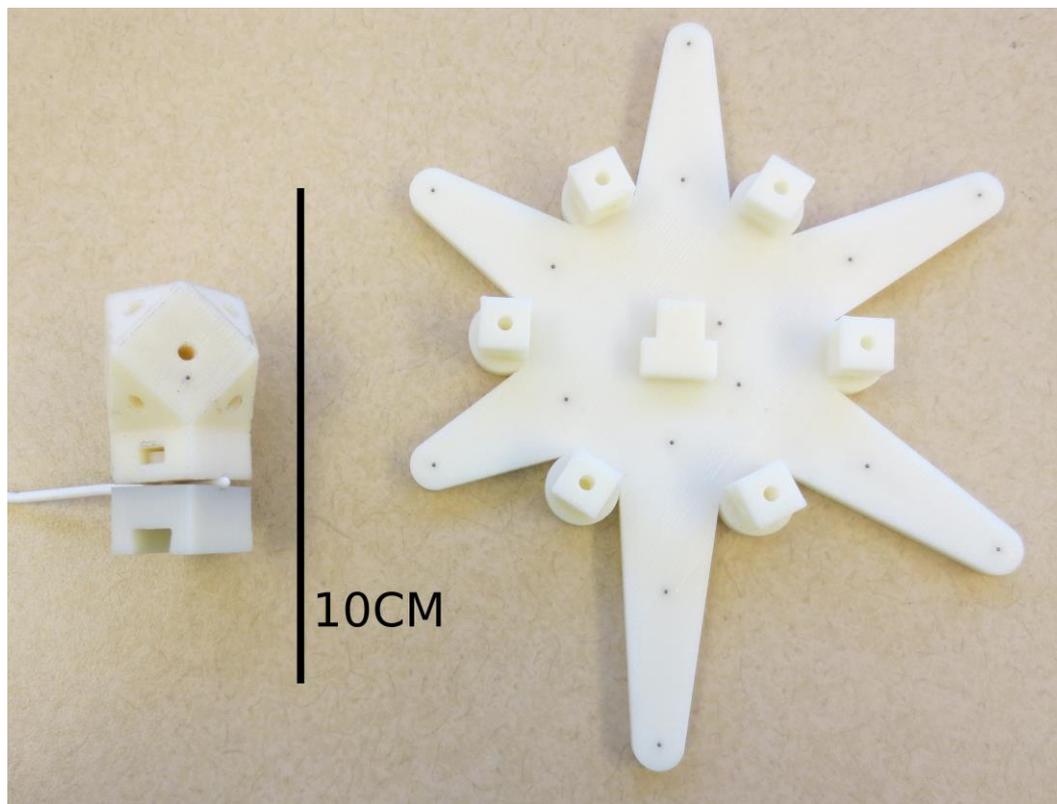


Figure 1: Calibrator (Left) and Target Registration Error (TRE) device (Right).

For calibration verification, the probe was placed in each path and a 1s recording was acquired and averaged to measure the probe axis and tip location relative to the calibrator. Axial error was calculated as the residual between the probed paths and designed manufactured axes. Translation error was calculated as the shortest inter-line distance between each path in the design and the measured probe longitudinal axis.

RESULTS

Hand-eye calibration was performed using 10 poses of the calibrator, captured in both EM and CBCT systems. Using the TRE device, the measured translation TRE was 3.14 ± 0.96 mm, and the measured angular TRE was 1.7 ± 0.7 degrees.

The calibration validation axes measured an inter-line distance of 0.92 ± 0.78 mm, and an axial difference of 1.1 ± 0.7 degrees.

DISCUSSION

The TRE assessment suggests that there was highly accurate orientation tracking in the surgical environment. This accuracy was consistent with optically-tracked drilling (Kunz 2008) and benchtop tests of EM (Lugez 2013). These promising results suggest the calibrator may be useful in a clinical setting.

The verification errors are of notably smaller magnitude than those measured using the TRE device. This is likely because of a different method of assessing translation. Using the line-line distance removes the need for precise probe depth measurement during verification, but means the result is not a point-to-point tracking accuracy. Regardless, this verification procedure provides a quantitative assessment of registration accuracy and could serve as a measure to compare registrations, identify calibrator sensor motion, or classify a poor registration.

Having a verification tool integral to the calibrator allows intraoperative registration verification without additional equipment, particularly if a tracked drill is used in a surgical procedure. The proposed registration process minimizes modifications to the surgical workflow while enabling intraoperative registration verification to potentially detect navigation anomalies.

This calibrator design is much smaller than many available optical tracking options, but somewhat large compared to wrist or shoulder anatomy. The overall size relates to the mechanical stability of the probe in each hole. A sensitivity study examining different sizes of cube or diameter of probe may allow the calibrator size to be reduced.

This technical study provides a proof of concept of this calibrator design for use in direct navigation for computer-assisted surgery.

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