Implementation on a New Tool Tip Calibration Method for Biomedical Applications

Woratit Onprasert, Songpol Ongwattanakul, and Jackrit Suthakorn*

Abstract. Tool tip calibration is an important procedure in most surgical navigations. Investigations on tool tip calibration have been done by several commercial navigation systems, such as, Medtronics, GE, BrainLAB and Materialize. Some of commercial navigation systems require a specific equipment to calibrate the tool tip. Such method is less flexible when performs with different tools. This paper proposes a new method to perform the tool tip calibration which requires the user to point the device's tool tip on a single pivot point for a set of motions. Optical tracking marker is employed by attaching it on the upper part of device to be calibrated. Position and orientation of the marker is calculated by capturing the motions of the marker rotated about the pivot point. The tool tip vector is computed and generated by our developed algorithm based on the concept of reversing the mean of homogeneous transforms or *SE(3)*. The experimental results have shown that collecting only 5 poses of the tool is the optimum point in term of computational time and accuracy for the algorithm.

Keywords: Tool tip calibration, Navigation system, Mean, Average, SE(3).

1 Introduction

Surgical navigation is increasingly used in various surgeries because performing the operation with guidance can be enhancing the accuracy and safety of the

Woratit Onprasert · Jackrit Suthakorn
Center for Biomedical and Robotics Technology, Faculty of Engineering,
Mahidol University, Thailand

Woratit Onprasert · Jackrit Suthakorn
Department of Biomedical Engineering, Faculty of Engineering Mahidol University, Thailand

Songpol Ongwattanakul
Department of Computer Engineering, Faculty of Engineering Mahidol University, Thailand
e-mail: egjst@mahidol.ac.th

* Corresponding author.

Z. Qian et al. (Eds.): Recent Advances in CSIE 2011, LNEE 129, pp. 385–392.
springerlink.com

pre-operative or intra-operative procedure. In conventional operation procedure, medical images are used during preoperative procedure for evaluation of pathology and anatomy then the surgeons will use their imagination to transfer this visual information to actual operation site. The decision to perform a surgery with or without navigation system depends on the expected benefit to the surgery.

In the last two decade, navigation technology become into a tool that solve problem in many clinical situations such as to map medical image on to real anatomy for image-guided surgery [1], use the position and orientation information in surgical robotics application[2], and many cases for neurosurgery. During operation, navigation markers are attached to surgical tools, three-Dimensional position and orientation of the navigation markers are given by surgical navigation system. In practical we need to know position of the surgical tool tip.

Tool tip calibration is the one that important procedure. It is a procedure to find the relationship between tool tip and attached marker which can be formed as a vector. The studies about tool tip calibration problem are implemented by some commercial navigation system such as Medtronics, GE, BrainLAB Vector Vision, and Materialize. Tool tip calibration for BrainLAB system is based on database. This method is lack of flexibility for every surgical tool. Materialize calibrates tool tip by using a special tool, surgical tools are pose on the special tool which attached with position sensor. The function of this special tool is like a reference marker. So this method require an extra tool which less flexibility [3].

The objective of this paper is to show the experimental result of our tool tip calibration method.

2 Applications

Tool tip calibration is one of procedure in navigation system. Figure 1 shows the diagram of ultrasound guidance system. This system is used in breast biopsy application to demonstrate the position of surgical tool and cancer image relatively in world coordinate system. This system is based optical tracking system which 3D position and orientation of all markers are given by using stereo camera. Homogeneous transformation matrices are used to describe the system. The significant relationship that will use in demonstration is the position and orientation of needle tip relative to cancer cell. Ultrasound image calibration and tool tip calibration are required to fulfill in the system equation.

The relationship ${}^{3}_{4}H$ is can be calculated by

$$ {}^{3}_{4}H = {}^{0}_{2}H\,{}^{2}_{4}H\left({}^{0}_{1}H^{-1}\right)\left({}^{1}_{3}H^{-1}\right) \tag{1} $$

From equation (1),

${}^{0}_{2}H$ represents position and orientation of attached needle marker relative to stereo camera coordinate.

${}^{2}_{4}H$ represents position and orientation of needle tip relative to attached needle marker.

${}^{0}_{1}H$ represents position and orientation of attached ultrasound probe marker relative to stereo camera coordinate.

${}^{1}_{3}H$ represents position and orientation of object in ultrasound image relative to attached ultrasound probe marker

Another example that requires tool tip calibration process is Dental implant surgical navigation system. For pre-surgical planning, this navigation system helps to visualize the target region and desire pathway associated with real organ and CT data.

3 Material and Method

3.1 Tracking Device

We use a navigation system based on optical tracking system (Polaris Vicra®, Northern Digital). The tracking system consists of a processing unit and a stereo camera that emits infrared light. The light will be reflected by some small spheres that arrange in a specific geometric configuration which we can call “passive marker”. Position and orientation of the marker are calculated and given by the Polaris software. Figure 2 shows the optical tracking system and the passive marker.

3.2 Algorithm Implementation

Raw data from tracking system has been collected as a .csv file. MATLAB® program is used to open .csv file and manipulated raw data. Implementation of our tool tip calibration algorithm also performs on MATLAB®.

3.3 Tool Tip Calibration Algorithm

In this article we use $\vec{P}_{tip}$ as a vector that represent the position of tool tip relative to coordinate frame of attached marker. The method to find $\vec{P}_{tip}$ is to use the device touch on the pivot point. Homogeneous transformation matrix is calculated all the time when the device moves to new position while the tool tip stays at the same point on pivot. Homogeneous transformation matrix is formed into 4x4 matrix, the matrix consists of 3x3 rotation matrix and 3x1 position vector. Figure 3 illustrates the method to find $\vec{P}_{tip}$.

From figure 3 $\vec{P}_{tip1}$, $\vec{P}_{tip2}$ and $\vec{P}_{tip3}$ is the same vector which are the vector represent the relationship between tool tip and each pose of the tool. For this case we can write

$$\vec{P}_{tip1} = {}^{0}_{1}H^{-1}({}^{0}_{2}H)\vec{P}_{tip2} \tag{2}$$
$$\vec{P}_{tip2} = {}^{0}_{2}H^{-1}({}^{0}_{3}H)\vec{P}_{tip3} \tag{3}$$
$$\vec{P}_{tip3} = {}^{0}_{3}H^{-1}({}^{0}_{2}H)\vec{P}_{tip1} \tag{4}$$

The idea is (1), (2) and (3) should give the same value of $\vec{P}_{tip}$. At first $\vec{P}_{tip1}$, $\vec{P}_{tip2}$ and $\vec{P}_{tip3}$ are unknown parameters so the step to find tool tip vector are

Step 1: Define initial 4x1 vector for example

$$\vec{P}_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \text{; The last row has to be "1"}$$

Step 2: Use vector $\vec{P}_0$ substitute on the right hand side of (1), (2) and (3) instead $\vec{P}_{tip1}$, $\vec{P}_{tip2}$ and $\vec{P}_{tip3}$ so these equation will be

$$\vec{P}_{tip1} = {}^{0}_{1}H^{-1}({}^{0}_{2}H)\vec{P}_0 \tag{5}$$
$$\vec{P}_{tip2} = {}^{0}_{2}H^{-1}({}^{0}_{3}H)\vec{P}_0 \tag{6}$$
$$\vec{P}_{tip3} = {}^{0}_{3}H^{-1}({}^{0}_{2}H)\vec{P}_0 \tag{7}$$

Step 3: Average $\vec{P}_{tip1}$, $\vec{P}_{tip2}$ and $\vec{P}_{tip3}$ from the second step by using follow equation

$$\vec{P}_1 = \overrightarrow{(P_{tip1} + \vec{P}_{tip2} + \vec{P}_{tip3})}/3 \tag{8}$$

Step 4: Use $\vec{P}_1$from step 3 substitute $\vec{P}_0$ in step 2

Step 5: Do the iteration from step 2 to step 4 until $\vec{P}_{tip1}$, $\vec{P}_{tip2}$ and $\vec{P}_{tip3}$ are about the same.

From step 2 to step 5 are iteration calculation. For k times of iteration and n number of the poses, equation (8) is developed into

$$P_k = \left(\frac{{}^{0}_{1}H^{-1}({}^{0}_{2}H) + {}^{0}_{2}H^{-1}({}^{0}_{3}H) + \cdots + {}_{n-1}{}^{0}H^{-1}({}^{0}_{n}H) + {}^{0}_{n}H^{-1}({}^{0}_{1}H)}{n}\right)^k P_0 \tag{9}$$

Consider that ${}^{0}_{1}\mathrm{H}^{-1}({}^{0}_{2}\mathrm{H}) = {}^{1}_{2}\mathrm{H}$ which is the homogeneous transformation matrix represent position and orientation of pose {2} relative to pose {3} e.g. So the reduction form of (9) is

$$P_k = \left(\frac{{}^{1}_{2}H + {}^{2}_{3}H + \cdots + {}^{n-1}{}_{n}H + {}^{n}_{1}H}{n}\right)^k P_0 \tag{10}$$

Let us denote $\widetilde{\mathrm{A}} = \left(\frac{{}^{1}_{2}\mathrm{H} + {}^{2}_{3}\mathrm{H} + \cdots + {}^{\mathrm{n}-1}{}_{\mathrm{n}}\mathrm{H} + {}^{\mathrm{n}}_{1}\mathrm{H}}{\mathrm{n}}\right)$. Matrix $\widetilde{\mathrm{A}}$ is constructed from summation of all homogeneous transformation matrixes between a pose and another pose divided by a scalar value. So matrix $\widetilde{\mathrm{A}}$ is 4x4 matrix which contain average of rotation matrix and average of vector which we can write

$$\tilde{A} = \begin{bmatrix} \frac{\sum \tilde{R}}{n} & \frac{\sum \vec{p}}{n} \\ \vec{0}^T & 1 \end{bmatrix} \tag{11}$$

The development of this algorithm comes up into 4x4 matrix multiplication. First we have to construct matrix $\widetilde{\mathrm{A}}$ then multiply this matrix k times which is $(\widetilde{\mathrm{A}})^{\mathrm{k}}$. The result from this calculation will be 4x4 matrix and we use the last column of this matrix to represent tool tip vector. For number of n and k that are suitable for this method will be discuss in the experimental result section.

4 Experiment Setup and Result

4.1 Tool and Equipment

1. Optical navigation system, Polaris Vicra®,Northern Digital with 20 Hz update rate, position and orientation data transmission to a PC via an USB 2.0 interface.
2. A passive optical navigation marker
3. Pivot phantom
4. MATLAB® program for calculation

4.2 Experimental Setup

The experiment has been implemented by pivoting the tool as show in figure 4b. There are 35 pivot points that we use to collect the data for testing our algorithm. The pivot phantom is made from acrylic because we desire to reduce the error during machining process. The pivot tip can be dislocation cause from corrosion of machining tool.

The distance between each pivot point is 20 mm. as show in figure 4a. All 35 data set are implemented by our algorithm to test repeatability of PATM algorithm. For each set of data, a hundred poses are collected and k value that we use is 10000.

4.3 Experimental Result

From all set of data the results come to be 35 vectors. The average of these vectors is (-17.55, 1.30, -159.61) in millimeter unit with the magnitude standard deviation is 4.40. The position of each pivot point is calculated by using rigid transformation calculation. Standard deviation parameter of each data set is used to identify repeatability of the algorithm. Magnitudes standard deviations of pivot positions are varying from 0.32 to 4.71.

The amount of pose (n) that effect to convergent ability of the algorithm is shown in figure 5.

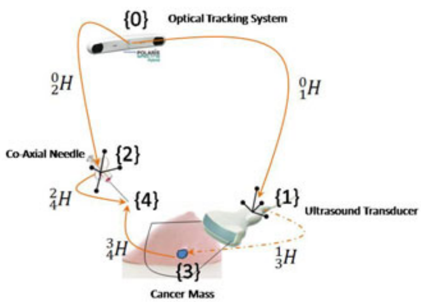

Fig. 1 Ultrasound Guidance System

Fig. 2 The Optical tracking system and the passive marker

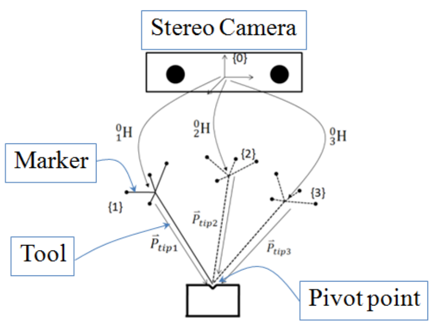

Fig. 3 All relationship for various pose of the tool.

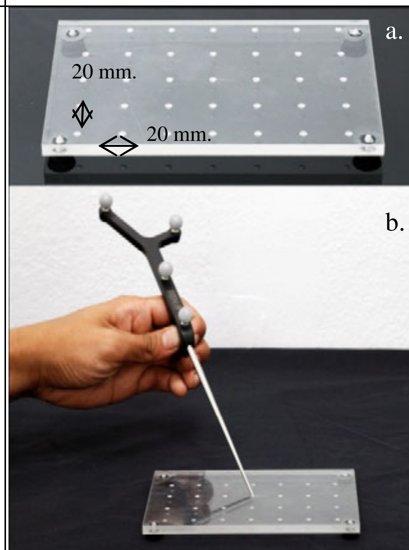

Fig. 4 Data collections from 35 pivot points.

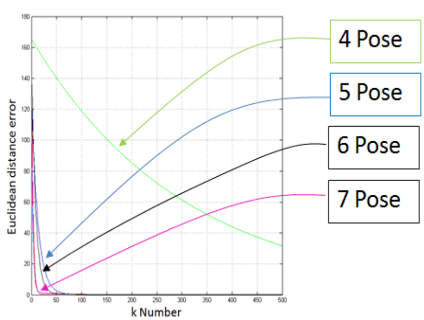

Fig. 5 Convergent evolution of the algorithm

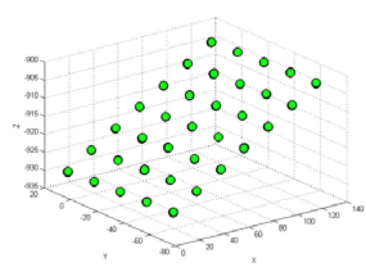

Fig. 6 Position of pivot point phantom in stereo camera coordinate

According to figure 5, increasing number of measurement pose which use in calculation is increasing convergent ability of the algorithm. For k number that make Euclidean distance error reduce to 0.01 is around 200 while n = 5. The result show that when n = 5 can give an affecting value of k compare with n = 8.

Another parameter that we observe is computational time requirement for calculation. For MATLAB® program, ten thousand times 4x4 matrix multiplications are taking time 7.1 millisecond. Refer to figure 5, we found that we can reduce computational time by taking only 200 times matrix multiplication while the Euclidean distance error is near to 10000 times multiplication. Computational time requirement for construct matrix $\tilde{A}$ and 200 times 4x4 matrix multiplications by using MATLAB® program for calculation is 6.6 millisecond.

For practical test, the average vector that we get from our experiment is tested by pointing all pivot point on pivot phantom. For each pivot point we collect ten position and orientation of the passive marker then multiply with the vector to get position of each pivot point in stereo camera coordinate. All of these position data is plot in 3D space coordinate as show in figure 6.

According to figure 6, all position of pivot points are relatively same as the actual pivot phantom.

5 Conclusion

This paper gives introduction about navigation system for surgical task. Many cases for surgical navigation require tool tip calibration procedure. Our tool tip calibration algorithm is described. Repeatability of this algorithm is tested by using 35 dataset. The algorithm always works for all of dataset. The standard deviation of the vectors that obtain from the experiment is (2.62, 1.16, 3.53). To implement tool tip calibration by using this algorithm require construction of a special matrix then repetitious matrix multiplication. From the experiment, collecting only 5 poses is a yield point in term of computational time requirement for this algorithm. This work is a one part of our project, ultrasound guidance system. This project requires tool tip calibration procedure for needle tip calibration.

Acknowledgment. We would like to thank you BART LAB, faculty of engineering, Mahidol University for all of equipment. All of BART LAB members for kindly help in everything. Professor Danai Laksameethanasan whose give an idea to further develops the algorithm. The project is support by the Thai Government Budget through Mahidol University and the National Metal and Materials Technology Center (MTEC) of Thailand under the Project No. MT-B-50-BMD-14-125-G.

References

[1] Hong Tran, H., Matsumiya, K., Masamune, K., Sakuma, I., Dohi, T., Liao, H.: Interactive 3D Navigation System for Image-Guide Surgery. The International Journal of Virtual Reality, 9–16 (2009)

[2] Stolka, P.J., Henrich, D.: Improving Navigation Precision of Milling Operation in Surgical Robotics. In: IEEE/RSJ, IROS (2006)

[3] Lorsakuul, A., Suthakorn, J., Sinthana, C.: Point-Cloud-to-Point-Cloud Technique on Tool Calibration for Dental Implant Surgical Path Tracking. Progress in Biomedical Optics and Imaging 9 (2008)
[4] Ewers, R., Schicho, K., Undt, G., Wanschitz, F., Truppe, M., Seemann, R., Wagner, A.: Basic Research and 12 years of clinical experience in computer assisted navigation technology: a review. Int. J. Oral Maxillofac. Surg. 34, 1–8 (2005)
[5] Lango, T., Lindseth, F., Tangen, G.A., Kaspersen, J.H., Ommedal, S., Hernes, T.A.N.: Tool navigation in ultrasound guided interventions. J. Ultrasound Med. Biol. (2002)
[6] Taylor, R.H., Stoinovici, D.: Medical Robotics in Computer-Integrated Surgery. IEEE Transactions on Robotics and Automation 10(3), 261–275 (1994)
[7] Craig, J.: Introduction to Robotics Mechanics and Control. Pearson Prentice Hall (2005)
[8] Moakher, M.: Means and averaging in the group of rotations. SIAM J. Matrix Anal. Appl. 24(1) (2002)