

On the Design and Development of A Breast Biopsy Navigation System: Path Generation Algorithm and System with Its GUI Evaluation

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Abstract— Breast cancer is a major problem for women throughout the world. It is the second most common factor for women’s death. Therefore, early detection by breast biopsy is a necessary process for decreasing the mortality rate. In the breast biopsy process, a surgical specialist is required. Moreover, the traditional breast biopsy procedure is based on 2D real-time ultrasound images guidance, while the procedure is done on a soft-breast tissue with 3D objects. To increase the surgeon’s performance in breast biopsy, and to reduce the error opportunity, we propose to develop a breast biopsy navigation system using optical tracking system and a passive robotic needle holder. This paper focuses on the process of developing the path generation algorithm, prototyped breast biopsy navigation system and its graphical user interface (GUI) that displays details to guide the surgeon in performing the procedure. A number of experiments have been done to test and evaluate the efficiency of the navigation system and its GUI. The result shows the success rate of this system is about 80%.

Keywords— Breast Cancer, Breast Biopsy, Surgical Navigation System, Optical Tracking System, Surgical Robot, 3D Slicer, GUI.

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I. INTRODUCTION

BREAST cancer is a major problem for women throughout the world. It is the second most common factor for women’s death [1]. Therefore, early detection by breast biopsy is a necessary procedure for decreasing the mortality rate [2]. Presently, a number of surgical navigation systems have been developed and deployed for guiding surgeons to perform their tasks with better accuracy and higher efficiency. These systems are extensively employed in several surgical applications, such as, neurosurgery, orthopedics, ear, nose and throat (ENT) surgery [3]. The traditional breast biopsy procedure is based on 2D real-time ultrasound image guidance which is insufficient for a diagnosis. To increase the surgeon’s performance and reduce human error in biopsy needle insertion, several research group have developed navigation system and graphic user interface to guide the breast biopsy process. For example, a real-time 3D virtual reality navigation system using an open MRI has been developed for breast conserving surgery [4]. The nonpalpable breast tumor can be detected in this system. Another research uses 3D ultrasound navigation system for breast cancer surgery [5]. This system is more accurate than palpation, and is also useful for visualizing and detecting the breast cancer. In our main research, we are developing a breast biopsy system which consists of soft-breast tissue modeling, a passive robotic needle holder with 5 degrees of freedom, and a navigation system with graphic user interface (GUI). The passive robot is developed for assisting the surgeon to hold the needle while they perform the breast biopsy. The GUI is developed for guiding the surgeon to insert the needle into the breast. This system uses optical tracking with high accuracy and high update rate (1.2 Mb/s) to follow the movement of the needle and breast phantom in real-time. Figure 1 shows the overview of system.

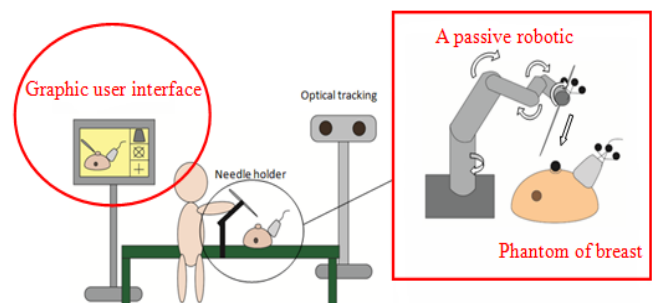


Fig. 1: The overview of our breast biopsy navigation system with a passive robotic needle holder.

This paper focuses only on the process of developing the navigation system and its GUI with interactive design. 3D slicer, an open source software that is conventionally used with medical imaging, is used for guiding the surgeon while performing breast biopsy in real-time. The process of calculating the insertion path is also described in this paper.

II. DESIGN AND DEVELOPMENT OF THE PROTOTYPED NAVIGATION SYSTEM FOR BREAST BIOPSY

The main purpose of our breast biopsy navigation system is to display its GUI for guiding the surgeon while inserting the needle in a breast biopsy procedure. The relationship between camera coordinate and objects is calculated by homogeneous transformation matrix. The insertion path is generated by considering the shortest way between the breast surface and cancer. The real-time 3D models of breast phantom, breast cancer, biopsy needle and insertion path are displayed in our GUI using 3D Slicer.

The process overview of the navigation system is shown in Figure 2. The position and orientation data of passive markers are imported to the system's computing unit using PC with Intel Core 2 Duo 2.8 GHz CPU and 4 GB RAM. A MATLAB program is developed to calculate the relationship of objects. The homogeneous transformation matrix of needle, breast phantom, and the insertion path are sent to 3D Slicer for displaying the movement of their models in real-time. The GUI is designed for displaying the insertion path and guiding the surgeon in needle insertion process.

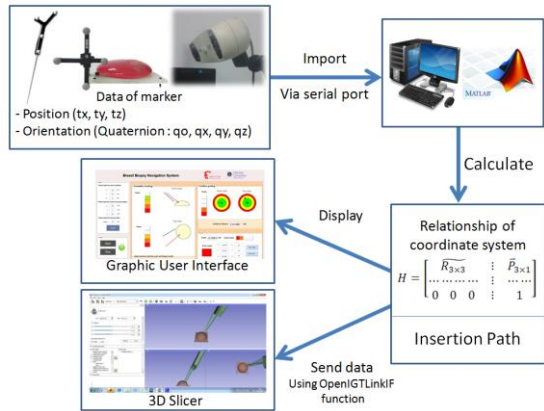


Fig. 2: Process overview of our breast biopsy navigation system.

Breast biopsy navigation is based on an optical tracking system. The Polaris®Vicon® optical is used for tracking the passive markers that are attached to the biopsy needle and the breast phantom base. The position and orientation of markers are calculated by Polaris software, and sent to the system's computing unit. The position vector with respect to the camera coordinate can be written as

$$\vec{P} = \begin{bmatrix} P_{x_{camera}} \\ P_{y_{camera}} \\ P_{z_{camera}} \end{bmatrix} \quad (1)$$

The rotation data from the optical tracking is described in quaternion [6], which is the four-dimension vector space. The quaternion equation can be written as

$$Q = q_o + q_x i + q_y j + q_z k \quad (2)$$

The quaternion data is converted into a rotation matrix using equation (3)

$$\tilde{R} = \begin{bmatrix} 1 - 2q_y^2 - 2q_z^2 & 2(q_x q_y - q_z q_o) & 2(q_x q_z + q_y q_o) \\ 2(q_x q_y + q_z q_o) & 1 - 2q_x^2 - 2q_z^2 & 2(q_y q_z - q_x q_o) \\ 2(q_x q_z - q_y q_o) & 2(q_x q_o + q_y q_z) & 1 - 2q_x^2 - 2q_y^2 \end{bmatrix} \quad (3)$$

A. Coordinate relationship between tools and phantom

The relationship between breast phantom, needle, and insertion path is calculated using a homogeneous transformation matrix [7] that can be written in equation (4).

$$\tilde{H}_{4 \times 4} = \begin{bmatrix} \tilde{R}_{3 \times 3} & \vdots & \vec{P}_{3 \times 1} \\ \dots & \vdots & \dots \\ 0 & 0 & 0 & \vdots & 1 \end{bmatrix} \quad (4)$$

Figure 3 shows the relationship between each marker with respect to the world coordinate system.

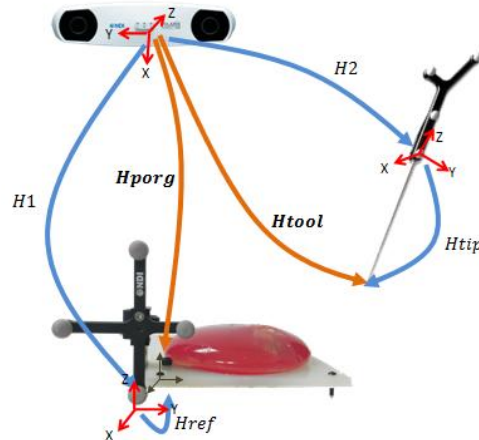


Fig 3: Homogeneous transform relationships among objects with respect to the world (Camera) coordinate system.

The position of the instrument's tip (\vec{P}_{tip}) is calculated by point-cloud-to-point-cloud tool tip calibration method from our previous work in [8] as shown in equation (5). The homogeneous transformation matrix is calculated with respect to time when the instrument moves with the same pivot point as shown in Figure 4.

$$R_k \vec{b}_{tip} - \vec{b}_{post} = -\vec{p}_k \quad (5)$$

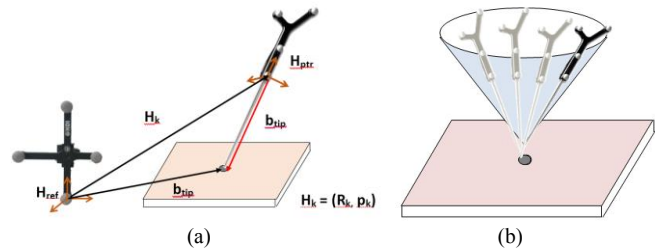


Fig 4: (a) Our point-cloud-to-point-cloud tool tip calibration method [8] (b) Various positions of P_{tip} to calculate the transformation matrix.

Then, the homogeneous transformation matrix between the camera and instrument's tip is calculated using equation (6), and the homogeneous transform between camera and reference point is calculated using equation (7), based on Figure 3.

$$H_{tool} = H_2 H_{tip} \quad (6)$$

$$H_{porg} = H_1 H_{ref} \quad (7)$$

B. Path generation algorithm

The surgical path generation for needle insertion is calculated for guiding the surgeon to move the needle into the correct position and orientation. The position of the needle insertion is calculated by the condition of the shortest distance between the breast phantom surface and cancer using Lagrange multiplier theorem [9] as shown in equation (8).

$$\nabla f(x, y, z) = \nabla \lambda g(x, y, z) \quad (8)$$

When $f(x, y, z)$ is a minimum distance between cancer and breast surface, so x , y and z on the constraint surface $g(x, y, z)$ makes $f(x, y, z)$ to be the shortest can be determined. $f(x, y, z)$ can be described by equation (9)

$$f(x, y, z) = (x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 \quad (9)$$

We are aware that the real breast is a non-rigid soft tissue. Therefore, the other part of our research is parallelly investigating and developing soft breast tissue model. However, in this part we assume a breast to be a simple hemisphere shape to separately explore the basic algorithm, so $g(x, y, z)$ can be described by equation (10)

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = r^2 \quad (10)$$

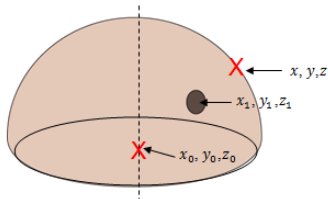


Fig. 5: Diagram shows the hemisphere origin (x_0 , y_0 and z_0), the cancer's position (x_1 , y_1 and z_1) and the position on the hemisphere surface that gives the shortest path.

C. Graphical User Interface (GUI)

3D Slicer software is used for visualizing a real-time movement of 3D models. Furthermore, the GUI on MATLAB is developed for displaying the trajectory insertion and guiding the surgeon to perform needle insertion.

Figure 6 shows the real-time movement of 3D models that consist of breast phantom, breast biopsy needle and insertion path. The insertion path is designed in tube shape and covered with the cone shape that can help the surgeon move the needle to the insertion path region easier.

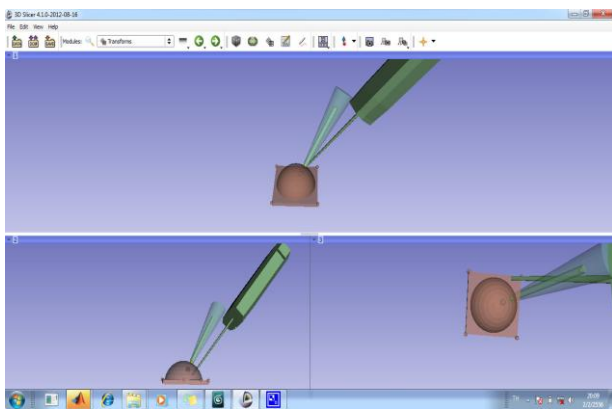


Fig 6: Real-time movement of 3D models in 3D Slicer Software.

The GUI of breast biopsy navigation system is developed using MATLAB. Our GUI is separated into 5 panels as shown in Figure 7.

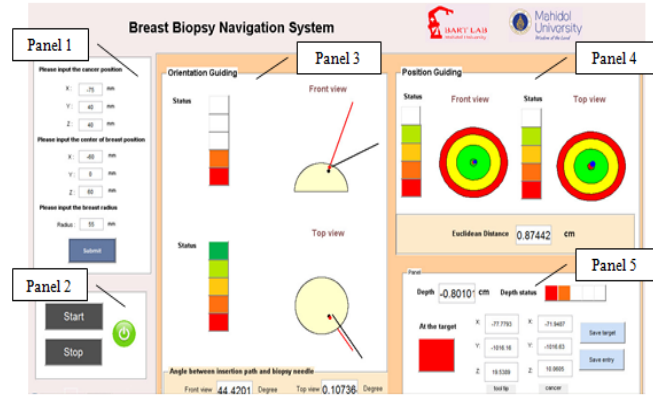


Fig 7: Graphic User Interface (GUI) of breast biopsy navigation system

Panel 1 is a panel to input the cancer's position, breast's center position and breast's radius. Panel 2 is a panel of "Start" and "Stop" buttons. Panel 3 is a panel of orientation guiding with "Front view" and "Top view" of breast. A red line shows the insertion path and black one shows the biopsy needle. While the surgeon is moving the needle, the black line is also moving and rotating with the same position as the needle in real-time. The status bar in Panel 4 shows the current status of an angle between the needle and the insertion path. The angle between the needle and insertion path shown in Figure 8, are determined by vector dot product as seen in equation (11).

$$\vec{V}_1 \cdot \vec{V}_2 = |\vec{V}_1| |\vec{V}_2| \cos \theta \quad (11)$$

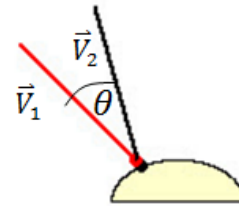


Fig 8: Diagram shows the breast phantom in the front view.

Panel 4 is a panel of position guiding. In this panel, the position of the needle's tip (blue point) and the entry point (red point) is displayed in Front view and Top view. The surgeon needs to move the needle until aligning at the same position as the entry point. The status bar shows the current status of the Euclidean distance between the needle tip and the entry point of the insertion path. The Euclidean distance is calculated using the equation (12).

$$d(P, Q) = \sqrt{(p_x - q_x)^2 + (p_y - q_y)^2 + (p_z - q_z)^2} \quad (12)$$

Where P is the position at the entry point of insertion path
Q is the position at the needle tip

Panel 5 is a panel that displays depth between needle tip and target. This panel also displays a sign that will change from red to green color when the surgeon reaches the target.

III. EXPERIMENTAL EVALUATION AND ITS RESULT

GUI compatibility experiment is emphasized on efficiency investigation on the navigation system alone without using the robotic needle holder. The experiment consists of 2 conditions; 1) displaying only MATLAB GUI and 2) displaying both MATLAB GUI and 3D Slicer GUI as shown in Figure 9.

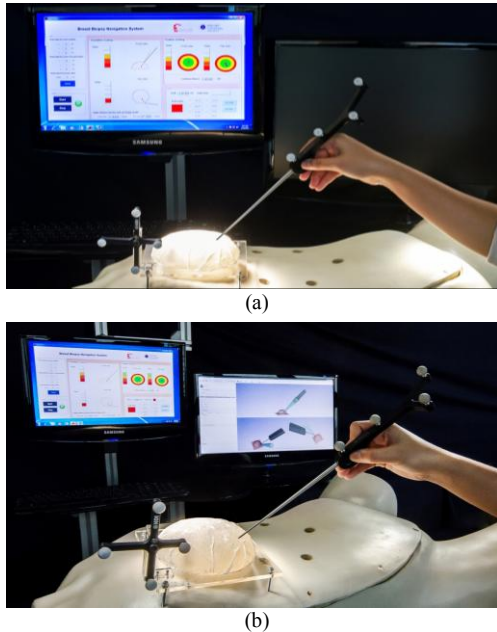


Fig 9: GUI compatibility experiment (a) MATLAB GUI (b) MATLAB GUI and 3D Slicer GUI.

The experiment is done by 10 users (without surgical experience) for 10 times per person. The result of average time and the success rate are compared on the bar chart in the Figure 10.

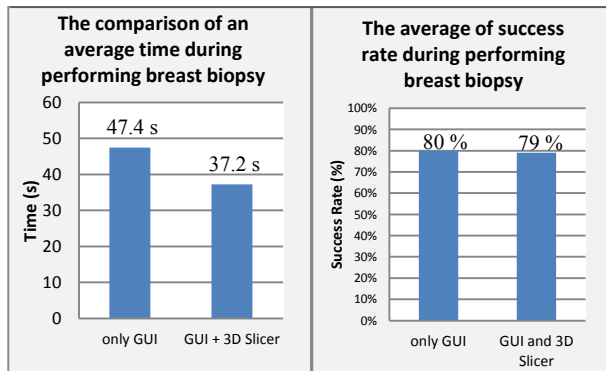


Fig 10: The bar graph shows the result of experiment

Parameter	Displaying only GUI on MATLAB	Displaying GUI on MATLAB and 3D Slicer
Root mean square Euclidean distance error (mm)	2.85	3.69
The average of breast biopsy performance time (s)	47.4	37.2
Success rate (%)	80%	79%

Table 1: Parameters and results from the evaluation in GUI compatibility for both groups of GUI and GUI plus 3D Slicer.

Table 1 shows the parameters of the evaluation of GUI compatibility from both conditions. From the results, the efficiencies from both conditions are not much different. In the other hand, to insert the needle and reach on the target by using only GUI has higher opportunity above using both GUI and 3D Slicer. This is because the users are easier to follow and make decision from looking at one screen of GUI only. Several users are unable to understand and follow the 3D objects in 3D Slicer.

IV. DISCUSSION AND CONCLUSION

An algorithm for Breast Biopsy surgical path generation was developed. An early prototyped navigation system for breast biopsy had been done with its GUI evaluation. The GUI consisted of 2 paths, (1) only GUI and (2) GUI plus 3D Slicer. The results from our evaluation on both, the GUI and GUI plus 3D Slicer, had shown high success rates. The GUI made by MATLAB is able to hold the up-to-date measured in this procedure. In the same experiment, the navigation system had an easy learning curve. Therefore, the users can perform breast biopsy procedure with our navigation despite limited experience with the navigation system. The limitation of our system is the path generated algorithm is based on hemisphere breast model. Our separated research works on soft-breast tissue modeling, Real-time 2D Ultrasound image acquiring, and robot-guiding system are to be integrated to the presented navigation system.

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