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On the Design of A Biopsy Needle-Holding Robot for A Novel Breast Biopsy Robotic Navigation System

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***Abstract*—Nowadays, breast cancer is the most common female cancer worldwide. The widely use of mammogram and ultrasound (US) increases the possibility to detect the nonpalpable lesions. Core needle biopsy (CNB) under US guidance for the lesions detected on US is the procedure of choice to retrieve tissue for histopathologic study, resulting in appropriate treatment planning. This procedure requires skill and experience of radiologist in order to obtain the sufficient tissue for accurate histopathologic diagnosis. Our new breast biopsy guidance system comprises of a passive robotic needle and its graphical user interfaces: GUI on MATLAB and 3D Slicer interface based on real-time data from optical tracking system. The passive robot consists of 5 DOFs; the first and the second DOFs are for translation curvature, the third and fourth DOFs are for rotation motions, and the fifth DOF is for needle insertion. The robot is designed based on breast features, and its movements are based on friction method. The robot has high tensile strength and good impact resistance due to Polyoxymethylene (POM) or Polyacetal is used as its material. The experimental results have shown very high success rates to perform simulated breast biopsy, and the robot can increase the accuracy and proficiency of needle insertion.**

Keywords—Breast biopsy; 3D Slicer; tracking system; needle insertion; passive robotic needle holder

I. Introduction

Breast cancer is the most common female cancer, comprised about 47.8% of all female cancers [1]. Early detection of breast cancer is very important, not only decreases mortality from breast cancer, but also decreases morbidity from treatment.

There are many methods to diagnose and to characterize breast cancer by using diagnostic tools, such as, mammogram, ultrasound, 3D-ultrasound, MRI and CT [2-6]. If the suspicious lesion is detected by diagnostic devices, tissue retrieval for histopathologic diagnosis for further treatment planning is mandated. An ultrasound-guided breast biopsy is a widely used method for hitopathologic diagnosis. This method is less invasive, and is causing minimal scarring. The radiologist firstly targets the suspicious lesion by ultrasound (US), then a biopsy needle is percutaneously inserted by free-hand technique. The biopsy needle is real-time monitored by US. The accuracy of needle insertion is important and necessary for accurate biopsy. Like the other medical intervention procedures, core needle biopsy (CNB) under US guidance requires skill and experience of the radiologists.

There are a number of researchers who investigate various methods to improve the accuracy of CNB under US guidance. Robotic assistance percutaneous was considered in [7-9], while [10] is an example of research on US guidance robot. One of the biopsy robots is the PAKY-RCM, developed for radiologic needle insertion [11]. Another research was to target and manipulate tumor by set of generating appropriate external force on a robotic manipulators with controlling system [12]. Its movements were similar to stereotactically guided breast biopsy [13], but their control systems were different. In terms of passive function, a passive manipulator was applied in a robotic system for US-guided hepatic microwave coagulation therapy [14]. The system consisted of 5 DOFs passive robot, a surgical planning providing graphic user interfaces and a magnetic tracking device.

In this paper, we aim to develop a breast biopsy navigation system with a passive robotic needle holder and GUI on MATLAB and 3D Slicer interface based on real-time data from optical tracking system as shown on Fig. 1.

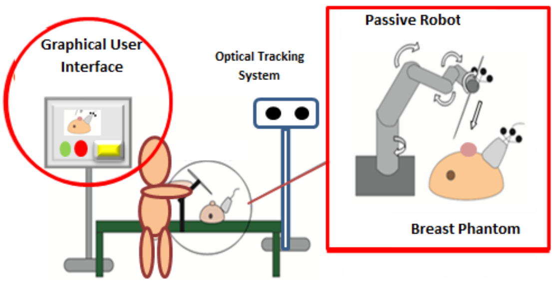

Fig. 1. The overview of our new breast biopsy

The research is supported by the Computer-Integrated Intelligent Medical System Project under the National Research University Grant through Mahidol University, and the Integration of Surgical Navigation and Surgical Robotics for Breast Biopsy in Breast Cancer using Mammogram and ultrasound Images on Breast Mathematical Model Project under the Government Research Budget through Mahidol University.

The overall research on our breast biopsy guidance system is separated into two parts; realistic breast modeling, and the investigation presented in this paper. Therefore, the system presented here is simplified to be a nondeformable hemisphere shape. The positions related to 3D breast model and tumor are designed and assumed as a set of known information from the realistic breast modeling part. These positions are, then, simulated in 2D and 3D images. The path generation algorithm of needle insertion is formulated based on 3D vector space and Lagrange equation. All guidance information is displayed on GUI using MATLAB and 3D slicer to guide the radiologist while the needle is held by the passive robotic needle holder and radiologist, simultaneously.

The passive robot is chosen in our system to remain the radiologist's role and reliability. The using of our robot along with the radiologist can make a better straight line of needle motion in comparing to the free-hand technique. Therefore, our breast biopsy guidance system can reduce human errors and fatigue. Moreover, the success rate and accuracy of breast biopsy are increasing based on our experimental results.

II. The Development of Robotic Design

The design requirements were based on the literature review and analysis of traditional breast biopsy procedure. Therefore, the design was to kinematically mimic the radiologist's arm to perform the breast biopsy in 3D space. The robot was expected to be a compact size with the bedside attached style.

The first iteration of our design on the passive robotic needle holder was a 6-DOF articulated robotic manipulator as shown in Fig. 2. 5 DOFs were for placing the needle to the entry point with proper orientation, employed 5 revolute joints. The sixth DOF was for inserting the needle, employed prismatic joint. In the second iteration of our design, rotary dampers were applied at most revolute joints due to a quite significant weight of needle bombarder as shown in Fig. 3. However, the size of market-available rotary dampers, which were able to hold the weight of needle bombarder, becomes too large and heavy. The third iteration of our design was to concern the gravitational direction. Therefore, the concept of combining the SCARA robot and articulated robot was implemented as shown in Fig. 4. Anyway, the robot had become bulky and heavy which would not be suitable to our application. Therefore, the design scheme of articulated robot was changed to a new design scheme based on the needle's motions along the spherical curvature, which matched to the breast contour.

III. The Final Design: Passive Robotic Needle Holder

The final iteration of our design is a new scheme based on breast shape and contour as shown in Fig. 5. This robot is designed to hold its position by friction method with Polyoxymethylene (POM) or Polyacetal, which are high tensile strength, high stiffness, good creep resistance, high dimensional stability, physiologically safe, and high impact resistance even at low temperature.

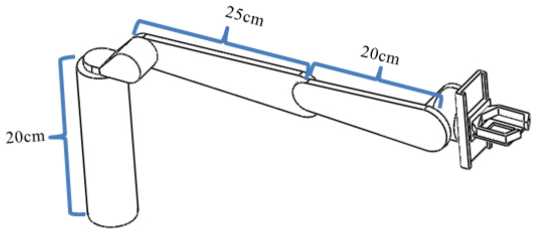

Fig. 2. The first iteration of the passive robotic needle holder design

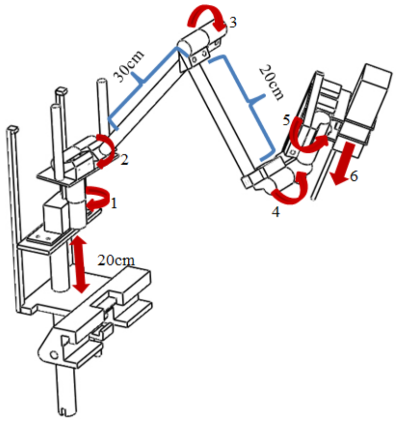

Fig.3. The second iteration of the passive robotic needle holder design

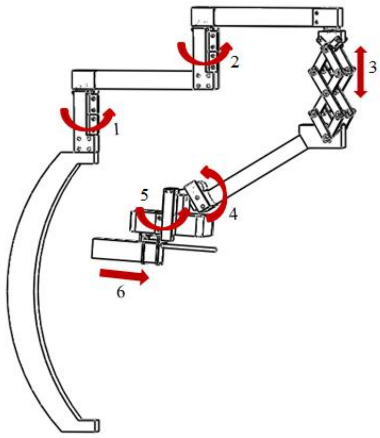

Fig. 4. The third iterations of the passive robotic needle holder design

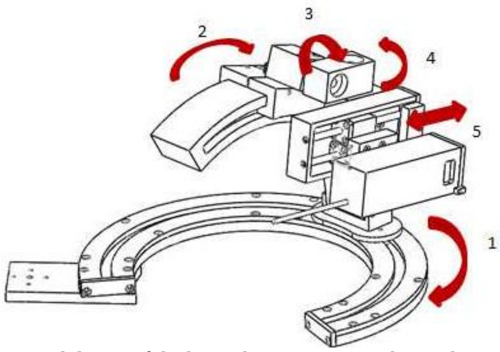

Fig. 5. Final design of the breast biopsy passive robot with its DOFs

This robot consists of 5 joints with 5 DOFs. Joint1 and joint2 are designed by curvature translation as shown on Fig.

6. Sliding parts are analyzed to slide on the base with few frictions, so their position can be held when no outer force.

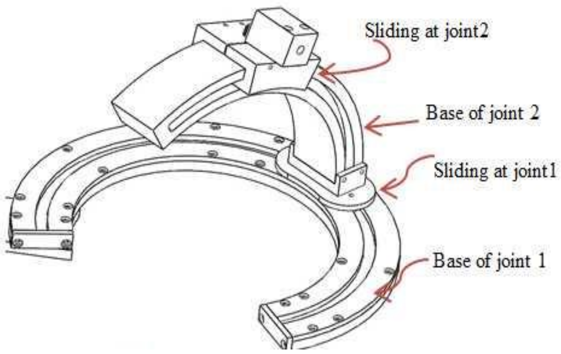

Fig. 6. The structure of joint 1 and joint 2

The other 2 DOFs are at joint3 and joint4 are designed to rotate on x and z axes for making a cone shape, which is important to let the needle align on the trajectory path at the entry point. Bearings and screws at these joints are applied to adapt amount of frictions.

The last joint is for needle insertion or translation. Linear bushing is a material that used for sliding work, so this part is designed with 2 linear bushings to avoid the needle rotation during sliding. Magnets are attached to this joint for locking during other joint's movement. Accordingly, a needle box can be moved for needle insertion by outer force that is greater than magnetic force after the needle already lied on the trajectory part. The position of needle tip is tracked in real-time by optical tracking system. A passive marker is attached on the needle box, so a tool-tip calibration method is needed to translate the position from the passive marker to the needle tip. From the procedure of tool-tip calibration, the needle box has to be designed with separated part from the whole robot. The details of this part are shown on Fig. 7.

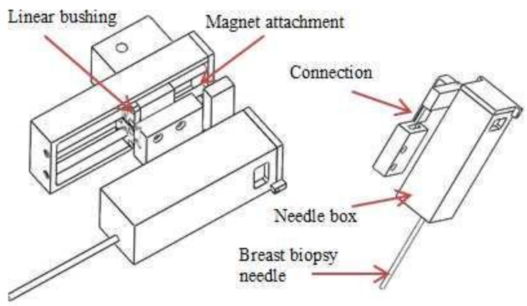

Fig. 7. The structure and component of joint 5

The robot's base is attached on 2 linkages 3D holder or magic arm in commercial to support its position above patient's breast before breast biopsy is started. Consequently, the robot's base is designed with three connections as shown on Fig. 8 to support the various locations of breast tumor.

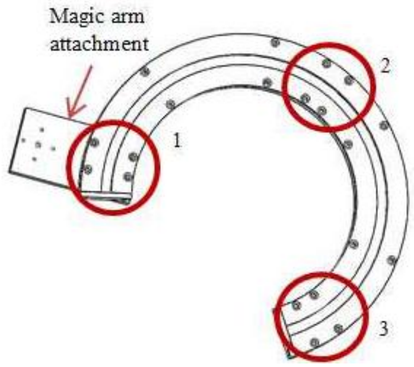

Fig. 8. Three positions of magic arm attachment

The performances of this robot are compared with the previous robots on Table 1.

TABLE I. The Comparison of Robotic Performances between The Previous Design and The Last Robotic Design

Comparison	**Previous Iterations Robotic Design**	**Last Iteration Robotic Design**
Feature	big and complex	middle and clearly
Degree of Freedom	6 DOF	5 DOF
Function	reasonable	reasonable
Tools	rarely	available

From the Table 1, the performances of the last robotic design are more suitable and reasonable than others to perform breast biopsy. Therefore, the last iteration of the passive robotic needle holder design comes out to be the first prototype as shown on Fig. 9.

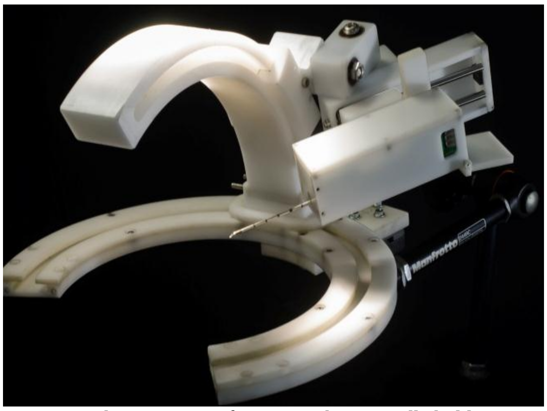

Fig. 9. The prototype of passive robotic needle holder

IV. GRAPHIC USER INTERFACES

Graphical user interfaces are essential to guide the radiologist during performing breast biopsy. The trajectory path, which is calculated by the shortest distance between breast surface and tumor and the alignment of the biopsy needle, are shown on GUI on MATLAB and 3D Slicer in real-time. Fig. 10 shows examples of GUI on MATLAB and 3D Slicer.

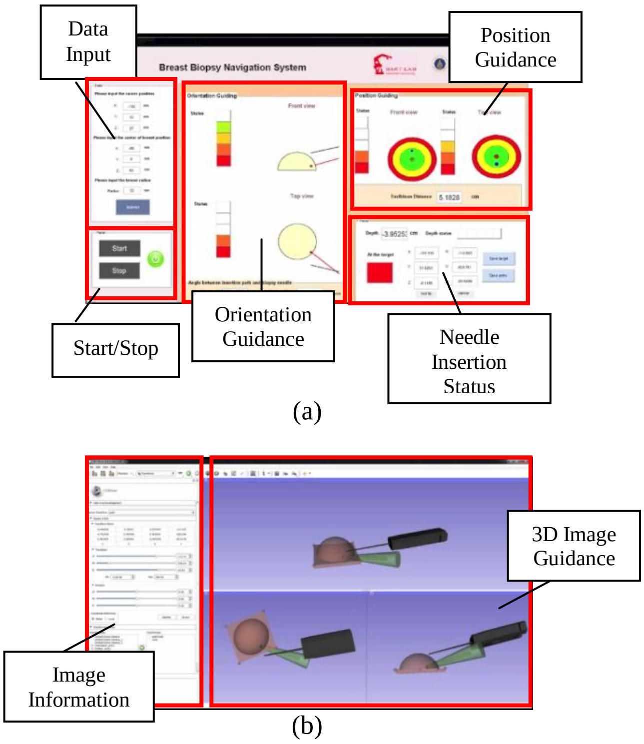

Fig. 10. Graphic User Interfaces on (a) GUI on MATLAB (b) 3D Slicer

V. BREAST PHANTOM AND PATH GENERATION

In this research, the breast phantom and the breast simulation are made and simulated to be the hemisphere shape and nondeformable, which are fundamental conditions for evaluating the performance. Then the trajectory path is calculated in the condition of the shortest distance between the entry point on breast surface and tumor by using Lagrange multiplier theorem and vector in 3-dimensional space. Because breast is assumed to be nondeformable breast, the position of tumor does not change during needle insertion.

VI. SYSTEM INTEGRATION

The overview of system integration is shown on Fig. 11.

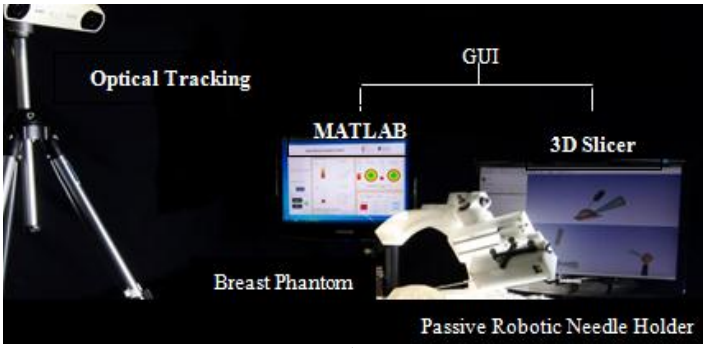

Fig. 11. The overall of system integration

The system integrated consists of the breast phantom, the optical tracking system, a personal computer with 2 monitors and the passive robotic needle holder. The camera is used for determining the position and orientation of passive markers that are attached with the phantom's base and the needle box. The 3D Slicer and GUI of breast biopsy guidance are shown on the monitors while the passive robotic needle holder is attached with the surgical bedside by using the magic arm. After setting the system, the radiologist can perform breast biopsy by moving the needle with breast biopsy guidance system.

VII. EXPERIMENT AND RESULT

Performance of a passive robotic needle holder experiment was conducted for testing our system performance with and without the passive robot as shown on Fig. 12.

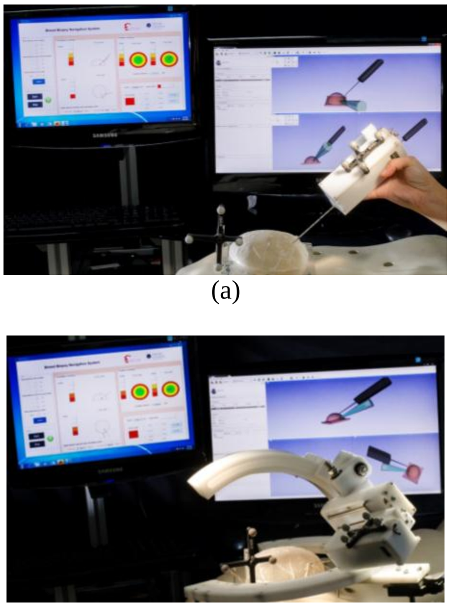

Fig. 12. Performance of a passive robotic needle holder experiment (a) without the passive robot (b) with the passive robot

In the experiment, 20 users performed breast biopsy with and without the passive robotic needle holder 10 trials in each condition by starting with performing breast biopsy without robot. The experiment was done with the breast phantom that consisted with many lesions (simulated breast tumors) inside it. In each trial; therefore, the users performed breast biopsy in different target position. A diameter of breast tumors in the experiment was assumed to be 2 cm, which was a standard of tumor size to be detected. If the users could reach the needle to these areas, the presence of green sign indicated the precise target.

In order to confirm the ability and accuracy of the robot, the error of Euclidean distance was calculated from the center of breast tumor and the entry point. Moreover, time to perform breast biopsy in each time was counted to estimate the effect of the robot. The results of the experiment are summarized and shown on Table 2.

TABLE II. Parameters for Evaluating The Performance of The System With and Without The Passive Robotic Needle Holder

Parameter	Without robotic needle holder	With robotic needle holder
Root mean square Euclidean distance error (mm)	4.33	3.44
The average of breast biopsy performance time (s)	65.4	130.2
Success rate (%)	88%	92%

VIII. CONCLUSIONS AND FUTURE WORK

From the result, root mean square Euclidean distance error in the experiment of performing breast biopsy with robot is lesser than without robot, and both of them have very high success rate. This can imply that an accuracy of performing breast biopsy with robot is higher than another one because the robot can control the line of insertion path when users move the needle to the trajectory path and start to insert the needle. On the other hand, the insertion path sometimes changes during the users insert the needle without robot because of human error. Moreover, the users feel fatigue when doing the experiments many times that leads to hand trembling and impaired consciousness.

Conversely, the users have to accustom with the passive robot and understand its function on the first time, which make them spend a lot of time to finish the experiment. After that, working time will be decreasing. Another reason is the users cannot control the robot at the needle box. The users have to move the robot at each joint, so the steps to move each joint have to be understood to reduce time-consuming. Though time to perform breast biopsy with robot is higher than without robot, the users feel confident and relaxed when work with it. If the needle lies on the needle insertion path that is shown on the graphical user interface, there are high percentages that the needle will reach on the target. An accuracy and safety are important things that should be considered first for biopsy or surgery. Nonetheless, there are some regions that this robot cannot perform breast biopsy, so its function needs to be analyzed, enhanced and improved.

This research proposed the passive robotic needle holder for breast biopsy, which consist of 5DOFs: 2DOFs for curvature translations, the other 2DOFs for rotational movements and the fifth DOF for needle insertion. Friction method is applied to this robot to hold its position during no movement. The purpose of this robot is to reduce human error and increase the radiologist performance, ability and confidence. Therefore, the new breast biopsy guidance system can increase the accuracy and proficiency of needle insertion. Nevertheless, this robot will be improved and developed the flexibility such as its workspace and its function.

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