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# Robot Assisted Real-time Tumor Manipulation for Breast Biopsy

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*Abstract*—**Breast biopsy guided by imaging techniques such as ultrasound is widely used to evaluate suspicious masses within the breast. The current procedure allows the physician to determine the location and extent of a tumor in the patient breast before inserting the needle. However, there are several problems with this procedure: the complex interaction dynamics between the needle force and the breast tissue will likely displace the tumor from its original position necessitating multiple insertions, causing surgeons' fatigue, patient's discomfort, and compromising the integrity of the tissue specimen. In this work, we present a new concept for real-time manipulation of a tumor using a robotic controller that monitors the image of the tumor to generate appropriate external force to position the tumor at a desired location. The idea here is to demonstrate that it is possible to manipulate a tumor in real-time by applying controlled external force in an automated way such that the tumor does not deviate from the path of the needle. A laboratory experiment has been presented on a phantom that demonstrates the essence of this concept. The success of this approach has the potential to reduce the number of attempts a surgeon makes to capture the desired tissue specimen, minimize tissue damage, improve speed of biopsy, and reduce patient discomfort.**

## I. INTRODUCTION

BREAST cancer is the most common cancer among American women and the second leading cause of cancer death in women. In 2007, the American Cancer Society (ACS) estimates 178,480 (26% of all female malignancies) new breast cancer cases with 23% mortality rate [1]. Early detection of breast cancer has been proven to reduce mortality by about 20% to 35% [2]. Histopathological examination is considered to be the "Gold Standard" for definitive diagnosis of cancer but requires tissue samples that are collected through biopsy. Of the two major approaches for breast biopsy, needle biopsy and open excisional biopsy, needle biopsy is more attractive because it is less traumatic, produces little or no scar, allows quicker recovery, and is less costly. Despite many benefits of needle biopsy, there are significant technical challenges concerning accurate steering and precise placement of a biopsy needle at the target in breast tissue. To successfully remove a suspicious small targeted lump (sometimes less than 5 mm in diameter) various issues must be addressed, such as architectural distortion and target deflection during needle insertion and poor maneuverability of the biopsy needle. These issues are even more important when the collection of a large and intact core becomes necessary for histopathological diagnosis. Although mammography, sonography, and magnetic resonance imaging (MRI) techniques have significantly improved early detection of breast cancer, accurate placement of a biopsy needle at the target location and reliable collection of target tissue remain challenging tasks.

There are two major problems to be addressed to improve the accuracy and reduce the difficulty of obtaining tissue samples during needle biopsies.

1. *Lesion mobility:* During needle insertion, the complex tissue of the breast induces the small target to deflect away from its original location. [3] describes a three dimensional (3D) finite element model of needle insertion that estimates the force distribution along the needle shaft. Results presented in [3] show that as the needle is inserted, large tissue deformation causes the target to move away from the line of insertion of the needle. This necessitates multiple insertions at the same biopsy site to successfully sample the target tissue.
2. *Difficulty of operation:* Needle biopsies are guided by stereotactic mammography, MRI or two dimensional (2D) ultrasound (US). Sonography is the widely used imaging technique because of its real-time capability and cost-effectiveness [4]. The current state-of-the-art US guided biopsy technique is highly dependent on the skill of the surgeon [5]. The surgeon performs this procedure by holding the US probe with one hand and inserting the needle with the other hand. It is critical to orient the imaging plane parallel to the needle, otherwise a false impression of the needle tip causes sampling errors. This freehand biopsy procedure requires excellent hand-eye coordination. Since stabilization of the breast is problematic [6] and steering of the needle inside the breast is extremely difficult, many insertion attempts are required to successfully sample the target tissue. This procedure is very fatiguing for the surgeon and uncomfortable for the patient.

As can be seen from the above discussion, a robot-assisted breast biopsy system can help the surgeon and address the above-mentioned problems by: 1) providing a mechanism that stabilizes the breast and allows the needle to access the lesion considering lesion movement; and 2) developing an automated image acquisition system that can be coupled with the needle insertion procedure. We are currently working on developing such a robot-assisted breast biopsy system. This paper presents a new approach to control the lesion location in the breast such that the needle can be placed at the target location easily and quickly, which will reduce many of the disadvantages of the current needle

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biopsy procedure as described above. This control approach is developed in such a manner that it can be coupled with an automatic image acquisition system, the work on which is currently underway.

The rest of the paper is organized as follows: Section II presents a review of the relevant literature. Section III casts the tumor positioning problem in a control framework and describes the overall architecture of the guiding mechanism. Section IV presents experimental results on a phantom with a stiff inclusion. Section V discusses the effect of the imaging technique on control performance. Section VI summarizes the conclusions of this paper.

## II. BACKGROUND AND SIGNIFICANCE

Currently there are several methods for performing needle biopsies. These methods differ in the size of the tissue samples obtained and the mechanism for obtaining the samples. The three common methods for obtaining core tissue samples are: core needle biopsy, vacuum assisted biopsy and large core biopsy. Commercially available Bard® Biopty-cut®, Mammotome® and ABBI® (Advanced Breast Biopsy Insturmentation) systems are used (respectively) to perform these procedures.

The above commercially available biopsy instruments do not compensate for lesion movement during needle insertion. Several groups have designed robotic systems to improve the accuracy of needle insertions [7]-[9]. "Although these innovations greatly improve accuracy by automating needle target alignment, they do not provide active trajectory correction in the likely event that trajectory errors arise" [10]. Needle trajectory errors and lesion mobility result in multiple insertions at the same biopsy site for accurate sampling.

As a result, significant research effort is being made to investigate techniques that can address the problem of lesion movement during needle insertion. In [10]-[13], steerable needle techniques are presented that allow steering the tip of the needle towards the target during insertion. The design presented in [10] can only be used for small caliber needles and hence is unsuitable for core needle biopsies. Also, with such a device the surgeon would have to manoeuvre the needle using one hand with image data from a US monitor while at the same time correctly orienting the US probe and stabilizing the breast with the other hand. As mentioned earlier, such a freehand biopsy technique is extremely difficult and fatiguing for the surgeon and uncomfortable for the patient. A visually controlled needle-guiding system is developed in [14] for automatic or remote controlled percutaneous interventions. In the automated mode, the needle insertion path is updated based on image feedback to the needle-guiding system. Though these systems potentially reduce the number of insertions required to sample the target, maneuvering a needle inside the breast causes tissue damage. In [15][16], a finite element model of the breast is used to predict the movement of the target. The needle path is planned based on this prediction to accurately sample the target. To get an accurate prediction of the movement of the target, finite element analysis requires the geometric model and mechanical properties of the breast. In [15], the average time for computation is 29 minutes.

We take a diametrically opposite approach to this problem i.e., instead of steering the needle towards the tumor during insertion, we guide the tumor towards the line of insertion of the needle. Our approach is to design an external robotic system that will be able to position the tumor inline with the needle during insertion. The real-time tumor manipulation system presented here is a set of position controlled actuators. These actuators are placed around the breast during the needle insertion procedure. They control the position of the tumor, by applying forces on the surface of the breast, such that the tumor is always placed inline with the needle. We demonstrate the success of this approach by casting this problem in a control framework. The idea is to design a controller that minimizes the tracking error in the position of the tumor. In this approach, needle insertion force is treated as a disturbance to the system.

This robotic device has the following potential advantages: (a) Success rate of the procedure (defined by the number of insertions required at a particular biopsy site to successfully sample the target tissue) will be increased since the tumor is accurately positioned inline with the needle. (b) Since the number of insertions required is expected to be less, it will reduce fatigue of the clinician and patient discomfort. (c) The entire procedure is predicted to be fast, making it clinically viable. (d) Since the needle is not steered inside the breast, and number of insertions reduced, tissue damage is also minimized and the structural integrity of the tissue specimen is preserved. (e) Geometric and mechanical properties of the breast are not required for precise positioning of the tumor.

## III. CONTROL FRAMEWORK

To remove a tissue sample, the physician inserts the needle through an incision in the skin. A schematic of needle insertion in a breast is shown in Fig. 1. The two dimensional plane of the figure represents a horizontal plane passing through the tumor (the target mass in Fig. 1). In the figure, a simplified anatomy for the breast is shown. In reality, breast tissue is inhomogeneous and its biomechanical properties are nonlinear. Hence, if the tip of the needle reaches the interface between two different types of tissue, its further insertion will push the tissue, instead of piercing it, causing unwanted deformations. These deformations move the tumor away from its original location, as shown in Fig. 1b. In this section, we present a controller design for the external actuators positioned around the breast as illustrated in Fig. 1c. These actuators apply forces on the surface of the breast based on the image of the tumor to guide the tumor towards the line of insertion of the needle.

During the biopsy procedure, the needle is inserted into the breast at a shallow angle (away from the chest wall) to the horizontal plane containing the tumor. The desired target position is the point where the line of insertion (of the needle) intersects the plane containing the target. While one can choose any plane that contains the target and has an intersection with the line of needle insertion, we choose this plane to be the horizontal plane for simplicity. The desired target position is determined by a planner based on the actual tumor location and needle direction. Our goal is to design a controller that acts on the position error to guide the tumor towards the desired location. Note that we only need to control the tumor position in two dimensions (horizontal plane) to be able to successfully position it along the line of insertion of the needle. In this framework, the force exerted by the needle is considered a disturbance to the system. The controller is designed such that the effect of the needle force (disturbance) on the breast is minimized.

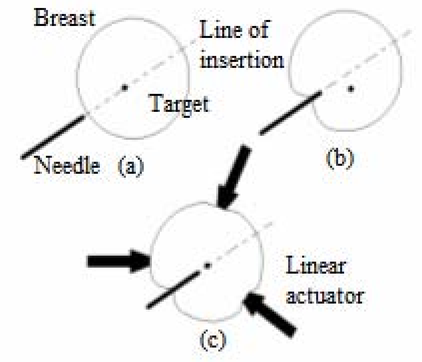

Fig. 1. Needle insertion schematic.

Before we discuss the design of the control system, we present a result from [17] to determine the number of actuators required to position the tumor at an arbitrary location in the horizontal plane.

*Result: The number of manipulated (contact) points must be greater than or equal to that of the positioned (target) points in order to realize any arbitrary displacement.*

In our case, the number of positioned points is one, since we are trying to control the position of just the target. Hence, ideally the number of contact points would also be one. But practically there are two constraints: (1) We do not want to apply shear force on the breast to avoid damage to the skin. (2) We can only apply control forces directed into the breast. We cannot pull the skin on the breast since the actuator is not attached to the breast. Thus our problem becomes more restrictive than [17] since we need to control the position of the target by applying only unidirectional compressive force.

However, there exists a theorem on force direction closure in Mechanics [18] that helps us determine the equivalent number of normal compressive forces that can replace one unconstrained force in a 2D (horizontal) plane. The ramification of this theorem for our problem is this: we need three control forces (actuators) distributed around the breast (as shown in Fig. 1c) such that the end points of their direction vectors draws a non-zero triangle that includes their common origin point. With such an arrangement we can realize any arbitrary displacement of the target point.

We have performed extensive simulations on a discretized model of the breast using a network of nonlinear mass-spring-dampers to determine the nature of the control laws that would be appropriate for this control problem. In particular, we investigated three generic class of controllers: adaptive controller, force feedback controller and a proportional-integral (PI) position error-based controller. Simulation results [19] suggest that adaptive controller and force feedback controller do not provide any significant advantage over the PI controller. Hence, a PI position error-based controller is chosen for this application since it is the cheapest and simplest controller with acceptable performance.

*PI control:*

$$v = \{K_P(y_d - y) + K_I \int (y_d - y) d\tau\} \text{ [17].} \qquad (1)$$

$y_d$ is the desired target position, $y$ is the actual target position, $K_P$, $K_I$ are the proportional and integral gains, $v$ is the actuator input. Note that in control law (1), geometric or mechanical properties of the breast are not required. Fig. 2 shows a schematic of the control structure. Target position data is obtained through image feedback. The desired target position is determined by the planner based on the current target location and needle direction. The desired target position is always along the line of insertion of the needle. The controller acts on the position error and drives the actuators to position the target at the desired location. The force exerted by the needle is the disturbance to the system. Effect of controller wind-up (when tissue compression is high) can be mitigated through saturation feedback compensation [20].

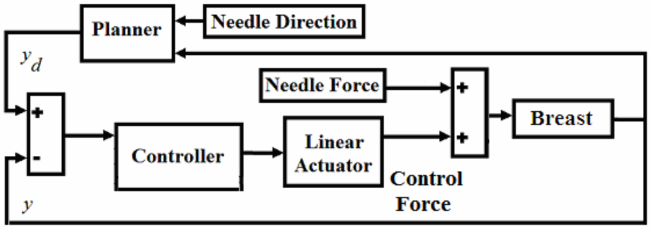

Fig. 2. Control structure.

The implicit assumption in equation (1) is that there exists kinematic coupling between the contact points and the target. More specifically, we assume that applying external control force (at the contact point) in a particular direction causes the target to move in a direction that has positive projection along the direction of force. This assumption is valid since breast tissue is a continuous medium, however inhomogeneous. Inhomogeneity might cause the target to deflect away from the direction of force application, but continuity of the medium ensures kinematic coupling. Weak coupling (when the target is located away from the line of action of the actuators or due to inhomogeneity in the tissue) may necessitate large external forces to position the target but theoretically this does not undermine the control framework. Large external forces are undesirable so as to prevent patient injury and discomfort. This can be avoided in two ways (1) By appropriate positioning of the external actuators such that their line of action is close to the target. (2) Since breast tissue is not inhomogeneous in all directions, this problem can also be obviated by distributing the actuators around the breast. The theorem and result presented above inherently address this problem and as an obvious consequence, the actuators are positioned $120^0$ apart (in Fig. 1c).

## IV. EXPERIMENTAL RESULTS

### *A. Experimental Setup*

A deformable plastic phantom (made of Plastisol) with a stiff inclusion (a plastic insert placed in the phantom to simulate a tumor) is created to test the efficacy of the PI (Proportional – Integral) controller in positioning the inclusion at a desired location. Details about phantom preparation and elastic properties of the phantom material can be found in [20]. A schematic of the experimental setup is shown in Fig. 3. The phantom is braced against a support on two sides and linear actuators apply force from the opposite sides.

Position feedback is obtained using a Creative Labs video camera (30 Frames per second, 640 X 480 pixels). The inclusion can be viewed using a video camera since the phantom is transparent. Image data from the video camera is converted from RGB to $YC_BC_R$ color space. The phantom is placed against a red background and the inclusion is blue in color. Hence, chrominance ($C_B$) can be used to track the inclusion in real-time. During a biopsy procedure, image data would be obtained through ultrasound imaging. The image frames from the video camera are sent to a computer (1.6 GHz and 2 GB RAM, shown as PC 1 in Fig. 3) running image processing algorithm in Matlab. Image frames are processed to extract position data of the inclusion. Each iteration of the image processing algorithm requires 0.2 seconds. This is the time delay in the feedback loop of the controller. Medical US systems have frame rates of 5 frames per second or higher. Hence the time delay in the feedback loop will be the same and the performance of the controller is not affected. Inclusion position data is communicated serially to a microcontroller (Freescale 68HC912B32, 8 MHz clock frequency). The microcontroller outputs this data in a 16 bit parallel format. This data is read by another computer (1.6 GHz and 1GB RAM, shown as PC 2 in Fig. 3) using a data acquisition card (Measurement computing PCIM DDA06/16). This computer runs the PI control algorithm and outputs control signals to power amplifiers for driving the linear actuators. The linear actuators (FA-PO-20-12-2”, Firgelli Automation) are lead screw driven with inbuilt potentiometers. They have a no load speed of 50 mm/s and a load capacity of 88N at 25% duty cycle.

### *B. Results*

We have performed three different experiments to demonstrate different aspects of tumor localization.

*Experiment 1:* In the first experiment, we have created a situation that is similar to the tumor deflection problem due to a needle insertion to demonstrate the feasibility of the concept. In a needle insertion situation, the task is to localize the tumor so that it remains inline with the needle. Any deviation of the tumor is seen as an error by the controller and a compensating force is generated to mitigate the error. We assume that the tumor is already deflected and the task of the controller is to move the tumor to a desired position by applying an external force.

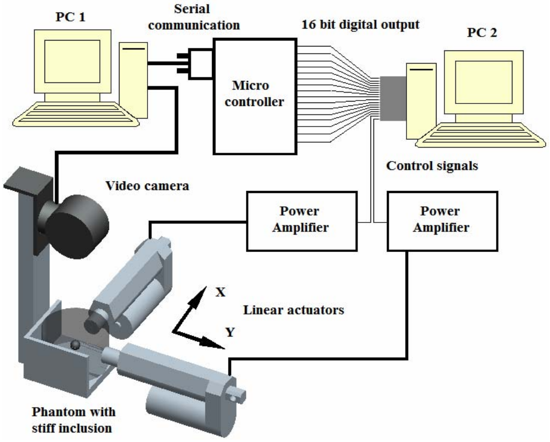

Fig. 3. Experimental setup

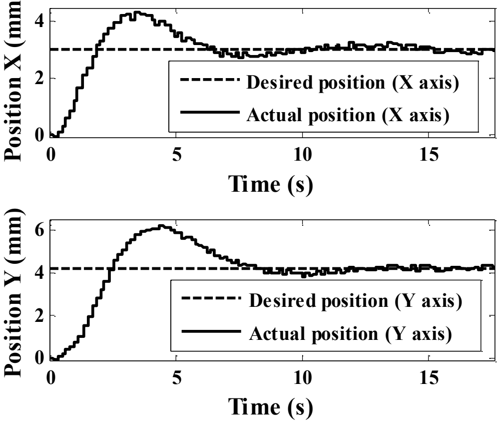

Fig. 4. Inclusion positioning in horizontal plane

Thus an experiment was conducted to move the inclusion to a desired location within the phantom using linear actuators. The initial position of the inclusion is set as the origin. Needle force acting as a disturbance on the system has not been included for this experiment. This experiment was designed to move the inclusion along two directions (X and Y axes as shown in Fig. 3) using two linear actuators perpendicular to each other. The goal is to be able to position the inclusion at any point in the horizontal plane (XY plane in Fig. 3). The phantom is braced against a support opposite to the linear actuators.

We have experimentally determined that using a DC voltage controlled linear actuator results in a position response that oscillates around the desired position. This behavior does not improve by changing the gains of the controller. These are friction generated limit cycles [21]. Many adaptive and fuzzy logic controllers [22] have been proposed for friction compensation. We propose to use pulse width modulation (PWM) [23] to overcome this stick-slip behavior. Hence, the duty cycle of the PWM signal is chosen as the actuator input in equation (1). We use a PWM signal with frequency of 4 Hz and amplitude of 2 Volts for driving the linear actuators. Proportional and integral gains were 0.02 and 0.01, respectively. The desired position of the inclusion is 3 mm along X axis and 4.2 mm along Y axis. It can be observed from Fig. 4 that the inclusion reaches the desired position in approximately 12 seconds. Note that any geometric or mechanical properties of the phantom are not used in the control scheme.

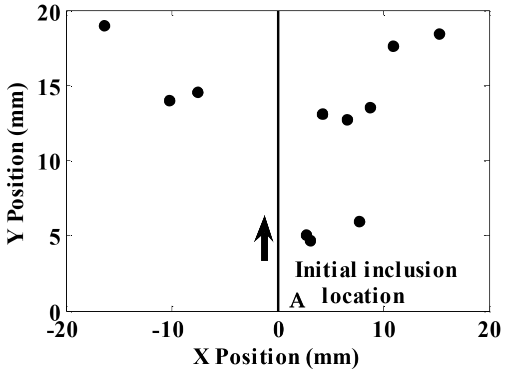

Fig. 5. Movement of inclusion

*Experiment 2:* In the second experiment, we demonstrate the movement of the inclusion during needle insertion. The phantom used for this experiment is inhomogeneous (as is actual breast tissue) such that during needle insertion the inclusion deflects away from the path of the needle. The needle used is a 10-gauge vacuum assisted device. Fig. 5 shows a scatter plot of the maximum deflection of the inclusion away from the needle path during multiple trials using different phantoms. Point A (origin) is the initial location of the inclusion before the needle is inserted. The arrow indicates the direction of needle insertion. During 11 trials, the average maximum deflection of the inclusion away from the needle path is 8.51 mm.

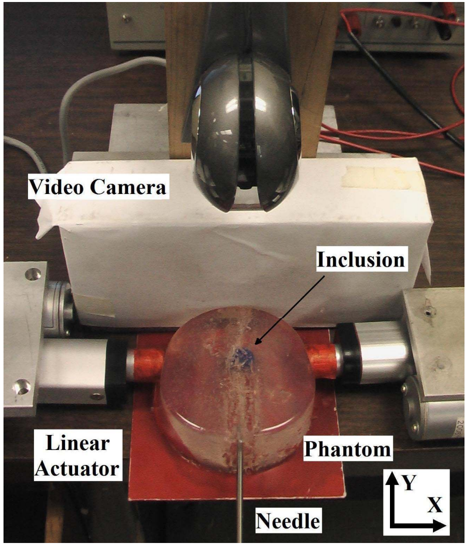

Fig. 6. Needle insertion task

*Experiment 3:* For the third experiment, we use linear actuators to position the inclusion during a needle insertion task. The experimental setup for this task is shown in Fig. 6. The inclusion is initially located at the origin and the needle is inserted along the Y axis. Due to inhomogeneity in the phantom the inclusion moves away from the needle path during insertion. We use linear actuators positioned along the X axis to steer the inclusion towards the needle path (Y axis). During this experiment the force applied by the needle on the phantom is treated as a disturbance to the system. The task of the controller is to position the inclusion on the Y axis. The position of the inclusion along the Y axis is not controlled since the needle will intersect with the inclusion no matter where it is located on the Y axis.

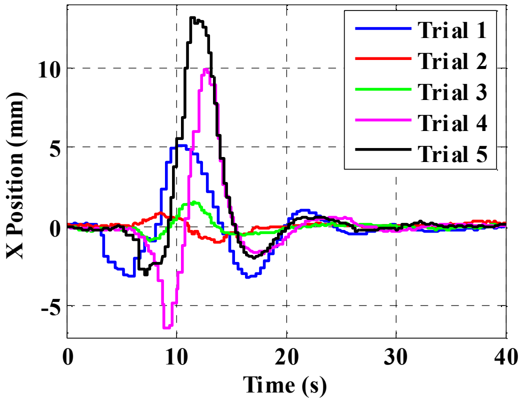

Fig. 7. Inclusion positioning during needle insertion

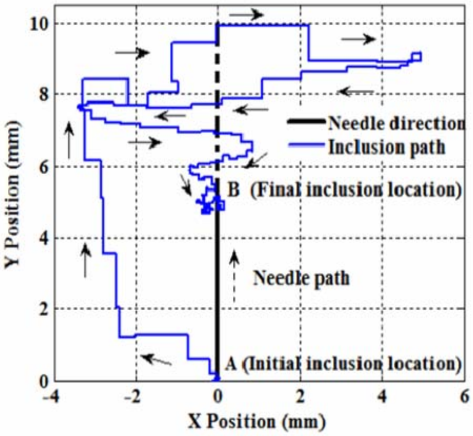

Fig. 8. Locus of inclusion position for Trial 1

Fig. 7 shows a plot of the position response of the inclusion (along the X axis) during five trials (shown as Trials 1, 2, 3, 4 and 5) on three different inhomogeneous phantoms. These phantoms have two kinds of material with elastic moduli similar to fat and glandular tissue. From Fig. 7 we can see that the inclusion is initially located on the Y axis (displacement along X axis is zero). As the needle is inserted the inclusion moves away from the Y axis (non zero displacement along X axis). This initiates a control action by the actuators which steer and position the inclusion on the Y axis (displacement along X axis is zero) at steady state. As we can see from Fig. 7, the inclusion is steered back to the needle path in about 30 seconds. In all five trials, we were successful in positioning the inclusion along the needle path. We could steer the inclusion back to the needle path even when the deviation of the inclusion is large (~10 mm).

Fig. 8 shows the locus of the inclusion position for Trial 1. We can see from Fig. 8 that the inclusion is initially located in the path of the needle (Point A), but as the needle is inserted it deviates away from the path and the PI controlled actuators steer it back towards the line of insertion. The final location of the inclusion is at Point B on the needle path.

## V. DISCUSSION

We have presented a technique for tumor manipulation that uses externally controlled actuators to position the tumor inline with needle during real-time insertion. A PI control architecture has been presented in the paper for guiding the tumor towards the line of insertion of the needle. The performance of the controller is tested on a phantom with a stiff inclusion. Results show that PI controlled actuators can be used to efficiently position an inclusion inline with needle during insertion. The results presented in this paper use image feedback from a video camera to guide the inclusion towards the desired location. The controller performance is independent of the imaging technique as long as the frame grabbing interval is less than or equal to 0.2 seconds (frame rate greater than or equal to 5 frames per second). This is the time required for one iteration of the image processing algorithm. Medical US systems have frame rates higher than 5 frames per second and hence the performance of the controller is not affected. In a clinical setting, image feedback would be typically provided through ultrasound since sonography is the most widely used and cost effective medical imaging technique.

## VI. CONCLUSION

The proposed technique of tumor manipulation for guiding breast biopsy has several potential advantages: (1) Success rate of the procedure is increased since the tumor can be accurately positioned inline with the needle. (2) The entire procedure is predicted to be fast, making it clinically viable. (3) Since the needle is not steered inside the breast, tissue damage is also minimized. Additionally, since multiple insertions are not required, the proposed technique will likely reduce clinician fatigue and patient discomfort and improve the structural integrity of the tissue specimen. (4) Geometric and mechanical properties of the breast are not required for precise positioning of the tumor.

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