ULTRASOUND GUIDED TRANSPERINEAL ROBOTIC BIOPSY SYSTEM FOR THE PROSTATE

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ABSTRACT
This paper focuses on introducing a robotic system for transperineal biopsy of the prostate guided by transrectal ultrasound images. It aims to improve cancer detection rate through maximal biopsy of the peripheral and apical regions. The mechanical units of the robot guide the urologist to position the system with respect to the patient. The software enables ultrasound image acquisition for prostate boundary delineation and biopsy core planning. It also calculates the required parameters of the needle’s trajectory and controls the motorized needle positioning for biopsy execution. Phantom experiments show the system is accurate, consistent and offers wide coverage.

KEY WORDS
Prostate cancer; Robot-assisted; Transperineal Biopsy; ultrasound guided.

1. Introduction
Prostate cancer remains one of the most common cancer afflicting men today [1]. Transrectal Ultrasound (TRUS) guided biopsy is the standard technique used for sampling the prostate gland. Studies have shown that using the traditional sextant biopsy protocol had a false negative rate of 30% [2]. Furthermore, a significant number of men need to undergo repeat biopsy because of clinical indications or atypical findings on the initial biopsy [3].

Prostate cancer is a multi-focal disease. The total volume of cores taken during a biopsy represent only about 0.6% of the prostate volume. Hence, for adequate sampling, multiple needle passes have to be made into the prostate gland. Biopsy protocols are intelligent suggestions of where and how to place a needle in the prostate to obtain the best possible results. Without prior accurate knowledge of cancer sites, it is unlikely that a biopsy protocol will yield consistently high cancer detection rates.

The two primary risks of needle biopsy are severe bleeding and infection of the prostate gland or urinary tract. The rectum is a passage through which the stool of the body passes through before being excreted out of the anus. In the conventional transrectal biopsy, multiple puncture wounds are created in the rectum in order to sample the entire prostate. This increases pain and discomfort to the patient, and also the risk of having blood in the urine if the needle hits the urethra. The presence of faecal material in the rectum may potentially lead to life threatening infection (sepsis).

The major challenges of current biopsy protocols are (1) inaccurate biopsy and inability to reach areas where tumours commonly occur, (2) inadequate coverage of the prostate gland, (3) multiple puncture points which may lead to morbidities, (4) unclear localization of cancer under imaging modality. An ideal protocol is one that yields high cancer detection rates with minimal needle passes and morbidities such as haematuria (blood in the urine) and sepsis (life threatening infection).

A robotic system, which can perform accurate biopsy of the prostate, would indeed eliminate many of the existing drawbacks of conventional prostate biopsy procedures. The robot’s greatest contribution would be accuracy. Fischer et al. [4] developed a computer integrated robotic mechanism for transperineal prostate needle placement in closed-bore MRI. They have also developed a transrectal needling system [5] that enables precise guidance and monitoring of prostate interventions with MRI. Envisioneering [6] has developed an endorectal probe with multi-plane mechanical transducer with 3D volume imaging capability. Its proprietary targeted biopsy system leverages the technology's scanning ability to increase the accuracy of transrectal biopsies. Schneider et. al [7] developed a handheld ultrasound guided device for transrectal biopsy and treatment delivery.

In this paper, we present a robotic system that can perform percutaneous biopsy of the prostate using the transperineal approach under ultrasound guidance. We have been developing transperineal prostate biopsy device since 2002. The first system, Biopsy Urobot [8] focused on accurate needle placement in the prostate. We have developed a new prototype called BioXbot (see Figure 1a), which focuses on operability, prostate coverage and reachability issues. It also aims to address the shortfalls of the first biopsy system in order to improve the cancer uptake rate.

2. Materials and Method
2.1 Robotic System

BioXbot is a computer based motion control system with software driven gantry mechanism for motorized positioning of the prostate biopsy gun (see Figure 1a).
Figure 1. BioXbot (a) Overview of the system (b) Robot head and gantry

The overall system is a compact mobile cart that provides support to the robot on top of a power lift and houses an industrial computer. The user interacts with the system via a movable touch screen monitor and keyboard, which are attached to the cart via multi-joint linkages. A video cable connects the output from the ultrasound machine to the frame grabber in the computer, for image acquisition purposes. The motion controller hardware, power supply, electrical components and wiring, and amplifier for motor driving are also contained inside the cart.

The major mechanical units of the system are the robot, power lift and movable platform. The power lift is used to move the robotic head upwards and downwards, the controls for which are ergonomically placed. An electromagnetic plate, activated by press button, controls the sideways movement of the robot. The robot sits on the movable platform supported by a ball joint, which is freed and locked by a lever. The ball joint gives the robot 6 DOFs, rotational.

The robot itself comprises of the gantry unit, the ultrasound probe holder and motorized needle positioning, as shown in Figure 1b. The probe holder can be manually moved and at the same time controlled by the software via an encoder. The gantry unit holds the motorized needle positioning system and the pivot points. It opens and swings out to allow for unhindered probe insertion.

The most important feature of the BioXbot is its ability to deliver a needle to any predefined point in the prostate. This is made possible by using a novel cone system, which covers not only the left and right side of the prostate, but also the supero-inferior aspects of the gland. This ensures maximal coverage of the whole prostate gland.

In the conventional transrectal biopsy, multiple puncture wounds are created in the rectum in order to sample the entire prostate. Likewise, template-based transperineal biopsy also requires multiple perineal skin punctures to cover the prostate sufficiently. The advantage of this system is that using only two puncture points to perform multiple-core biopsy. Emiliozzi et al. [9] used a fan technique to obtain 12 biopsy cores with only 2 puncture points at the perineal wall. Using the same approach, BioXbot can pivot the needle at a one-puncture point at the perineal wall and change its trajectory to reach multiple sites in one-half of the prostate. Hence, by using only two pivot points on the perineal wall, any part of the prostate can be biopsied. While a single cone system may potentially cover the prostate but there is a definite risk of injuring the urethra (urinary passage), which runs through the middle of the prostate gland. BioXbot ensures maximal coverage of the prostate gland without any damage to the vital structures.

The ultrasound probe is driven step by step within the defined range, and captures images at 0.5mm intervals using the frame grabber. The system computes the co-ordinates and orientates the motorized positioning facility automatically for the needle trajectory. The gantry houses the motors for the x-y axis (horizontal and vertical) position while the z-axis (depth) is determined at the gun stopper. Any commercially available prostate biopsy gun can be used.

The system software manages the workflow under user’s instruction and also the system hardware. The software for the system is written in C++ programming.
language. The application is built on top of a cross-platform application framework, called Trolltech Qt, and the open source visualization toolkit (VTK). To simplify the usage, the user interface is highly dynamic and sensitive to the view selection and state of workflow.

BioXbot builds a patient-specific 3D model using the ultrasound images obtained. The urologist delineates the prostate boundary on the ultrasound images. From the delineation, the software uses NURBS (non-uniform rational B-splines) modeling system to reconstruct the 3D surface of the prostate. Based on the individual patient’s prostate model, the BioXbot automatically offers an ‘ideal’ biopsy plan, which the urologist can also modify. Biopsy planning determines how the prostate will be sampled. A biopsy plan consists of a list of trajectories. The software aligns all the cores to sample the apex and peripheral zone maximally (see Figure 2). Moreover, the software plans multiple cores on the same trajectory ensuring that long prostates are also thoroughly sampled. Cores are always at a distance of 7mm away from the base of the prostate.

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2.2 Ultrasound Calibration

The process of recovering the transformation between the 2D imaging space and the 3D robot space is called ultrasound calibration (shown in Figure 3a). An accurate and repeatable ultrasound calibration result is crucial for an effective TRUS-guided biopsy procedure to ensure that the needle is placed exactly where it was intended to be.

![Image](https://via.placeholder.com/150)

Figure 3. Calibration (a) Transformation between imaging and robot space (b) Ultrasound image of the calibration box

The ultrasound calibration can be formulated mathematically as below:

\[ q_i = R \cdot (S \cdot p_i) + t + i \cdot \Delta t \]  

where, \( p_i \) is the 2D coordinates of a pixel in \( i \)-th the image and \( q_i \) is the corresponding point in the 3D robot space. The aim of the calibration procedure is to compute the rotation matrix \( R \), the translation vector \( t \), and the scaling factor \( S \).

A calibration box with three edges at predetermined distances has been specially designed. These edges are identified on the ultrasound image and the transformation is calculated (See Figures 3a and 3b).

3. Validation Studies

A phantom box has been designed for the purpose of validation studies. The length of the box is 150mm, the height is 110mm and the depth is 60mm. The centre of the box is hollow and filled with gelatin mixture (18% gelatin and 82% water). The top side of the box has a template of 15 equally spaced holes (rows of 5 and columns of 3) to
allow for thin metal sticks with 1mm diameter to be inserted and scanned.

3.1 Accurate Needling and Coverage Tests

The experiments are conducted two-folds; first sticks are inserted at random holes from the top and second a hard boiled egg is inserted in the middle of the gelatin and the sticks are inserted inside. These experiments test accurate needling capabilities of the machine and also maximal coverage.

The tip of the stick is identified on the ultrasound image and a biopsy core is planned. Then using the BioXbot, which is set up as it would be during a patient trial, the biopsy needle is fired. If the x-, y-, z- coordinates of the planned and the actual trajectory are different, the tips of the stick and needle do not touch.

The boundary of boiled egg can be identified on the ultrasound image. After the surface is modeled, the biopsy cores are planned again at the tip of the sticks and executed. The egg removes the bias of seeing the stick tip while inserting the biopsy needle.

3.2 Repeatability Tests

Without removing the sticks, using only the saved data (such as the model and the biopsy plan) from the previous experiments, the system repeats the biopsy execution process. This experiment is to test if the robot can go back to the same position each time without rescanning with ultrasound.

3.3 Prostate Modeling and Biopsy Planning Tests

Between May 2006 and June 2006, ‘warm up’ trials on 3 patients were conducted to get familiar with the system and understand the operating protocol. Patients, placed in lithotomy position, underwent ultrasound scanning. The urologist modeled the prostate on the acquired images and planned the most optimal cores to be taken. The clinical trials were conducted with the approval of the Medical Ethical Committee and the consent of the patients. However, no needling of patient was done.

4. Results

4.1 Accurate Needling and Coverage

The phantom experiments showed that the metal stick and its tip are clearly visible on the ultrasound and when the needle touches the stick, it can also be distinguished. In 20 experiments, the average placement errors were less than 1.00mm in gelatin, measured using electronic vernier calipers. As accuracy was tested in detail for our previous system [8], our focus was on the coverage and the ability of the robot to reach the extremes using the dual cone system. The eggs were around 50cc - 60cc, which is the volume of an average sized prostate. The presence of the egg did not deteriorate the accuracy of the needling. At the same time, we were able to needle even the boundary of the egg without rupturing the surface.

4.2 Repeatability

Moreover, the system was able to go back to the same position using the saved data, with a placement error of less than 0.5mm. This was verified by measuring the width of the needle trajectory after the experiment. This repeatability is important for treatment delivery in patients diagnosed with prostate cancer. Hence the urologist can treat the same position where the cancer was found without affecting surrounding healthy tissue.

4.3 Prostate Modeling and Biopsy Planning Tests

The ultrasound imaging was for the urologist to get familiarized with the system. On an average, the urologist managed to complete the modeling in less than 4 minutes and the planning in 2 minutes. Currently the system is ongoing clinical trials with patients. This test was conducted because it is important that the surgeon be able to use the machine comfortably and complete the procedure in a timely manner during the trials.

5. Comments

BioXbot is capable of performing accurate biopsy with consistent results, which are very important for confident diagnosis and exclusion of prostate cancer. The dual cone can comfortably cover large (above 60cc) and grade 3 (with protrusion into the bladder) prostates. It is the first robotic assistive device in performing transperineal biopsy with ultrasound image guidance. It is capable of accurately delivering the needle to any predefined point in the prostate using only two pivot points, without injuring the urethra. Patients would experience lesser pain and discomfort as fewer traumas are afflicted. Moreover, the perineum (skin), where the needle goes into the patient, is an area with no contact to faecal material hence reducing the risk of infection.

With the transrectal approach there is adequate sampling of the posterior part of the prostate gland, which is just next to the rectum. In transperineal biopsy, the needles enter the prostate via the apex to reach the peripheral zone. Studies [10] have shown that not only is
there higher concentration of tumours located in the peripheral and apical regions of the prostate but, also, that the transperineal approach accesses these regions better than the transrectal approach [11].

BioXbot uses 2D TRUS as it is the current “gold standard” for guiding prostate biopsy due to its real-time nature, low cost, and apparent ease of use. Although MRI has high sensitivity for detecting prostate tumors and excellent soft-tissue contrast, it is very expensive and requires specialized equipment for use within the imaging chamber. Moreover, due to the high cost of the MRI machine and maintenance, they are found only in hospitals or big medical facilities that can afford them. Unlike X-ray imaging systems, ultrasound is radiation-free. They can be used in an outpatient setting which makes the BioXbot user-friendlier. The main disadvantage is that TRUS-guided biopsy has a poor detection rate (20-30%) [12], because ultrasound has low sensitivity (60%) and poor positive predictive value (25%) [13].

The major limitation of the system is the size, which makes portability and storage difficult. Aligning the machine properly also takes time as it takes up space and all activities need to be done around it.

Ideally, the accurate target reaching capability of BioXbot should be combined with imaging modalities which can identify cancer so that lesion targeted biopsy can be performed. This will not only reduce the number of cores the patients will need to undergo but also improve cancer detection significantly. BioXbot can be easily adapted for use with any ultrasound-based system, such as 3D ultrasound or Microbubble contrast agents [14], where cancer localization is possible. Even an ultrasound to MRI registration module [15] has also been developed to extend the use of the BioXbot with MR based imaging modalities.

BioXbot can play a pivotal role in prostate cancer diagnosis as it meets the increasing demands for an accurate and effective prostate biopsy device. For the patient, it could offer a solution that is pain free with less morbidity. Being thorough in the sampling of the important areas of the prostate gland, the patient can avoid unnecessary repeat blood tests and biopsies. Hence a single session of BioXbot biopsy may be sufficient to exclude prostate cancer, making it cost-effective for both the hospital and the patient.

BioXbot can also play vital role in the delivery of treatment for prostate cancer. With its precise positioning system, treatment is delivered to the affected parts of the prostate. These applications include delivery of radioactive seeds (brachytherapy), gene therapy, vaccine therapy and laser. Through accurate early diagnosis and treatment, prostate cancer mortality rate can be significantly reduced in Singapore and worldwide.

6. Future Work

A smaller and compact handheld ‘office version’ of the BioXbot is in progress. The new version would require minimal setup. Work is ongoing to include the gun stopper mechanism into the needle positioner. The user can avoid an extra step of getting the depth separately. The motorized needle positioning will automatically take care of x-axis, y-axis and z-axis of the biopsy position in the prostate. Also, an automatic prostate boundary recognition and modeling program is underway, to reduce the overall execution time and eliminate an additional step.

7. Conclusion

A novel ultrasound robotic transperineal biopsy system, called BioXbot, has been developed. It is a computer based motion control system with software driven gantry mechanism to assist in the positioning of the biopsy gun. It uses two pivot points to form a non-crossing, dual-cone protocol on the left and right side of the prostate to cover the whole gland. Phantom experiments have shown the capability of the robot in giving consistent results with an absolute placement error of less than 1.0 mm. It has great potential not only as a biopsy tool but also as a treatment delivery device.

References


