Increasing the precision of the biopsy with robots: two case studies

1st Bogdan Maris
Department of Computer Science
University of Verona
Verona,Italy
bogdan.maris@univr.it

2th Paolo Fiorini
Department of Computer Science
University of Verona
Verona,Italy
paolo.fiorini@univr.it

3nd Andrea Calanca
Department of Computer Science
University of Verona
Verona,Italy
andrea.calanca@univr.it

4rd Chiara Tenga
Department of Computer Science
University of Verona
Verona,Italy
chiara.tenga@univr.it

5th Françoise J. Siepel
Robotics and Mechatronics
University of Twente
Enschede, The Netherlands
f.j.siepel@utwente.nl

6th Vincent Groenhuis
Robotics and Mechatronics
University of Twente
Enschede, The Netherlands
v.groenhuis@utwente.nl

7th Stefano Stramigioli
Robotics and Mechatronics
University of Twente
Enschede, The Netherlands
s.stramigioli@utwente.nl

***Abstract*—Robotics is a rapidly advancing field and its introduction in healthcare can have a multitude of benefits for clinical practice. Especially applications depending on the radiologist's accuracy and precision, such as percutaneous interventions, may profit. Percutaneous interventions are relatively simple and the quality of the procedure increases a lot by introducing robotics due to the improved accuracy and precision. This paper provides the description of two robotic systems for percutaneous interventions: breast biopsy and prostate biopsy. The systems presented here are complete prototypes in an advanced state ready to be tested in clinical practice.**

***Index Terms*—robotics, medicine, biopsy, prostate, breast**

I. Introduction

Early cancer diagnosis with improved detection and precise delivery of therapeutic measures challenges the perceptual and dexterity capacities of the physicians. In this context, robotics may play a significant role to direct the future of the percutaneous procedures toward more precise biopsies and targeted therapies.

During a biopsy procedure, a tissue sample is removed from a suspected lesion for further pathological examination, to confirm a cancer diagnosis. Traditional biopsy relies on manual insertion of the needle by the radiologist, while robotic approaches may add higher stiffness and precision by a more stabilized robotic manipulator compared to human hands. The robots could support the retraction of the needle including a tissue sample more accurately. Imaging techniques such as magnetic resonance (MRI), ultrasound (US), computed tomography (CT) and other technologies are applied to localize lesions before the intervention, and to guide the needle through the procedure using image feedback.

Breast cancer is one of the most common cancers and the leading cause of cancer death in females [1], while the prostate cancer is the second most common cancer and is affecting men [2]. Early and reliable detection of breast and prostate cancer has a huge impact for optimal treatment of high-risk patient or to avoid overtreatment in low risk patients. The most reliable technique to detect breast and prostate cancer and to estimate of the aggressiveness is the needle biopsy. The prostate and breast biopsy share some common aspects: they can be performed under US guidance or MRI-guided and multiple core specimens are taken, sometimes following sample schemes. The US guided procedure is the simplest and quickest but is not always precise. The MRI or stereotactic biopsies are expensive and cumbersome to perform. From here the idea to use a robot that may combine the best of the two approaches: the US imaging for real-time guidance and the US-MRI image fusion for precise targeting. The availability of pre-operative MRI and the identification of the target is a prerequisite in this case.

While there were several attempts to introduce robotics especially in the prostate biopsy [3], there is still no widely accepted and diffused solution. Most of the works in robotic breast and prostate biopsy are research prototypes (see references [4] to [8]).

We introduce in the following sections two robotic systems and workflows that assist the radiologists in targeting MRI-detected breast and prostate lesions under US guidance. The two setups use different designs of the biopsy robot: a seven degree-of-freedom (7DOF) serial manipulator equipped with a linear US probe and a 3DOF actuated needle guide in the case of breast biopsy, and a parallel robot with spherical joints that act in parallel planes giving 3DOF for the orientation of the needle, integrated with a US probe holder with 1DOF in the case of prostate biopsy.

II. Robotic biopsy of the breast - MURAB robot

The MURAB project [9], has the ambition to drastically improve precision of diagnostic biopsies and effectiveness

This research has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme, ARS (Autonomous Robotic Surgery) project, grant agreement No. 742671

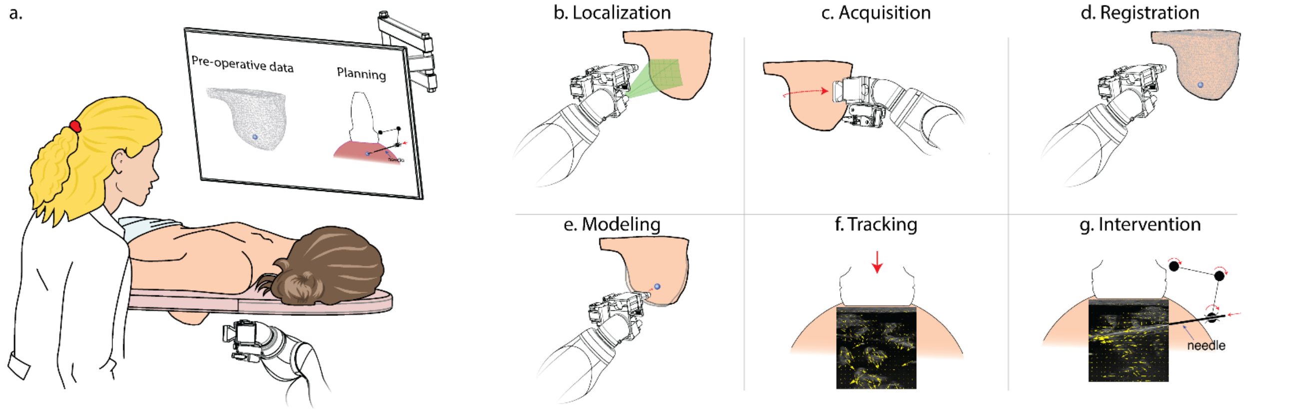

Fig. 1. Phases of a robotic breast biopsy. a. The radiologist checks the pre-operative images and suggested path. b. The robot localizes the patient. c. The robot acquires US data of the site. d. The robot registers the available pre-operative data. e. and f. Modeling and tracking are utilized to determine the target location after probe positioning. g. The robot orient the needle and the doctor perform manually the insertion of the needle.

of the workflow, reducing the usage of expensive (MRI) to a minimum and at the same time yield the same precision during samples targeting due to a novel MRI-Ultrasound (US) registration [10], [11]. A robotically steered US transducer with additional acoustically transparent force sensing will be autonomously moved to optimally acquire volumetric and elastographic data. In this project a 7DOF robotic manipulator (KUKA Med 7 R800, KUKA GmbH, Germany) to which an end-effector, equipped with a US probe (Siemens AG, Germany) and a 3DOF actuated needle guide, was mounted [12]. The use of the serial manipulator was preferred to have a large workspace and many degrees of freedom, though stiffness and strength are more difficult to achieve.

Figure 1 shows the workflow for ultrasound guided robotic breast biopsies on MR detected lesions and its most important steps, as indicated in the MURAB project. The radiologist is mostly there to supervise the procedure and to confirm the suggested planning. Localization of the patient can be performed utilizing stereo camera recognition of projections or skin markers. Based on this information, the robot acquires volumetric ultrasound data of the site, which is subsequently registered with the MRI data to obtain the lesion position in robot coordinates. Based on these coordinates, the robot makes a planning for the intervention.

During probe positioning, the US probe is positioned on the patient's skin while the system tracks skin contact and tissue deformation [13]. During the intervention phase, the radiologist inserts the needle through the actuated guide. During insertion, the tissue deformation is tracked and the needle path is adjusted accordingly. The insertion is done manually buy the physician.

In a recent paper [14], the authors showed through an in-vitro study that the MURAB system can reach targets with a radius down to 3mm.

The robot-assisted breast biopsy minimizes the MR-time, since the biopsy takes place under US guidance, the time per biopsy is less, because the system automatically navigates to the correct US plane, and the radiologist gains robotic accuracy, even while he or she is in control like in the conventional procedure. Thus, the radiologist can still respond appropriately to either haptic or patient feedback.

III. Robotic biopsy of the prostate - PROST robot

Compared with the breast biopsy, the US probe is transrectal and its movement is limited to 1 or 2DOF, making the design of the robot simpler.

The robotic system PROST [15] has a mechanism to orient the needle which is composed by two SCARA arms with spherical joints that act in parallel planes (Figure 2). They are coupled through an axis passing through the center of two joints. Each SCARA arm is composed by four links: the first one rotates around a common axis (the roll axis in figure 2 right). The roll axis includes coaxially the US probe. With this configuration, the robot has 3DOF for the needle orientation and 1DOF for the US probe rotation. The robot allows for needle orientation, while the insertion is done manually. A position sensor is attached to the cannula that drives the biopsy needle so to ensure the tracking of the needle tip. The calibration of the sensor with the robot ensures an error on needle tip of less than one millimeter. The PROST robot integrates the SonixTouch US system with a compatible bi-planar US probe (Ultrasonix Medical Corporation, Vancouver, BC, Canada). In general, parallel developed manipulators are preferred for precise positioning, since these mechanisms can be designed to have a higher accuracy with higher stiffness compared to serial robots.

A dedicated graphical user interface (GUI) was designed (Figure 3) to allow the physician to load pre-operative images, check the image fusion process, define the target area, which is automatically sent to the robot, and actuate the motors to position the needle in the correct orientation that gives the linear trajectory toward the target. The insertion will be done manually; therefore, the orientation of the needle is derived from the motor's encoder and kinematics. During the manual

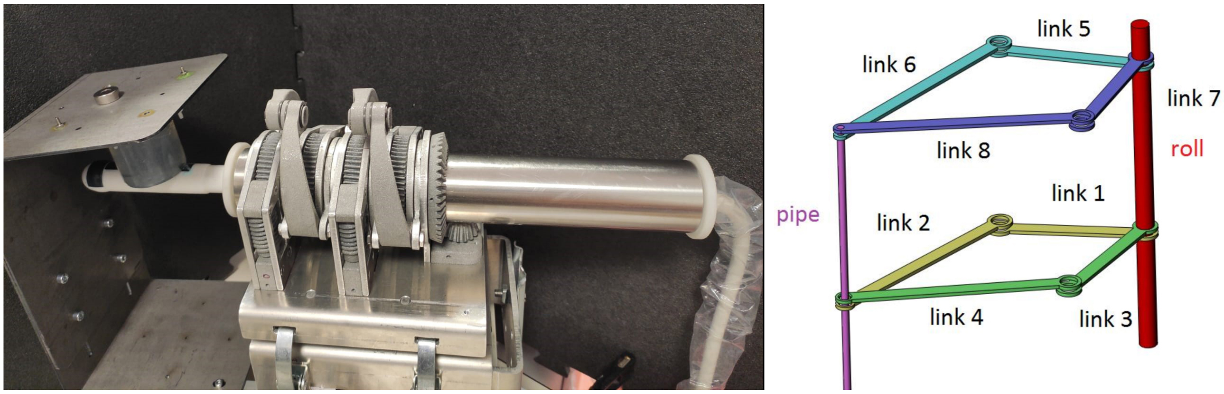

Fig. 2. Left: The PROST robot with the US probe inserted. The US probe has two imaging planes: the sagittal plane and the transversal plane. The image shows also a measuring phantom inserted in US transparent gel under US sagittal scanning. Middle: PROST robot scheme. The roll axis includes the US probe in the physical realization. The other common axis (called pipe in the figure) is free to orient and will give the position of the biopsy needle.

insertion the position sensor updates continuously in real-time the distance to the target (see figure 3).

While in the case of the breast biopsy the emphasis is on the organ deformation, in the case of the prostate robot you have to work on image processing. A 3DSlicer [16] module for semantic segmentation of US images is implemented in PROST software [17]. The module is based on the neural network architecture U-Net [19]. The creation of the data for learning used a semiautomatic algorithm [18]. Since the transperineal procedure employs a bi-planar US probe, we have tested the algorithm on both coronal and sagittal image plane. With a proper ground-truth and training, this method can be applied to any anatomy and even for different types of images (e.g. US and MRI). The precision we have achieved is around 80% (expressed as Dice Coefficient) and the computation time for a sequence of 300 frame is 10 seconds. A single 2D frame may be segmented in 30 milliseconds, therefore is compatible with the frame rate of the US machine, making our approach feasible in real-time.

PROST is designed for transperineal biopsy procedure integrating also image fusion. The image fusion between pre-operative MRI, where the target was identified, and real-time intra-operative US calibrated with the robot reference frame, allows the mapping of the target in the coordinate system of the robot. The image fusion is based on the segmentation in MRI and US.

We proved that with the PROST system inexperienced users in needle biopsy reach the same level of accuracy as expert users. PROST allows the coverage of the whole prostate gland with just two punctures which act as pivot points, giving a biconical configuration of core positions, thus reducing the trauma to the patient but with the same accuracy as a template biopsy.

In a synthetic test on a 3D printed phantom with 9 targets of a diameter of 3mm we have reached an accuracy of 1.30 ± 0.44, while in a test performed on an anatomical phantom with 3 target lesions we have reached similar accuracy of 1.54 ± 0.34 (see figure 3).

Using the PROST robotic system has several potential clinical advantages: precise targeting comparable with MRI guided or MRI-US fusion targeted biopsy, repeatability of the biopsy for active surveillance by mapping all the biopsy cores in the robotic reference system, standardization of the biopsy procedure regardless of the experience of the user, less trauma for the patient, possibility to combine the robot with therapeutic devices.

IV. Conclusions and Outlooks

The current diagnostic and therapeutic workflow will change and improve with the introduction of robots. The benefits of a robotic system for biopsy procedures are: more accuracy and precision, stability, better hand-eye coordination, less insertions. Additionally, a robot does not suffer from fatigue or musculoskeletal issues due to prolonged execution of the same task, and a robot could introduce improvements at interpreting 3D pre-operative data. Due to these advantages, the procedures will be faster, less expensive and produce less trauma for the patient. The biopsy workflow will shift to a one-stop source procedure, with short period of time between detection of a suspicious lesion and cancer confirmation. The robotic procedure is divided into the following phases: image scanning, localization of the target by sensor fusion, pre-planning with deformation prediction and intervention, as described in Figure 1. The role of the physicians will shift to a check-and-evaluation role of the more difficult cases.

The two prototypes presented here are in an advanced state, reaching a technology readiness level (TRL) of 6-7, so the systems were tested in operational environment.

In the case of the breast biopsy robot MURAB, the team is working to obtain the ethical approval for clinical trials. The robot design went through iterative phases and the final prototype has been completed.

PROST robot will be soon tested on cadavers and these tests will be the last trial of the first version of the prototype. The real-time segmentation module will include a segmentation model trained on real patients dataset. The real-time segmentation will also cope with the movement of the prostate during the biopsy procedure through 2D contour registration.

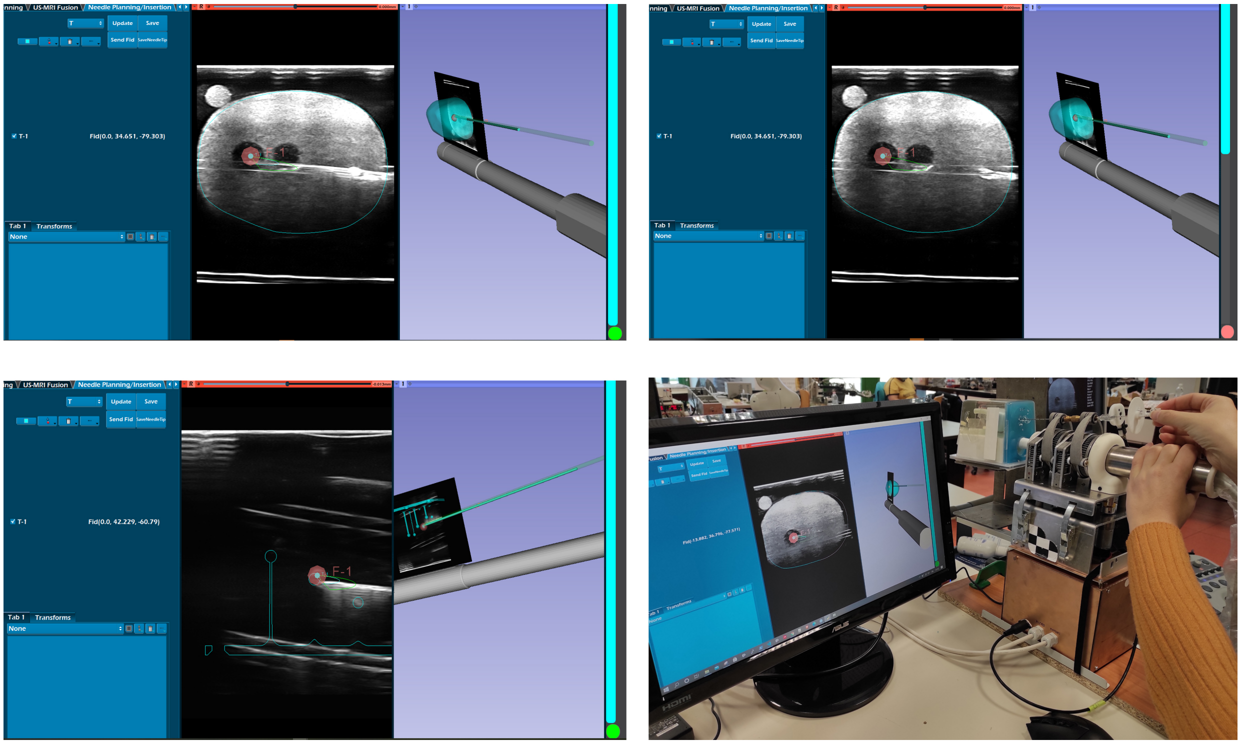

Fig. 3. Graphical user interface and the biopsy procedures. Left top: US image of the anatomical phantom registered with MRI contours during a needle insertion; the US image contains 2 targets of which one is selected (in pink); the needle reached the target and can be seen in the US image as the hypoechoic line; the whole procedure can be seen in 3D; on the right, a progress bar shows the distance to the target showed as a green circle. Right top: before reaching the target, a green path shows the prevision of the trajectory both in 2D and 3D, while under the progress bar the target is red. Bottom left: targeting of the synthetic phantom. Bottom right: overall view of the system during the insertion in the anatomical phantom.

References

[1] Bray, Freddie, Jacques Ferlay, Isabelle Soerjomataram, Rebecca L. Siegel, Lindsey A. Torre, and Ahmedin Jemal. ”Global cancer statistics 2018: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries.” CA: a cancer journal for clinicians 68, no. 6 (2018).

[2] Siegel, Rebecca L., Kimberly D. Miller, and Ahmedin Jemal. ”Cancer statistics, 2016.” CA: a cancer journal for clinicians 66, no. 1 (2016).

[3] A. Patel et al., “Robotic MRI/US fusion transperineal biopsy using the iSR’obot Mona Lisa: Technique, safety and accuracy,” Eur. Urol. Suppl., vol. 16, no. 3, 2017.

[4] S. Lim, C. Jun, D. Chang, D. Petrisor, M. Han, and D. Stoianovici, “Robotic Transrectal Ultrasound Guided Prostate Biopsy,” IEEE Trans. Biomed. Eng., vol. 66, no. 9, pp. 2527–2537, Sep. 2019.

[5] C. Poquet, P. Mozer, M.-A. Vitrani, and G. Morel, “An Endorectal Ultrasound Probe Comanipulator With Hybrid Actuation Combining Brakes and Motors,” IEEE/ASME Trans. Mechatronics, vol. 20, no. 1, pp. 186–196, Feb. 2015.

[6] T. Zhang, Y. Wen, and Y.-H. Liu, “Developing a Parallel Robot for MRI-Guided Breast Intervention,” IEEE Trans. Med. Robot. Bionics, vol. 2, no. 1, pp. 17–27, Feb. 2020.

[7] Y. Zhang, M. Lu, and H. Du, “Kinematics analysis and trajectory planning for a breast intervention robot under MRI environment,” 2017 IEEE Int. Conf. Cyborg Bionic Syst. CBS 2017.

[8] W. Liu, Z. Yang, S. Jiang, D. Feng, and D. Zhang, “Design and implementation of a new cable-driven robot for MRI-guided breast biopsy,” Int. J. Med. Robot. Comput. Assist. Surg., 2020.

[9] https://www.murabproject.eu/

[10] Nikolaev, Anton, Hendrik HG Hansen, Leon De Jong, Ritse Mann, Eleonora Tagliabue, Bogdan Maris, Vincent Groenhuis et al. ”Ultrasound-guided breast biopsy of ultrasound occult lesions using multimodality image co-registration and tissue displacement tracking.” In Medical Imaging 2019: Ultrasonic Imaging and Tomography, vol. 10955.

[11] Maris, Bogdan Mihai, and Paolo Fiorini. ”Deformable surface registration for breast tumors tracking: A phantom study.” In 2017 13th IASTED International Conference on Biomedical Engineering (BioMed), pp. 20-25. IEEE, 2017.

[12] M. K. Welleweerd, F. J. Siepel, V. Groenhuis, J. Veltman, and S. Stramigioli, “Design of an end-effector for robot-assisted ultrasound-guided breast biopsies,” Int. J. Comput. Assist. Radiol. Surg., vol. 15, no. 4, 2020.

[13] Groenhuis, Vincent, Eleonora Tagliabue, Marcel K. Welleweerd, Françoise J. Siepel, Juan D. Munoz Osorio, Bogdan M. Maris, Diego Dall’Alba, Uwe Zimmermann, Paolo Fiorini, and Stefano Stramigioli. ”Deformation Compensation in Robotically-Assisted Breast Biopsy.” In 11th International Conference on Information Processing in Computer-Assisted Interventions, IPCAI 2020.

[14] M.K. Welleweerd, D. Pantelis, A.G. de Groot, F. J. Siepel and S. Stramigioli “Robot-assisted ultrasound-guided biopsy on MR-detected breast lesions,” IROS conference, October 25-29, 2020, Las Vegas, NV, USA.

[15] https://metropolis.scienze.univr.it/project/prost/

[16] Kikinis, Ron, Steve D. Pieper, and Kirby G. Vosburgh. ”3D Slicer: a platform for subject-specific image analysis, visualization, and clinical support.” In Intraoperative imaging and image-guided therapy, pp. 277-289. Springer, New York, NY, 2014.

[17] L. Palladino, B. Maris, P. Fiorini, ”3ADAGSS: Automatic Dataset Generation for Semantic Segmentation” Int J CARS (2020) 15 (Suppl 1):S1–S214

[18] L. Palladino, B. Maris, P. Fiorini, ”3D Slicer module for semantic segmentation of ultrasound images in prostate biopsy using deep learning techniques” Int J CARS (2020) 15 (Suppl 1):S1–S214

[19] Ronneberger, Olaf, Philipp Fischer, and Thomas Brox. ”U-net: Convolutional networks for biomedical image segmentation.” In International Conference on Medical image computing and computer-assisted intervention, pp. 234-241. Springer, Cham, 2015.