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Needle and Biopsy Robots: a Review

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Abstract

Purpose of the review 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. This paper provides an overview of recent robot-assisted percutaneous solutions.

Recent findings Percutaneous interventions are relatively simple and the quality of the procedure increases a lot by introducing robotics due to the improved accuracy and precision. The success of the procedure is heavily dependent on the ability to merge pre- and intraoperative images, as an accurate estimation of the current target location allows to exploit the robot's capabilities.

Summary Despite much research, the application of robotics in some branches of healthcare is not commonplace yet. Recent advances in percutaneous robotic solutions and imaging are highlighted, as they will pave the way to more widespread implementation of robotics in clinical practice.

Keywords Biopsy · Robot · Needle · Image-guided interventions · Medical · Diagnostic

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 add higher stiffness and precision by a more stabilized robotic manipulator compared to human hands. It supports 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.

The robotic biopsy was introduced in the following anatomical sites: the bone [1], lung [2], breast [3], brain or brainstem [4], prostate [5•], and liver [6]. In addition, needle

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approaches can be extrapolated for treatment purposes such as thermal ablation [6] or brachytherapy. These treatments can substitute more complicated and invasive surgeries.

In the mid-1980s, the first computed tomography (CT)–guided neurosurgical robotized biopsy was performed by a team at the Memorial Medical Center by using a modified PUMA industrial robot (Advance Research & Robotics, CT, USA) [7]. Since then, several different robots for needle interventions were presented using different imaging modalities, such as CT, magnetic resonance imaging (MRI), ultrasound (US), and fluoroscopy.

A commercial success story, The Da Vinci Robotic System (Surgical Intuitive, Inc., Mountain View, CA) occupies a monopoly position in minimally invasive robotic surgery. The complex surgery that Da Vinci robot assists, and the type of images used in navigation, makes its autonomy very limited or actually not existing. Even if this type of robots operates for more than 20 years, their superiority over the manual procedure is still an issue of discussion in contradicting studies [8, 9].

In case of percutaneous interventions, the trajectory that the robot should follow is most of the time a straight line, while the images used for guidance are standard radiological images. In this case, the robot may have a double utility: on one side, it can integrate diagnostic and interventional images through a fusion process; on the other side it can use the image fusion to impose the linear trajectory from a suitable external position to a target point. This type of interventions can support the awareness that robotics showed improvements in precision.

However, the benefits of robotic applications in hospital settings, such as improvements in accuracy, precision, and repetition of small tasks; better ergonomics; and immunity of fatigue, are not used to the full extent. There seems to be a gap between sophisticated robotic technology and clinical needs. Recent advances in minimally invasive treatments have brought the attention to new types of robots specifically designed for a particular type of intervention or even systems personalized for each patient through 3D printing [10].

This paper explains the essential workflow phases and design elements of robotic-assisted percutaneous solutions and will discuss current and future trends to demonstrate the potential in interventions and impact on the cancer workflow.

Biopsy Robots—Design and Developments

The design of a biopsy robot starts with analysis of the medical procedure that will give insight to the physical constraints, therefore the mechanical design. The imaging source, used during intervention, will be supplemented with other sensors required for the navigation. Last but not least, the design of the software integrated in the robot will face all the other aspects of the procedure: control of the robot, navigation and image processing, user interface, and real-time functionality. All these aspects should fulfill the medical standard and constraints, while the robot should be compliant with other equipment already used in the procedure (e.g., ultrasound system, standard needles and probes, MRI compatibility).

Mechanical Design

There are several challenges in the design and construction of interventional biopsy robots. Table 1 shows an overview of biopsy robots presented and optimized in the last 5 years. An effective mechanical design should provide the ability to access any point in the target organ and should have the flexibility to avoid critical structures upon needle insertion. Not only specialized robotic systems were developed to target the needle to the biopsy target but also commercially available industrial robotic arms and systems were embedded. The degrees of freedom (DOF) determine which positions and poses the system can take with respect to the target. As shown in Table 1, systems ranging from 2 to 7 DOFs were presented with different types of kinematics for robotic manipulators using parallel, serial, and hybrid approaches, which influences individual joint values to the end-effector's position and orientation using platforms or a specific gripper as end effector.

Considerations regarding to structure and workspace are essential in biopsy. Serial manipulators are preferred for a large workspace and many degrees of freedom, but stiffness and strength are more difficult to achieve. In general, parallel manipulators are preferred for precise positioning since these mechanisms can be designed to have a higher accuracy with higher stiffness compared to serial robots.

Actuators are located near the base in parallel designs and on the links in serial approaches. The type of actuation is based on output power, speed, acceleration, and maximum force and is environment dependent. The following actuation -methods were used: electric actuators including ultrasonic/piezoelectric, pneumatic actuators, hydraulic actuators, and electromagnetic actuators; Bowden tubes; and chain transmission [11]. Actuation is mainly limited for MRI applications due to the high magnetic field, interaction with radiofrequency (RF) signals, and switching gradients [12••]. MR-safe systems and actuation methods were presented for several applications including mainly prostate applications [5•, 13, 14] and, to a lesser extent, breast applications [15, 16•, 17].

Needle devices are based on passive, semi-active, and active approaches ranging from assistive holders to autonomously insertion. Many computer-aided design (CAD) and computer-aided manufacturing (CAM)–based biopsy systems were developed and insert the needle autonomously using image guidance. These systems are mainly meant for implementation of iterative optimization in an early stage development but are not mature for market introduction.

Table 1 Image-based percutaneous interventions

Author	Robot	Imaging	Mech design DOF	Mech actuation	Published	Accuracy (mm)	Organ	Application
JH Zhu [32]	Robot assistance skull base biopsy	CBCT	5 DOF	Electric	2017	0.56–1.73	Skull	Prototype tested on phantom
G Minchev [4, 33]	Robot-guided minimal invasive brain	Guided by MRI	A tubular instrument set was custom-designed for the iSYS-1 robot	Electric	2020	0.6–1.5	Brain	Prototype tested on humans
M. Ye [50]	Semi-autonomous stereotactic brain biopsy robot	-	7 DOF (6 DOF in UR5 robot, 1 DOF in biopsy module)	Electric	2020	1.01	Brain	Prototype + ex vivo experiments
A Carai [34•, 35]	Robot-assisted stereotactic biopsy	Guided by MRI/CT	Robotic stereotactic-assisted system (ROSA) 6 DOF	Electric	2017	Feasible (n =7)	Brain stem	ROSA robot tested on humans
V Groenhuis [3]	Stormram 3: a MRI-compatible robotic system	MRI	5 DOF	Pneumatic	2017	2	Breast	Prototype tested in vitro
V Groenhuis [16•]	Stormram 4: an MR-safe robotic system	MRI	4 DOF	Pneumatic	2018	1.29	Breast	Prototype tested in vitro
M Lu [15]	MRI-compatible breast biopsy robot	MRI	DOFS for space location, posture adjustment, and biopsy needle puncture	-	2018	Demonstration of functionality	Breast	Design
D Navarro-Alarcon [51]	Compact robotic needle driver for MRI-guided biopsy	MRI	3 DOF	Piezoelectric and pneumatic actuation	2017	Demonstration of functionality	Breast	Prototype
T Zhang [17]	Parallel robot for MRI-guided intervention	MRI	2 DOF	Cable-actuated system and piezoelectric motors	2020	0.84–1.99	Breast	Prototype
Y Zhang [52]	Kinematics analysis and trajectory planning for an intervention robot	MRI	Positioning module: 4 DOF, puncturing module 1 DOF, biopsy module 1 DOF, storage module 1 DOF	-	2017	Demonstration of functionality	Breast	Prototype
W Liu [53]	Cable-driven robot for MRI-guided breast biopsy	MRI	3 DOF	Ultrasonic motors	2020	0.7	Breast	Prototype tested
Y Zhang [54]	MRI-compatible robot for intervention	MRI	7 DOF total	Cables, belts	2015	N/A	Breast	N/A
T Zhang [55]	A novel palm-shape robot for MRI-guided biopsy	MRI	2 DOF (rigid), 5 pneumatic bladders	Piezoelectric motors, pneumatics for bladders	2016	N/A	Breast	Prototype tested on phantom
M Chen [47]	Needle insertion medical robot for tumor surgery	Computer vision	2 DOF for needle guide, 2 DOF for tumor manipulation system	Electric cylinders	2017	0.6	Breast	Prototype validated on transparent phantom

Table 1 (continued)

Author	Robot	Imaging	Mech design DOF	Mech actuation	Published	Accuracy (mm)	Organ	Application
MK Welleweerd [20•]	MRI and ultrasound robotic-assisted biopsy (MURAB)	US (+ preop MRI)	7 DOF robot arm + 3 DOF needle guide	Electric motors with force sensing	2020	3	Breast	Prototype
S Amack [2]	Compact modular robot	CT	Four carriages, each with the ability to control the rotation and translation	Electric	2019	0.46±0.28	Lung	Prototype tested on phantom
Y Moon [56]	End-effector robotic multichannel biopsy	CT based	4 DOF	Electric motors	2015	Demonstration of functionality	Lung	Prototype tested on phantom
DA Schreiber [57]	An open-source 7-axis, robotic platform to enable dexterous procedures within CT scanners	CT	7 DOF total (3 DOF exo-bore, 4 DOF in-bore)	Belt-driven (exo-bore), cables (in-bore)	2019	<1	Lung	Prototype, phantom validation
N Hungr [38]	CT- and MRI-guided robot for percutaneous needle procedures	CT, MRI	5 DOF total	Ultrasonic, Bowden cables, and pneumatics	2016	3.3±1.7	Thorac, abdomen	Prototype tested on gelatin phantom
E Franco [6]	Needle-guiding robot for laser ablation	MRI	4 DOF	Pneumatic	2016	<1.5	Liver	Prototype and tested in phantom
HJ Won [58]	CT-guided intervention robot for biopsy and radiofrequency ablation	CT/CT fluoroscopy	Five-axis robot arm + end effector	Electric	2017	<3	Liver/abdomen	Prototype and tested in phantom
Ben-David [59]	CT-guided robotic system for precise percutaneous needle insertion	CT-guided robotic system	5 DOF	Electric	2018	1.78	Retroperitoneum, lung, liver, kidneys	Animal study
P. Tucan [60]	Control system of a medical parallel robot BIO-PROS1	MR-US-guided	5 DOF	Electric stepper motors	2017	Demonstration of functionality	Prostate	Prototype
JGR Bomers [37•]	MR-compatible manipulator for biopsy guidance	MRI	5 DOF	Pneumatic	2017	(*n* =20) feasible and safe	Prostate	Commercial system (Soteria) used in clinical practice
D Stoianovici [5•]	MRI-safe robot for biopsy MrBot	MRI	6 DOF	Pneumatic	2016	2.55	Prostate	Prototype tested on humans
P Moreira [14]	Miriam robot	MRI	5 DOF parallel robot + a 4 DOF needle driver	Piezoelectric motors	2017	1.84	Prostate	Prototype tested in vitro
L Chen [61]	MRI-compatible robot	MRI	5 DOF	Pneumatic	2015	0.4	Prostate	Commercial device in use
NA Patel [40]	Robotic MRI/US fusion transperineal biopsy using the iSR'obot Mona Lisa	US and US-MRI fusion	4 DOF (1 for the US probe, 3 for the needle)	Electric motors	2017	1.5	Prostate	Commercial system used in clinical practice
S Lim [48]	Robotic ultrasound-guided biopsy	US based	4 DOF at/around RCM	Electric motors	2019	1.35	Prostate	Prototype + mock-up test and clinic trial
D Pisla [39]		US	Two parallel modules, each 5 DOF	Electric motors	2016	Simulations	Prostate	Model

Table 1 (continued)

Author	Robot	Imaging	Mech design DOF	Mech actuation	Published	Accuracy (mm)	Organ	Application
	BIO-PROS-2: an innovative parallel robotic structure for transperineal prostate biopsy							
C Poquet [49]	Ultrasound probe manipulator with hybrid actuation combining brakes and motors	US	6 DOF	Electric motors, cables, brakes	2015	3	Prostate	Prototype tested in vitro
H Su [62]	Piezoelectrically actuated robotic system for MRI-guided therapy	MRI	6 DOF total 3 DOF Cartesian motion, 3 DOF needle driver	Piezoelectric	2015	0.87	Prostate	Prototype tested on phantoms
M Li [36]	MRI-compatible needle driver for in-bore prostate biopsy	MRI	7 DOF total 4 DOF base, 3 DOF needle driver	Piezoelectric	2015	0.92–1.65	Prostate	Prototype tested on soft plastic phantom
KY Kim [63]	MRI-compatible modularized needle driver for in-bore MRI-guided interventions	MRI	7 DOF total	Piezoelectric	2015	N/A	Prostate	N/A
M Wartenberg [64]	Automated needle steering for MRI-guided interventions	MRI (but prototype MR-unsafe)	2 DOF	Electric DC motors	2016	2.7	Prostate	MR-unsafe prototype, tested on gelatin phantom
AN Alvara [65]	MRI-compatible pediatric surgical robot with modular tooling for bone biopsy	MRI	5 DOF	Piezoelectric ultrasonic	2018	1.65±1.77	Bone	Prototype tested in vitro
SO Orhan [66]	Parallel robot for ultrasound-guided needle interventions	Ultrasound	5 DOF total	Electric DC motor	2015	0.7–2.2	Various	Prototype tested on phantom
KY Kim [67]	Development of a needle driver for CT-guided needle interventional robotic system	CT	2 DOF	Electric DC motors	2017	0.16	Various	Prototype, in vitro validation
NA Patel [68]	Body-mounted robot for image-guided percutaneous interventions	MRI, CT	4 DOF	Piezoelectric, timing belts driving two scissor mechanisms	2018	1.4	Various (arthrography, biopsy, brachytherapy)	Prototype, in vitro validation

The safety of the mechanism and the sterilizability are important requirements to keep into account when designing the robot. Some systems use passive mechanisms to ensure safety [18], while in other approaches, compliant robots, such as the KUKA lightweight robot [19], are employed [20•]. The sterilizability can be ensured by using detachable elements that can be sterilized or by using disposable parts.

Besides needle punctures through the skin, intraluminal navigation through the gastrointestinal tract for biopsy purposes is another attractive field. An overview of endoscopic applications is shown in Table 2. Progression in developments was mainly focused on enabling biopsies in the gastrointestinal (GI) tract [21, 22] and stomach [21–23]. The capsule endoscope robot was introduced including structures which are relatively complex by the use of external magnetic actuation and size limitations due to the swallow capacity of patients. In addition, robotic catheters for flexible navigation were optimized to take for example transbronchial biopsies.

Trends are seen in the development of compact robotic designs compatible with several imaging modalities. Multimodality approaches were introduced to combine morphological, functional, and real-time data. Prostate and breast use cases are shown, but applications include lung and brain sites as well (see Table 1).

Image-Based Needle Navigation and Robotic Control

Preoperative imaging provides an anatomical roadmap to guide the needle during the procedure to the correct target, and the intervention/needle path is based on planning algorithms. Real-time navigation through complex anatomical areas is a challenge, as during the insertion, the tissue deforms and patient movement or breathing requires re-localization of the predefined target [24].

The intraoperative image modality is chosen based on the application: many procedures implement US as a real-time image feedback modality in their application to improve needle insertion due to immediate image generation, no setup constraints, cheap, and limited patient discomfort, and therefore, US is seen as the gold standard for biopsy. CT introduces X-ray radiation, but is relatively fast, while MRI provides high-quality soft tissue images, no radiation, and high spatial resolution, but requires that robotic devices are compatible with the magnetic field and are free of ferromagnetic materials. A device is called MR-safe if no metallic, ferromagnetic, or conductive materials are present and MR Conditional if any material and device allowed are safety-validated under given conditions.

A so-called registration process is required to align preoperative images, where the diagnosis was made and the target was identified, with the intraoperative images or with the patient. In the case of a robotic orthopedic surgery, this task is easier because of the rigid nature of the anatomy and the possibility to invasively attach the robot directly to the patient [25], while in the soft tissue sites, the registration is more challenging and is still an open research area [26, 27].

There are several reviews that deepen the topic of image registration for robotic applications (e.g., [28, 29]). The mapping of the preoperative images to the intraoperative images can be performed once, before the robotic intervention, or can be updated during the intervention, in case the patient moved or the organ deformed. Correct image registration, such that the current target position is known to the robotic system, is of vital importance for the success of the procedure. Image registration is a time-consuming process, and since registration assists robotic navigation in real-time, a suitable choice of the registration algorithm that minimizes the time delay should be made.

New algorithms for image registration, based on AI, are showing very promising results both in terms of time efficiency and accuracy [30, 31]. These new approaches require the use of large amount of data and the involvement of the radiologists to create the dataset that will be used to train the algorithms so, despite their novelty and innovation, they are not implemented in the actual clinical biopsy robots.

In the case of brain procedures or, more generally, in orthopedic applications, the registration is rigid and is based on a weighted combination of points and surfaces. The registration is performed before the procedure to align the reference system of the robot with the patient and with the preoperative data (e.g., MRI, CT), while the rigid fixation of the robot to the patient ensures keeping the target fixed with respect to the robot (e.g., [32, 33], [34•,35]). The MRI-safe robots are designed to operate inside a closed-bore MRI scanner to automatically align a needle guide to the target lesions, while still employing manual needle insertions outside the bore (e.g., [5•, 36, 37•]). The robot should include MRI-compatible markers to be visualized in the image.

In addition, the robots guided by CT images may be mounted on the patient's body and the doctor positions and inserts the needle according to the trajectory and target chosen by the radiologist in the image. The robot is visible in the CT images and can be easily segmented and registered [38].

US-guided biopsy robots have the advantage of intraoperative real-time imaging to be used for navigation, but most of the time, the target is defined in preoperative MRI or CT, since a tumor is not always visible in US. This is the most challenging task for a biopsy robot. Typical application are breast and prostate biopsy (e.g., [39, 40, 20•]). They will be discussed in the next subsections.

Several solutions for robot-assisted needle insertion are applied and include conventional stiff needles, precurved needles, concentric tube approaches, and tendon-based steering biopsy needles under robotic control [41]. Biopsy needles are mainly classified as symmetric (e.g., conical or triangular prismatic) or asymmetric (e.g., beveled). Stiff

Table 2 Endoscope-based interventions

Author	Robot	Imaging	Mech design DOF	Mech actuation	Published	Accuracy (mm)	Organ	Application
Y Gao [69]	Continuum robot with follow-the-leader motion biopsy	Endoscopic	A wire-driven continuum robot	Push pull wire	2020	<1.49	Brain	Prototype tested on humans
C Girerd [70]	Optical biopsy of olfactory cells using concentric tube robots with follow-the-leader deployment	OCT	Three concentric tubes, 6 DOF	Electric stepper motors 3× linear stage, 3× rotational stage	2017	0.020	Nasal cavity	Prototype, phantom validation
L Dupourqué [71]	Biopsy catheter enhanced by a multisection continuum robot with follow-the-leader motion	Endoscope/US	Three bending sections, each with two degrees of freedom (DOF), resulting in 6 DOF	Electric	2019	0.94±0.50	Lung	Prototype tested on phantom
D Son [72]	Magnetically actuated soft capsule endoscope for fine-needle biopsy	Endoscope	Magnet with sufficient magnetic force and torque	Manipulated by the external magnetic field	2020	Demonstration of functionality	Stomach	Prototype tested in vitro
D Ye [23]	Magnetically driven wireless capsule robot with targeting biopsy function	Camera	Capsule magnet with sufficient magnetic force	Magnetically actuated wireless capsule robot	2019	Demonstration of functionality	Stomach	Prototype
X Pan [21]	Microcapsule endoscope robot with biopsy function	Endoscopy	Two capsule shells and a biopsy function module	Stepper motor (electric)	2018	Can obtain tissue samples successfully	Intestines	Prototype tested in vitro
F Zhang [22]	Biopsy capsule robot	-	Three modules: biopsy module, anchoring module, and decouple-drive module	Shaft fixed with a circular radial magnetizing magnet	2019	Demonstration of functionality	Intestines	Design
A Shakoor [73]	A high-precision robot-aided single-cell biopsy system	CCD camera	3 DOF micro manipulator plus XY stage	Electric motors and linear actuators	2017	0.025 Demonstration of functionality	Small adherent cells	Prototype
Y Baran [74]	OCT-based position control of a concentric tube robot	Endoscope/OCT	Three curved tubes to obtain 6 DOF	Electric stepper motor	2017	0.055	Nonspecific	Prototype tested
GD Giudice [75]	Continuum robots for multi-scale motion: micro-scale motion through equilibrium modulation	OCT (optical coherence tomography)	3 DOF/continuum	Wires, electric DC motors	2017	0.010	Nonspecific	Prototype, in vitro validation

needles with a symmetric tip require that no critical structures are located between insertion point and target, as only small corrections during needle insertion are possible. Recently, needle steering came more into focus to deflect the needle with bevel tips toward the target [36]. Each needle needs its own guide as several needle sizes are used in biopsy procedures. The robot-assisted approaches will reduce the number of reinsertions and caused scar tissue afterwards. In addition, needle insertion and the shooting mechanism to take the biopsy should be aligned and release the needle on distance before the target has been reached.

In a Cartesian or joint space of the robot, the needle should be directed smoothly via trajectory planning to the target. There are several control schemes which can be implemented in the biopsy workflow. Autonomous scanning and needle insertion are complex tasks due to patient movement and tissue deformation. Important aspects include stability, safety, controllability, and robustness. Hybrid and impedance control are often used. In case of impedance control, the behavior between the manipulator and environment is controlled as an impedance with motion input and force output. Hybrid position or vision/force control uses trajectory or visual servoing tracking information. Most often, external force sensors are used to receive force feedback and guarantee constant force interventions. Trajectory planning is often based on localization of identifiable markers on the human body or preimaging data. Most often, a 3D virtual patient-specific model is built using surface or volume rendering. During registration, the preoperative data is aligned with the intraoperative (biopsy) view based on rigid or deformable methods with manual, point-based, or surface-/volume-based methods. The entire biopsy plan and intervention is relatively complex due to the deformation of the 3D structures and the multiple parameters to embed during the biopsy [42, 43].

Use Cases

Breast Cancer Use Case

Breast cancer is one of the most frequently diagnosed types of cancer among women. Imaging modalities, such as mammography, US, and MRI, are commonly used for the detection of lesions. Currently, a biopsy is preferably taken under US guidance, since this technology gives real-time feedback during the procedure, causes relatively little patient discomfort, and is cheap. However, a US-guided biopsy may be complex if the lesion is detected on MRI. The lesion may not be visible on US, and interpreting the relation between the 3D MRI data and the actual patient is difficult. On one side, the breast is a relatively basic structure to perform procedures on, since the structure is isolated from the rest of the body, and contains no vital structures. On the other hand, the structure is highly deformable, so determining the target location is a challenge. Figure 1 shows a possible workflow for ultrasound-guided robotic breast biopsies on MR-detected lesions and its most important steps, as indicated in the MURAB project [20•]. 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 performs planning for the intervention. Deformation modeling and tracking during the initial probe positioning is necessary, as the breast is highly deformable. Once the robot is in its final position, the lesion position is updated and the intervention starts.

As an alternative to this approach, which takes place outside the MRI, there is the possibility to utilize MRI-safe robots. These robots fit inside the MRI, and hence, the MRI images themselves can be used as feedback for the procedure. The advantage of this type of robot is that registration between the patient and the robot is less complex, since both are visible on the same dataset. Additionally, there is no need to merge several types of datasets, so just the conventional MR images may be used during the intervention. However, the design requirements for the robot itself are more strenuous since the robot should fit inside the MRI bore and all materials should be MR-safe.

Prostatic Cancer Use Case

One of the most successful and promising applications of the robotic percutaneous approach is prostate biopsy and needle treatment. The prostate has a favourable location in the body such that there is little deformation while imaging the site with a transrectal ultrasound (TRUS) probe. Moreover, there is little risk for the needle to penetrate other organs since the access is through the perineal wall, which is a fibromuscular mass, or through the rectum.

The gold standard of the manual biopsy is the so-called fusion biopsy [44] that allows the navigation for a targeted biopsy based on the mpMRI (multiparametric MRI) preoperative images, where the suspicious lesion is identified, registered with real-time US taken with an elongated rectal probe. The targeted procedure is followed, in most of the cases, by the saturated biopsy since the targeted biopsy misses a large number of clinically significant prostate cancer (PCa) detected by systematic biopsy [45, 46].

The prostate biopsy is highly dependent on the experience of the doctor and the learning curve is long.

Hence, the reasons to introduce robotic assistance are manifold: standardization of the procedure, operator independence, improvement of the precision, and improved image fusion, therefore better targeting, reduced trauma by reducing

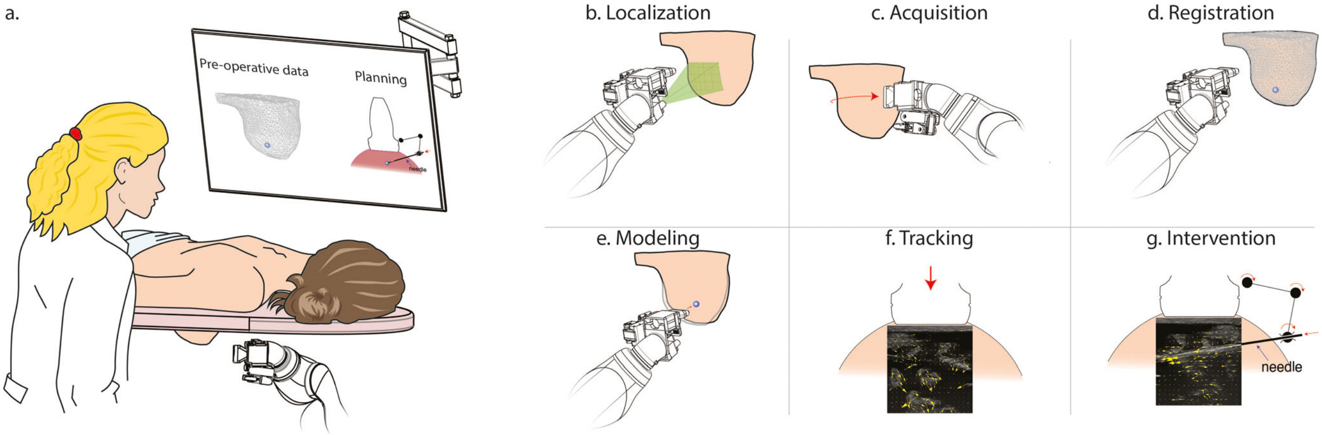

Fig. 1 Phases of a robotic breast biopsy. **a** The radiologist checks the preoperative images and suggested path. **b** The robot localizes the patient. **c** The robot acquires US data of the site. **d** The robot registers the available preoperative data. **e** and **f** Modeling and tracking are utilized to determine the target location after probe positioning. **g** The intervention takes place

the number of insertions, shorter hospital time, and improved and earlier diagnosis.

There are currently two trends in robotic prostate biopsy: one is the in-bore solution, that is, an MR-compatible robot (e.g., [5•, 14, 37•, 47]), and the other one uses the US images or MR-US fusion to guide the robot toward the target (e.g., [40, 48, 49]).

An example of the architecture of a US-guided prostate robot is shown in Fig. 2. The robot handles the needle and the US probe separately, while dedicated sensors and the encoders of the motors track the movements in the reference frame of the robot. Vision processing and control of the robot is implemented in one or more dedicated PCBs. The middleware will interface the low-level architecture with the graphical user interface (GUI). The GUI allows the physician to load preoperative 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 can be performed automatically; therefore, the position of the needle is given by the motor's encoder, or manually. During the manual insertion, a proximity sensor may give hints on the distance to the target.

Conclusion and Outlook

The current diagnostic and therapeutic workflow will change and improve with the introduction of robots. The benefits of a robotic system for percutaneous interventions include: higher accuracy and precision, standardization of the procedure, stability, improved hand-eye coordination, and 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 preoperative data. Due to these advantages, the procedures

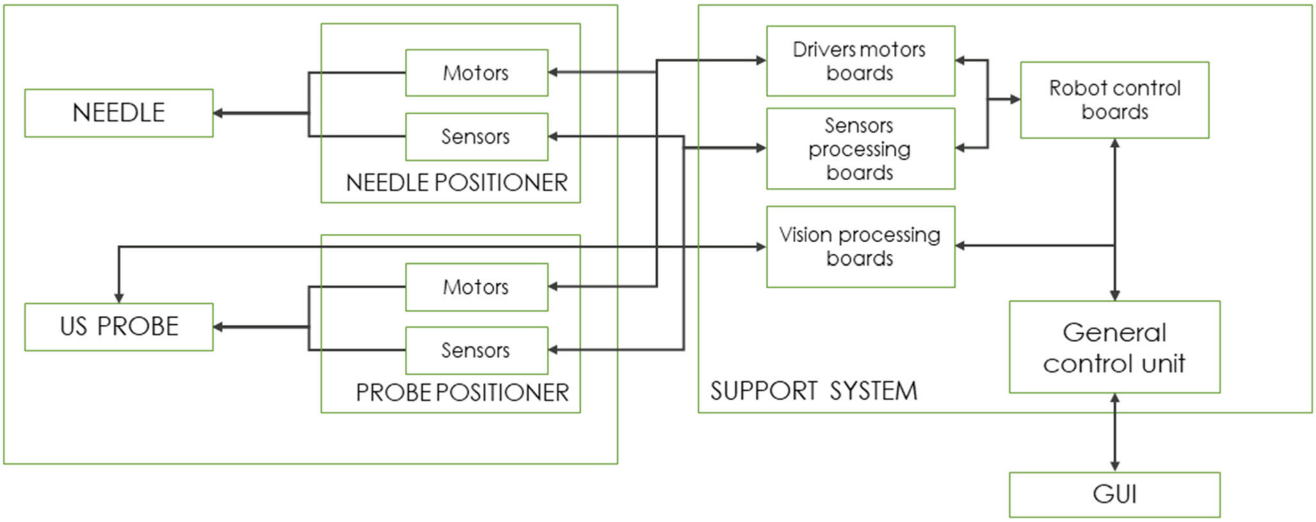

Fig. 2 System architecture of a US-guided prostate biopsy robot

will be faster, less expensive, and produce less trauma for the patient. The biopsy workflow will shift to a one-stop source procedure, with a 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, preplanning with deformation prediction and intervention, as described in Fig. 1. We envision that more than 75% of the diagnostic procedures can be standardized and interventions will be performed by autonomous or semi-autonomous robots. The role of the physicians will shift to a check-and-evaluation role of the more difficult cases.

The spread of minimally invasive procedures and the use of smaller needles and robotic manipulators will reduce scars and trauma to the patients. Consequently, a new generation of interventional radiologists/surgeons will become more and more familiar with this technology. In the context of robot design, the introduction of biopsy robots began with the modification of industrial robots which were large, complex, and expensive. The current trend is to introduce smaller, less expensive alternatives which are compatible with all types of image modalities dependent on the required application. Complex needle navigation will be boosted by fusion of image data and patient modeling to improve patient-specific treatment such as drainage, drug delivery, thermal ablation, and radioactive seeds. In addition, high-level autonomous features will be implemented to a greater extent. More attention will be on safety, reliability, and sterilizability of systems to embed them in clinical robots. In general, few systems reach the market due to the extensive trajectory of certification and approval that requires to guarantee safety in all circumstances. Therefore, more high-quality test facilities and validation for the systems in vivo or animal studies should be available to evaluate the feasibility and guarantee safety. End-user involvement becomes more and more crucial to adjust technology to the real needs of the physician and patient.

Robotics is an interdisciplinary field combining computer science, electrical engineering, and mechanical engineering, and it is important to collaborate with physicians even more to boost the technology. In addition, it is crucial due to multitude of benefits to facilitate and accelerate the application of robotic technologies across healthcare.

Compliance with Ethical Standards

Conflict of Interest The authors FJS, VG, SS have the following patent EP3504445, US16/326,442. The other authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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