INVITED PAPER

Robot-Assisted Medical Imaging: A Review

This article provides an overview of the current state of the art and potential research directions for robotic imaging systems, with special emphasis on instances in which the accurate placement and trajectory control of the imaging system using a robot are of paramount importance.

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ABSTRACT | Robot-assisted medical imaging entails the use of a robot to acquire a medical image. Examples include robot-assisted endoscopic camera imaging, ultrasound imaging where the transducer is held by a robot, X-ray imaging where the source and detector are positioned by robots, and actuated capsule endoscopy, where the capsule is maneuvered by external magnetic actuation. Robot assistance enables the controlled trajectory of the imaging system with high precision and accuracy. This makes it possible to compound acquisitions for increased aperture and for volumetric or tomographic imaging, to track medical instrumentation, and to adjust imaging trajectory in a feedback loop as a function of the patient. Intraoperative robotic medical imaging can provide valuable information to the physician and facilitates the registration of preoperative imaging to the patient. In this review article, we describe some of the robotic imaging systems developed for diagnosis and intervention guidance. In particular, based on the surveyed research activity, we will describe our view of the state of the art in ultrasound, endoscopy, X-ray, optical coherence tomography, and nuclear medicine. We will discuss approaches to autonomous scanning and physics-driven approaches such as elastography and photoacoustic tomography, where the accurate placement and trajectory control of the imaging system using a robot are of paramount importance. We will map out the current state of the art and discuss potential avenues of research.

KEYWORDS | Autonomous systems; medical imaging; medical robotics; robotic imaging; telemedicine; telerobotics.

Manuscript received October 20, 2021; revised December 30, 2021 and February 28, 2022; accepted March 19, 2022. Date of publication April 13, 2022; date of current version June 20, 2022. This work was supported by the National Sciences and Engineering Research Council of Canada. The work of Septimiu E. Salcudean and Hamid Moradi was supported by the C. A. Laszlo Chair. *(Corresponding author: Septimiu E. Salcudean.)*

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Digital Object Identifier 10.1109/JPROC.2022.3162840

I. INTRODUCTION

There are many reviews surveying medical robotic systems [1], [2]. These typically involve robotic implementation or assistance in surgery or radiation treatment, as surveyed with a technological development timeline in [3]. We can classify the medical robotic products or advanced systems developed into the categories detailed in Table 1. Many of the robotic systems developed rely on intraoperative endoscopic cameras and some employ preoperative imaging, such as computed X-ray tomography, for image guidance, but there are few that use robotic image acquisition.

The goal of this survey is to present an overview of robot-assisted medical imaging, where the main function of the robot is to acquire or facilitate the acquisition of a medical image, through sensing, actuation, and decision/feedback. This is in contrast with the use of a robot in an image-guided procedure, where the image is acquired through conventional means.

To the best of our knowledge, the first system to integrate robot-assisted medical imaging into a medical robotic solution was developed by Davies *et al.* [4]. The robot (called a "motorized frame" in [4]) was used to acquire transurethral ultrasound images of the prostate at 5-mm intervals with a rotating probe. The images were manually annotated and used to obtain a 3-D prostate segmentation that was registered with the robot. The robot system was designed so that the position of the prostate is not changed by the changes of surgical instruments during the procedure (endoscope for coarse localization of the bladder

Table 1 Classification of Medical Robotic Products or Systems According to Their Main Function

Procedures	Robotic system by company
To control an endoscopic camera in surgery	AESOP™ by Computer Motion, FreeHand®, SOLOASSIST by AKTORmed, AutoLap™ by OrionPax.
To teleoperate endoscopic instruments and camera for surgery	da Vinci® S/Si/Xi/SP systems by Intuitive Surgical, Telelap and Senhance® systems by Asensus Surgical, Versius® by CMR, Hugo™ by Medtronic
To perform a surgical task accurately with pre-operative image guidance	Robodoc® by IBM and Integrated Surgical Systems, CASPAR® by ortoMaquet, MAKO™ by Stryker, Navio™ by Smith & Nephew, KINEVO 900 by Carl Zeiss, Velys™ Digital Surgery by Johnson and Johnson
To examine the gastrointestinal tract with endoscopic capsules	PillCam™ by Medtronic, OMOM® by Jinshan Science & Technology, Capsule Endoscopy by Olympus, NaviCam® by Anx Robotica
To deliver radiation to a target	CyberKnife® by Accuray, Novalis® by BrainLab, TrueBeam™ by Varian
To deliver rigid instruments to a precise target	NeuroMate® by Renishaw, AcuBot by Johns Hopkins, PathFinder™ by Armstrong Healthcare Ltd, NeuroArm™ from the University of Calgary, Renaissance® by Mazor Robotics, ROSA ONE® by Zimmer Biomet Robotics.
To position catheters or flexible endoscopes, including bronchoscopes	Niobe™ by Stereotaxis, Sensei® by Lightpoint Medical, Ion™ by Intuitive Surgical, Monarch™ by Auris Health, EndoDrive® by ECE Medical Systems
To position ultrasound transducers	Melody by AdEchoTech, MGIUS-R3 by MGI, Histosonics®
To position microscopes	Aesculap Aeos® by B. Braun, ARTEVO® 800 by Zeiss, Proveo 8 by Leica Microsystems.

neck and the apex, ultrasound transducer to scan from the bladder neck to the apex, and then resectoscope to remove tissue). It was used in a clinical study with 39 patients with results similar to those obtained with the conventional manual method [5]. The complete integrated "Probot" system in [6] later made use of automatic segmentation of the prostate [7]. While the "Probot" imaging system is similar to the many motorized 2-D ultrasound systems used to produce 3-D ultrasound images [8], 3-D ultrasound systems do not employ sensory feedback during the image acquisition, nor do they adapt to the patient or the operator input, other than starting and stopping the process.

Ultrasound is the main imaging modality that requires an operator to maneuver a probe against the patient, and therefore, it has also been the main target of robotics researchers interested in using robots for medical image acquisition. Several reviews of robot-assisted ultrasound have been published [9]–[11]. Endoscopy has also been an area of very active research and significant clinical impact and is the subject of multiple reviews, e.g., [12]–[15].

However, there are other areas that include robots and use sensing, actuation, and decision to acquire medical images. These include robot-assisted X-ray imaging, intraoperative single photon-emission computer tomography (SPECT)-like 3-D imaging using a miniaturized gamma camera mounted on a robot [16], optical coherence tomography (OCT) scanning using micromanipulators [17], OCT possibly integrated into a full robotic system [18], photoacoustic [19], and elastography [20] scanning using the da Vinci robot, tremor canceling smart tools [21], and molecular imaging, combined with macroscale localization [22].

We organized the review as follows. In Section II, we provide a bird's eye view of the field, by surveying published research and providing some statistics on which areas have received attention. In Section III, we provide an overview of robot-assisted medical ultrasound, including approaches to conventional (B-mode) imaging and unconventional imaging, such as increased aperture imaging, by exploiting the accurate placement of the ultrasound transducer. In Section IV, we summarize robotic endoscopic imaging, widely used in surgery, and capsule endoscopy. Robot-assisted X-ray imaging is described in Section V, OCT imaging in Section VI, and molecular and microscopy imaging in Section VII. Each section is accompanied by a discussion. Section VIII presents a brief discussion and conclusions. Table 2 presents an overview of the papers discussed in Sections III–VII.

II. METHODOLOGY USED FOR THE SURVEY

Robot-assisted imaging papers published up to December 24, 2021 were searched on Google Scholar using the following search term: allinTitle: (robot OR robotic OR robotically OR roboticized OR "visual servoing") AND (imaging OR scanning OR "coherence tomography" OR CT OR MRI OR ultrasound OR sonography OR "X ray" OR photoacoustic OR OCT OR telepathology OR SPECT OR endoscopy OR endoscope OR bronchoscopy OR microscope OR microscopy OR tele-echographic OR tele-echography OR fluorescence OR ultrasonography OR echocardiography), where MRI stood for magnetic resonance imaging and CT for computed tomography.

The purpose of this search was to map the overall research activity in which the robot plays a role in the medical imaging process. The above search was iterated upon using narrower searches in the areas familiar to the authors. These narrower searches were also used to test whether the results were consistent with our goal of including potentially impactful papers. As Google Scholar has limitations on the number of characters per search term and cuts off after 1000 papers per search, we split the criteria into several parallel search terms. The union of all the results from the different searches constituted the total set of included papers.

In total, 5009 papers were found and subsequently manually filtered by removing papers that were: 1) nonmedical and 2) related to image-guided robotic intervention where

Table 2 Summary of Robot-Assisted Medical Imaging Review

Section/sub-section			Method	References
Ultrasound Scanning	Direct control		Tele-ultrasound was introduced and integrated into surgical system.	[24][25][26][27]
			Patient safety and controlling/predicting contact force discussed.	[28][29][30][31]
			Tele-ultrasound for COVID-19 pandemic was proposed.	[32][33]
	Shared control		Automatic axial contact force or virtual fixture was used in a robotic ultrasound system	[24][11][34]
			Shared control was used for ultrasound visual servoing	[35][25][36]
			Automatic optimization of ultrasound image quality.	[37][38]
	Autonomous		Autonomous robotic ultrasound to track or compensate motion	[39][40][41][42]
			Image processing used for automatic transducer placement	[43][44][45][46][47] [48]
			Camera/sensor used for automatic surface scanning	[49][50][51][52][53] [54][55][56][46][57]
			Machine learning used to compute force for stiffness controller	[44][58][59][60]
			Machine learning to navigate a virtual/actual transducer	[38][61][62][63]
	Non-standard	Increased aperture	Multiple ultrasound systems were calibrated and utilized for larger detection surface	[64][65]
		Transmission tomography	Multiple Robotic data acquisitions from the same region of interest	[66][67]
			Robotic arm maneuvers the transducer for 3-D data acquisitions	[68][69]
		Photoacoustic	Robot used to control the ultrasound transducer and/or the illuminator or exciter.	[19][64][70][71][72] [73]
			Providing surgical tool tip visualization or localization	[74][75][76][77]
		Elastography	Providing tissue stiffness feedback for robotic surgical systems	[20][78]
			Robots used for the stability of the ultrasound transducer and knowledge of applied forces	[79][80][81]
Endoscopy	Categories and use		Rigid endoscopes held or controlled by a robotic arm	[82][83][84]
			Robot-assisted flexible endoscopy with complex motion control and stabilization	[85][86][87][88][89] [90][91][92]
			Wireless capsule endoscopy and its localization, actuation, and sensor	[12][13][15][85][93] [94][95][96][97]
	Image examination		Processing of high volume endoscopic image and classification	[13][15][98]
	Control and autonomy		Human-robot interfaces for rigid endoscope control	[99][100][101]
			Eye-gaze has also been used for automatic camera control	[102][103][104]
			Navigation system using force or tactile sensing or vision	[105][106][107]
			Autonomous navigation for robotic flexible or capsule endoscopy	[107][108]
X-ray Imaging			Robot-assisted X-ray imaging, in the form of the familiar "C-arm"	[109][110][111]
			Dual robotic arms used to generate CT images	[111][112]
OCT imaging			Micromanipulators holding OCT source for tool tip stabilization	[17][21]
			Autonomous robot for OCT imaging of freestanding individuals	[18]
			Robotic OCT imaging for accuracy, safety, and larger region of interest (ROI)	[113][114][115]
			Teleoperation of the robot holding the OCT probe	[116]
Microscopy and Molecular Imaging			Robotic and portable gamma camera for imaging and biopsy procedures.	[117][118][119][120] [121][122][123][124]
			Robotic SPECT used for tomography and co-registration to CT	[16][125][126]
			Robotic mosaicking scanning provides large area images	[127][128][129]
			Robotic pCLE used for intra-ocular imaging in a shared platform	[130]
			Robot-holding optical probes to cover large area and repetitive scan	[131][132][133][134]

the imaging itself was not carried out by a robot. This excludes papers that describe nonrobotic imaging carried out before or after a robotic procedure. This eliminated many papers, e.g., papers describing MRI-compatible robots for needle biopsies, which can be found in a different survey [23].

Paper data were exported in the CSV format from the authors' Google Scholar libraries and MATLAB was used to remove duplicates, sort by date and topic, and generate Fig. 1. Ultimately, 1113 papers were included. The historical trends in papers published in each of the most popular topics are shown in Fig. 1(b), as is the overall

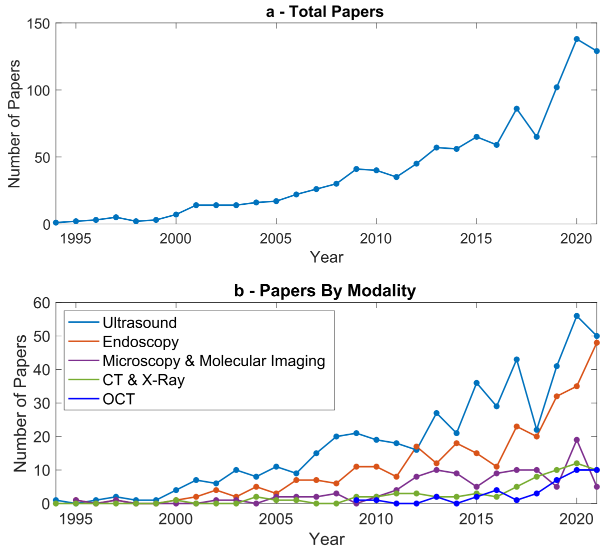

Fig. 1. ***Robot-assisted imaging papers: (a) reports the total number of papers by year and (b) reports subsets of robotic medical imaging where significant activity was found. The search covered 2021 up to December 24.***

trend for all robot-assisted medical imaging papers in Fig. 1(a).

III. ULTRASOUND SCANNING

We will start by first surveying ultrasound imaging with conventional imaging modes, such as B-mode and Doppler.

A. Conventional Imaging Modes

We will provide a historical context and a survey of some of the recent work in robot-assisted ultrasound imaging. We focus especially on work since the review papers [9], [10], and [135] were published.

The use of robotics, including sensing, actuation, and shared control for ultrasound image acquisition, has been proposed first in [24] and [25]. Several other groups, e.g., [136], as surveyed in [9], [10], and [135], for example, have followed similar approaches. Motivating the development was the high rate of musculoskeletal injuries among sonographers [137], a problem that remains according to more recent studies [138]–[140]. A robotic ultrasound would deal with such injuries by optimizing the ergonomics of the user interface for the operator independently of the specific ultrasound scan, required forces, motion range, and so on. For example, in [141], admittance force control was used to drastically reduce the applied force by the sonographer, using the robot as a force amplifier.

In addition, robot-assisted ultrasound provides a number of benefits such as reduced operator dependence (developing countries lack trained sonographers [142]), more consistent 3-D acquisition over extended ranges [143], [144], and automated scans, for special image acquisition as discussed in the following.

Depending on the type of control of the ultrasound transducer, there are several possible approaches to robot-assisted teleultrasound.

1) Direct Operator-Driven Control: In its most basic form, the robotic teleultrasound system involves the operator maneuvering a joystick or hand controller, with the robot and ultrasound transducer following the operator's hand motion in [24]. The approach may involve unilateral operator control of the ultrasound transducer position or velocity [24] or a linear combination of velocity/position and force [25]. Indeed, for example, setting the joystick command to $(v_{\text{transducer}} + \lambda f_{\text{transducer}}) = x_{\text{operator}}$ enables simple control of the ultrasound transducer velocity along directions in which the forces are small and control of the probe forces along directions in which the probe velocity is small. In a typical scenario, the elevational direction and transducer rotation about its face will be controlled in the velocity/position mode, while at the same time, the axial direction and axial–lateral rotation would be controlled in force/torque modes. Bilateral control with haptic feedback to the operator is also possible when the control device used by the operator is actuated. Integration of ultrasound teleoperation with a surgical system has been presented in [26], and a system for rendering the ultrasound image as an overlay at the correct physical location in the patient was presented in [27].

Though more recent work has focused largely on autonomous or partially autonomous scanning as described next, Santos and Cortesão [28] developed a novel control architecture for teleoperated ultrasound where contact stiffness is predicted before contact based on a depth camera and force data, thus enabling better transitions between contact and free-space force control. A method to correct for deformations caused by the applied force in robotic 3-D ultrasound was proposed in [29]. Beyond force-related research, a dual-arm teleultrasound system for fetal examinations was developed with novel clutch joints for safety in [30] and [31]. The clutch joints limit the applicable torque to guarantee patient safety, while the dual-arm configuration allows investigation of new scanning techniques such as parallelism for increased efficiency. Finally, the COVID-19 pandemic has triggered an increase in teleoperated ultrasound to isolate patient from sonographer, with multiple studies evaluating the efficacy of such an approach [32], [33].

2) Shared Control: In this operation mode, the operator controls the basic scanning trajectory, but the controller provides assistance in one of several ways. For example, the operator can control all the degrees of freedom except for the ultrasound transducer axial force, which is controlled by the robot controller [24]. Alternatively, virtual fixtures can also be used for operator guidance [11], [34].

Visual servoing can be integrated into the controller to track segmented anatomy [35], such as the carotid artery during a manual scan with the ultrasound transducer normal to the vessel. A 3×6 image Jacobian can be used to control the three degrees of freedom (DOF) in the ultrasound image plane directly. Shared control is often needed for ultrasound visual servoing because transducer translation in the elevational direction and rotation about the axial direction or about the lateral direction do not produce a significant change in the acquired images; furthermore, applying sufficient force in the axial direction in order to maintain adequate contact with tissue is always of utmost importance. Combining the force and image servoing can be done using an external control loop with a sharing control matrix [25] or with more advanced control approaches outlined in [36].

Moving beyond motion compensation, automatic optimization of ultrasound image quality using motion in the axial–lateral plane has also been presented [37]. Using a per-pixel quality measure of ultrasound images, computed using an approximation of sound propagation [38], the transducer can rotate automatically in the image plane, while a prescribed force is applied, in order to optimize overall image quality.

3) Autonomous Scanning: In this operation mode, a scan can be executed autonomously based on the sensory information available. A recent survey of this area can be found in [11].

Ultrasound image-based visual servoing was used in an autonomous system in [39], where two ultrasound transducers are used to provide 3-DOF translation to track kidney stone motion during lithotripsy procedures. Radio frequency data were used for segmentation of the kidney stones, before the log compression leading to B-mode images.

Automatic compensation for organ motion using intensity-based visual servoing has been proposed in [40] where volumetric data are used to compute a 6×6 ultrasound image Jacobian based on robot-acquired small volumes with a 2-D transducer and on larger volume, smaller frame rate acquisition with a 3-D transducer.

A prototype robotic system to study robotic transesophageal echographic (TEE) imaging was presented in [43]. The system uses a reference heart MRI model and image processing to produce TEE placement for standard ultrasound views of specific patients using deformable registration. It was evaluated in phantoms.

Zettinig *et al.* [53] presented a robotic ultrasound system for volumetric imaging during semiautomatic spine injections. The robotic system automatically acquires a US scan, compounds it into a volume, and registers it to preoperative data. The needle is then injected manually through a calibrated needle holder, ensuring that the correct needle trajectory is followed. The authors tested the navigation part of the pipeline on volunteers and the full pipeline, including the injection, on phantom data. Esteban *et al.* [54] took a step forward and tested a similar US-robotic system in a real clinical scenario. Compared to [53], the physician manually defines the target needle location on the compounded US volume without the need for preoperative data registration. The system was tested on patients in nine facet joint injection procedures and showed comparable performance to standard, X-ray-guided procedures, proving the feasibility of integrating robotic US imaging in real clinical scenarios. Tirindelli *et al.* [55] proposed a further extension of the robotic US system to: 1) integrate additional sensor information into the control loop and 2) include automatic US data interpretation. In particular, they proposed to use both imaging and force sensor data to identify the vertebral levels during the US scan, thus relying on both visual and tactile information.

In [56], a robotic US approach for thyroid volumetry is compared against manual 2-D US volumetry. First, a 3-D point cloud of the patient's neck surface is acquired through an RGB-D camera mounted on the robot. Afterward, the operator plans the US path on the surface reconstruction, and the robot executes this path. A 3-D compounding of the US scan is reconstructed by recording transducer poses and US images during scanning. The results indicate that robotic US acquisitions increase repeatability in thyroid volumetry measurements. Live segmentation of the thyroid in the US image was integrated into the system and evaluated in phantoms [46], with the goal of reducing operator input to placing the probe once on each thyroid lobe. Furthermore, a deep neural network is included in the framework to segment the resulting 3-D US volume after the scan is completed. A phantom study shows a significant decline in variability in measurements with the robotic approach compared to 2-D measurements, both for experts and nonexperts.

A scanning system that uses a depth camera, a path planner, and a force control system is presented in [49]. This system uses a Kinect system to obtain a surface point cloud and a covering path that will complete the scanned surface. A force controller is used by the robot to maintain the probe along the normal to the surface while performing the scan. A similar autonomous robotic scanning system was recently presented in [50], where a depth camera is used to obtain a tissue point cloud. The robot follows a path generated to cover the region of interest (ROI) using an impedance controller. The reconstructed ultrasound volume can be used to segment the anatomy. In another approach that uses an RGBD camera [51], the spine is localized spatially by using a modified U-net segmentation approach that encodes the RGB and D data separately and sums the results. The transducer array is aligned to the surface by using force control (two piezoresistive force sensors are used, with the common mode providing the contact force, and the differential mode the torque in the imaging plane).

In [44], a method is presented to estimate the normal to the tissue by using both the measured transducer

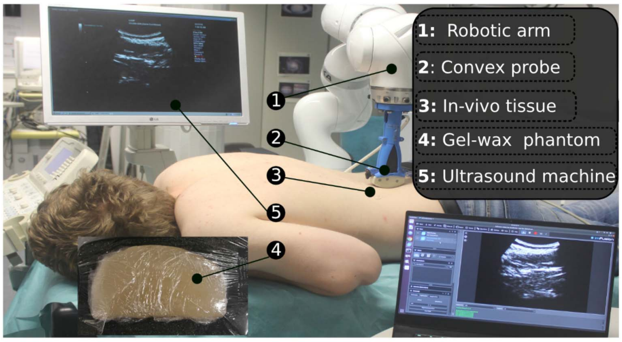

Fig. 2. ***Robot carries the ultrasound transducer and aligns it with the orientation of the tissue normal. Reprinted from [44]. Copyright 2020 IEEE.***

forces and US confidence map [38], and the transducer is oriented by the robot to align the axial direction to that of the tissue normal (Fig. 2). Jiang *et al.* [59] further developed a mechanical model-based method to achieve a more accurate estimation of the tissue's normal direction only using force cues.

A stiffness controller with a commanded force computed from reinforcement learning (RL) was presented in [58]. Only force information is used in this approach, and it is unclear whether this provides an advantage relative to [44]. The stiffness controller from [44] was modified in [58] to accept commanded forces from RL based on RGBD camera data of the patient, force sensing, and a reward function that optimizes the mutual information between an ultrasound image template and the actual acquired image. The scanning goal is to obtain a single specific ultrasound image similar to the template, given the patient surface, measured transducer forces, and acquired ultrasound images. There was no comparison of this approach with a visual servoing approach, which can also handle a single target image through several techniques.

An approach to image-based probe positioning is presented in [45], where a convolutional neural network is used to predict the necessary probe relative motion (translation and rotation quaternion) toward a reference view, given a development dataset comprising images and relative transducer positions. The work was carried out using 3-D transducers, in a fetal phantom, without patient surface and transducer force constraints.

Autonomous scanning of tubular structures has been presented [59]. The approach combines a U-net for vessel segmentation, with a joint-space stiffness controller that makes use of the torque sensing at each of the robot joints and a path planner that finds the vascular structure centerline from the point clouds generated by the U-net and moves the robot along this centerline. This system does need a rough initial location of the ultrasound transducer and the local tissue normal, acquired by using the robot as a pointer.

In [47], a robotic ultrasound system for catheter tracking and navigation is presented. A robotically acquired 3-D US volume with its detected vessel centers and preoperative image data is registered to the robot frame. This registration enables robotic catheter tracking based on the computed vessel locations. The proposed system indicates the potential of robotic US-based navigation in endovascular procedures to eliminate the use of ionizing radiation.

Hase *et al.* [63] introduced RL for automatic robotic navigation using US frames as input. The agent's input comprises the current US frame plus the four previous frames and actions. Spine ultrasound was acquired from volunteers, and inter-patient navigation was evaluated in a virtual environment with 2 DOF. They showed that by breaking the problem of navigation and detection of the target into two different tasks, the performance significantly increases. The proposed method correctly guides and stops the robot at the target location with an 82.91% success rate.

In recent work [61], the potential of RL to navigate a virtual ultrasound transducer with 6-DOF to a standard scan plane was evaluated for spine ultrasound from volunteers. The reward function is proportional to the amount of transducer pose improvement and may include a measure of image confidence [38]. Limits on pose changes and other constraints on the transducer location are included in the algorithm. A modified SonoNet-16 architecture [62] is used for standard ultrasound plane detection. This article demonstrates the potential of RL to consider multiple goals and constraints. It demonstrates the importance of considering image quality while seeking the standard ultrasound plane and the potential difficulties in transferring learning from one dataset to another.

In [52], learning from demonstration approach is used for autonomous carotid artery scanning. As in other systems, an admittance/stiffness loop is used to maintain the transducer in contact with the skin, and RGBD data are used to initialize the scan. The scan is partitioned into tasks based on expert-identified states of the examination: transverse examination from midneck in the superior direction and identification of the bifurcation site where the carotid splits into the internal and external carotid arteries, followed by an axial view of the common carotid artery. U-Net detected features are used to identify the three states and design visual-based velocity controllers for each of these identified states. The prediction error in detected features is used to determine their reliability, with the robot carrying out an exploration motion when feature confidence is low.

Finally, the COVID-19 pandemic has triggered an increase in teleoperated ultrasound to isolate patients from sonographers, with multiple studies evaluating the efficacy of such an approach [32], [33]. Point-of-care ultrasound scanning (POCUS) can be used for diagnosis and staging of COVID-19 and is safer and more efficient than other methods such as CT [145] but requires close contact and consequent risk of transmission. Thus, autonomous systems are of particular interest. An autonomous protocol using a depth camera and force sensor on a robotic arm and a convolutional neural network to determine scan points between the ribs is proposed in [57]. This allows pulmonary and cardiac examination without exposure risk. A similar system in [48] uses the correlation, compression, and noise characteristics of ultrasound images in a support vector machine (SVM) classifier to evaluate image quality in real time and automatically adjust the probe accordingly. Such systems can reduce the risk and strain on healthcare workers.

B. Nonstandard Ultrasound Imaging Enabled by Robots

The use of robots for ultrasound medical imaging clearly enables 3-D conventional ultrasound image acquisition through both sensing and control of the scanning trajectory. Furthermore, the ability to control the ultrasound transducer or a set of transducers accurately further enables other interesting applications: increased aperture image formation, including photoacoustic and elastographic imaging, and transmission tomography.

1) Increased Aperture Imaging: Ultrasound image quality is affected by the physical size of the ultrasound transducers. To increase the aperture size, multiple imaging systems can be calibrated and utilized; however, this solution could be very bulky and expensive. Alternatively, a robot holding the ultrasound transducer can be used to accurately track the transducer position and orientation to form images with high resolution and target detectability as discussed in [64]; the design, simulation, and experimental evaluation of such a robotic system can be found in [65].

2) Transmission Tomography: For deep and tomographic ultrasound imaging, multiple data acquisitions from the same ROI are needed. This requires challenging transducer calibration and alignment, which can be achieved by mounting the ultrasound transducers on robots. In [66], a robot-assisted ultrasound tomography system was proposed, in which a robot holds the ultrasound transducer that follows and aligns with another freehand transducer to have a larger field of view into the ROI. In another study, each of the two transducers was held by robots, in a dual-robotic ultrasound system. This system was specific to an *in vivo* prostate study and the clinical workflow was described [67]. Robots can also be used for 3-D robotic ultrasound tomography, similar to the *in vivo* data acquisition system in [68], where the F3 CRS robotic arm holds and maneuvers the linear transducer over a line to image the normal femoral artery of a volunteer at multiple intersections to form a 3-D image. In addition, robotic transmission tomography can be employed for 3-D surface imaging as in [69] where a robotic positioning linear transducer was moved over different paths to reconstruct the 3-D surface of a knee joint model.

3) Photoacoustic Imaging: Photoacoustic imaging, an imaging modality capable of visualizing blood vessels and cancers, was integrated into a robot-assisted setting in a few studies, although not in a clinical setting. Surveys of photoacoustic imaging for surgical guidance can be found in [146] and [147]. Generally, the robot is used to control the ultrasound transducer and/or the illuminator or exciter. In [64], a UR5 robot holding a linear ultrasound transducer was employed to rotate the transducer within a plane for 2-D photoacoustic tomography. Robots can also be used to build a 3-D photoacoustic system; for example, in [73], 3-D photoacoustic imaging of *in vivo* blood vessels was performed with a robot-controlled transducer. In [19], the feasibility of intraoperative robot-assisted photoacoustic imaging of the prostate using the da Vinci robot was investigated. The robot maneuvered a "pickup" linear ultrasound transducer [148] to perform photoacoustic tomography and collect acoustic signals from a 3-D volume. This prostate study was further investigated in [70], where a shared-controlled teleoperation platform with virtual fixtures was designed to collect photoacoustic and ultrasound signals from a 3-D volume.

Robots are also used to facilitate optical excitation for photoacoustic imaging. In [71], a SCARA robot arm was employed to hold the optical fiber and to scan the entire ROI to provide signals for photoacoustic and fluorescence imaging, or in [74], robotic photoacoustic guidance was introduced for nerve sparing during robot-assisted prostatectomy, in which the da Vinci robot maneuvers the laser source followed, in real time, by a robotized transrectal ultrasound transducer. In another study [72], robots were used to maneuver both the transducer and illuminator, where the authors used robot-assisted photoacoustic imaging to find a safe region for robotic drilling. The photoacoustic system was integrated with the telerobotic system, where the laser fiber was attached to the drill controlled by one robot and the ultrasound transducer is held and controlled by another robot.

Robot-assisted photoacoustic imaging was also used for visual servoing. In [75], a photoacoustic source was attached to the surgical tool so that it is autonomously followed by a robot-holding ultrasound transducer. More recently, in [76], a similar concept and setup were used for cardiac catheter visualization and validated during an *in vivo* animal study (see Fig. 3). Toward real-time visual servoing, a deep learning algorithm using photoacoustic raw data, without relying on image reconstruction and segmentation, was also investigated [77].

4) Elastographic Imaging: Although the da Vinci surgical system is used for an increasing variety of procedures, it still does not provide information regarding the tissue stiffness for the surgeon. This has been investigated in a few robotic elastography studies. Schneider *et al.* [20] described a system in which an external exciter generates shear waves in the tissue and an intraabdominal "pickup"

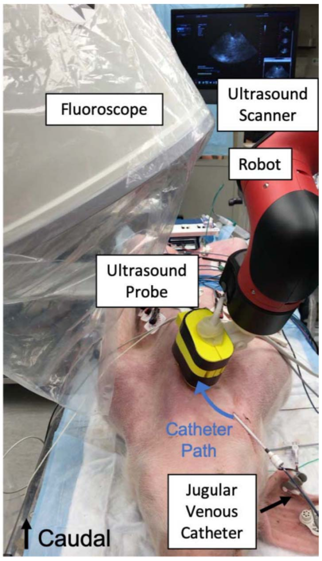

Fig. 3. *Sawyer robot holding an ultrasound transducer provides visualization of the catheter tip. Reprinted, with permission, from [76]. Copyright 2020 Author(s), licensed under a Creative Commons Attribution 4.0 License.*

ultrasound transducer [148] held and controlled by a da Vinci arm (see Fig. 4) is used to record acoustic signals. Volumetric tissue displacements are used to calculate the absolute elasticity of the tissue.

In [78], a real-time laparoscopic ultrasound elastography system is reported, in which the abdominal "drop-in" ultrasound transducer was held and controlled by the da Vinci arm for ultrasound recording. In addition, an autonomous sinusoidal palpation motion along the axial direction of transducer is generated and overlaid onto the master motion for elastography images. Robots can also help with the stability of the ultrasound transducer and knowledge of applied force in strain imaging studies. For example, in [79], a human–robot scanning system was developed in which the sonographer chooses the transducer location and the robot holds the transducer and preserves the stability during strain imaging. In [80], a robot arm was used to hold the ultrasound transducer and apply different forces to tissue while performing acoustic radiation force (ARF)-based quantification on phantoms and in abdominal scanning of three healthy volunteers. A robot-held transducer was also used to perform quantitative elastograms where the robot sensory information, including joint encoders and force/torque, was used for the reconstruction [81].

C. Discussion

Autonomous robot-assisted ultrasound is an active area of research. Several state-of-the-art systems can control transducer force and pose or can recognize the patient with RGBD cameras and plan a scanning motion. Some systems can combine RGBD imaging with transducer force measurement and ultrasound imaging to fully complete standard ultrasound scans of static structures, e.g., the carotid or the spine.

For spine imaging, good US images using robotic techniques can be achieved if the patient remains motionless by accurately controlling the acquisition parameters (position, force, and orientation). However, in most other scans, there is involuntary motion; furthermore, subjects are often adjusted by sonographers to better visualize the target anatomy during scans. Thus, the ability to compensate for patient motion [41] is crucial for further extending the usability of robotic US in clinical applications. Moreover, since a certain pressure between a probe and objects is necessary to guarantee imaging quality, soft tissue deformation is unavoidable. This prevents the accurate reconstruction of anatomy and deteriorates the performance of registration of live 3-D robotic US and preoperative images. To extract the zero-pressure 3-D image from deformed ones, force information and the estimated tissue stiffness from robotic palpation can be used as in [42].

For more challenging ultrasound scanning, e.g., fetal, liver, or cardiac exams, there are view optimization approaches that are able to quickly find a "standard image" [62]. These can be combined with learning by demonstration approaches to guide a robot through large motion. Indeed, in [60], images acquired by experts were recorded at the same time with ultrasound transducer orientation from an inertial measurement unit and used to train a network, US-GuideNet, to predict the expert probe rotations. US-GuideNet works well even for large angles, so such an approach would be suitable for robot path planning around a real-time stiffness controller based on ultrasound transducer forces. As an alternative approach for complex tasks, such as finding an intercostal acoustic

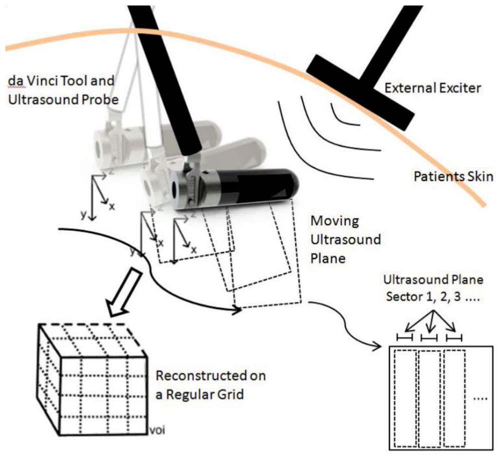

Fig. 4. *da Vinci robot holding the "pickup" transducer for freehand elastography scanning. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature [20], Copyright 2012.*

window into the liver, or to accommodate the movement of the fetus, one promising approach is to infer an anatomical model from priors (either 3-D ultrasound or MRI, see, e.g., [149]) in order to place the ultrasound transducer on the patient and get close enough to a standard view, so an image-feature approach would work reliably.

In addition to diagnostic ultrasound imaging, ultrasound also has an important role in facilitating intraoperative registration to preoperative imaging. For example, in [150], endorectal 3-D ultrasound is used to register preoperative MRI to the patient. In orthopedic surgery, 3-D rigid registration between CT and partial volume ultrasound has been reported [151], [152]. To facilitate intraoperative registration, robotic ultrasound could be used to acquire coregistered images at the time of preimaging within the CT or MRI scanner. An optical ultrasound system [153] would achieve this while reducing imaging artifacts. This would facilitate intraoperative registration based on ultrasound. Robotic ultrasound imaging also has the ability to track patient motion accurately and can be used to control radiation therapy [154].

The possible advantages of the robotic approach are given as follows:

1) repeatable trajectories with consistent application of force, leading to similar and possibly registrable volumes from one scan to another, allowing patients to be followed longitudinally in a consistent manner;
2) better acquisition of large volumes, e.g., of the spine or leg vasculature, as the transducer can be moved by keeping the imaging plane parallel to a reference, leading to better interpolation than achievable with hand scanning;
3) more consistent scans through machine learning, by, for example, optimizing quality measures;
4) ability to carry out remote procedures.

Some of the possible disadvantages of the robotic approach, and some of the questions for further research are given as follows:

1) long robot setup time and examination time (could computer vision and artificial intelligence accelerate this process?);
2) difficulty of patient repositioning (could future bimanual robotic systems perform such a complex task?);
3) risks regarding robot–patient communication;
4) expensive hardware (could the use of robots reduce the need for training a large number of sonographers? and could telemanipulated or autonomous robotic ultrasound systems provide needed examinations in areas lacking sonographer/radiologist experts in an economical manner?);
5) safety concerns (could robotic US systems guarantee patient safety? and will future systems offer previews of their intended actions in an augmented reality setting, allowing for easy human supervision and shared control?).

With the availability of commercial robotic ultrasound systems, we can expect more reports on clinical outcomes. For example, in [155], 340 tele-echography cases have been examined. Telerobotic systems were able to deliver diagnoses in 97% of the cases. Failure cases were related to obese patients, imaging of leg veins or with substantial leg edema. In general, robotic examinations tended to last longer than those carried out by a novice with guidance from a remote expert.

An approach that combines the advantages of a robotic method with the flexibility of and inherent safety provided by a human has been proposed in [156]. In this approach of "human teleoperation," the remote robot is replaced by a person or "follower" controlled by a remote expert through a real-time, mixed reality (MR) interface such as the Microsoft HoloLens 2. A 3-D virtual ultrasound transducer is projected into the follower's MR environment at a location (6 DOF position and orientation) controlled by the expert through a haptic device. The follower aligns the actual transducer to the virtual one, which represents the desired location. In turn, the expert is presented visually with the MR capture of the follower's environment with the virtual tool in place. The haptic device uses the capture to display a haptic surface barrier where the patient is located. If transducer forces are measured, they can also be rendered to the expert through the haptic device. Autonomy can be provided in the same way as provided for a robotic system, in the form of MR guidance of the transducer.

IV. ENDOSCOPY

Endoscopes are necessary tools for minimally invasive surgery and are the main means of guiding interventions. A recent article [85] provides an excellent introductory review, including history, categorization, main application areas, and some of the design principles involved in commercial systems. Rigid, flexible, and capsule robotic endoscopic systems have been developed and are commercially available.

A. Endoscope Categories and Use

Rigid endoscopes provide the visualization needed for interventions in laparoscopic procedures. In conventional manual laparoscopic procedures, these are held by an assistant. Robotic assistance provides a stable view and reduces miscommunications between the surgeon and the assistant. A comprehensive review of endoscope robots and automated camera guidance can be found in [82].

In robot-assisted surgery, rigid endoscopes are positioned and repositioned when needed by the surgeon. Typically, they are "end-firing," with the camera view aligned with the axis of insertion, for safety reasons. Their basic design has not changed in decades. "Pickup" cameras and wristed cameras that allow more flexibility in positioning (6DOF versus 4DOF) inside the body have been recently proposed [83]. By having both end-firing and side-firing cameras, these allow more flexibility in the camera view toward the surgical site; they also allow a larger baseline distance between the left and right cameras and better depth perception [84].

Flexible endoscopy is used for imaging the gastrointestinal tract for diagnosis, biopsy, and surgery, such as endoscopic submucosal dissection; several reviews can be found in [86]–[89].

Robot-assisted flexible endoscopy is complex as steering, advancing, rotating, and stabilizing are all required for visualization and intervention. New approaches are being developed for actuation using magnets that will enable controlling the tip of the endoscope in order to reduce the discomfort associated with pushing and steering the endoscope [90]. More ergonomic design and practice, as well as new robotic systems, could reduce the rate of musculoskeletal injuries to endoscopists, which has been reported to be high [89]. Operating instruments have been added at the tip of the endoscope for surgical procedures and are being evaluated [85].

Wireless capsule endoscopy is now widely used for diagnosis of patients with gastrointestinal bleeding, for evaluation of Crohn's disease, small bowel tumors, and surveillance of inherited polyposis, because it is easy to administer and well tolerated by patients [93]; some pertinent reviews are [12], [13], and [15], with clinical perspective in [94]. It is mostly a passive video acquisition technique, but there are now several active navigation systems on the market using magnetic actuation and several systems in development [85]. Localization techniques for magnetically actuated endoscopic capsules have been developed, which are based on electromagnetic sensors alone, e.g., [95], or based on combining EM sensor information with vision [96]. Active capsule endoscopy provides better inspection of suspicious regions. Active systems have been evaluated in patients with excellent promise, e.g., for screening for gastric cancer [97].

B. Endoscope Image Examination

The use of AI approaches in robotic gastrointestinal endoscopy is reviewed in [157].

A major challenge of endoscopic imaging using flexible and capsule endoscope is the need for the examination of tens of thousands of images; a typical capsule endoscopy examination reading time is 30–40 min with an average examination time for colorectal cancer endoscopy of 45 min [13]. Deep learning techniques have been applied for image classification and have shown very high accuracy, mostly in high 90%, for multiple diseases relative to expert annotations. The fast screening time and operator independence of AI-based techniques have the promise to revolutionize colon cancer screening based on capsule endoscopy. The difficulty in implementing effective deep learning techniques with high accuracy lies in the large number of images needed for training. With large datasets, CNN-based systems can classify abnormalities with close to 100% sensitivity and specificity (in both per image and per patient evaluation) with expert consensus as the gold standard using over 100 million images for testing and over 150 000 images for training [98]. The method from [98] reduced the mean reading time by over an order of magnitude.

Future research in image classification of capsule endoscopy data could be targeted at analyzing the video data, as opposed to the individual images, and providing accurate multilabel classification. A classification of current research in this area is provided in [15], where capsule endoscopy video analysis is classified in segmentation/detection, redundancy removal/summarization, classification/recognition, and personalization; a comprehensive list of available datasets is also given. Clinically, prospective studies are needed before these will be widely accepted in standard clinical practice.

C. Endoscope Control and Autonomy

As in the case of robot-assisted ultrasound image acquisition, direct manipulation by the user, shared control and autonomous control have been investigated.

With conventional human–robot interfaces for rigid endoscope control, which involves joystick/pedal/voice control, the surgeon is distracted from the main surgical task whenever a camera adjustment is necessary. Therefore, there is a benefit to automatic camera movement, for which many systems have been proposed, starting more than two decades ago [99], typically based on centering the surgical tools into the camera view, e.g., [100] and references therein. There are commercial systems available, such as the FDA-approved AutoLap system [101], which utilize image guidance to control the endoscope to a location pointed at by the surgeon. Eye gaze has also been used for automatic camera control, as the heat map of eye fixations is indicative of surgeon's attention [102]–[104].

The feasibility of navigation using only force sensing was explored in [105]. Tactile sensing for autonomy has been proposed in [106].

Vision-based navigation is discussed in the review by Fu *et al.* [107]. Modalities for endoscopic vision include white light endoscopy, fluorescence endoscopy, virtual chromoendoscopy, and magnified observation. Visual simultaneous localization and mapping (SLAM) has been used to estimate the location of the endoscope and the 3-D structure of the surgical scene. Depth information was obtained using deep learning, especially generative adversarial networks (GANs), from monocular video, but stereo matching has also been applied to endoscopic data. Image fusion with preoperative medical imaging and intraoperative video has also been employed.

Autonomous navigation is a very challenging task for robotic flexible or capsule endoscopy. When manipulating the endoscope from the base, the motion depends on the entire state of the endoscope, which in turn is affected by deformation and the presence of tissue folds. In the simpler case where the endoscope distal end is actuated by magnetic forces from an external robot, autonomous scanning that combines vision and sensing information has been presented in [90]. A hierarchical approach is defined where the external robot and sensors can insert the endoscope, with the insertion direction being the center of the lumen as determined from endoscopic images.

Some of the issues involved in autonomous navigation have been studied using a scaled model [108].

D. Discussion

Rigid endoscope-related performance metrics are indicative of surgeon experience and linked to technical performance [158]. Therefore, it is possible that autonomous camera movement adaptation to a surgeon's skill and "style" is possible, based on the surgical scene observation, including instrument motion and eye gaze. To achieve this, one may be able to use a learning from demonstration approach using, for example, a behavioral cloning framework as done in [60].

Eye-gaze information can be provided for the da Vinci surgical system by a console-mounted gaze tracker [159]. This tracker was demonstrated to facilitate task completion and was integrated into user interfaces for controlling ultrasound machines directly from the da Vinci console [160], [161].

We are not aware of approaches that combine vision with position and/or force/tactile sensing to enable autonomous navigation of base-actuated flexible endoscopes. For navigation, the views do not change much, so information has to be integrated with historical motion data and maybe other prior data, e.g., patient height and body mass index, to determine a likely geometry. Preoperative imaging, such as MRI and CT, would be very useful; in the same way in which CT can be used for virtual colonoscopy, it is possible that the same information can be used for navigation and autonomous motion planning. However, CT would expose the subject to unnecessary radiation, and such preoperative imaging is not always accessible. There is also the complexity of having to have two appointments for the patient.

One potential approach that could be simpler is to use capsule endoscopy to map the intestine/small bowl/colon and use the map to go backward with a conventional colonoscope to perform the necessary biopsy and/or polyp removal.

In addition, robotic bronchoscopy, recently reviewed in [162] and [163], has the potential to enable the robotic endoscopy system to address challenges related to biopsy of suspected lung lesions [91]. The recently developed robot-assisted bronchoscopy technology, Ion Endoluminal System (Intuitive Surgical, Inc., Sunnyvale, CA, USA), described in [92], provides 3-D airway visualization, a flexible catheter, a peripheral vision probe, and biopsy needles. Despite all the benefits, during robotic bronchoscopy procedures, airway bleeding may impair guidance and further research is needed [164].

V. X-RAY IMAGING

Robot-assisted X-ray imaging, for diagnosis and interventional procedures, can take the form of the familiar "C-arm" with four degrees of freedom, but also with more sophisticated systems, with seven degrees of freedom, such as the Siemens Artis Zeego system. The CyberKnife system (Accuray, Sunnyvale, CA, USA), localizes the patients using X-ray imaging and uses high-energy X-rays for radiation therapy. Dual robot systems, one carrying the source and the other the detector, have also been developed in [109] and hold promise for integration in robotic surgery and 2-D and 3-D cone-beam imaging [165].

Task-driven orbit design for an optimized source-detector orbit was discussed and implemented on a clinical robotic C-arm system [110]. Dual robotic arms have also been used to generate cone-beam micro-CT images for middle and inner ear pathologies [112] This work takes advantage of advances in X-ray source and detector technologies, machine learning, and integration with conventional imaging to lead to high-resolution CT. A major problem with C-arm guidance is radiation exposure to medical staff. To avoid the exposure, teleoperated robotic arms could be working collaboratively with X-ray imaging arms.

A. Discussion

While robotic X-ray imaging has been around for more than a decade, it has mostly provided the community with better control of acquisition trajectory, flexibility, and precision in a telemanipulated setup. Some of the issues involved in integrating intraoperative cone-beam CT with surgery have been addressed in the context of head and neck surgery [166]. Advances in AI, resulting in semantic understanding of surgical workflow [167], could allow robotic X-ray systems to work automatically but safely in collaboration with action robots and remotely supervised by surgeons and surgical staff. The idea is to automatically position the C-arm in an optimal configuration in relation to the anatomy of interest and allow the robots to finalize the surgical task. Pekel *et al.* [168] worked toward integration of robotics into intelligent X-ray CT imaging to enable arbitrary nonstandard acquisition trajectories and aimed at extending this to phase-contrast and dark-field imaging.

Robotic X-ray imaging can be used to actively seek effective images with low-dose radiation. An interesting approach to radiation exposure reduction in X-ray guided interventions is presented in [111] where image processing is used to automatically track the ROI, real-time control of a lead shutter system is used for collimating the X-ray beam to the ROI, and the high frame rate ROI X-ray imaging is blended with the lower frame rate entire image presented to the operator. This robotic approach to catheter imaging with reduced X-ray radiation exposure could be extended to a robotic C-arm such as the Artis Zeego system or a dual-arm source-detector system. These systems could employ a rapid-shutter system as described above for small ROI motions and could center, subject to workspace constraints, the X-ray image onto a larger area of interest by repositioning the source and detector automatically.

There is also considerable synergy between robotic X-ray imaging for medical and industrial applications. Ziertmann *et al.* [169] mounted the X-ray source and detector on robotic arms in order to be able to scan a whole car. Therefore, despite its ionizing radiation as a major drawback, intelligent and flexible robotic X-ray and CT imaging seem to have interesting applications to offer.

VI. OCT IMAGING

OCT imaging, mainly used for ophthalmology and well surveyed in [170] and more recently in [171] for surgical guidance, can be performed using micromanipulators or robots in a teleoperated, shared-controlled, or fully automated environment.

An OCT system can benefit from the accuracy and repeatability of a robotic system. In [17], a robot, here a handheld Micron, controls the distance between the probe and the tissue for safety and image quality reasons.

In [21], another robot-assisted system, with an OCT source attached to a micromanipulator, was developed to cancel the surgeon's hand tremor. The robotic system improves the tool tip stabilization, targeting accuracy, and maintenance of the distance between the tool tip and the tissue.

Robotic OCT imaging can also be fully autonomous. An interesting work for robot-assisted OCT imaging of freestanding individuals was presented in [18], in which a robotic OCT scanner performs the contactless OCT imaging autonomously, meaning that there is no need for head stabilization or an operator. The robotic scanner adjusts itself to the eye and collects OCT volumes in less than 8 s.

In the robotic system described in [113], the scanner performs automatic focusing to correct refractive errors. The field of view of OCT can also be broadened using a robot, for example, as in [114], where the robot, shown in Fig. 5, maneuvers and tracks the OCT probe to perform a surface scan, or in [115], where force sensors are also used to accommodate anatomical constraints for brain imaging. Finally, a robot holding the OCT probe can be teleoperated by a surgeon. In [116], a 7-DOF robot tracked and delivered the surgeon's hand motion to the OCT probe for multiple data acquisitions.

A. Discussion

Robotic OCT takes advantage of the ability of robots to move faster and with higher accuracy than the human hand. This type of augmentation is not new in medical robotics, where many other systems have been developed in order to enable microsurgery with microscopy guidance. Rapid scanning with tiling of images enables quick examination of tissue for tumor margin delineation and could have a significant role in many types of cancer surgery.

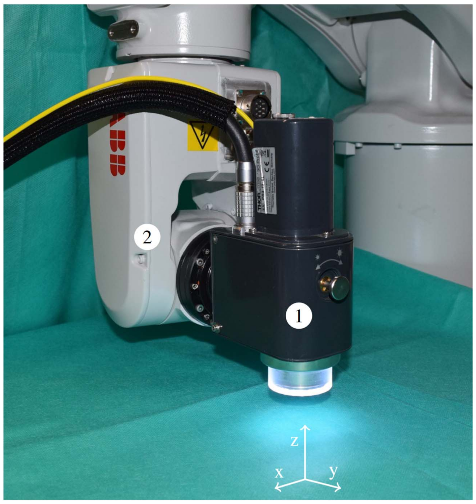

Fig. 5. ***Robot-mounted OCT scanner to move over the sample. Reprinted from [114]. Copyright 2021 IEEE.***

VII. MOLECULAR AND MICROSCOPY IMAGING

Molecular imaging involves the *in vivo* measurement of molecular and cellular pathways of disease. Radiolabeled molecules, or fluorescent, magnetic, bioluminescent, or fluorescent labels are used and they have an increasing role in surgical guidance, as surveyed in [22]. Robotic mini gamma camera for SPECT was presented first in [117]; trajectory optimization for the robot holding the detector was discussed in [118]. Portable gamma counters have been used for intraoperative sentinel node detection using a drop-in/pickup probe that is placed inside the patient and localized through the robot kinematics [119]–[121]. Real-time robotic gamma imaging can be integrated with ultrasound-guided sentinel lymph node biopsy to provide live anatomical and nuclear guidance, and cancer staging [122], [123].

Robotic SPECT using autonomous scans for tomographic reconstruction was presented in [16] where the robot facilitates high accuracy, reproducibility, and fast data acquisition, and intraoperative SPECT/CT feasibility was presented in [125]. In another study [126], a personalized robotic SPECT/CT was developed to perform imaging in the angiography suite providing SPECT reconstruction coregistered to the C-arm CT. In [124], a flexible robotic functional nuclear imaging system was developed in which the robot, replacing the human operator in the imaging process, carries the gamma probe and, with the help of the optical tracking system, ensures a sufficient coverage of the ROI.

Probe-based confocal laser endomicroscopy (pCLE) provides cellular-level imaging of biological tissue. Several systems have been developed, which combine robotic mechanical scanning with mosaicking to produce large-area images from microscopy images, e.g., [127]. Robotic scanning with pCLE was also presented in [128] where large images were acquired by scanning a custom-designed high-precision stage. Images were

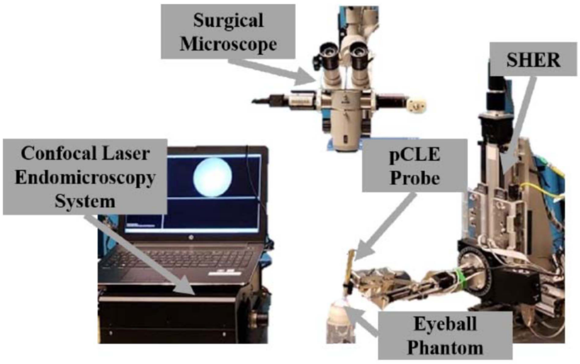

Fig. 6. *Hopkins Steady-Hand Eye Robot was controlled to position a pCLE probe. Reprinted from [130]. Copyright 2020 IEEE.*

stitched using nonrigid registration. Both manual and robotic scanning were demonstrated, showing the potential for the development of an optical biopsy system.

Because of the small size of the probe, pCLE is suitable for intraocular imaging. In [130], the Hopkins Steady-Hand Eye Robot, shown in Fig. 6, was controlled to position a pCLE probe using a shared approach in which the surgeon maneuvers the probe laterally with micrometer level precision, and an autofocus algorithm, based on pCLE images, controls the probe-to-tissue distance.

Optical biopsy (Cellvizio, Inc., Mauna Kea Technologies, Paris, France) has demonstrated potential for intraoperative optical biopsy for various pathologies. Combining this type of technology with robotic devices can be used to scan large areas of tissue. Large areas scans using a handheld robot and mosaicking of microscopic were demonstrated in [131].

Robotic tissue scanning with a biophotonic Raman spectroscopy probe has been designed for repetitive scanning to generate a database of tissue properties for eventual real-time intraoperative margin assessment [132].

Mosaicking methods to stitch images from microscopy [129] could be combined with a similar "steady-hand" approach as in [130] to create large-area images intraoperatively.

The use of microscopes mounted on robotic manipulators has had particular commercial success for neurosurgery and ophthalmology. This includes B. Braun's Aesculap Aeos and the KINEVO 900 from Carl Zeiss AG for neurosurgery as well as Zeiss' ARTEVO 800 and the Proveo 8 from Leica Microsystems for ophthalmology. Such systems can be passively driven by the surgeon but can also move actively to saved viewpoints. They have enabled greater precision, speed, and comfort for surgeons [133], as well as superior visualization through robot-assisted fluorescence spectroscopy [134].

A. Discussion

While robotic imaging has allowed the integration of different functional imaging techniques into real-time surgical visualization, a major challenge is to modify training and education of surgeons enabling them to act both as a surgeon and as a medical physicist. In fact, radiology and nuclear imaging departments include both physician and physicists and they work hand-in-hand to make sense of complex functional and molecular imaging taking both patient-specific physiology and the properties of the biomarkers and molecular imaging physics into account. Robotic molecular imaging provides surgeons with much valuable information, but they need to go through additional educational and training to take full advantage of this valuable but complex information.

VIII. CONCLUSION AND DISCUSSION

Safety of robotic imaging is of paramount importance for the deployment of this technology. All the systems that are in contact with humans must be safety certified and approved by the manufacturer for such tasks, e.g., the Kuka LBR iiwa robot (KUKA AG, Augsburg, Germany) or the Kinova Gen 3 (Kinova, Inc., Boisbriand, QC, Canada). Similarly, robotic X-ray imaging, in instances in which the radiation dose is determined by software, must be carefully controlled and follow regulatory requirements and must be monitored by an interventional radiologist and/or medical physicist.

Regulatory compliance for robotic medical imaging is covered by multiple standards; ISO 14971, IEC60601 (with extensions -2-77, -2-78, -4,1 specific to medical robots and autonomy). The software of the systems discussed in this review involves multiple components; their integration is the subject of principled software design [172] and is aided by open-source software for medical image analysis (e.g., 3-D Slicer) and image guidance software, e.g., Slicer IGT [173] and MITK [174]. The development of fully autonomous systems faces additional legal, regulatory, and ethical issues [175].

Robot-assisted imaging has been used to improve the user interface in ultrasound and surgery, to improve upon or enable novel imaging modalities, and to provide remote expertise. The integration of robot-assisted surgery with robot-assisted imaging offers new avenues of presenting surgeons with anatomical and functional images acquired preoperatively that are registered to the patient intraoperatively. They also enable intraoperative 3-D and tomographic reconstruction for multiple imaging modalities. Because it is precise and repeatable, robot-assisted scanning can provide an extended imaging area/volume, allowing for repeatable high-quality images, e.g., of the spine and leg vasculature, and the stitching of small high-resolution images into large tissue maps that can be used for pathology assessment, with great potential for accurately determining treatment boundaries.

Shared control between an operator and the robot system has obvious benefits as it overcomes human dexterity limitations. Autonomous imaging may be viable for certain applications, but there is much research to be done to reduce safety risks, robot setup and dismantling, and dealing with difficult cases that may require a human operator anyway. However, great progress has been made and the techniques used in providing autonomy could also be used for expertise transfer and training; this will be beneficial regardless of how successful full autonomy becomes in the next few years. Robotic techniques are pervasive for localization and navigation, even for passive systems such as endoscopic capsules, and so are the techniques for image understanding for rapid screening.

This review has provided a brief snapshot into the active and rapidly evolving field of robot-assisted medical imaging, which has the potential to revolutionize not only the imaging modalities themselves but also robot-assisted surgery, diagnosis, and interventions more generally. ■

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