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Robotic Platforms for Ultrasound Diagnostics and Treatment

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***Abstract*—Medical imaging introduced the greatest paradigm change in the history of modern medicine, and particularly ultrasound (US) is becoming the most widespread imaging modality. The integration of digital imaging into the surgical domain opens new frontiers in diagnostics and intervention, and the combination of robotics leads to improved accuracy and targeting capabilities. This paper reviews the state-of-the-art in US-based robotic platforms, identifying the main research and clinical trends, reviewing current capabilities and limitations. The focus of the study includes non-autonomous US-based systems, US-based automated robotic navigation systems and US-guided autonomous tools. These areas outline future development, projecting a swarm of new applications in the computer-assisted surgical domain.**

I. Introduction

Ultrasound (US) is a rather popular imaging technique in numerous fields of medicine. Its widespread use can be accounted to several factors:

- Affordable costs (probably lowest of all modalities);
- No radiation to the human body. Its only known side effect is that the targeted tissue may heat up, which is non–critical during regular examination;
- Good time resolutions, thus it can visualize tissue motion. US with Doppler models, even cellular motion can be measured precisely.

Despite the fact that the method to obtain US images has been known for several decades, US technology continues to improve dramatically regarding resolution and portability. US imaging continues to conquer new fields of medicine, replacing other, more invasive techniques.

In this article, we examine how robotics and US devices can work together to achieve better medical outcome. The goal is to combine the non–invasiveness and portability of US devices with the precision, accuracy and dexterity robots can provide. Robotics may be needed to improve the quality of US diagnostics: in most cases, US-based diagnosis consists of identifying tissue structures in the US plane, however finding these accurately largely depends on skills of the operator. It has been shown that separate US measurements on the same patients—even if performed by the same operator—yield to very diverse results. Robot-driven US procedures should lead to reproducible measurements.

Combining robotic dexterity with US diagnostics elevates manual diagnostics to a new level. We can either use the robotic platform to focus the US to a specific location, and create therapeutic effect through heating, or based on the US imaging, we can use robotic manipulators to reach areas of the body which otherwise would require explorative surgery.

At the dawn of robotic surgery, robotic manipulators operating the US probe were already introduced [1]. There were two main goals behind this concept:

1) when US technicians are unavailable, the robotic US could be teleoperated by a far away operator;
2) the robotic US device provides accurate position information on the US probe's physical locaion.

US-based robotic diagnostic systems can mostly be used together with the generic telerobotic control concept. Two main branches diverged over the years:

1) smaller robots have been developed, which only require an assistant to hold and place the robot location on the patients skin, after which an expert physician executes the local motions of the probe remotely;
2) when the expert physician can fully control the probe posture through independent robotic architectures [2].

These systems and their functions are summarized in Table I.

II. Non-autonomous US-based robotics

Back in 1999, the Hippocrate project lead to a robot-assisted US diagnostic system—originally created to prevent cardiovascular diseases [3]. This project employed a teleoperation approach for diagnostic US [4]. In this setup, the transducer was targeted with an electromagnetic position and orientation sensor and a force/torque sensor. The tele-manipulated probe holder was equipped with automatic visual tracking capabilities, making it possible to the operator to only focuse on the movement along the vessel, and the robotic arm automatically adjusted the joint positions. A very similar work was presented in [5], but it attains higher rigidity to the robotic device by adopting radius guides.

Delgorge et al. presented a teleoperated mobile US scanner for real-time image acquisition and diagnosis with the usage of a 6 Degrees of Freedom (DOF) light-weight robot in 2005 [6]. A medical expert could control the US probe remotely with a 1 DOF device (the "virtual probe"). The expert receives the images—depending on the bandwidth—in almost real-time. The operator received the instructions from the remote expert, and could positions the robot on a reference point on the patients skin. A force sensor gave information about the contact force between the real probe and the patients skin. The system was able to use a diverse type of communication link trogh satellites.

OTELO was a lightweight telerobotic US diagnostic system, portable and a fully integrated with the robotic device [7]. It was remotely controlled with a pseudo-haptic fictive probe, which was able to control the positioning of the remote robot. The used communication software was based on the IP protocol and could be used trough different communication means (ISDN, ADSL, LAN, Satellite, mobile).

Kozumi et al. developed a remote US master–slave diagnostic system to recognize shoulder diseases. Their system had continuous-path control feature for the orientation of the slave manipulator to provide smooth and accurate motion of the US probe, if the transmission's sampling rate is not sufficient [8].

The MELODY US system (AdEchoTech) is a recently commercialized robotized US diagnostics product [9]. This device has a remote US imaging system, which can address the growing issues of the shortage of medical care in underserved areas. In the expert center, the operator uses very fine movements that cannot be guided solely by voice commands or by video. The radiologist uses a robotic arm with real-time visual feedback to position the US probe on the patients skin. The master and the slave sides are connected through the Internet (the minimum bandwidth is 1 Mbit/s). MELODY contains a videoconferencing system, which lets the physician see and speak with the patient.

More recently, UR5 (Universal Robots) was used to create a teleoperated robotic US system [10]. The motivation behind this research was to reduce the physical impact (e.g., shoulder pain) on the radiologist caused by poor ergonomics when using the US device.

Vitrani et al. developed a system with a robot-guided US probe for breast cancer detection and localization, where the procedure consists of a mammography followed by supplementary US scan [11]. The major issue during these examinations is the change of breast geometry due to the different positions of the patient; the breast is compressed between the image receptor and the compression paddle during mammography, while the patient simply is laying on her back during US scan. To simplify the searching for the lesion area during the US examination, the article shows a new setup for the procedure. The US scanning is performed through the compression paddle after the mammography to eliminate the changes of breast geometry. Moreover a robotically co-manipulated US probe was used, which guides the operator by virtual fixtures (the robot only enables movements about the estimated lesion area) to help the localization of the tumor found on the X-ray image.

III. Automated robotic US navigation

Apart from diagnosis, in several cases, the robotic device is used to operate a surgical instrument based on US positioning. Within Minimally Invasive Surgery (MIS), US-based navigation is a rapidly developing field.

Fig. 1. The MELODY system (Image credit: AdEchoTech [9]).

Fig. 2. Teleoperated US system using the UR5 robotic arm [10].

An important concept of improving imaging quality during US imaging is visual servoing, where the control mode is based on the features of the US images. Visual servoing can be an effective tool to automatize the movement of the probe during the procedure, and thereby facilitate the examination for the physician. In [12], a visual servoing design and application developed. This visual servoing framework was designed to optimize the positioning of the robot–assisted US probe, thereby improving the quality of the US images. This visual servoing method was based on the *confidence map* of the US images. US confidence map is a per-pixel measure of the confidence for US images, therefore confidence map is a type of US signal loss estimation method. With visual servoing techniques, it was also possible to position the US transducer by a robot, and the operator, the robot controller, and an US image processor shared the control over the motion. The US image features can be selected by the user and tracked by

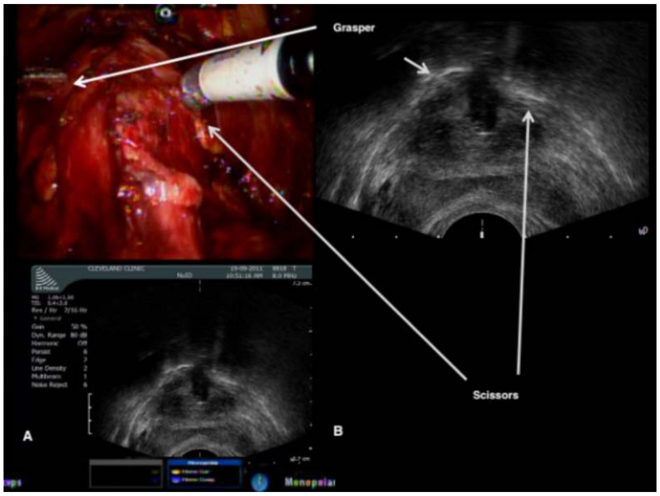

Fig. 3. Robotic transrectal US probe holder is image-guided surgery, and the simultaneous display of 3-dimensional robotic and US images [14].

feature tracking [13].

An automatic guidance system was developed for surgical instruments with US-based visual servoing [11]. To manipulate the intra-cardiac instrument, the 4 DOF MC2E robot (developed in the Laboratoire de Robotique de Paris) was used. The instrument tracking was based on direct visual servo control of the points corresponding to the intersection of the instrument with the US plane (Fig. 3).

Long et al. developed a real-time robotic transrectal US navigation during robotic radical prostatectomy [14] (Fig. 4). In this research, the ViKY endoscope holder (EndoControl, Dover, DE) was used for surgical assistance; this endoscope holder has a hands-free command interface, and it was modified to handle the US transducer. The robotic system could position the transducer with 3 DOF, and the physician could control this device by foot pedals through the da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA) [15]. The US image is then projected to the da Vinci's HD stereo viewer for the surgeon to see. This US probe holder can be an important part of urological procedures by calculating the prostate volume, defining the reference points, identifying the neurovascular bundle and visualizing the tool tip. This systems feasibility and safety was proved with clinical tests.

Recently, an autonomous MRI-based (Magnetic-Resonance Imaging) US navigation system (Fig. 4) was presented [16]. They used structured-light 3D sensor for patient-to-robot and image-to-patient registration to plan 3D US probe trajectory. These trajectories were followed autonomously by a KUKA iiwa robot arm (KUKA Roboter GmbH, Ausburg, DE), which was developed for direct human–machine interaction.

Zettinig et al. presented a fully image-based visual servoing implementation for neurosurgical intervention and needle guidance [17]. They used 3D US transducer, mounted on a robotic arm, extended with a needle guide. It continuously registered the US frames with the pre-operative CT or MR image (Fig. 5). They validated the servoing capabilities on

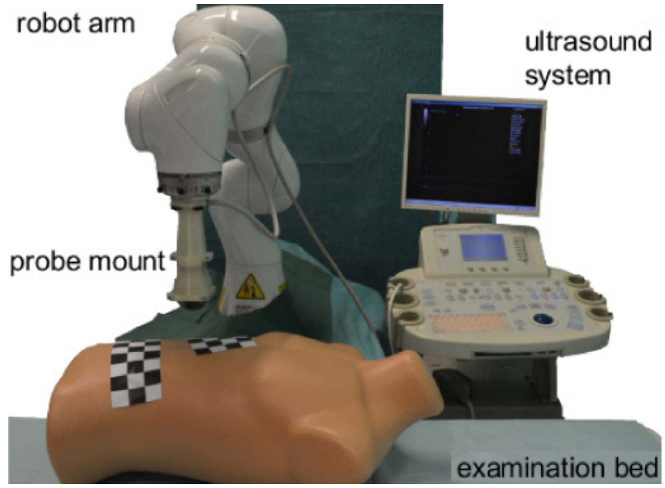

Fig. 4. Configuration of the MRI-based ultrasound navigation system [16].

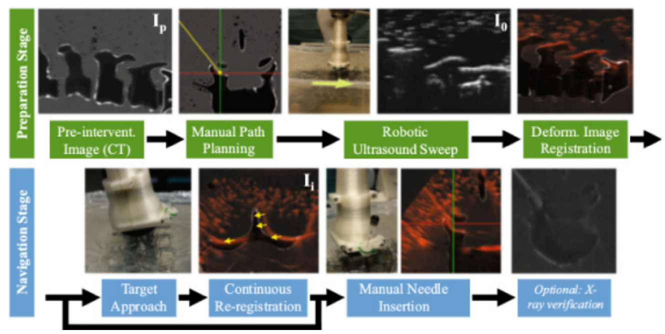

Fig. 5. Workflow for facet joint needle insertion using the proposed US-based visual servoing guidance framework [18].

a phantom and real human anatomy; and verified the needle targeting accuracy with CT images.

Chatelain et al. presented a real-time ultrasound based needle detection and tracking implementation [19]. A 3D US probe was mounted on a robotic arm (Adept Viper s850). The robotic arm responsible for 3D US probe navigation. With 3 DOF visual servoing, the robot could automatically keep the needle axis aligned with the longitudinal axis of the probe. It moved the probe horizontally to keep the needle in the center of image and align it with a given axis (Fig. 6).

IV. Automated US-guided Interventions

Automation in surgery has several advantages: increasing precision, improving surgical efficiency and execution, real-time utilization of biosignals for interventional care, and computer-aided guidance under various medical imaging and sensing modalities [20]. While in the previous two categories, projects only employed the robot as a tool holder, more recent applications fundamentally changed that concept, allowing active robotic execution of surgical actions under US control. Robot-assisted MIS is trending in the field of Computer-Integrated Surgery (CIS), yet it is too much dominated by the da Vinci telerobotic concept, where no autonomy of the system is allowed. It eliminates the safety issues associated

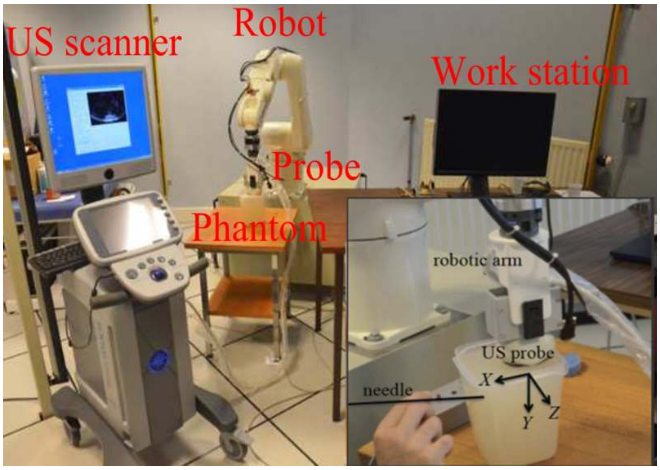

Fig. 6. Configuration of the US-based needle tracking system [19].

with automated decision making and responsibility of the device by keeping the surgeon in direct control over the instruments. This paradigm is about to change quickly with the introduction of cooperative robots: the principle of these robotics is that the surgical tool is co-manipulated by the robot and the surgeon; the tool is manipulated by the surgeon, while the robot gives some kind of guidance by force feedback or blocking movements to prevent the entrance into the predefined areas by e.g., virtual fixtures (forbidden regions). US based robotic systems allow for less invasive procedures to be carried out, which could not be done without the dexterity and precision of a robotic device (e.g., skullbase surgery).

A fine example for that is needle insertion. Needle-based techniques are used in MIS for treatment and diagnosis, such as biopsy and brachytherapy. The accurate needle tip positioning is critical during these types of interventions, the inaccuracy can cause severe damage (misdiagnosis or inappropriate treatment). The usage of stiff needles is preferred nowadays for needle insertion procedures, even though, they result in increased tissue damage. Needle steering is an emerging topic, where some mechanical properties of the needle are exploited to achieve certain (limited) targeting under image control. For instance, when employing a bevel-tip needle, by rotating it around its axis it can be steered during the insertion, avoiding obstacles, reaching the target location more precisely [21].

In the work of Abayazid et al., a US-guided needle insertion method is presented [22]. In this solution the slave robot is controlled by the operator, while the navigation cues about the calculated optimal needle orientation are provided by haptic and visual feedback. Other systems under current research are showing advanced methods for needle steering control by duty-cycled algorithms [23], or tracking of the needle by US imaging [24].

One of the current automated needle insertion systems in research is developed by Moreira et al. (Fig. 7). In their setup, the needle is inserted into the tissue by a robotic device, which is able to rotate it axially, using optimal steering control. The Young modulus of the tissue is determined by acoustic

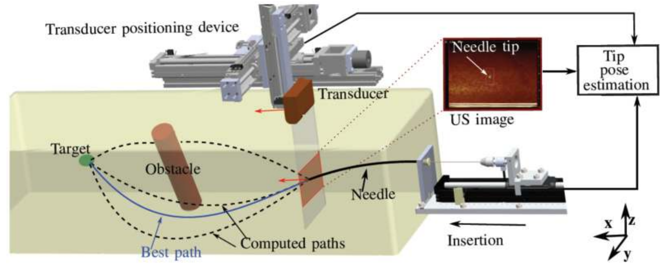

Fig. 7. The Needle insertion setup, the needle tracking and path planning used by [21].

radiation force impulse measurement, to eliminate the need of preliminary insertions. They used offline curvature estimation employing the biomechanical model of the current tissue. During the insertion, the position of the needle tip is estimated by the known insertion depth from the robotic device and US imaging. Moreover, an online curvature estimation was also used to compensate for changes of the Young modulus inside the tissue. Extending this system with adaptive control, they were successful in the insertion of the needle into moving target inside a multi–layer phantom containing moving obstacles. The precision of the insertions was 1–2 mm, which falls in the same range with the smallest detectable object of the US image [21], [25].

During a high-precision radiotherapy compensating for patient movements and minimizing normal tissue damage is one of the biggest challenges of todays robotized radiation therapy systems. These systems are typically using X-ray images/Computed Tomography (CT) scans to define the treatment target [18]. Their system can dynamically locate the target region with ultrasound imaging, by using the Kinect v2 sensor (Microsoft) and an industrial robot (Adept viper s850) to locate the patient. The setup also localize the specific ultrasonic view ports previously defined in the planning CT.

There are several research groups working on extending the capabilities of existing robotic systems. The advantage of this approach is that these robotic systems have been previously approved for human medical interventions, and extending them with US capabilities does not increase their safety requirements significantly. A promising project aiming for autonomous tumor dissection using US and camera based visual servoing was presented by Pratt et al. [26]. This system is implemented on the da Vinci Research Kit (DVRK) [27], and able to perform tissue dissections on a phantom with 0.7 mm accuracy.

Lastly, we mention an interesting concept: a ”pick-up” US transducer for intra-abdominal robot-assisted MIS. This system can be inserted through an abdominal incision and remains in the abdominal cavity during the intervention. It can be grasped by the da Vinci ProGrasp tool repeatedly, which enables precise positioning using the surgical robot. It has built in 3D tracking capabilities, which enables the registration of US images to CT scans [28].

TABLE I
ROBOTIC PLATFORMS USING ULTRASOUND IMAGING

Ultrasound Robotics Architectures	Design Feature	Medical Procedure & Target Anatomy	Status	Ref.	Date
Hippocrate	teleoperation robot approach system for medical diagnostic US	prevent cardiovascular diseases	research	[3]	1999
OTELO system	teleoperated mobile US for real-time image acquisition and diagnosis	general US-based diagnosis	research	[6]	2005
UR5	tele-operated robotic ultrasound system	reduce the physical impact on the radiologist	research	[10]	2016
impedance controlled master–slave system	remote US master–slave diagnostic system	diagnose shoulder diseases	research	[8]	2003
MELODY US system	remote US master–slave diagnostic system	general US-based diagnosis	commercial	[9]	2008
2DOFs robotized probe	robot guided US probe; the procedure consists of a mammography followed by supplementary US scan	breast cancer detection and localization	research	[29]	2015
MC2E	automatic guidance system	surgical instruments with US-based visual servoing	research	[11]	2005
ViKY + da Vinci Surgical System	real-time robotic transrectal US navigation	radical prostatectomy	research	[14]	2012
KUKA iiwa	autonomus MRI-based US navigation system	needle insertion	research	[16]	2017
KUKA LWR	fully image-based visual servoing	neurosurgical interventions and needle guidence	research	[17]	2015
Viper s650	US image quality optimization with visual servoing	general US–based diagnosis	research	[12]	2015
Adept Viper S850	real-time US based needle detection and tracking	needle detection and tracking	research	[19]	2013
transducer positioning + needle insertion device	US guided needle insertion	needle insertion	research	[22]	2015
US control master-slave system	automated needle insertion	needle insertion	research	[21] [25]	2014
Adept viper S850	dynamically locate the target region (patient) with US imaging	radiotherapy	research	[18]	2015
da Vinci Surgical System addon	autonomous tumor dissection using US and camera based visual servoing	tumor treatment	research	[26]	2015

V. RESEARCH PROJECT FORMULATION

The primary aim of our review was to overview the existing capabilities of the US-driven robotic setups, and identify certain niche segments for future research. Conclusively, it can be stated that the primary functionalities a US-incorporated robotic system should be:

- tracking the US probe (deriving objective position and orientation information);
- measuring the contact forces with the body;
- recording the imaging planes together with the probe position;
- option for remote control;
- possibility for increased accuracy through an independent navigation system.

At the Antal Bejczy Center for Intelligent Robotics (Óbuda University, Budapest, HU) a KUKA iiwa robot was equiped with a Telemed portable US transducer (TELEMED Ltd., LV) through a custom developed socket, incorporating 3 DOF force sensors. The motions of the robot are also tracked with an external navigation system for reference, employing a Micron Tracker Sx60 stereo camera system (Claronav Ltd, ON). This integrated setup is operational, aimed to fulfill the above requirements, while the development of a detailed clinical protocol, validation and verification is still a work in progress.

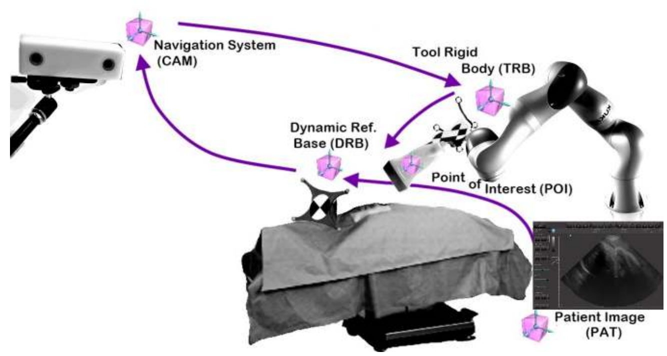

Fig. 8. Control concept of a US-guided robotic setup at Óbuda University.

VI. Conclusion

This article presented the high potential in the combination of traditional medical ultrasound imaging and modern robotics. The different scale of automation in the recently developed systems provides benefit to the patient and also to the physicians. The portable, non-invasive US imaging systems can be combined effectively with accurate robotic devices. This US-based robotic systems can be remotely controlled by a human operator in teleoperation mode, or navigated based on the acquired images. We aim to create a capable setup of robotic US system for invasive US-guided interventions, such as needle insertion based on the concepts and functionalities available already in research facilities.

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