EchoBot: An open-source robotic ultrasound system

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1 Purpose

Autonomous robotic systems for ultrasound (US) imaging could offer distinct advantages in several medical procedures, especially where great precision and repeatability is required. Among many, this includes needle insertions, quantitative measurements based on standardized views, therapeutic US and radiosurgical procedures, but also more complex soft-tissue surgeries. Robotic US may also reduce costs for examinations that are performed very frequently, such as screening for abdominal aortic aneurysms (AAAs), by automating the entire examination. While clinical use of autonomous robots is challenging due to both the complex and dynamic setting and the large anatomical variations between patients, new developments within machine learning, computer vision and collaborative robots have brought autonomous US examinations closer to reality.

Robotic US has been an active field of research for many years [9]. Recently, more or less autonomous systems have been presented, especially for needle-based procedures [3, 5, 7], but also for abdominal artery examinations [13]. In addition to hardware such as robot arm, US scanner and cameras, many software components are needed to conduct research on ultrasound robotics. To our knowledge, there is currently no open-source framework available which supports US and 3D camera streaming, real time (RT) image processing including machine learning, as well as controlling a robot arm. Thus, in this work, our aim is to develop a new and generic open-source framework that integrates core libraries for building autonomous robotic US applications. Hopefully, this framework can be useful for other research groups and facilitate more research and collaboration on robotic US.

2 Methods

When connected to a robot arm, a US scanner and a depth camera, the EchoBot application can currently be used to: 1) Manually control the robot, 2) Process US images in RT using neural networks, 3) Interactively select scanning targets

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in the RT point cloud, 4) Patient registration using point clouds, 5) 3D reconstruction while scanning and 6) Calibration with support for common hand-eye calibration methods. US probe calibration is so far performed using an external application [2], but this will soon also be included and integrated with the camera calibration.

The EchoBot framework is open-source and available online[1] along with stored point cloud and US recordings which can be used to test the system even without the robot and imaging hardware. The robot operating system (ROS) is the most popular framework for robotics in research. However, ROS is not used in this project mainly because of the need for RT processing of large amounts of imaging data. ROS was designed for modularity, not high performance computing, thus EchoBot instead relies on FAST, a C++ framework for high performance medical image computing, and a simple robot controlling framework called libromocc. The next two sections will describe these two libraries briefly and how they are used in the EchoBot system.

2.1 libromocc - Robot modelling, communication and control

The library libromocc is a lightweight framework for robot modelling, communication and control. It consists of an abstract communication interface, which allows setting up TCP/IP connection with custom encoders/decoders for message passing. It supports basic control for frame-to-frame motion and visual servoing, where Orocos KDL and Eigen is utilized for modular handling of kinematics and manipulator configuration. Currently, only the robot manipulator UR5 from Universal robots is supported, but the framework is readily extendable for other robot arms using the Denavit-Hartenberg convention [4]. To simulate the robot motion and communication we use the simulator provided by the manufacturer.

2.2 FAST - Image processing and visualization

FAST [11] was developed as a framework for high performance medical image computing and visualization using multi-core CPUs and GPUs. In EchoBot, FAST is used for RT visualization, image processing, patient registration, deep learning inference, as well as 3D camera and US streaming.

US data streaming is supported by using the OpenIGTLink protocol [12]. The system supports streaming of RGB and depth data from both Intel RealSense and Microsoft Kinect cameras. The color and depth data are registered, enabling RT colored point clouds which can be used for visualization and patient registration. Deep learning has quickly become the main approach for computer vision, including processing of medical images such as US. Through FAST, the EchoBot has access to several inference engines such as Google's TensorFlow, NVIDIA's TensorRT and Intel's OpenVINO. These inference engines enable high performance neural network inference by using GPUs. The EchoBot can thus use

[1] https://github.com/SINTEFMedTek/EchoBot

neural networks to process both the US and camera images. Training of the neural networks is done in other training software, while the trained network graph and weights are stored in files on disk which can be loaded into the inference engines in FAST at runtime.

Patient registration is an essential step in most computer assisted interventional procedures. FAST has implementations of two point cloud registration methods: iterative closest point (ICP) [1] and coherent point drift (CPD) [8] which can be used to register the patient point cloud coming from the 3D camera and preoperative CT and MR images. Given enough training data, this might also be achieved by deep learning.

3 Results

For testing the EchoBot, the clinical application of scanning for AAA was selected. This procedure was chosen due to its simplicity and clinical relevance as screening programs for AAA are already established many places. The AAA US examination consists of scanning the abdominal aorta of the patient from the diaphragm to the iliac branch. The cross-sectional diameter of the aorta is then used to detect an aneurysm.

The experimental hardware setup consisted of a UR5 robot arm, an Ultrasonix SonixRP US scanner with a curved linear probe, and an Intel RealSense D435 depth camera. B-mode images were streamed with the OpenIGTLink protocol using the Plus toolkit [6]. An AAA US phantom from Blue Phantom was used for testing the system. RT segmentation of the incoming US images was performed using a fully convolutional encoder-decoder neural network similar to that used by Smistad et al. [10].

The neural network was trained on a set of annotated images from the phantom at different positions and angles. The segmentation was also reconstructed in 3D in RT by using the known movement of the robot arm and the transform between the robot arm and the US image found through calibration. Fig. 1 shows

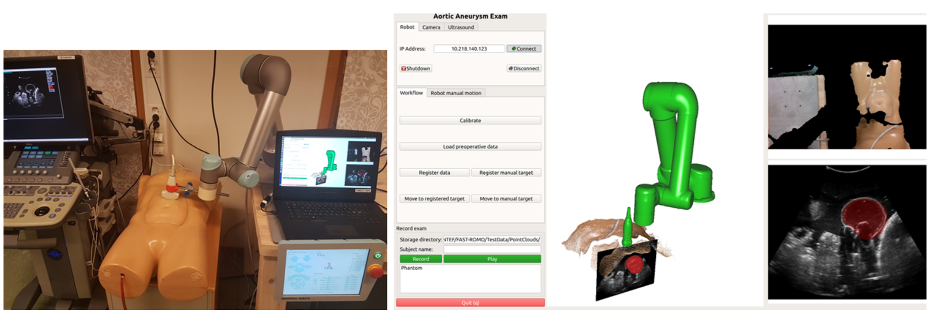

Fig. 1. Left: Photograph showing the hardware setup. **Right:** A screenshot of the EchoBot graphical user interface during the AAA demo.

the hardware setup and a screenshot of the EchoBot application. A video of the AAA demo can be found online[2].

4 Conclusion

An open-source framework for robotic US was demonstrated. The framework will be developed further over the next years adding features such as automatic calibration, force feedback, collision avoidance and motion compensation with the end goal of creating a fully autonomous system for abdominal aortic aneurysms screening.

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