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Evaluation of the reconstruction accuracy of 3D robotic ultrasound on in-vitro phantoms for the geometrical characterization of abdominal aortic aneurysms

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Abstract: Abdominal aortic aneurysms (AAAs) pose a significant health risk, particularly in the elderly population, due to the potential for life-threatening rupture. Conventional 2D ultrasound surveillance and guidelines for surgical intervention based on aneurysm size have limitations, necessitating a more individualized approach to assessing rupture risk. This study investigates the overall accuracy of a novel robotic ultrasound system using a single transducer on a collaborative robotic arm. High quality phantoms were used to test the accuracy of the 3D resolution. The system demonstrated promising lateral reconstruction accuracy for large vessels, with dimensions close to the true vessel size of 6 mm. Some slight deviations existed for the reconstructed longitudinal vessel dimensions due to vessel compression by the probe. Future work will focus on optimizing the reconstruction algorithm and system setup, with plans for testing on abdominal phantoms and human subjects to ensure broader applicability and reliability in clinical settings.

Keywords: robotic ultrasound, 3D reconstruction, collaborative robot arm, abdominal aortic aneurysm.

1 Introduction

Abdominal aortic aneurysm (AAA) is a major concern because of the significant health risks it poses, with an incidence of over 5% in older people, making it a significant issue for this population [1]. An AAA is characterised by a localized dilation of the aorta, exceeding 50% of its normal

diameter. The primary concern with AAAs is their potential to rupture, which can lead to life-threatening bleeding and is fatal in about 80% of cases [2].

To manage this risk, AAAs are routinely monitored using 2D ultrasound to observe changes in its maximum anterior-posterior diameter [3]. Surgery is considered when the risk of rupture outweighs the risks associated with the repair procedure itself [3]. At the moment, surgery is recommended when the aneurysm diameter exceeds 55 mm in men and 50 mm in women [4, 5]. Surgery is also recommended if the aneurysm is growing at a rate of more than 1 cm per year [6]. However, these criteria are not sufficiently patient-specific, as some smaller aneurysms rupture (2-10%) and some larger ones remain stable [7, 8, 9]. A more individualised approach is needed to avoid under- and over-treatment.

In recent years, several alternative approaches have been proposed to assess abdominal aortic aneurysms. These alternative risk assessment methods [10, 11, 12, 13] involve analysing aortic stress using patient-specific geometry and blood pressure to calculate peak wall stresses, thereby providing insight into the mechanical state of the abdominal aortic wall, considering factors such as full aneurysm geometry, wall motion dynamics, strain, volume, stiffness, compliance and distensibility, all of which are vital in assessing rupture risk. Therefore, there is a need for an imaging technique capable of capturing the full geometry of AAAs throughout the cardiac cycle, which should be non-invasive and provide functional data.

One promising approach is multi-perspective ultrasound. This overcomes the anisotropic contrast and resolution in ultrasound images by merging images from different transducers. It has been shown to improve contrast and field of view of the abdominal aorta [14].

Building on the idea of multi-perspective imaging, our approach makes use of a single transducer that is mounted on a collaborative robotic arm. Our system is designed to be retrofitted or added to an existing ultrasonic unit. The setup allows the transducer to be repositioned to different locations,

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capturing multiple perspectives without the need for multiple transducers and scanning along a vessel.

This work consists of the 3D reconstruction of ultrasound phantoms based on images acquired by our robotic system. The main focus lies in the accuracy of the reconstruction in order to verify whether the system is suitable for the intended application.

2 Materials and Methods

2.1 Phantoms

Two high quality ultrasound phantoms from Erler-Zimmer (Erler-Zimmer GmbH & Co. KG, Germany) were used to assess the capabilities of our robotic ultrasound system. The first is the 'Vessel' phantom, which contains a 6 mm diameter blood vessel at a continuously variable depth

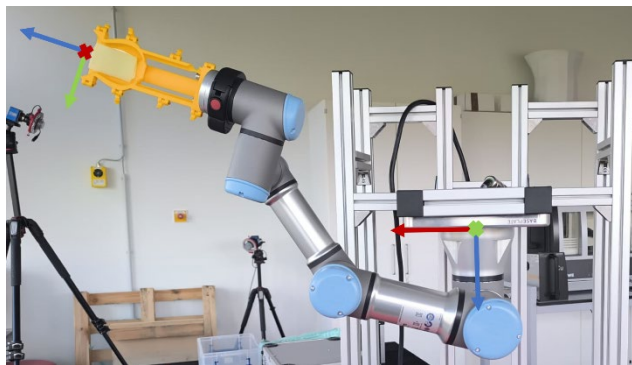


Figure 1: UR3e with mounting bracket for an ultrasound probe. The base coordinate system and the coordinate system for the tool center point are visualised (x-axis: red, y-axis: green, z-axis: blue)

ranging from 5 mm to 30 mm, allowing assessment of the imaging performance at different penetration levels. The second is the 'Branched Vessel' phantom. This model features a primary blood vessel, also 6 mm in diameter, which branches into a smaller vessel of 3 mm in diameter. These structures represent a more complex vascular scenario and require a higher resolution.

The focus of the reconstruction is on the 6 mm vessels, as these are closer in size to the aorta.

2.2 Data acquisition

Our system consists of a UR3e collaborative robotic arm from Universal Robots (Universal Robots A/S, Denmark). This robotic arm, equipped with a force and torque sensor, serves as a stable platform for the ultrasound probe mounted

on the end effector with a mounting bracket (see Figure 1). The tip of the probe is defined as the tool centre point for the robot's movements. The robot is securely mounted in a downward orientation on a portable aluminium profile frame, allowing it to be positioned above the examination area. Throughout the imaging process, precise position and orientation data of the ultrasound probe are recorded during the movement of the robot at a frequency of 500 Hz. The contact force exerted by the probe is controlled at 5 N to ensure consistent and accurate measurements.

The data acquisition protocol follows the same steps for both phantoms, the robotic arm moves the probe from one end of the phantom to the other on the flat top of the phantoms, repeating this movement three times, roughly aligned with the centre of the phantoms.

The ultrasound system used for these experiments is the MyLab 9 from Esaote (Esaote SPA, Italy), featuring the C 1-8 curved array probe. For both phantoms, cross-sectional views are captured. A frame grabber from Magewell (Magewell Electronics Co., China) is used to record the ultrasound system's monitor input at a rate of 60 Hz, ensuring high quality data acquisition for subsequent analysis.

After acquisition robot data and ultrasound images were cut to the relevant intervals and expandable data was discarded. Robot data and ultrasound images are then synchronised in time to get the coordinates and the orientation of the probe for every image.

2.3 Image processing

Image processing was performed in MATLAB version 2024b (The MATHWORKS inc., United States of America).

The position and orientation of the first ultrasound image are chosen as $\vec{p}_0$. In preparation for vessel detection each frame was translated in x and y using the corresponding robot position with reference to the robot position $\vec{p}_0$ of the first frame. Afterwards the image was cropped to the relevant area.

Image filtering was performed in two steps. Firstly, a speckle-reducing filter using anisotropic diffusion was applied by using the *specklefilt* function. This was followed by a 7x7 median filter to increase the contrast between light and dark areas. The median filtered image is used to create a starting contour which is smaller than the vessel to be recognised. This is achieved through binarization by thresholding of the median filtered image.

The initial contour is used to detect the vessel in each image by an expanding active contour algorithm utilising the *activecontour* function. Since the vessel is scanned multiple times there are multiple images and multiple vessel contours

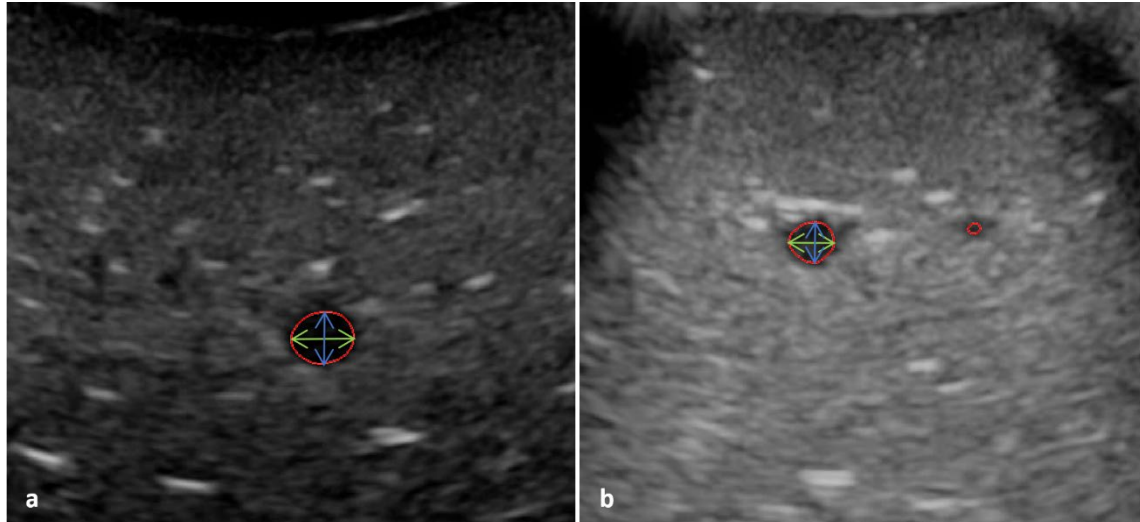


Figure 2: Detected vessels for the 'Vessel' phantom (a) and the 'Branched Vessel' phantom (b). Detected vessel height shown with blue arrow and detected vessel width shown with green arrow.

per probe position. For every probe position all the vessel contours are fused into one final contour. From those contours the dimensions of the vessels are computed.

3 Results

Image acquisition for both phantoms was performed successfully. The vessels detected in the ultrasound images of both phantoms are shown in Figure 1. The recordings of the 'Vessel' phantom and the 'Branched Vessel' phantom were used to reconstruct their vascular structures.

For the 'Vessel' phantom, the reconstruction process yielded an average maximum vessel height of 5.5 ± 0.37 mm and an average maximum vessel width of 5.8 ± 0.18 mm. This results in an average error of -0.45 mm or 7.5% of original vessel diameter for vessel height and -0.17 mm or 2.8% of original vessel diameter for vessel width respectively.

The reconstruction of the 'Branched Vessel' phantom included both the large and the small vessel of the phantom. For the large vessel component, the mean maximum height was recorded at 5.4 ± 0.14 mm, while the mean maximum width measured 5.9 ± 0.25 mm. The mean error was found to be -0.56 mm equivalent to 9.3% of the original vessel diameter for height, and -0.07 mm equivalent to 1.2% of the original vessel diameter for width, respectively.

4 Discussion

The lateral reconstruction accuracy was found to be promising when comparing the reconstructions of the 'Vessel'

phantom and the large vessel of the 'Branched Vessel' phantom to their actual size of 6 mm. Both phantoms displayed slight discrepancies in the lateral vessel size, with reconstructed sizes falling slightly below the true diameter, yet these deviations were accompanied by similar standard deviations, indicating a consistent performance in lateral measurements over the whole vessel.

The longitudinal reconstruction accuracy was consistent between the 'Vessel' phantom and the large vessel of the 'Branched Vessel' phantom. However, a larger deviation of the calculated vessel dimension to the original diameter of 6 mm was noted, likely due to compression caused by the robotic system pressing the ultrasound probe onto the phantom from above. The measurements of the 'Vessel' phantom exhibited a higher standard deviation, which can be attributed to the varying depth of the vessel; deeper sections experienced less compression relative to those nearer to the surface.

Future work should focus on optimizing the current structural setup and a revision of the reconstruction algorithm to improve its performance and enable easy application for multi-perspective imaging. An adjustment of the structural setup should be considered since the ultrasonic probe bobbed up and down slightly when there was greater resistance during movement. A revision of the current reconstruction algorithm is necessary because it is highly dependent on the quality of the ultrasound images which depends greatly on the settings of the ultrasound system. In particular, the algorithm's susceptibility to brightness variations, which results in inaccurate contours, requires attention. Furthermore, the system should be used with abdominal phantoms and volunteers in the future.

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