Visual servoing for semi-automated 2D ultrasound scanning of peripheral arteries

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Abstract: 2D ultrasound (US) is a commonly used imaging technique for diagnostic and aftercare purposes in vascular medicine. Nonetheless, the acquisition is still a user-dependent and time-consuming process. To overcome these disadvantages, we propose a semi-automated scan of peripheral arteries by means of a robotic arm with an US probe at its end effector. The system was evaluated by checking its feasibility to scan the femoral artery of a leg phantom and measuring the duration of a scan. In 27 out of 30 trials the robot reached its target point along the leg phantom with a mean duration of 61.4 s.

I. Introduction

The number of patients with vascular diseases has been rising continuously for years [1]. Studies show that 20 % of persons older than seventy years suffer from peripheral arterial occlusive disease [2]. For diagnostic and aftercare purposes, ultrasound (US) and Duplex US have become first choice [3], as it is an affordable, safe and real-time imaging technique. Additionally, Duplex US provides information about the blood flow kinetics within the vessel, which gives supplementary hemodynamic information. Apart from all its advantages, US is still a highly user-dependent and time-consuming process. Automation of this process has the potential to make the image acquisition process more reproducible (for instance, in terms of a steady contact force) and more time efficient.

In order to overcome the above-mentioned disadvantages and to take a first step towards general automation, we propose a semi-automated scanning of peripheral arteries. To this end, a robotic arm with an US probe at its end effector follows the artery according to its location within the US image and the robot's initial pose. The aim of this initial study was to prove the feasibility of scanning the femoral artery of a leg phantom based on this approach and to measure the duration of the scanning.

II. Material and methods

A 2D linear US probe (L12-3, Philips Healthcare, Best, Netherlands) was mounted on the end effector of a robotic arm (LBR iiwa 7 R800, KUKA, Augsburg, Germany) using a custom-made probe holder. A software interface allows real-time streaming of 8-bit grayscale US images from the US station (EPIQ 7, Philips Healthcare, Best, Netherlands) to a computer. Additionally, a custom-made middleware allows for sending commands from the same computer to the robot arm. A C++ program, running on the computer, performs the image processing and sends the resulting commands for repositioning the US probe at the end effector using the standard inverse kinematics of KUKA. The workflow of the scanning procedure is as follows:

1. Using a custom developed hand guidance mode [4], the physician places the US probe (attached to the robot arm) such that a cross-sectional image of the artery is visible in the US image (Fig. 1(a)).
2. Within the streamed US image, the physician can select the region of interest, namely the initial template containing only the artery.
3. On subsequent images, template matching is performed to find the artery in the image (Fig. 1(b)). The sum of squared differences is used as a metric for the template matching. In order to keep the artery in the horizontal center of the US image, the robot arm moves in ± x direction of the end effector coordinate system (Fig. 2) based on the information extracted from template matching. On average, the end effector is moved along its x-axis based on the information gathered from the last eleven images.
4. If a vessel is found, the robot arm moves 1 cm further in distal direction (same direction as the positive y-axis [Fig. 2] of the end effector). Otherwise, it will move 1 cm in proximal direction. The target z-position of the end effector is set to an intracorporeal position during the whole procedure. To avoid a non-appropriate pressure, this process is controlled by a proprietary Cartesian impedance control, which is configured with a spring constant 200 N/m in the z-axis (Fig. 2) while maintaining a higher axial and transverse spring

constant of 500 N/m for accurate positioning. In addition, the maximum possible force in the z-axis was set to 6 N as a safety restriction.

5. Steps three and four are repeated until the robot arm has moved 15 cm along the y-axis of the end effector.

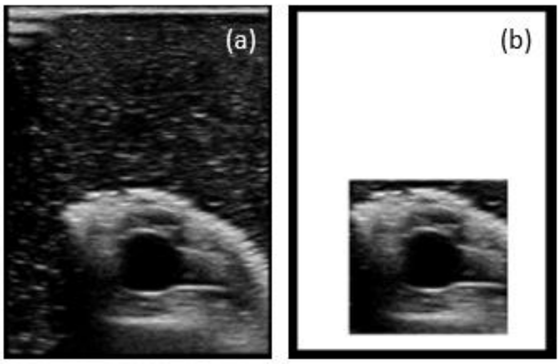

Figure 1: (a) US image containing the femoral artery of the leg phantom. (b) Region of interest selected after template matching. This image patch is then used as the template for the next iteration.

The feasibility of the system was evaluated by using a customized US leg phantom (HumanX, Wildau, Germany). US images were acquired with the following settings, which provided the best visibility of the phantom artery: Arterial vessels mode, R-1 mode, overall gain of -5 dB and manually selected depth of 5-7 cm. The workflow was performed 30 times. The leg phantom was placed ten times in its initial position, ten times rotated by roughly 30° and ten times rotated by roughly -30°, in both cases around the z-axis (Fig. 2). For additional evaluation purposes, the time needed to scan the 15 cm was measured.

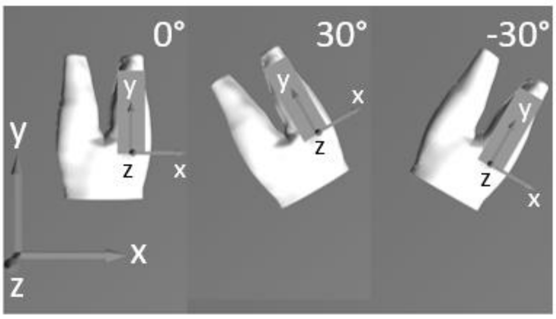

Figure 2: The world coordinate system (bottom left) and the end effector coordinate system after placing the US probe using the hand guidance mode for each rotation of the phantom. Note that the z-axes of both systems are always identical.

III. Results and discussion

The mean time needed to realize the template matching process per US image was 65 ± 7 ms (mean ± standard deviation). In 27 out of 30 trials, the leg phantom was successfully scanned 15 cm along the artery. Fig. 3 illustrates one scan. In one trial, the robot reached the end of its workspace and thus could not finish the scanning. Additionally, in two trials the robot arm ran into a singularity, thus not finishing the scanning. The mean duration of the scans was 64.3 ± 19.2 s, 91.7 ± 57.2 s and 31.4 ± 2.5 s for the initial position, 30° rotated and -30° rotated, respectively. This corresponds to a mean tracking velocity of 2.3 mm/s, 1.6 mm/s and 4.8 mm/s, respectively.

This difference in duration of the scans is mainly due to changes in the configuration parameters (e.g. elbow-up, elbow-down) depending on the pose of the phantom.

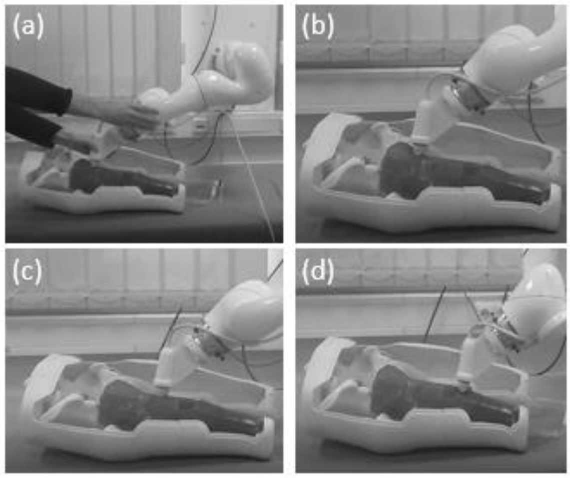

Figure 3: (a) The hand guidance mode allows to place the US probe on the leg phantom. (b)-(d) The robot arm moves along the leg, the artery center always in the horizontal center of the US image.

In most cases, our approach was feasible, but it assumes that the leg always lays in the x-y plane of the world coordinate system (Fig. 2), the leg does not move during acquisition and there is no vessel bifurcation. Additionally, the applied pressure on the leg phantom depends on the target position of the end effector in z-axis. Therefore, having a different height of the patient table would lead to non-appropriate forces. These limitations can be solved by a spatial calibration of the end effector and the US probe. Future work will also focus on handling singularities.

IV. Conclusions

This study showed that a semi-automated 2D US scanning of peripheral arteries using a robotic arm was feasible, with a mean duration of 61.4 s for all scans. This approach can potentially make the acquisition more reproducible. The work presented lays the groundwork for a more complex and autonomous system for ultrasound scanning of peripheral arteries.

AUTHOR'S STATEMENT

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