Ultrasound-based Robot-assisted Drilling System for Pedicle Screw Placement

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I. INTRODUCTION

Pedicle screw placement (PSP) is a common procedure for spine surgery with proven benefits. However, some drawbacks exist; the screw can be misplaced or may loosen. Inaccurate screw placement may cause neurological impairment such as pain, weakness or sensory loss. Thus, screw placement accuracy is of utmost importance and is critical for a successful surgery [1].

Computer-guided systems, such as fluoroscopy-based navigation, are primarily applied to the lumbar spine. During the past years, ultrasound (US) navigation systems have been developed and investigated for use in spine surgery. This eliminated the need for multiple fluoroscopic images to update instrument positioning and also significantly improved pedicle screw insertion. However, intraoperative navigation requires the human in the loop and manual manipulation.

Therefore, the adoption of a robot-assisted system is necessary for pedicle screw placement. Several studies have been proposed to assist the pedicle screw placement with a robot-assisted system. Smith *et al.* also implemented a camera-based supervisory controlled autonomous robot for polyaxial spine screw placement [2]. They reported an entry point accuracy of 0.49 ± 0.17 mm and a destination point accuracy of 1.49 ± 0.46 mm compared to the registered CT model by the attached reference marker. However, the optical system suffers from line-of-sight problems.

This paper aims to develop a non-radiation robot-assisted system for pedicle screw placement. To achieve this, the pre-operative surgical plan is registered to the 3D US reconstructed model. Then, the robot could automatically conduct the drilling procedure by replacing the US probe. Finally, this system is validated with an ex-vivo lamb spine. To the best of our knowledge, this is the first work to automatically perform the robotic pedicle screw placement without an external tracking system.

II. MATERIALS AND METHODS

Figure 1 shows the robotic system, consisting of a MED7 robot (KUKA Robot MED7, Augsburg, Germany) that can hold a US probe (Sonosite, FUJIFILM, USA) during the scanning phase or a custom-designed drill system in drilling phase. The robot end-effectors can be swapped without losing calibration thanks to a tool exchanger(G-SHW063-2UE, GRIP GmbH, Germany). During US scanning, a frame grabber (Epiphan Systems Inc. Palo Alto, Canada) is employed to capture the US images via a USB port at 50 Hz. Two 6 DoF force torque sensors (Nano25, ATI Industrial Automation Inc.) are separately assembled at the US probe and drill, measuring the interaction forces and torques. Ex-vivo lamb cadaver experiments were carried out for qualitative and quantitative assessment. Four trajectories were predefined on the pedicle by the operator on the lamb spine.

A framework is developed as shown in fig. 1. A deep learning network, U-Net, is implemented for realizing automatic image segmentation and US 3D reconstruction, as described in [3]. The US images are processed into gray images. Then the bone contours are automatically extracted by applying Canny edge detection to the images segmented by the network. Subsequently, the reconstruction algorithm transmits the 2D US image sequences and corresponding robot end effector poses simultaneously to generate 3D points. The pixels of the segmented contour (u, v) are converted into a point cloud with coordinates (x, y, z) expressed relative to the robot base frame $\{R\}$. With the iterative closest point algorithm (ICP), the preoperative CT model with the screw trajectories is converted from the CT frame to the robot base frame to assist the robotic drilling procedure. Then the rotation and translation matrix to register the model together is found and applied to the CT model. The phantom model and predefined screw trajectories are then transformed into their correct position using the registration transformation matrices.

After US scanning and reconstruction, the custom-designed drilling system is connected to the robot end effector by using the tool changer. To achieve good drilling accuracy, a calibration of the drilling system is conducted to identify the geometry transformation. A pivoting calibration is performed to estimate the position of the drill tip $\{tip\}$ with respect to the robot end effector $\{EE\}$. Then, with position control, the robot is moved towards the screw trajectory. Then, drilling starts at a constant 350 RPM. During the drilling, the wrench is also monitored, and a force limitation along the Z axis of 20 N is maintained.

After drilling, a post-operative CT scan is taken to generate the 3D model as a ground truth. The system is evaluated by registering the post-operative CT and screw trajectories with the pre-operative CT. The entry and stop points of the screw trajectory are summarized.

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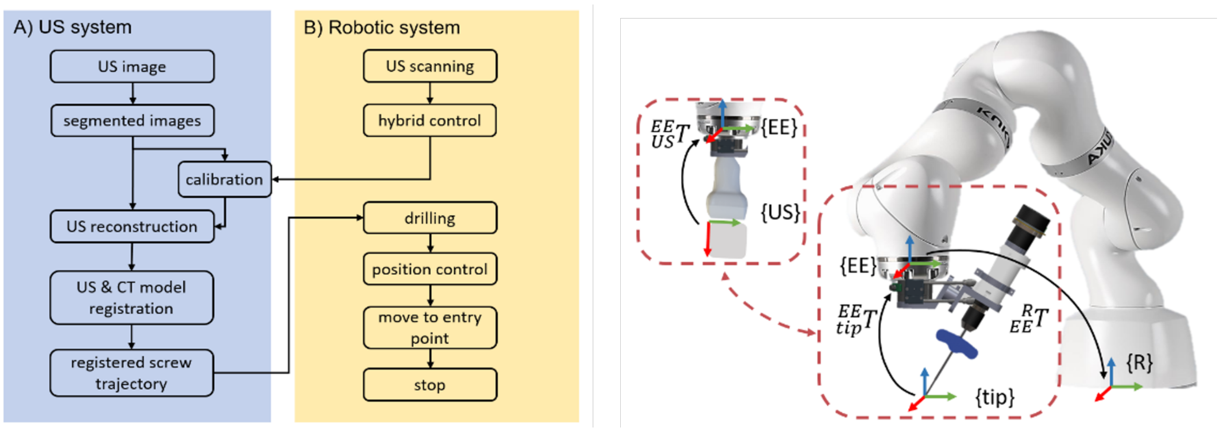

Fig. 1: The workflow (left), the experimental setup (right) and the transformations applied in the proposed system.

III. RESULTS

The mean error from the entry point is found to be -1.75 ± 0.98 mm, 1.38 ± 1.40 mm and -0.39 ± 0.94 mm along X, Y and Z axis, respectively. The mean error from the stop point is found -1.88 ± 2.00 mm, -1.76 ± 3.32 mm and -1.26 ± 3.08 mm along X, Y and Z axis, respectively. The largest error is -5.79 mm at the stop point of the screw trajectory 2. The 3D error is 2.78 ± 0.58 mm at the entry point and 4.82 ± 2.11 mm at the stop point.

TABLE I: The errors of the entry point and the stop point after robot-assisted drilling. All measurements are in millimeters.

	Axis	Exp.1	Exp.2	Exp.3	Exp.4	Mean	Std. Dev.
Entry Point	X	-1.37	-1.03	-3.20	-1.39	-1.75	0.98
	Y	1.99	2.75	-0.53	1.29	1.38	1.40
	Z	-1.28	0.10	-1.07	0.68	-0.39	0.94
	3D	2.73	2.94	3.41	2.01	2.78	0.58
Stop Point	X	-0.58	-1.08	-4.86	-1.02	-1.88	2.00
	Y	-2.92	-5.79	1.84	-0.18	-1.76	3.32
	Z	-5.03	2.50	-1.15	-1.37	-1.26	3.08
	3D	5.85	6.40	5.32	1.72	4.82	2.11

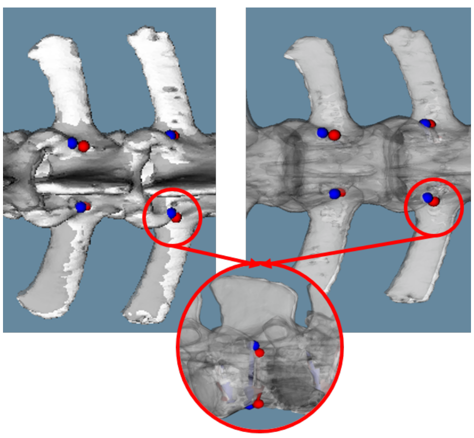

Fig. 2: The registered post-operative CT model (grey) and drilled screw trajectories (red) overlaid with the pre-operative CT model (white) and surgical plans (blue).

Figure 2 demonstrates the registered post-operative CT model and pre-operative CT model of the lamb vertebrae.

IV. CONCLUSIONS AND DISCUSSION

This study presents the first automated robotic system for PSP without the need for an external tracking system. The proposed system utilizes a U-Net-based framework to segment 2d US images and reconstruct 3D anatomy features, enabling visualization of the spinal structure. Then, the desired screw trajectories are automatically registered to the 3D reconstruction. By employing this robot-assisted system, the reliance on guide-tube-based approaches is eliminated, reducing the physical demands of the procedure and allowing the surgeon to focus more on planning and evaluation rather than execution.

Experimental evaluation on two lamb vertebrae yielded four screw trajectories. The mean 3D error is 2.78 ± 0.58 mm at the entry points and 4.82 ± 2.11 mm at the stop points. Compared to commercial robotic systems, the use of non-radiation imaging decreases the second harm to the patient and surgeons. Meanwhile, it gets rid of the bone pin, which can lead to an incision in the patient's body.

However, there are limitations to consider. Firstly, the execution time of the procedure is not addressed. The robot's motion and drilling are programmed conservatively, resulting in longer procedure times compared to conventional approaches. Secondly, further research is needed to investigate a more robust drilling program capable of predicting and preventing breaches to improve success rates.

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