A Collaborative Robotic System with Autonomous In-Plane Orientation Adjustment for Lung Ultrasonography

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***Abstract*—This paper presents a collaborative robotic system that can autonomously horizontalize pleural lines in ultrasound images during teleoperated lung ultrasonography. The system deploys a shared control strategy that exposes the out-of-plane pose of the robot-held ultrasound transducer to human teleoperation and autonomously adjusts the in-plane orientation of the transducer with visual servoing technique. Preclinical tests show that the system successfully works in the restricted autonomous manner as designed.**

I. INTRODUCTION

THE coronavirus disease 2019 (COVID-19) pandemic has stimulated research of robotic ultrasonography systems (RUSS) in recent years, among them, teleoperated RUSS and artificial intelligence (AI) empowered autonomous RUSS are two of the most distinct modalities [1]. However, in the practice of introducing robots in to clinical procedures, neither pure teleoperation nor pure autonomy may be best practices at the current stage. The former does not take full advantage of the stability and accuracy of robotics. As for the latter, although there have been cases of autonomous ultrasound examination of the carotid arteries [2] and thyroid [3], AI has not yet demonstrated the robustness with which it can handle more complex clinical scenarios. In addition, there are still ethical and legal issues to be addressed regarding AI entering the healthcare industry [4]. Given these situations, a promising approach is to allow robots to work collaboratively with human in restricted autonomy. To achieve this, the overall control task of the robotic system should be divided into a user teleoperated portion and a robot autonomous portion, and a shared control [5] strategy should be deployed to coordinate them.

There is no universal form of task division for medical robotic systems as this requires comprehensive consideration of clinical protocols, clinician preferences and AI algorithm robustness. This paper aims to contribute to the RUSS community by providing an instance following the restricted autonomy fashion. In the remainder of this paper, we present a collaborative robotic system for lung ultrasonography (Fig. 1). While accepting remote control from the operator, the robot is designed to autonomously adjust image orientation to horizontalize pleural lines in ultrasound images, as required by clinical protocols [6].

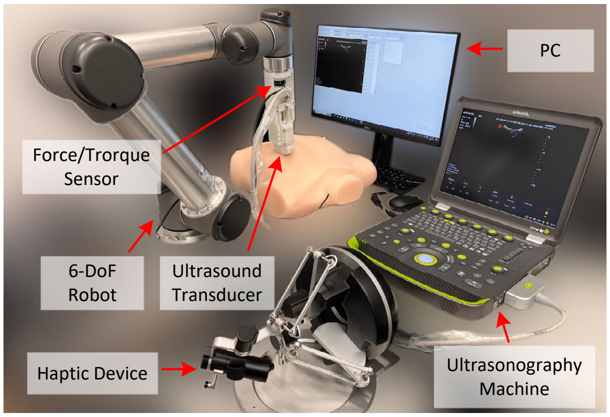

Fig. 1. The presented system comprises a ultrasonography machine (Wisonic Clover 60) for ultrasound image acquisition, a 6-DoF manipulator (Universal Robots UR5) for maneuvering the ultrasound transducer, a 6-axis force/torque sensor (Sunrise Instruments M3733C) mounted on the robot end flange for measuring the robot-patient contact wrench, a 7-DoF haptic device (Force Dimension omega.7) for teleoperation and a PC (ROS Humble) running the essential system software.

II. METHODS

This system deploys a shared control strategy. The 6-DoF Cartesian pose of the robot-held ultrasound transducer is divided into 3-DoF Cartesian position (x, y, z), 2-DoF out-of-plane orientation (roll α, pitch β), and 1-DoF in-plane orientation (yaw γ) (Fig. 2a). The first two (together called out-of-plane pose) are teleoperated and the last one is left to the robot to adjust autonomously.

The operator interacts with the system by maneuvering the teleoperation handle. Let the Cartesian pose of the handle be $X_h = [x_h, y_h, z_h, \alpha_h, \beta_h, \gamma_h]^\top$, then the corresponding robot end-effector pose is

$$X_r = [x_r, y_r, z_r, \alpha_r, \beta_r, \gamma_r]^\top = \lambda X_h \tag{1}$$

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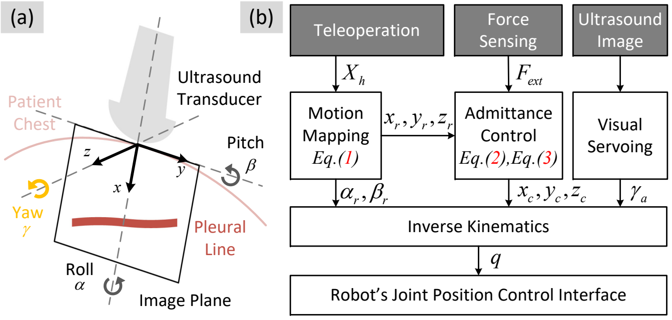

Fig. 2. (a) Cartesian pose decomposition and (b) control scheme of the robot-held ultrasound transducer.

where $\lambda = [\lambda_x, \lambda_y, \lambda_z, \lambda_\alpha, \lambda_\beta, \lambda_\gamma]^\top$ is the motion mapping vector between the handle and the robot. Specifically, we let $\lambda_\gamma = 0$ to exclude the in-plane orientation from teleoperation.

For safe robot-patient contact, we apply admittance control to robot end-effector's Cartesian position.

$$e = X_c - [\mathbf{1}^{1\times3}, \mathbf{0}^{1\times3}]^\top X_r \tag{2}$$

$$M\ddot{e} + D\dot{e} + Ke = F_{ext} \tag{3}$$

where $X_c = [x_c, y_c, z_c]^\top$ is the computed compliant Cartesian position for the robot, $M, D, K \in \mathbb{R}^{3\times3}$ are the virtual inertia, damping, and stiffness for compliance computation, and $F_{ext} \in \mathbb{R}^3$ is the external force measured by the force/torque sensor. The 2-DoF out-of-plane orientation is not included in admittance control because sometimes the operating clinician may need full control over them.

In order to horizontalize pleural lines in ultrasound images, we adopt a visual servoing technique using an ensemble U-Net model [7] trained with lung ultrasound images collected from volunteers. The model identifies the pleural line in the image and calculates the angle γ_a between it and the horizontal reference, which is the angle that needs to be eliminated.

Combining above control laws, we get the overall Cartesian pose command of the robot

$$X = [x_c, y_c, z_c, \alpha_r, \beta_r, \gamma_a]^\top \tag{4}$$

This command will be executed by sending the corresponding joint position command q computed by inverse kinematics to the joint position control interface of the robot. The complete control scheme is summarized in Fig. 2b.

III. PRELIMINARY RESULTS AND DISCUSSIONS

We validate the presented system with preclinical tests on volunteers. Results show that the operating doctor can effectively regulate the motion of the ultrasound transducer and the contact force with the patient through teleoperation. The ensemble U-Net model can segment pleural lines in ultrasound images with a Dice score of 90.04. During teleoperated lung ultrasonography, the system is capable for autonomously horizontalizes pleural lines through in-plane orientation adjustment, as shown in Fig. 3. Compared with the autonomous solution [8], our collaborative solution has a shorter setup time because it does not require computationally intensive preparation like path planning and image registration. In addition, if emergencies occur, our system could have a faster response since robot's autonomy is restricted to in-plane orientation adjustment, which makes it easier for the operator to intervene.

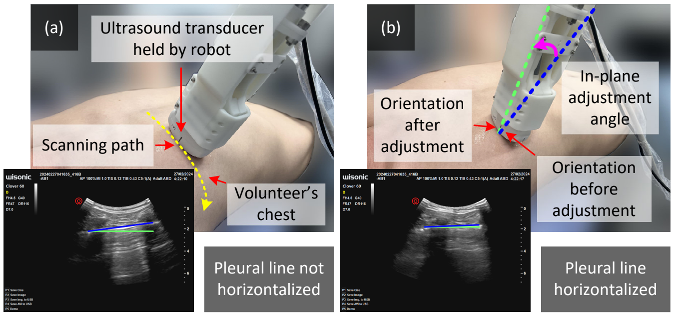

Fig. 3. Snapshots taken (a) before and (b) after the autonomous in-plane orientation adjustment during teleoperated lung ultrasonography on a volunteer. The blue line in the ultrasound image marks the pleural line and the green line marks the horizontal reference.

IV. CONCLUSION AND OUTLOOK

This work presents a collaborative robotic system for lung ultrasonography driven by a shared control strategy. Preclinical tests on volunteers show promising preliminary results regarding autonomous pleural line horizontalization while accepting teleoperation. Our future research goals are twofold. One is to continue validating the system's robustness so that it can be put into clinical use. The second is to study different task divisions in shared control and explore how robots can better collaborate with clinicians.

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