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Toward eFAST autonomous robotic ultrasound imaging: system integrations and experimental studies

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Recent years have witnessed remarkable advancements in the application of robotics across various medical fields, such as ultrasound examination. Characterized by their inherent attributes of repeatability, flexibility, and high accuracy, many robotics ultrasound scanning systems (RUSS) have emerged, demonstrating their potential value in relieving the workloads of sonographers from daily repetitive operations [1].

The RUSS can be broadly classified into robot-assisted teleultrasound and automatic types. Wu et al. [2] evaluated the feasibility of teleultrasound via 5G to address challenges related to early imaging assessment of COVID-19. However, the complex design of the system often leads to low stability, failing to relieve the sonographers' workload and address repeatability and autonomy issues. Huang et al. [3] used depth cameras to collect structural data, allowing a robotic arm to perform abdominal scans automatically. However, the contact force strategy lacks depth, posing challenges to operating safeties and optimal imaging qualities.

In practice, contact force control is the key factor in reproducing the scanning skills of the sonographer. Traditional force control methods include impedance control, admittance control and hybrid force/position control. However, achieving accurate force tracking using these methods generally requires prior information, such as environmental position and stiffness. To address this issue, Duan et al. [4] presented an adaptive variable impedance control (AVIC) method to compensate for unknown environmental parameters. Nevertheless, this method suffers from a significant overshoot at the moment of contact with the environment.

Among the applications of ultrasound, extended focused assessment with sonography for trauma (eFAST) (detailed introduction can be found in Appendix A) is a standardized bedside ultrasound examination strategy that is suitable for patients with thoracic or abdominal trauma. The injuries of trauma patients are critical and complex, and there is a golden period for the treatment of various critically injured patients. The application of eFAST with scientific and fast examination characteristics in this scenario can minimize the mortality rate of trauma patients [5].

Based on the above analysis, an autonomous robotic ultrasound system toward eFAST ultrasound scanning is proposed. The system integrates multiple modules such as robotic eFAST scanning guidelines, scanning tissue target positioning, end load force calibration and compliance interaction force tracking strategy. Experiments are conducted on the 3D abdomen phantom and five human volunteers. The main contributions of this study are as follows.

(1) A flexible autonomous robotic eFAST ultrasound scanning system (REUSS) that integrates multiple functional modules is elaborately developed.

(2) A force tracking strategy of AVIC with a dynamic update rate law (DAVIC) is proposed which shows significant superiorities in the sense of both suppressing transient overshoots and an accurate steady-state force tracking.

(3) 300 eFAST ultrasound experiments on five human volunteers are conducted, and the success rate of the image acquisition is no less than 96%. To the best of our knowledge, this is the first time that the autonomous robotic ultrasound scanning system is used to complete the entire eFAST scanning task, and professional sonographers are invited to evaluate the qualities of the images acquired by the autonomous REUSS.

Overview of the integrated system. The framework of the proposed REUSS is shown in Figure 1. The REUSS comprises four components, with each module serving specific functions in the pipeline. The eFAST scanning rules are robotic scanning guidelines derived from eFAST clinical examinations and incorporate the expertise of professional sonographers. These rules outline the targets, paths, and contact force of the robotic eFAST ultrasound scanning. Special thanks go to the sonographers from Beijing Friendship Hospital, Capital Medical University, for providing professional suggestions on this guideline. Subsequently, the system conducted the eFAST ultrasound scan following these rules. First, eFAST target positioning is achieved

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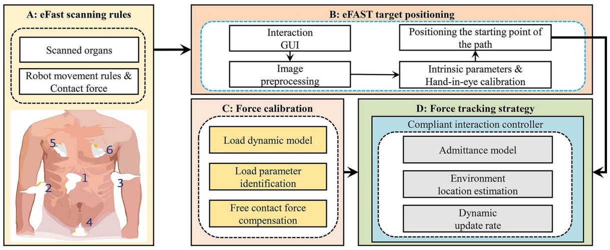

Figure 1 (Color online) System framework of the proposed REUSS.

through the touch interactive interface, and the representation of the target in the robot base coordinate system is determined utilizing hand-in-eye calibration techniques and so on. Before robotic ultrasound scanning, load parameters calibration and non-contact force compensation are carried out, which is essential. Building upon the preceding preparations, an enhanced force-tracking strategy is integrated to ensure both the safety of ultrasound scanning and the quality of ultrasound images. Detailed information on the system can be found in Appendix B.

Force compensation of the external load. To obtain the accurate reaction force component during the ultrasound scanning process, the inertial parameters (mass m, coordinates of the center of mass $\boldsymbol{c}$) of the load, comprising probe, sensors, and flanges are identified and then compensated. Practically, the F/T sensor measurements ${}^s\boldsymbol{F}_m$ include true contact force (${}^s\boldsymbol{F}_e$), the load gravity (${}^b\boldsymbol{W}$) and the sensor offset (${}^s\boldsymbol{F}_o$), and the actual force (except for static forces generated by loads) acting on the contact point is

$$ {}^s\boldsymbol{F}_e = {}^s\boldsymbol{F}_m - ({}^s_b\boldsymbol{R} \cdot {}^b\boldsymbol{W} + {}^s\boldsymbol{F}_o), \tag{1} $$

where ${}^s_b\boldsymbol{R} = {}^e_s\boldsymbol{R}^{-1}\,{}^b_e\boldsymbol{R}^{-1}$, ${}^e_s\boldsymbol{R} = [1\,0\,0; 0\,1\,0; 0\,0\,1]$, ${}^b_e\boldsymbol{R}$ is the rotation matrix from $\{e\}$ to $\{b\}$, which is obtained from the forward kinematics. The least squares algorithm is employed to identify the unknown parameters ${}^b\boldsymbol{W}$ and ${}^s\boldsymbol{F}_o$ based on the force data obtained from experimental recordings. Detailed information on the implementation can be found in Appendix C.

Positioning of the eFAST targets. Robotic eFAST scanning requires the acquisition of ultrasound images of multiple organs. The skin surfaces to be scanned lack distinct features, which makes it difficult for the current target recognition and positioning methods to obtain the starting points of the ultrasonic scanning path. To address this problem, the system autonomously captures the image from the view of the RGB-D camera. The pixel coordinates and the depth of the target point (u, v, d) are obtained from the image. Subsequently, according to imaging principles and intrinsic parameters of the camera, the representation $\boldsymbol{P}_c$ of this point in the camera coordinate system is gained. Consequently, the target location can be determined by utilizing the hand-eye calibration results and the robotic kinematic

$$ \boldsymbol{P}_b = {}^b_e\boldsymbol{T} \cdot {}^e_c\boldsymbol{T} \cdot \boldsymbol{P}_c, \tag{2} $$

where the transformation ${}^b_e\boldsymbol{T}$ from the robot end to the robot base coordinate system is easily determined through forward kinematics, and the transformation ${}^e_c\boldsymbol{T}$ from the camera to the robot end is the eye-in-hand calibration result. The detailed processes can be found in Appendix D.

Force tracking controller based on AVIC. The alignment of the probe with the scanning organs, typically ensured through force control technology, has a significant impact on the quality of ultrasound images. Safety stands as the paramount concern in the development of automatic robotic systems, with particular emphasis on medical robots. Moreover, the objective of this study is to facilitate autonomous robotic eFAST scanning, encompassing multiple tissues with varying and unknown surface skin stiffness. Therefore, it is imperative to control the contact force exerted by the probe precisely. To this end, a compliant interactive controller based on AVIC is designed aiming at precise force tracking along the z-axis. Specifically, the discrete format of the controller can be expressed as follows:

$$ \begin{cases} \Delta F^z = F_e^z - F_d^z = M^z \ddot{\hat{E}}^z + B^z(\dot{\hat{E}}^z + \Psi), \\ \Psi(t) = \Psi(t-T) + \mu \frac{(F_d^z(t-T) - F_e^z(t-T))}{B^z}, \\ \mu = \frac{1}{\mathrm{e}^{-\beta|\Delta F^z|} + K_{\mathrm{lim}}}, \end{cases} \tag{3} $$

where F_e^z, F_d^z and ΔF^z denote the robot-environment interaction force, the desired contact force, and the force tracking error, respectively; M^z and B^z are inertia and damping gain; E^z represents the position error between the reference position trajectory P_r^z and the command position trajectory P_c^z, $\hat{E}^z$ is the estimated value of E^z; $\Psi(t)$ is the adaptive compensating law for the force tracking error; and μ represents the designed dynamic update rate law which is used to improve the performance of the force tracking. Detailed analysis and design can be found in Appendix E.

Experimental studies. Experimental results are shown in Appendix F.

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Supporting information Appendixes A–F and video. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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