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Robotic ultrasound platform for ultrasound and radioacoustic imaging for monitoring radiotherapy

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ABSTRACT

Accurate radiotherapy requires precise soft-tissue anatomy at the time of treatment, yet current workflows lack volumetric imaging immediately prior to irradiation. Ultrasound offers real-time, radiation-free imaging but is limited by operator dependence. We present a fully autonomous robotic ultrasound platform for pre-treatment volumetric imaging in radiotherapy. CT-based scan trajectories are registered to the patient surface using an RGB-D camera, and a 6-DOF robotic arm performs surface-conforming, force-controlled B-mode scans with optically tracked 3D reconstruction. Validation in a human torso phantom demonstrates high-precision visualization of organ boundaries with strong correspondence to CT. This approach enables low-cost pre-treatment 3D imaging and establishes a foundation for future real-time dual-modality ultrasound and radioacoustic imaging (RAI) for combined anatomical and dose monitoring during treatment.

Keywords: Robotic ultrasound, Image-guided radiotherapy, 3D ultrasound, Real-time monitoring, Radioacoustic imaging

1. INTRODUCTION

Ensuring accurate radiotherapy delivery requires precise soft-tissue anatomical information at the time of treatment, yet current clinical workflows rely largely on imaging acquired during treatment planning, with limited volumetric soft-tissue information available immediately prior to irradiation.¹ This limitation is particularly problematic for tumors in mobile anatomical regions such as the abdomen, where intra-fraction motion from respiration and peristalsis and inter-fraction variations due to gastrointestinal filling or patient setup can significantly alter treatment geometry.^{2,3} As a result, discrepancies between planned and delivered anatomy may reduce tumor coverage and increase irradiation of surrounding healthy tissues.⁴

Patient alignment is typically performed using surface imaging, implanted fiducials, or x-ray-based techniques.¹ While effective for geometric verification, these methods provide limited soft-tissue contrast and are not well suited for detecting day-of-treatment anatomical changes in deformable tissues. Repeated volumetric x-ray imaging also increases imaging dose and workflow complexity, limiting its feasibility for routine or adaptive use.⁵ Consequently, clinically relevant misalignments may persist undetected at the time of treatment.

These challenges are amplified in proton therapy, where the sharp distal dose fall-off of the Bragg peak enables highly conformal treatments but also makes dose delivery highly sensitive to millimeter-scale anatomical changes.^{6,7} Small misalignments or tissue density variations along the beam path can produce substantial range errors. Although MRI offers superior soft-tissue contrast, its integration with proton beam delivery is technically challenging due to magnetic field-induced beam perturbations, and remains costly and complex to integrate into

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clinical environments.¹ There is therefore a need for a low-cost, modality-agnostic solution capable of providing volumetric soft-tissue imaging immediately prior to treatment.

Ultrasound offers real-time, radiation-free soft-tissue imaging at low cost, but its use in radiotherapy is limited by operator dependence and poor reproducibility of volumetric acquisitions.^{8–10} To address these limitations, we present a fully autonomous robotic ultrasound platform for pre-treatment volumetric imaging. This approach enables reliable visualization of internal anatomy immediately prior to irradiation, supporting improved patient alignment and potential plan adaptation.

The platform is also designed to support future integration of dual-modality pulse-echo ultrasound and radiation-induced acoustic imaging (RAI). RAI exploits acoustic signals generated by radiation energy deposition to enable direct monitoring of dose delivery.^{11–14} Using the same transducer for anatomical imaging and RAI detection, the system could provide complementary anatomical and dosimetric information during treatment, enabling real-time verification and adaptive radiotherapy in complex clinical scenarios.

2. METHODS

A robotic ultrasound platform was developed to autonomously acquire volumetric ultrasound images of the full abdominal region in a pre-treatment radiotherapy setting. The system is designed for seamless integration into the clinical workflow and provides high-resolution soft-tissue imaging immediately prior to treatment. It leverages the patient's treatment planning CT scan to define a surface-conforming scan trajectory, ensuring anatomically accurate probe positioning along the abdominal surface. Custom trajectories can also be specified to target regions of specific clinical interest.

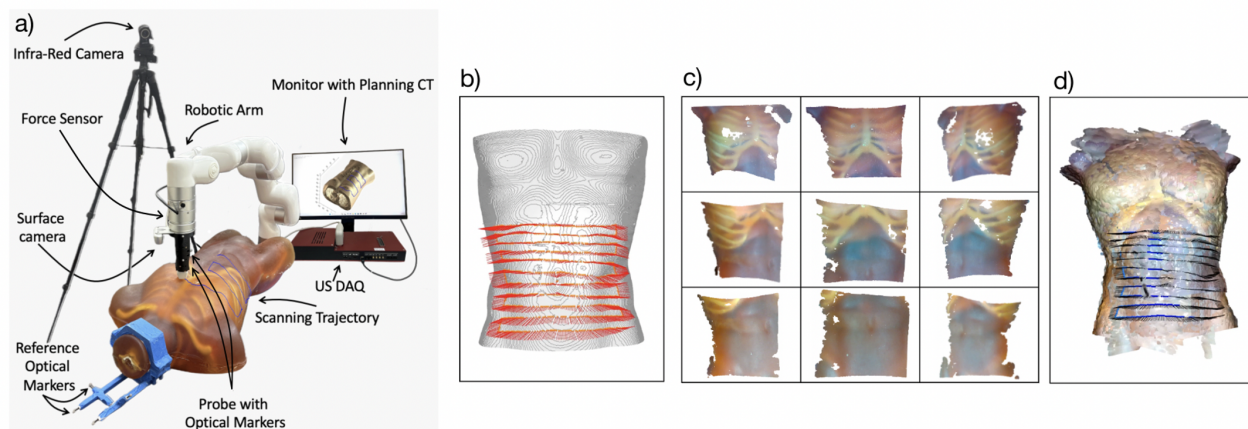


Figure 1. Robotic ultrasound acquisition system (a) and surface registration workflow (b–d). (a) Experimental setup of the robotic platform, including a six-degree-of-freedom robotic arm, phased-array ultrasound transducer, six-axis force sensor, custom probe holder with optical markers, a four-camera infrared tracking system, and an RGB-D surface camera. A human torso ultrasound phantom is used for validation. (b) Surface mesh extracted from the phantom's CT scan, overlaid with the pre-planned scan trajectory oriented normal to the surface. (c) Individual surface point clouds acquired from multiple viewpoints using the RGB-D camera. (d) Globally registered surface point cloud aligned to the CT reference frame, with the planned scan trajectory mapped into the robot coordinate system.

The acquisition workflow is divided into two main stages: surface-based registration and robotic ultrasound scanning. In the first stage, a depth-sensing RGB-D camera (Intel[®] RealSense™ D435i) mounted on the robot end-effector captures the three-dimensional surface geometry of the patient in the treatment position. Multiple point clouds are acquired from different viewing angles and globally registered using a Fast Point Feature Histogram (FPFH) descriptor and a Random Sample Consensus (RANSAC)-based registration algorithm to generate a complete 3D model of the patient's external surface. This point cloud is then rigidly registered to the surface contour extracted from the planning CT. The resulting transformation defines the spatial relationship

between the CT and the robot coordinate frame, enabling accurate mapping of the planned scan trajectory into physical space (Fig. 1).

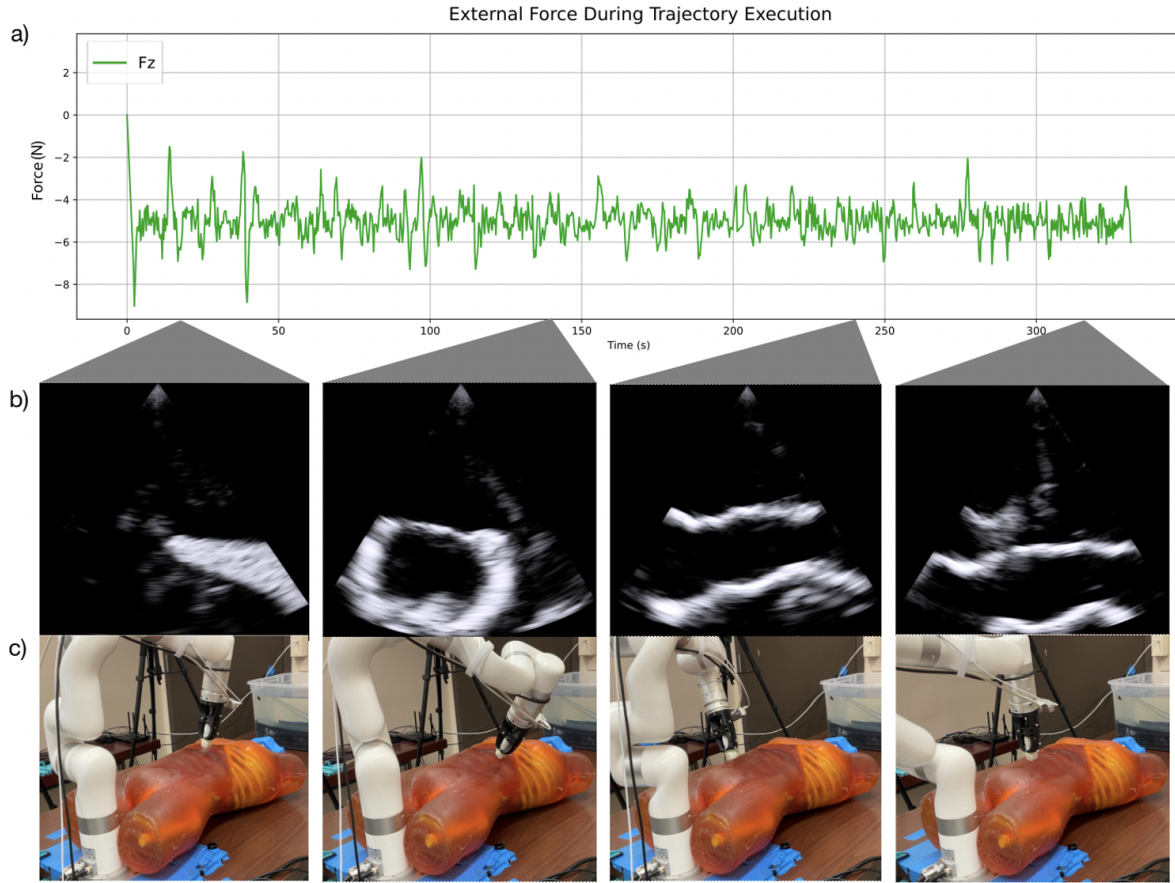


Figure 2. Force control and probe behavior during autonomous ultrasound scanning. (a) Force applied along the probe axis over time, demonstrating consistent contact throughout the scan. (b) Representative two-dimensional B-mode ultrasound images acquired at selected time points along the scan trajectory. (c) Corresponding robot orientations at each time point, illustrating adaptive probe alignment to the phantom surface.

In the second stage, the robot autonomously executes the ultrasound scan along the registered trajectory. A six-degree-of-freedom robotic arm (xArm 6, UFACTORY, China) is used to manipulate the ultrasound probe, which is mounted on a custom 3D-printed holder equipped with a six-axis force/torque sensor. The sensor enables stable acoustic coupling by maintaining a constant contact force of 5 N along the probe axis while minimizing soft-tissue deformation during scanning (Fig. 2).

Ultrasound imaging is performed using an ultrasound system (PhotoSound Inc., USA) with a 1-5 MHz phased-array probe (Teled P5-1S15-A6), acquiring two-dimensional B-mode images to a depth of 9 cm. The probe position and orientation are tracked in real time using an external infrared optical tracking system consisting of four OptiTrack Flex 13 cameras. Optical markers are attached to the custom probe holder to enable continuous motion tracking throughout the scan. Image data and corresponding tracking information are streamed to 3D Slicer and reconstructed using the Public Library for Ultrasound Toolkit (PLUS),¹⁵ generating a spatially accurate three-dimensional ultrasound volume.

3. RESULTS

To evaluate the performance of the robotic ultrasound platform, a validation experiment was conducted using a human torso ultrasound phantom. The system autonomously executed a predefined surface-conforming scan trajectory, as shown in Fig. 1b, with the objective of generating a complete three-dimensional ultrasound reconstruction of the abdominal region.

Figures 3a and 3b show representative two-dimensional B-mode ultrasound frames acquired during the scan. These images illustrate the soft-tissue contrast and anatomical structures captured at different cross-sectional locations, as well as the continuity between frames that enables volumetric reconstruction. Figure 3c presents a preliminary three-dimensional rendering of a subvolume within the scan, in which the cavity of the large intestine is clearly visualized, demonstrating the system's ability to resolve internal anatomical features in three dimensions.

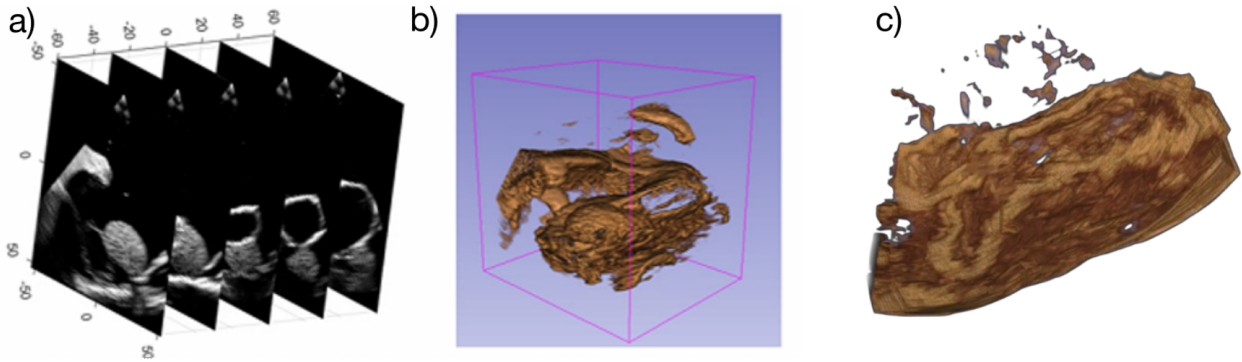


Figure 3. Ultrasound image acquisition and volumetric reconstruction. (a) Representative two-dimensional B-mode ultrasound frames acquired during the robotic scan. (b) Reconstructed three-dimensional ultrasound volume generated from the frames in (a). (c) Three-dimensional rendering of a selected abdominal subvolume, highlighting the cavity of the large intestine.

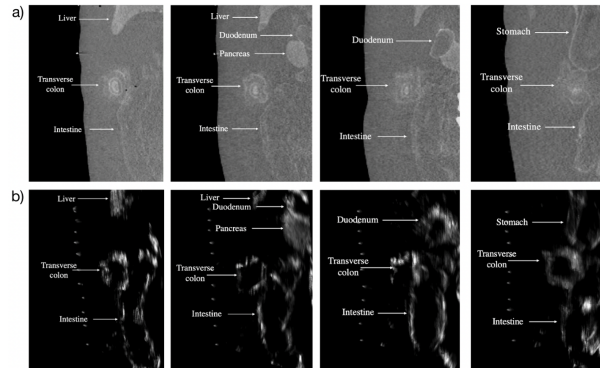


Figure 4. Comparison of whole-abdomen volumetric ultrasound with CT in a human torso phantom. Anatomical structures are labeled for reference. (a) Sagittal slices from the phantom CT. (b) Corresponding sagittal slices from the reconstructed three-dimensional ultrasound volume.

To assess anatomical fidelity, Fig. 4 compares sagittal slices from the reconstructed three-dimensional ultrasound volume with corresponding sections from the phantom's CT scan. Key abdominal structures were manually annotated in both imaging modalities for visual comparison. The strong spatial agreement between the ultrasound and CT images supports the geometric accuracy of both the robotic scanning trajectory and the three-dimensional reconstruction workflow.

These results demonstrate the feasibility of using the proposed system to autonomously acquire clinically meaningful three-dimensional ultrasound volumes of the abdominal region. The anatomical detail, reproducibility, and hands-free operation of the scans highlight the platform’s potential as a practical and scalable solution for pre-treatment imaging. By enabling volumetric soft-tissue assessment immediately prior to irradiation, the system supports improved patient alignment and has the potential to enhance adaptive radiotherapy workflows.

4. CONCLUSION

We developed and validated a fully autonomous robotic ultrasound platform capable of acquiring volumetric three-dimensional ultrasound images of the abdominal region in a pre-treatment radiotherapy setting. The system integrates patient-specific CT-based planning, surface registration, force-controlled probe manipulation, and real-time tracking to enable hands-free and reproducible imaging. Validation using a human torso phantom demonstrated the platform’s ability to generate high-fidelity three-dimensional ultrasound volumes with strong anatomical correspondence to CT.

This technology offers a practical and cost-effective solution for soft-tissue visualization immediately prior to treatment, addressing limitations in current workflows that lack volumetric soft-tissue guidance at the time of irradiation. Furthermore, it establishes a foundation for future integration of dual-modality imaging using radiation-induced acoustic signals, supporting the development of adaptive radiotherapy strategies with real-time anatomical and dosimetric monitoring.

5. ACKNOWLEDGEMENT

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6. CONFLICT OF INTEREST

Liangzhong Xiang has financial interest in SoundDose, Inc., which, however, did not support this work. The remaining authors declare no conflict of interests.

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