Abstract

Ultrasound imaging is a widely used medical imaging modality to visualize several structures and tissues inside the human body. It has proven effective in several diagnostic and therapeutic procedures. It has several advantages over other imaging modalities, such as Magnetic Resonance Imaging (MRI), Computed Tomography (CT), and X-rays. It is relatively inexpensive, radiation-free, and provides real-time feedback. However, the manual ultrasound imaging procedure has a few disadvantages. One significant drawback is its dependence on the experience and skill of the sonographers. But, expert availability is limited in rural and underserved regions. This limits the accessibility of ultrasound imaging for patients in these areas, leading to delayed diagnoses and potentially poorer health outcomes. The emergence of COrono VIrus Disease 2019 (COVID-19) pandemic further exposed the disadvantages of manual ultrasound procedure, which poses a risk of virus transmission to both sonographers and patients due to direct physical contact. Further, sonographers often end up having musculoskeletal disorders due to challenging postures and repetitive probe motions involved in ultrasound acquisitions. These issues emphasize the need for automation of ultrasound procedures.

Robotic Ultrasound System (RUS) is an important alternative to manual ultrasound procedures. RUS can broaden the pool of skilled sonographers, enhance the safety of healthcare workers during pandemics, and improve the accessibility of ultrasound in rural areas where experienced sonographers are scarce. However, the realization of RUS poses a critical challenge. It requires precise control of probe maneuvers in high-dimensional space over the patient's body while effectively interpreting complex ultrasound images, similar to the perception-to-action skill of an experienced sonographer. This thesis addressed this challenge by developing a RUS that incorporates the domain expertise of sonographers in multiple forms. First, an Expert-supervised RUS (E-RUS) is proposed that enables an expert sonographer to conduct the procedure from a remote station. This system also incorporates a novel robotic gripper that enables autonomous gel dispensing, making ultrasound scanning fully remote. Then, deep-learning-based models for UltraSound Image Quality Assessment (US-IQA) are proposed, which are trained using a dataset of ultrasound images labeled fully or partially for quality by expert radiologists. Finally, an autonomous probe controller is developed using a Bayesian Optimization (BO) framework to efficiently search for high-quality images within the scanning region. This framework incorporates the expert's prior knowledge of probing techniques in the form of Gaussian Process (GP) model priors and kernels. The GP model is gleaned from experts' demonstrations of high-quality probing maneuvers by E-RUS and image quality feedback by the US-IQA model.

The feasibility study of E-RUS was conducted with 21 human trials at All India Institute of Medical Sciences (AIIMS), Delhi. The results demonstrated a P-value of less than 0.05 when comparing E-RUS and manually acquired ultrasound images. The system also achieved a gradual improvement of NASA-TLX test parameters and high acceptability on a questionnaire survey of doctors and volunteers. The US-IQA models were validated using ultrasound images of the human urinary bladder. The results showed that the prediction of image quality by these models closely aligned with the manual rating of expert radiologists. These models also surpassed the accuracy of the state-of-the-art models by 4-20%. The experiments on urinary bladder phantoms were conducted to validate the autonomous probe controller. The proposed framework acquired a high-quality image in relatively low 5-10 steps and sampled 50-60% more high-quality images than the standard BO. These results demonstrate the effectiveness of incorporating domain expertise for realizing an effective RUS.