Remote Ultrasound Palpation for Robotic Interventions Using Absolute Elastography

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Abstract. Although robotic surgery has addressed many of the challenges presented by minimally invasive surgery, haptic feedback and the lack of knowledge of tissue stiffness is an unsolved problem. This paper presents a system for finding the absolute elastic properties of tissue using a freehand ultrasound scanning technique, which utilizes the da Vinci Surgical robot and a custom 2D ultrasound transducer for intra-operative use. An external exciter creates shear waves in the tissue, and a local frequency estimation method computes the shear modulus. Results are reported for both phantom and *in vivo* models. This system can be extended to any 6 degree-of-freedom tracking method and any 2D transducer to provide real-time absolute elastic properties of tissue.

Keywords: Ultrasound, Absolute Elastography, Robotic Surgery.

1 Introduction

During laparoscopic procedures, surgeons face challenges such as limited vision of the surgical site and lack of dexterity and haptic feedback. In this type of surgery, the organs are only touched with the distal ends of long surgical instruments that must pass through the patient's abdominal wall. While the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA) has overcome with some of the issues that make laparoscopic surgery difficult, including stereoscopic vision and improved tool dexterity [7], the issue of haptic feedback remains unsolved.

Ultrasound elastography has the potential to offer an alternative to providing haptic feedback by instead providing a full image of tissue stiffness and viscosity - the very properties that surgeons try to measure during manual palpation. Ultrasound imaging is relatively inexpensive, non-ionizing and real-time, making it an advantageous imaging modality for intra-operative navigation. Conventional ultrasound has been integrated previously into the da Vinci Surgical System using multiple types of ultrasound transducers [14,15].

Previous ultrasound elastography has been primarily based on *strain* imaging. Ultrasound strain imaging, which provides images of relative tissue deformation in response to various compression levels applied by the ultrasound transducer

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[12], has also been integrated with the da Vinci Surgical System [4]. That system uses the 'Read-Write' Application Programming Interface (API) to overlay a palpation motion onto the movements of the surgeon. This removes some of the user-related difficulties of creating quality strain images by moving the transducer with a known amplitude and frequency. Strain imaging can be used to determine the tumour extent and for image registration [16], but is more affected by boundary conditions.

Acoustic radiation force imaging (ARFI) has shown promising results, and been tested *in vivo* [10,5]. This method of imaging uses the acoustic force produced by the ultrasound transducer to create a shear wave in the tissue, whose speed is then captured through fast imaging techniques and correlation based methods. Unfortunately, this method requires high powered ultrasound machines.

This paper proposes a novel freehand *absolute* elastography method for the da Vinci robot. The method uses an external exciter to induce vibrations into the patient's body, while a 2D intra-operative transducer, manoeuvred by the surgeon, is used to acquire 1D axial vibration amplitude and phase over a volume. These vibration phasors are acquired at known 3D locations by using the da Vinci 'Read' API to determine the position and orientation of the transducer. In the paper, 'axial' will refer to the direction in the image away from the transducer face.

To the best of our knowledge, this is the first time that an absolute elastography approach with external excitation has been developed using the position and orientation of a 2D transducer for freehand sampling of a tissue volume. Contributions of this paper include the novel use of 2D tracked ultrasound to create 3D absolute elastograms, the use of external excitation which does not require specialized ultrasound hardware and the integration of elastography with robotic surgery.

2 Methods

2.1 Elastography

Absolute ultrasound elastography is based on the measurement of shear wave propagation in tissue in response to a mechanical excitation. The excitation can be generated by an acoustic impulse radiation force [10] or by an external vibrator [11]. We use an external vibrator in our work because there are no issues related to penetration depth and tissue heating and because we can use a standard, limited power ultrasound machine. For a harmonic excitation, shear wave propagation in a homogeneous elastic solid, for small strain and linear approximations, is described in the frequency domain by the following wave equation:

$$\rho(j\omega)^2\hat{\boldsymbol{u}}(x, j\omega) = \mu\nabla^2\hat{\boldsymbol{u}}(x, j\omega) \ . \tag{1}$$

We make the assumptions that the density of tissue ρ is homogeneous and equal to that of water, although tissue density does change with tissue type and effects the wave speed slightly, this assumption is common in the elastography community. We also make the assumption that the displacement phasors $\hat{\boldsymbol{u}}(x, j\omega)$