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Robotic tissue tracking for beating heart mitral valve surgery

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ABSTRACT

The rapid motion of the heart presents a significant challenge to the surgeon during intracardiac beating heart procedures. We present a 3D ultrasound-guided motion compensation system that assists the surgeon by synchronizing instrument motion with the heart. The system utilizes the fact that certain intracardiac structures, like the mitral valve annulus, have trajectories that are largely constrained to translation along one axis. This allows the development of a real-time 3D ultrasound tissue tracker that we integrate with a 1 degree-of-freedom (DOF) actuated surgical instrument and predictive filter to devise a motion tracking system adapted to mitral valve annuloplasty. *In vivo* experiments demonstrate that the system provides highly accurate tracking (1.0 mm error) with 70% less error than manual tracking attempts.

1. Introduction

Beating heart surgery is a promising alternative to conventional procedures performed on the stopped heart (Angelini et al., 2002). This approach not only avoids the morbidities associated with the use of cardiopulmonary bypass (Zeitlhofer et al., 1993; Murkin et al., 1999; Bellinger et al., 1999), but also allows the surgeon to judge the efficacy of the procedure while the heart continues working. This is useful in the repair of structures like the mitral valve that open and close in response to changing pressure gradients during the heart cycle (Gersak, 2003). However, recent off-pump animal trials indicate that beating heart modification of the mitral valve cannot be performed reliably due to its fast motion (Downing et al., 2002; von Segesser et al., 2003) which exceeds the approximately 1 Hz tracking bandwidth of humans (Falk, 2002; Jacobs et al., 2003).

A robotic tracking system could assist the surgeon in this setting by synchronizing the motion of the instrument with the motion of the heart. This approach has been studied for coronary artery bypass graft procedures using multiple degree-of-freedom (DOF) robots and exploiting near periodicity in heart motion to track the external heart wall (Ginhoux et al., 2005; Bebek et al., 2007). Operating on the mitral valve includes additional challenges from working inside the heart. First, space restrictions make using a multi-DOF robot difficult. Second, an imaging technology that can image inside the heart at real-time rates must be used for robot guidance.

In this work, we consider the use of 3D ultrasound because it is capable of imaging tissue through blood while providing essential spatial information to guide complex intracardiac procedures which is not available in traditional 2D ultrasound images (Cannon et al., 2003). Although other imaging modalities like 3D computed tomography and magnetic resonance imaging offer higher spatial resolution, they have prohibitively slow imaging speeds, require special facilities, incur high costs, and cannot be moved into a standard operating room. In contrast, 3D ultrasound is relatively cheap, portable, and operates in real-time (25–30 Hz). 3D ultrasound is also becoming the preferred imaging technology among cardiac surgeons for guiding intracardiac beating heart repairs (Suematsu et al., 2004, 2005; Vasilyev et al., 2006, 2008) and it is advantageous to use it in the system to reduce training and the need for additional imaging equipment.

In our previous work, we showed that position-based eye-to-hand 3D ultrasound servoing of a handheld, 1 DOF motion compensation robot can enhance surgical task performance for beating heart mitral valve annuloplasty (Yuen et al., 2009); however, the system used a robot whose size limited surgical access into the heart and whose weight led to user fatigue. The system was also limited to tracking X-shaped fiducial targets in 3D ultrasound. A system suitable for intracardiac surgery must have real-time tissue tracking capabilities to guide the surgical instrument.

In this work, we present a new 3D ultrasound-guided motion compensation system for use in beating heart intracardiac

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procedures. The system builds on our previous work (Yuen et al., 2009) with a new, real-time 3D ultrasound tissue tracker and a miniaturized surgical robot that can be used in the operating room. The guiding principle behind the new system is to leverage the surgeon's proficiency at aiming the instrument toward the desired surgical site, then to automatically track the tissue in front of the instrument under 3D ultrasound guidance. This approach is suited to our application because the mitral valve annulus has a predominantly uniaxial motion trajectory (Yuen et al., 2009). This enables the development of a novel, real-time tissue tracker that is robust to ultrasound noise because it draws on the high spatial coherence of the instrument to locate the tissue target. It also permits the design of a light, handheld motion compensation instrument with sufficient bandwidth to track the mitral valve annulus. In the following we describe this system and its components, then validate its performance in experiments conducted in a water tank and an *in vivo* Yorkshire pig beating heart model.

2. Methods and materials

2.1. 3D ultrasound-guided motion compensation system

The motion compensation system assists the surgeon by following intracardiac structures that undergo rapid movement primarily in a single direction. As shown in our previous work, this includes the motion of the mitral valve annulus (Yuen et al., 2009). The system in this work builds on the system developed by Yuen et al. (2009) but incorporates a new tissue tracker that we term the "flashlight" tracker that can track arbitrary tissue targets in real-time 3D ultrasound. This is integrated with a miniaturized version of the actuated, handheld 1 DOF motion compensation instrument and predictive extended Kalman filter used by Yuen et al. (2009). A block diagram of the resulting system is shown in Fig. 1. The flashlight tissue tracker supplies measurements to the filter which, in turn, provides the reference trajectory for a PID controller to command the instrument. The surgeon designates the desired surgical site by aiming the tip of the instrument toward it.

Fig. 2 illustrates the surgical procedure that we are prototyping to perform beating heart mitral annuloplasty using this system. In the procedure, the motion compensation instrument is inserted through the left atrial appendage and aimed toward the mitral annulus. A custom annuloplasty ring is inserted through an adjacent incision and positioned by the surgeon. The instrument is tipped with a modified 14 gauge needle (OD 2.108 mm) that deploys surgical anchors (Vasilyev et al., 2006) to attach the ring to the annulus. The surgeon maneuvers the ring and anchor driver to appropriate locations over the annulus and deploys the anchors to secure the ring and reshape the annulus.

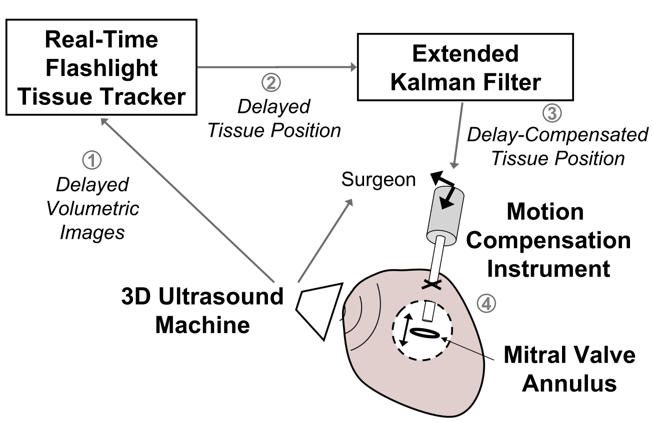

Fig. 1. The motion compensation system uses 3D ultrasound imaging to automatically synchronize the motion of an actuated, handheld surgical instrument with a tissue target. Circled numbers indicate the order of data flow through the system (1–3) and the resultant tracking position of the motion compensation instrument (4).

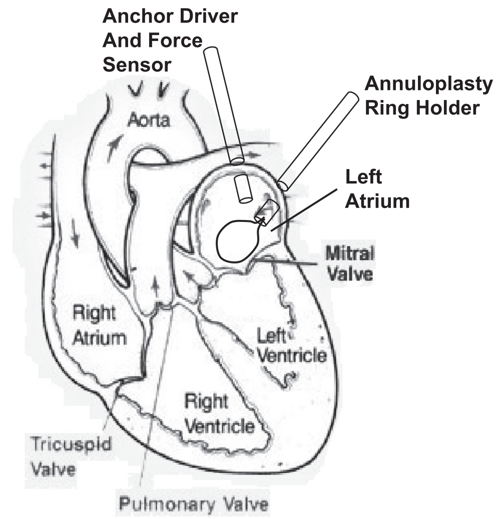

Fig. 2. The prototype beating heart mitral valve annuloplasty uses two instruments inserted through the left atrial appendage. One instrument deploys anchors that secures a stiff ring to the annulus to reshape it. Note that the anchor driver approaches along the valve's axis, which corresponds to the valve's major component of motion.

Preliminary experiments on freshly excised porcine heart indicate that a contact force of 2–3 N is required to deploy the anchor firmly into the annulus, but that forces must stay below 5.5 N to avoid tissue damage. This can be difficult to achieve when operating on moving heart tissue. The system described in this paper actuates the surgical instrument to compensate for heart motion to allow anchors to be deployed into the moving annulus. To do so, the instrument must be able to match the maximum annulus speeds and accelerations of 210 mm s^{-1} and 3.8 m s^{-2} (respectively) and have a 20 mm range of motion (Yuen et al., 2009). In order to synchronize instrument motion with that of the annulus, the system must also be able to automatically track the location of the annulus using 3D ultrasound while overcoming the latencies inherent to this imaging modality (Novotny et al., 2007).

2.1.1. Real-time 3D ultrasound "Flashlight" tissue tracker

Segmenting and tracking the mitral valve annulus in 3D ultrasound is inherently difficult due to noisy imaging and poor shape definition (Noble, 2006). Furthermore, the requirement for real-time (25–30 Hz) processing constrains the computation time available per volume. Rather than track the entire annular structure, we instead propose to track the tissue that the instrument is pointed toward. This simplification is clinically motivated: at any given moment, the surgeon only interacts with the small region of annulus directly in front of the instrument. Our approach allows the tracker to take advantage of the high spatial coherence of the instrument, which appears as a bright and straight object in the volume, to locate an otherwise poorly defined anatomical target. In this way the instrument is similar to a flashlight that highlights the tissue target (Fig. 3).

Fig. 4 charts the data flow in the flashlight tracker. It consists of two consecutive operations: instrument detection followed by target segmentation. We employ the modified Radon transform for real-time detection of the ray that passes through the central axis of the instrument shaft in 3D ultrasound (Novotny et al., 2007). Next, we turn to distinguishing between the target and instrument