

3D Ultrasound-Guided Motion Compensation System for Surgery Inside of the Heart

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I. ABSTRACT

Surgeries on internal cardiac structures currently require stopping the heart and using a cardiopulmonary bypass (CPB) machine to pump and oxygenate the blood. CPB has a number of well-known adverse effects, including an increased risk of stroke and a decline in cognitive performance (Zeitlhofer et al. 1993, Murkin et al. 1999). Beating heart surgeries, surgeries conducted without stopping the heart, eliminate the need for CPB and its attendant side effects. Additionally, these procedures allow the surgeon to evaluate the outcome of the surgical procedure in real-time since the heart continues to beat and circulate blood throughout the body. The benefits of such procedures are clear, however, the rapid motion of the heart poses a serious challenge to the surgeon. This is especially true of procedures involving intracardiac structures such as the mitral valve (Figure 1), which recoils rapidly with every heartbeat. The difficulty of manipulating tissues undergoing fast motion must be addressed in order to realize the potential of beating heart intracardiac procedures.

One appealing approach to the beating heart repair of intracardiac structures is robotic assistance. In this setting, the robot controller would track the motion of the heart and drive the robot to compensate for its fast motion, so that the surgeon could interact with a virtual stopped heart. The robot designed for this task would require a sufficient bandwidth to compensate for the fast moving structures in the heart, as well as a sufficient force output to perform suturing and stapling tasks on the heart tissues.

Another major consideration for beating heart intracardiac procedures is guidance inside of the heart, which requires imaging tissue through blood in real-time. Currently, 3D ultrasound (3DUS) is the only imaging tech-

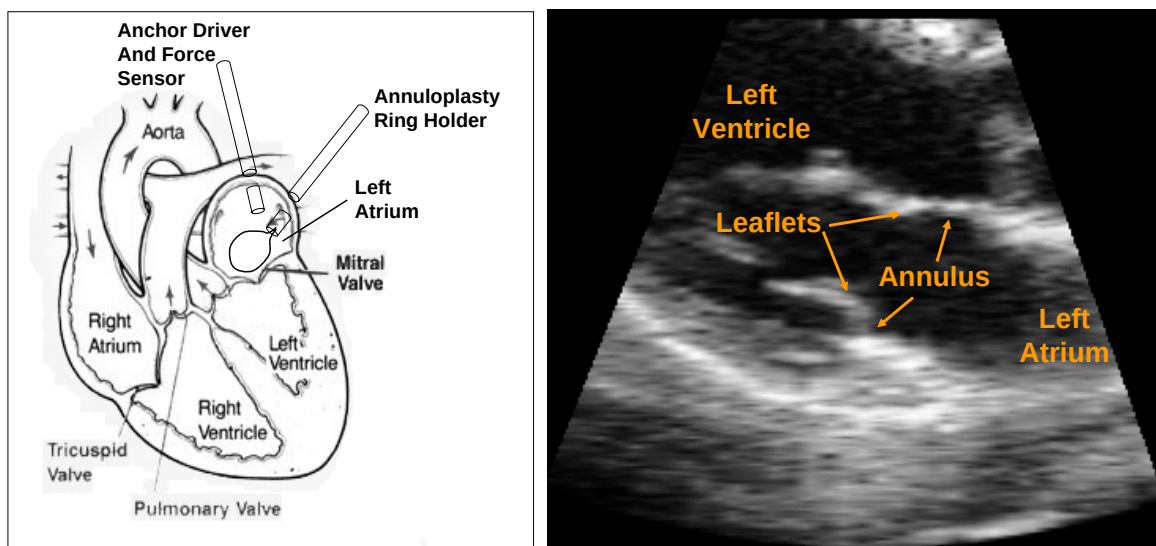


Fig. 1. The mitral valve is an internal heart structure that regulates unidirectional blood flow from the left atrium to the left ventricle. Its basic structural elements are two leaflets joined to an annulus. (Left) Mitral valve motion is mostly uniaxial and may potentially be operated on with a 1 DOF motion compensated anchor driver guided by 3D ultrasound (Kettler et al. 2007). (Right) A mitral valve imaged by 3D ultrasound.

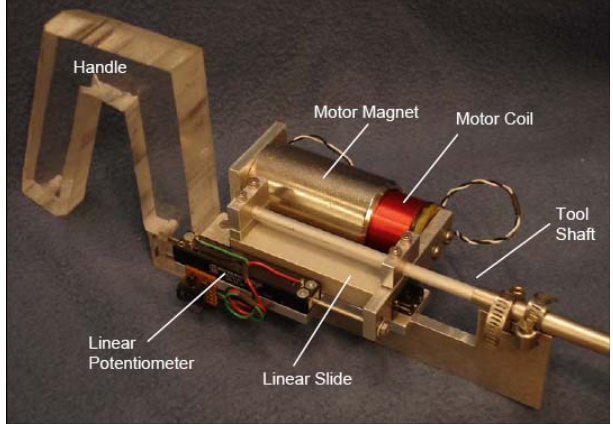
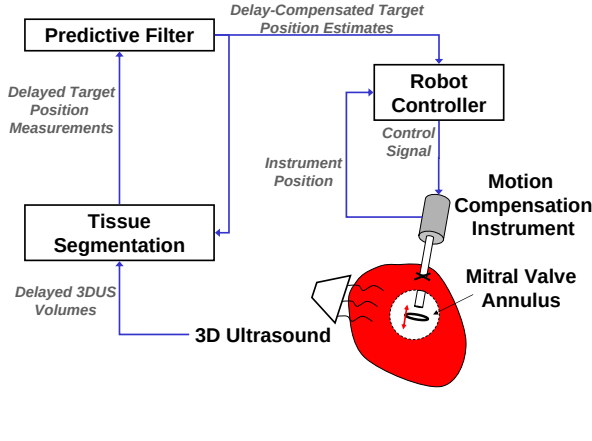


Fig. 2. (Left) Motion compensation system architecture. (Right) Motion compensation instrument.

nology that has these capabilities. However, 3DUS also introduces a substantial time delay during which time certain intracardiac structures like the mitral valve can move significantly (Novotny 2007). Servoing a robot with these measurements directly would result in large errors that could damage the heart. This challenge must be overcome to realize image-guided, motion compensated technologies for intracardiac surgery.

In this paper, we describe a 3DUS-guided robotic motion compensation system that is compatible with the space limitations inside the heart and that also counteracts the delays inherent in 3DUS imaging. The system, illustrated in Figure 2, comprises an actuated 1 DOF instrument commanded by a predictive filter (extended Kalman filter). This system can be used in situations where the motion of the cardiac tissue is largely in a single direction. This includes the motion of the mitral valve annulus and so may be used for procedures like mitral annuloplasty (Figure 1). Using this system, we demonstrate high accuracy tracking of heart motion in the presence of noise, time delay, and a variable heart rate. Furthermore, in a series of user studies, we show that the use of the proposed system greatly enhances dexterity and reduces applied forces to tissue targets in surgical tasks.

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III. BIOGRAPHY

Shelten Yuen is a Ph.D. candidate in Engineering Sciences in the Harvard BioRobotics Laboratory directed by Prof. Robert D. Howe (School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA). Previously, he worked in defense tracking systems at MIT Lincoln Laboratory (Lexington, MA, USA) and automated semiconductor test systems at Agilent Technologies (Santa Rosa, CA, USA). He received a B.S. in Electrical Engineering at the University of California, Davis in 2001 and a S.M. in Applied Mathematics at Harvard University in 2007. Shelten's research interests include medical robotics, estimation, signal processing, and control.