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Motion Compensated Catheter Ablation of the Beating Heart Using Image Guidance and Force Control

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Abstract Cardiac catheters allow physicians to access the inside of the heart and perform therapeutic interventions without stopping the heart or opening the chest. However, conventional manual and actuated cardiac catheters are currently unable to precisely track and manipulate the intracardiac tissue structures because of the fast tissue motion and potential for applying damaging forces. This paper addresses these challenges by proposing and implementing a robotic catheter system that use 3D ultrasound image guidance and force control to enable constant contact with a moving target surface in order to perform an interventional procedure, in this case tissue ablation. The robotic catheter system, consisting of a catheter module, ablation and force sensing end effector, drive system, and image-guidance and control system, was commanded to apply a constant force against a moving target using a position-modulated force control method. As compared to a manual catheter system, the robotic catheter was able to apply a more consistent force on the target while maintaining ablation electrode contact with 97% less RMS contact resistance variation. These results demonstrate that the 3D ultrasound guidance and force control allow the robotic system to maintain better contact with a moving tissue structure, thus allowing for more accurate and repeatable tissue ablation procedures.

1 Introduction

Advances in cardiac catheter technology allow physicians to treat a range of conditions inside the beating heart while avoiding both the invasiveness of opening the chest and the cognitive impairment risks associated with cardiopulmonary bypass [1-3]. However, the majority of catheters currently used for cardiac interventions only allow for slow manual motions of the catheter tip and are unable to control the forces applied to the tissue surfaces. Commercially available robotic catheter systems, such as the Artisan Control Catheter (Hansen Medical, Mountain

View CA, USA) or the CorPath Vascular Robotic System (Corindus Vascular Robotics, Natick MA, USA), achieve manual catheter manipulation speeds while allowing the operator to utilize robotic teleoperation to reduce radiation exposure [4, 5]. However, neither the manual nor the commercial robotic catheter systems are able to compensate for the fast cardiac motion or regulate the forces applied to the tissue surface.

The goal of our work is to enable a robotic catheter to track the fast motions of the heart while controlling the forces applied by the catheter end effector to the tissue in order to improve the safety and efficacy of medical procedures. This objective is achieved through the use of 3D ultrasound (3DUS) guidance, active motion compensation, and catheter tip force control. The medical application selected for this project is the radiofrequency (RF) ablation of cardiac tissue. Ablation is used by interventional cardiologists and cardiac surgeons to destroy cardiac conduction pathways that contribute to arrhythmias, or heart beat abnormalities [6]. The outcome success of this procedure is dependent on the electrode contact with the tissue and force application, and therefore can benefit from the robotic system proposed here [7-10].

In previous work, we have demonstrated *in vivo* the ability of the robotic catheter system to compensate for the fast motion of the heart [11]. A custom catheter tip force sensor was developed to enable the catheter to maintain a constant force relative to a target. However, the force control system has to date only been evaluated on the bench top using noise-free simulated position signals without actual ultrasound image-derived signals [12, 13]. Other work in cardiac motion compensation has focused primarily on interacting with the exterior of the beating heart [14-16]. In addition, the previous work in robotic catheters has primarily focused on teleoperation and position control [4, 5]. To the authors’ knowledge, the work presented here represents the first time 3DUS image guidance and force control has been used to enable a robotic catheter to accurately interact with a moving target. Furthermore, this paper presents the first application of the 3DUS-guided and motion compensated catheter system to a clinical procedure, improving the therapeutic efficacy of ablation on the beating heart.

The following paper presents the robotic catheter system, the force sensing and ablation end effector, and the force control method. Next, the paper presents the system evaluation method, the experimental results, and finally concludes with a discussion of the implications and limitations of the results. This work demonstrates the potential benefits of integrating motion-compensation and force control with cardiac intervention catheters.

2 Technical Approach

The goal of the robotic catheter system is to use real-time 3DUS to measure the target tissue motion and then drive a robotic catheter to synchronize with the motion and apply a constant force to the tissue with a RF ablation end effector. The system (Fig. 1) is composed of three main modules: the drive system that actuates

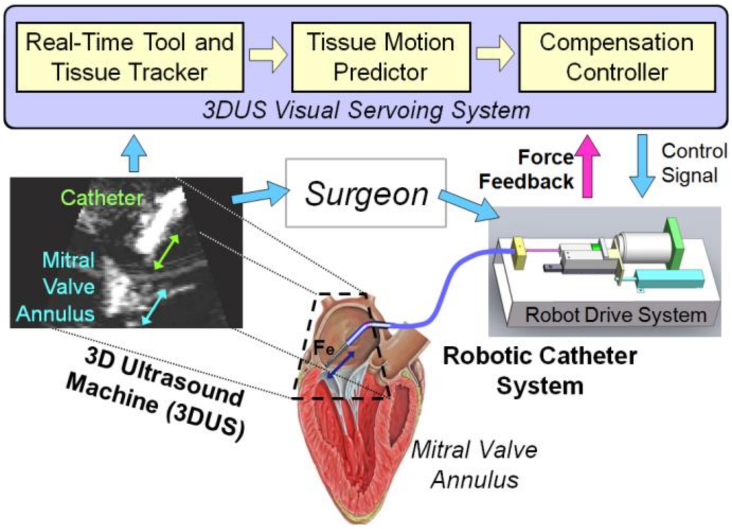

Fig. 1. The robotic system servos the catheter using 3DUS guidance and force feedback.

the catheter, the catheter module that is inserted through the vasculature into the heart, and the 3D ultrasound visual servoing system that tracks the tissue and commands the catheter to follow the motion. The drive system contains a linear voice coil actuator and a position sensor that are able to rapidly adjust the catheter position. The catheter module is composed of a stainless steel coil guidewire inside of a nylon sheath. The sheath is positioned inside of the vasculature to guide the actuated catheter into the heart and the guidewired is servoed by the drive system to compensate for the heart motion. Finally, the visual servoing system utilizes a 3DUS machine (Fig. 2, SONOS 7500 with X4 Ultrasound Transducer, Philips Healthcare, Andover, MA, USA) and a tissue tracking and motion prediction system to determine the real-time motion of the cardiac tissue and control the catheter [17-20]. A more detailed description of the mechanical design of the robotic catheter system is provided in [11].

A novel integrated force sensing and ablation end effector is presented here for the first time (Fig. 3). The design goal of the ablation tool design is to enable the catheter system to apply RF energy to the fast-moving tissue inside the heart while applying a constant normal force. The functional requirements of the ablation end effector are to sense forces, to ablate tissue using a clinical RF generator with the same efficacy as conventional ablation catheters, and to be robust enough to operate in the intracardiac environment. The device consists of a force sensor described in [12], a stainless steel electrode, and a fine wire that runs though the catheter to the RF current generator. The current prototype is approximately 5 mm in diameter and is created using rapid prototyping 3D printing technology. The size of the end effector can be further reduced with improved fabrication such as laser micromachining and metal laser sintering. See [12] for a more detail description of the 3D printed force sensor technology. Fig. 3b presents examples of

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3DUS Image

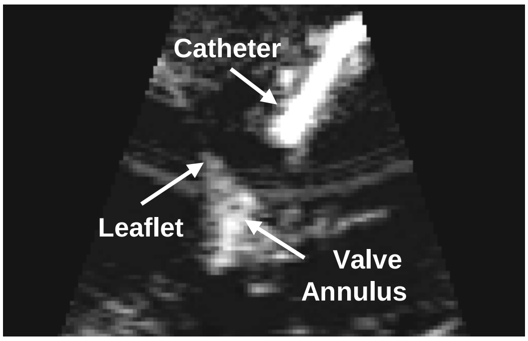

Fig. 2. Ultrasound image showing the catheter, mitral valve annulus, and mitral valve leaflets.

the RF ablation lesions created with this tool on porcine skeletal muscle tissue (RF generator: Stockert 70, Biosense Webster, Diamond Bar, California, USA).

The objective of the control system is to apply a desired force on a fast moving target with the robotic catheter end effector. A standard error-based force control approach will not work for the robotic catheter system because of the limitations identified in [11], including backlash and friction in the catheter transmission system [21, 22]. These limitations prevent a standard force regulator from correctly responding to the force tracking error in a stable manner because the internal dynamics of the catheter obstruct the controller action from being accurately transmitted from drive system to the catheter tip. To overcome these issues, we propose a method that uses the force error term to modulate the commanded position trajectory of the catheter. This approach is similar to the inner position loop force control approaches used to implement force control on high-friction industrial manipulators [23]. In addition to improved system stability, the use of an inner position loop also allows the controller to directly compensate for the catheter friction and backlash as these limitations are position and velocity dependent [11]. See Fig. 4 for a block diagram of the control system.

In this force control approach, the drive system is commanded to follow a desired position, x_d, that is the sum of the position of the moving target, x_e and the position offset required to maintain the desired force, x_f

$$x_d = x_e + x_f \tag{1}$$

The force modulation term is

$$x_f = K_f(F_d - F_e) + K_{fi}\int (F_d - F_e)dt \tag{2}$$

where F_d is desired force, F_e is the force applied to the environment, and K_f, and K_{fi} are controller gains. This control law is similar to the method presented by Villani et al in [24].

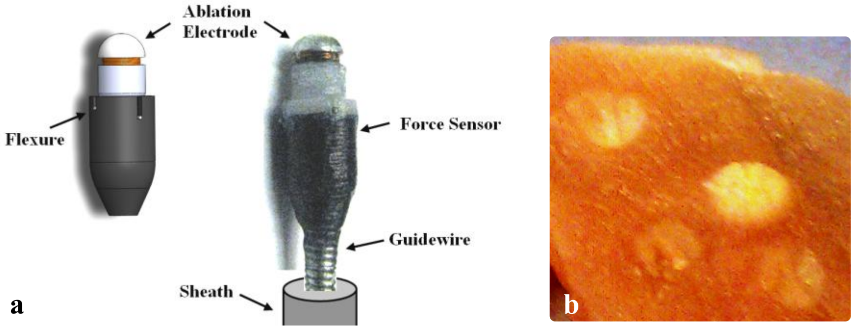

Fig. 3. a) Ablation end effector solid model and prototype. b) Tissue sample (porcine skeletal muscle) ablated with the RF ablation end effector. Lesions are approximately 4 mm in diameter.

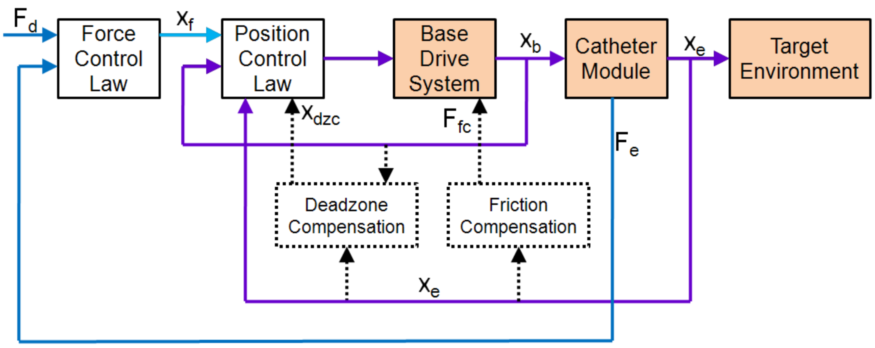

Fig. 4. The force control system block diagram. The blue lines indicate force values and the purple lines indicate position values.

3 Experimental Evaluation

The robotic ablation catheter system was evaluated in a water tank experiment to examine the ability of the system to maintain good RF ablation electrode contact against a moving surface while applying a constant force. A number of studies have demonstrated that cardiac ablation efficacy is directly related to the forces applied by the catheter tip and the quality of the electrode-tissue contact [7-10]. Manually operated catheters do not adequately ablate tissue if they are bouncing or sliding on the tissue surface, in poor contact due to low forces, or creating tissue perforations due to large contact forces [9, 10]. The objective of this evaluation was to demonstrate that the robotic catheter system can improve ablation quality by maintaining good contact while accurately controlling the force.

The system was evaluated by commanding the catheter to maintain a constant contact force against a moving target. The target was composed of a conductive

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pad used as the current return path electrode in clinical ablation and electrocautery procedures (REM Polyhesive II Patient Return Electrode, Tyco Healthcare, Gosport, UK) backed with compliant foam (thickness: 25 mm, approximate stiffness: 0.1 N/mm). The target was translated with a 12 mm amplitude at a frequency of approximately 1 Hz (60 beats per minute). Two motion patterns were tested: a sinusoidal trajectory and a human mitral annulus trajectory [25]. The ablation quality was evaluated by measuring the electrical resistance between the catheter tip electrode and the return electrode pad using an instrumented voltage divider (Fig. 5). The water tank environment was used to allow the 3DUS guidance system to visualize the catheter and target.

The evaluation experiment was conducted using both the robotic catheter and a commercial manual ablation catheter (RF Marinr MCXL, Medtronic, Minneapolis, Minnesota, USA) for comparison. A manual catheter was select for comparison to demonstrate the limitations of the current technology due to a lack of motion compensation and force control. For the manual catheter, a load cell was also added to the target to record the forces applied by the catheter tip (LCFD-1KG, Omega Engineering, Stamford, CT, USA; range: 10 N, accuracy: +/-0.015 N). The robotic catheter was instrumented with the force-sensing ablation end effector and was operated under force control with 3DUS guidance. Both catheters were rigidly braced 100 mm from the ablation tip at orientations perpendicular to the plane of the moving target. The manual catheter was positioned so its ablation electrode was able to remain in contact during the entire target trajectory (Fig. 6).

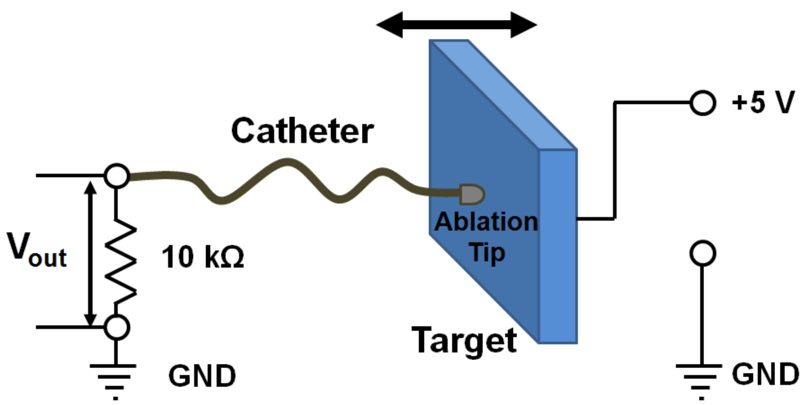

Fig. 5. The catheter ablation experimental setup. The moving target was connected to a 5 V DC signal and the catheters were instrumented with a voltage divider to measure the ablation resistance. Resistance measurements were used to evaluate tip contact quality for both a manual catheter and the robotic catheter system.

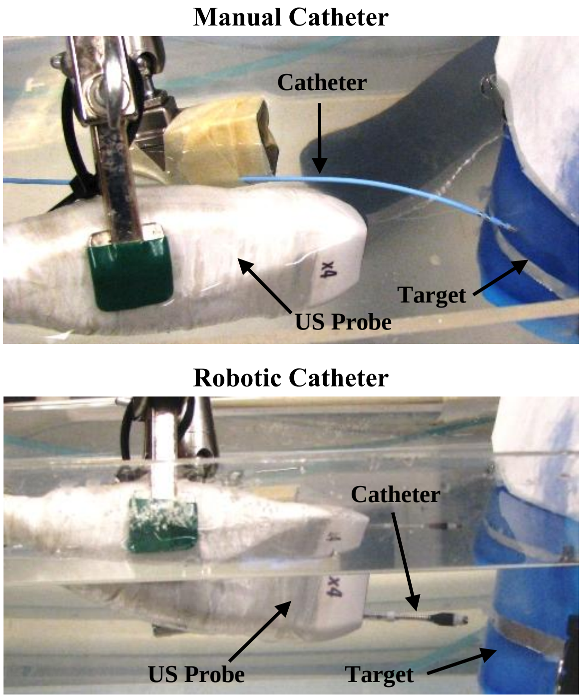

Fig. 6. The water tank setup for the manual catheter (top) and the robotic catheter (bottom). Both images show the catheters, the white 3DUS imaging probe, and the blue motion target.

4 Results

Fig. 7 presents the position trajectories of the 3DUS tracking system, robotic catheter, and motion simulator during the experiments. Fig. 8 presents typical results of the ablation experiment on the sinusoidal motion target. Both the manual and robotic catheters were in contact with the moving target for over 5 s during each trial, sufficient time to perform ablation. The manual catheter was not able to apply a constant force or maintain a constant resistance.

The reason for the manual catheter's poor performance was because the motion of the target caused the manual catheter ablation tip to slide and tilt relative to the target surface as the motion simulator pushed on the catheter and caused it to buckle. Compliance is a desirable feature in manual catheters because it prevents them from applying large forces and perforating cardiac tissue. However, this bending compliance makes it challenging to achieve reliable ablation performance. As shown in Fig. 8, the manual catheter generated peak-to-peak resistance variations of over 20 kOhm and peak-to-peak force variations of 0.4 N.

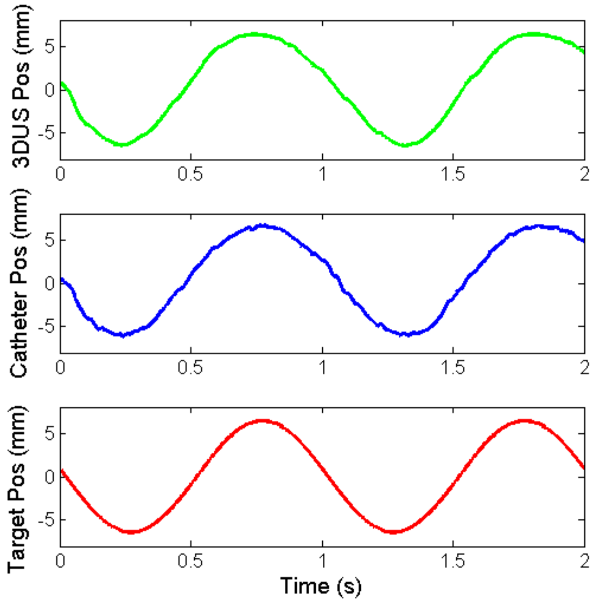

Fig. 7. The position trajectories during the robotic catheter experiment: (top) The 3DUS tracking system; (middle) The robotic catheter position commanded by the force control system; (bottom) The actual target trajectory.

The robotic catheter, in contrast to the manual catheter, achieved almost constant resistance values while maintaining a desired force of 1 N with a force tracking error of 0.11 N RMS. The RMS variation of the resistance value for the robotic catheter was 0.25 kOhms, 97% less than the RMS variation of 9.88 kOhm for the manual catheter system. The robotic catheter was able to achieve this level of performance because the 3DUS-guided motion compensation system and the force control algorithm enabled the ablation tip to maintain consistent contact with the target despite the fast motion (Fig. 8). Similar force tracking results were obtained using the human mitral valve trajectory.

5 Discussion

These results demonstrate that image-guided motion compensation and force control can improve key parameters that determine ablation quality. This confirms that our robotic approach has the potential to increase clinical efficacy of intracardiac procedures. The system was able to apply a constant force while maintaining a constant ablation resistance with the ablation end effector on a moving target. In contrast, the force and electrical contact provided by the manual catheter in the same experimental setup varied greatly. This variation can primarily be attributed to the buckling, sliding, and tilting behavior of the manual catheter

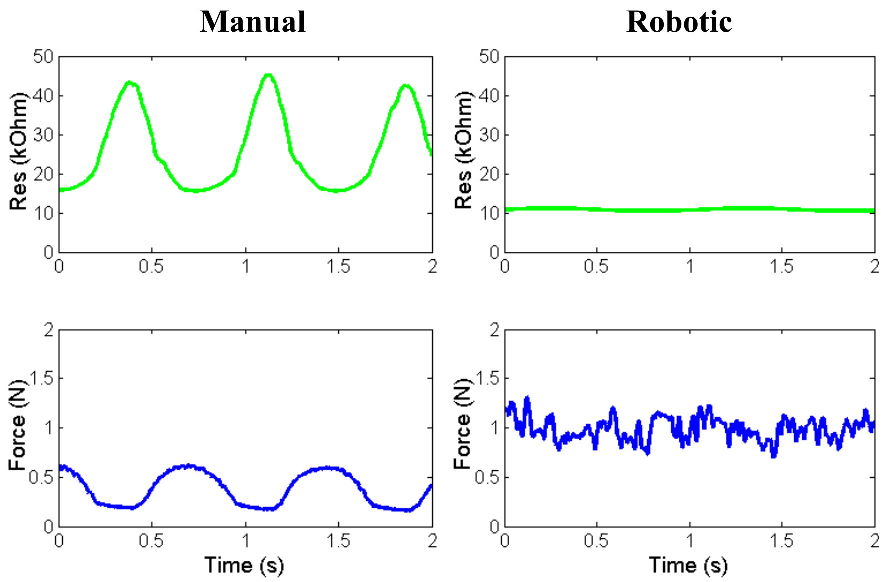

Fig. 8. A comparison of the electrical resistance and interaction forces between a conductive target and a manual catheter (left) and the robotic catheter system (right). The manual catheter applies a force and resistance that vary with the motion of the target. In contrast, the robotic catheter achieved consistent contact with the moving target while applying a constant force.

tip due to the target motion. The 3DUS motion tracking enabled the robotic catheter to compensate for the target motion and maintain good ablation electrode contact without the buckling behavior of the manual catheter.

One insight from this work is that multiple forms of sensor information are required to command a catheter to safely and effectively interact with the moving target. Force sensing alone is not sufficient for the catheter to track the target motion, as described in [13]. This is due to the fact that the catheter performance limitations of backlash and friction prevent the system from responding fast enough to the quick tissue motion using only force feedback. Motion tracking must also be used to overcome these limitations and maintain system stability [13]. The image guidance provides the desired position trajectory for the tip of the catheter and the force feedback allows for minor adjustments in the tip position to regulate and maintain the tool-tissue interactions forces. Without either 3DUS guidance or force sensing, the catheter would be unable to maintain the consistent ablation electrode contact and could either penetrate or retract from the target surface.

Although the experimental results demonstrate that the robotic catheter system is able to apply a constant force while maintaining a consistent ablation contact, there are a number of limitations in this initial validation study due to the challenges of accurately simulating *in vivo* cardiac ablation in a laboratory setting. First, measuring the DC resistance of the contact does not consider the electrical frequency response of the cardiac tissue at the 500 kHz frequency used by the RF energy generator. In addition, the system was tested in water instead of electrically-conductive blood or saline, which alters the electrode conduction properties. Finally, the experimental setup did not accurately approximate the exact mechanics of intracardiac ablation, including the compliance of the vessels in the heart and the tool orientation relative to the moving tissue structures. The manual catheter performance depends on its orientation with respect to the moving tissue target, although similar fluctuations in force and resistance would have resulted for other orientations. We anticipate that these issues will not impair the demonstrated advantages of the robotic system because of the known properties of the ablation process and the success of previous *in vivo* tests of the image guidance systems [11, 26, 27].

6 Conclusions

This paper presents the experimental evaluation of the robotic catheter system for cardiac ablation. The system uses motion compensation and force feedback to maintain a constant force and ablation resistance on a moving target. The experimental results presented here demonstrated that the robotic system is able to maintain consistent ablation electrode contact with a translating motion simulator with a 97% reduction in RMS resistance variation over a manual catheter. The result can be explained by the fact that a compliant manual catheter slides and buckles while in contact with a quickly moving structure, such as the actively contracting heart wall.

Future work in this project will focus on the demonstration and evaluation of the technology in an *in vivo* setting. While the motion compensation and robotic catheter system has been demonstrated previously *in vivo* [11, 26], the force control ablation system has not yet been tested inside a beating heart. One possible challenge the system will encounter *in vivo* is how to respond when the tissue stiffness changes over the course of the heart cycle. In addition, safety issues such as system stability and preventing tissue collisions will need to be further investigated. The project objective is to enable a range of beating heart surgical procedures with a catheter, and the ablation procedure presented here is a first step toward this ultimate goal.

References

[1] D. S. Baim, Ed., *Grossman's Cardiac Catheterization, Angiography, and Intervention.* Philadelphia, PA: Lippincott Williams & Wilkins, 2005.

[2] J. M. Murkin, W. D. Boyd, S. Ganapathy, S. J. Adams and R. C. Peterson, "Beating heart surgery: why expect less central nervous system morbidity?" *Annals of Thoracic Surgery,* vol. 68, pp. 1498-1501, 10, 1999.

[3] G. W. Roach, M. Kanchuger, C. M. Mangano, M. Newman, N. Nussmeier, R. Wolman, A. Aggarwal, K. Marschall, S. H. Graham and C. Ley, "Adverse cerebral outcomes after coronary bypass surgery," *N. Engl. J. Med.,* vol. 335, pp. 1857-1864, 1996.

[4] D. B. Camarillo, C. F. Milne, C. R. Carlson, M. R. Zinn and J. K. Salisbury, "Mechanics Modeling of Tendon-Driven Continuum Manipulators," *IEEE Transactions on Robotics,* vol. 24, pp. 1262-1273, 2008.

[5] R. Beyar, "Navigation within the heart and vessels in clinical practice," *Ann. N. Y. Acad. Sci.,* vol. 1188, pp. 207-213, 2010.

[6] S. K. Huang, S. K. S. Huang and D. J. Wilber, *Radiofrequency Catheter Ablation of Cardiac Arrhythmias: Basic Concepts and Clinical Applications.* Wiley-Blackwell, 2000.

[7] Y. Okumura, S. Johnson and D. Packer, "An analysis of catheter tip/tissue contact force-induced distortion of three-dimensional electroanatomical mapping created using the Sensei robotic catheter system," *Heart Rhythm,* vol. 4, pp. S318, 2007.

[8] J. M. Kalman, A. P. Fitzpatrick, J. E. Olgin, M. C. Chin, R. J. Lee, M. M. Scheinman and M. D. Lesh, "Biophysical characteristics of radiofrequency lesion formation in vivo: dynamics of catheter tip-tissue contact evaluated by intracardiac echocardiography," *Am. Heart J.,* vol. 133, pp. 8-18, 1997.

[9] D. C. Shah, H. Lambert, H. Nakagawa, A. Langenkamp, N. Aeby and G. Leo, "Area Under the Real-Time Contact Force Curve (Force–Time Integral) Predicts Radiofrequency Lesion Size in an In Vitro Contractile Model," *J. Cardiovasc. Electrophysiol.,* vol. 21, pp. 1038-1043, 2010.

[10] D. Shah, H. Lambert, A. Langenkamp, Y. Vanenkov, G. Leo, P. Gentil-Baron and B. Walpoth, "Catheter tip force required for mechanical perforation of porcine cardiac chambers," *Europace,* vol. 13, pp. 277, 2011.

[11] S. B. Kesner and R. D. Howe, "Position Control of Motion Compensation Cardiac Catheters," *IEEE Transactions on Robotics,* vol. 27, pp. 1045 - 1055, 2011.

[12] S. B. Kesner and R. D. Howe, "Design Principles for Rapid Prototyping Forces Sensors Using 3-D Printing," *IEEE/ASME Transactions on Mechatronics,* vol. 16, pp. 866 - 870, 2011.

[13] S. B. Kesner and R. D. Howe, "Force control of flexible catheter robots for beating heart surgery," in Proc. of *IEEE Int. Conf. on Robotics and Automation,* 2011, pp. 1589-1594.

[14] R. Ginhoux, J. Gangloff, M. de Mathelin, L. Soler, M. M. A. Sanchez and J. Marescaux, "Active filtering of physiological motion in robotized surgery using predictive control," *IEEE Transactions on Robotics,* vol. 21, pp. 67-79, 2005.

[15] O. Bebek and M. Cavusoglu, "Intelligent control algorithms for robotic assisted beating heart surgery," *IEEE Transactions on Robotics,* vol. 23, pp. 468–480, 2007.

[16] Y. Nakamura, K. Kishi and H. Kawakami, "Heartbeat synchronization for robotic cardiac surgery," in Proc. of *IEEE Int. Conf. on Robotics and Automation,* 2001, pp. 2014–2019.

[17] P. M. Novotny, J. A. Stoll, N. V. Vasilyev, P. J. Del Nido, P. E. Dupont, T. E. Zickler and R. D. Howe, "GPU based real-time instrument tracking with three-dimensional ultrasound," *Med. Image Anal.,* vol. 11, pp. 458-464, 2007.

[18] P. M. Novotny, J. A. Stoll, P. E. Dupont and R. D. Howe, "Real-time visual servoing of a robot using three-dimensional ultrasound," in Proc. of *IEEE Int. Conf. on Robotics and Automation,* 2007, pp. 2655-2660.

[19] S. G. Yuen, P. M. Novotny and R. D. Howe, "Quasiperiodic predictive filtering for robot-assisted beating heart surgery," in Proc. of *IEEE Int. Conf. on Robotics and Automation,* 2008, pp. 3875-3880.

[20] S. G. Yuen, D. T. Kettler, P. M. Novotny, R. D. Plowes and R. D. Howe, "Robotic motion compensation for beating heart intracardiac surgery," *The International Journal of Robotics Research,* vol. 28, pp. 1355, 2009.

[21] S. Eppinger and W. Seering, "Understanding bandwidth limitations in robot force control," in Proc. of *IEEE Int. Conf. on Robotics and Automation,* 1987, pp. 904-909.

[22] W. Townsend and J. Salisbury Jr, "The effect of coulomb friction and stiction on force control," in Proc. of *IEEE Int. Conf. on Robotics and Automation,* 1987, pp. 883-889.

[23] J. Maples and J. Becker, "Experiments in force control of robotic manipulators," in Proc. of *IEEE Int. Conf. on Robotics and Automation,* 1986, pp. 695-702.

S. B. Kesner, R. D. Howe, “Motion Compensated Catheter Ablation of the Beating Heart Using Image Guidance and Force Control”, in Proc. of ISER June, 2012.

[24] S. Chiaverini, B. Siciliano and L. Villani, "A survey of robot interaction control schemes with experimental comparison," *IEEE/ASME Transactions on Mechatronics,* vol. 4, pp. 273-285, 1999.

[25] D. T. Kettler, R. D. Plowes, P. M. Novotny, N. V. Vasilyev, P. J. del Nido and R. D. Howe, "An active motion compensation instrument for beating heart mitral valve surgery," in Proc. of *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems,* 2007, pp. 1290-1295.

[26] S. G. Yuen, S. B. Kesner, N. V. Vasilyev, P. J. del Nido and R. D. Howe, "3D ultrasound-guided motion compensation system for beating heart mitral valve repair," in Proc. of *Medical Image Computing and Computer-Assisted Intervention,* LNCS vol. 5241 2008, pp.711-719.

[27] S. B. Kesner, S. Yuen and R. Howe, "Ultrasound servoing of catheters for beating heart valve repair," in Proc. of *Information Processing in Computer-Assisted Interventions,* LNCS vol. 6135, 2010, pp. 168-178.