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# Control Algorithms for Active Relative Motion Cancelling for Robotic Assisted Off-Pump Coronary Artery Bypass Graft Surgery

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***Abstract*— Use of intelligent robotic tools promises an alternative and superior way of performing off-pump coronary artery bypass graft (CABG) surgery. In the robotic-assisted surgical paradigm proposed, the conventional surgical tools are replaced with robotic instruments which are under direct control of the surgeon through teleoperation. The robotic tools actively cancel the relative motion between the surgical instruments and the point-of-interest on the beating heart, in contrast to traditional off-pump CABG where the heart is passively constrained to dampen the beating motion. As a result, the surgeon operates on the heart as if it were stationary. We call the proposed algorithm "Active Relative Motion Cancelling (ARMC)" to emphasize the active cancellation. In the paper, a model-based intelligent ARMC algorithm is proposed to achieve effective motion cancellation. This is followed by an analysis of local motion of the heart collected using a sonomicrometry system to determine the specifications for ARMC system. Finally, the experimental results of the algorithm implemented on two 1-DOF robotic test-bed systems are reported.**

## I. INTRODUCTION

Off-pump coronary artery bypass graft (CABG) surgery is done while the heart is still beating instead of using a cardiopulmonary bypass machine and stopping the heart to perform the surgery. Off-pump CABG is preferable over on-pump CABG because of the significant complications resulting from using the bypass machine, which include long term cognitive loss [12], and increased hospitalization time and cost [13]. However off-pump CABG technology is crude and only applicable to a small portion of the cases because of the technological limitations, inadequate for all but the largest diameter target vessels, not effectively applicable to the coronary arteries on the side and the back of the heart, and limited to small number of bypasses. Off-pump procedures represent only 15-20% of all CABG, at best. Use of robotics technology promises an alternative and superior way of performing off-pump CABG surgery. The goal of the telerobotic tools being developed in this project is to actively track and cancel the relative motion between the surgical instruments and the heart by Active Relative Motion Cancelling (ARMC) algorithms, allowing CABG surgeries to be performed on a beating heart with technical perfection equal to traditional on-pump procedures.

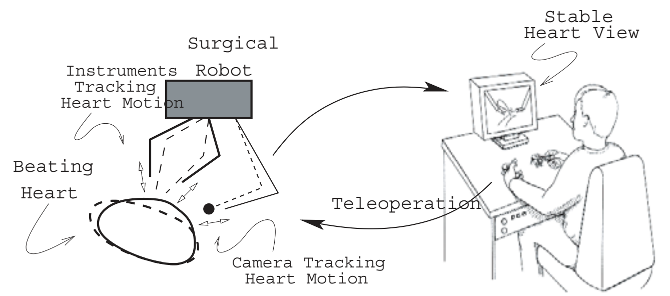


Fig. 1. System concept for Robotic Telesurgical System for Off-Pump CABG Surgery with Active Relative Motion Cancelling (ARMC). Left: Surgical instruments and camera mounted on a robot actively tracing heart motion. Right: Surgeon operating on a stabilized view of the heart, and teleoperatively controlling robotic surgical instruments to perform the surgery.

### *A. System Concept for Robotic Telesurgical System for Off-Pump CABG Surgery*

In the robotic assisted surgical paradigm proposed, conventional surgical tools are replaced with robotic instruments which are under direct control of the surgeon through teleoperation, as shown in Fig. 1. The surgeon views the surgical scene on a video display with images provided by a camera mounted on a robotic arm, which follows the heart motion, giving a stabilized view. The robotic surgical instruments also track the heart motion, cancelling the relative motion between the surgical site on the heart and the surgical instruments. As a result, the surgeon operates on the heart as if it were stationary, while the robotic system actively compensates for the relative motion of the heart. This is in contrast to traditional off-pump CABG where the heart is passively constrained to dampen the beating motion. We call the proposed control algorithm "Active Relative Motion Cancelling (ARMC)" to emphasize this difference. Since this method does not rely on passively constraining the heart, it would be possible to operate on the side and back surfaces of the heart as well as the front surface, using millimeter scale robotic manipulators.

### B. Related Work in the Literature

Madhani and Salisbury [10] developed a 6 DOF telesurgical robot design for general minimally invasive surgery, which was later adapted by Intuitive Surgical Inc., Palo Alto, CA, for their commercial system, called *daVinci*$^{TM}$. Computer Motion Inc., Goleta, CA (now part of Intuitive Surgical, Inc.), developed a 5 DOF telesurgical robotic system, called *Zeus*$^{TM}$, with scaled motions for microsurgery and cardiac surgery. Both of these systems are currently in use for cardiothoracic surgery applications. These systems are designed to enable dexterous minimally invasive cardiac surgery, and they are neither intended nor suitable for off-pump CABG with active relative motion cancelling, because of their size, bandwidth, and lack of motion tracking capabilities. These systems can only perform on-pump CABG or off-pump CABG by using passive stabilizers, and therefore have the same limitations as conventional tools described above.

Trejos et al. [17] proposed the use of a heart-tracking hand support to allow coronary artery bypass grafting surgery to take place on the beating heart. Nakamura et al. reported a vision sensor based ARMC system for heart motion tracking [11], however with unsatisfactory tracking results (error in the order of few millimeters in the normal direction), due to inherent limitations of computer-vision based tracking. Most recently, Ginhoux et al. [6], [7] reported tracking of beating heart and breathing motions with a model-predictive control and adaptive observer based control algorithm using a 500 Hz vision sensor system. Their results indicated a tracking error variance in the order of 6-7 pixels (approximately 1.5-1.75 mm calculated from the 40 pixel/cm resolution reported in [6]) in each of the directions in a 3-DOF tracking task. Although the reported tracking results are impressive, they are still very large compared to the dimensions of the targets (blood vessels with 2-mm or less diameter) that need to be manipulated using the robotic system (please also see Section II).

There are also other studies in the literature on measuring heart motion. Thakor et al. used a laser range finder system to measure one-dimensional motion of a rabbit's heart [16], Groeger et al. used a two-camera computer vision system to measure local motion of heart and performed analysis of measured trajectories [8], and Koransky et al. studied the stabilization of coronary artery motion afforded by passive cardiac stabilizers using 3-D digital sonomicrometry [9].

## II. Model Based Active Relative Motion Cancellation: Motivation and Methodology

The control algorithm is the core of the robotic tools for tracking heart motion during CABG surgery. The tools need to track and manipulate a fast moving target with very high precision. During free beating, individual points on the heart move as much as 7–10 mm. Although the dominant mode of heart motion is in the order of 1–2 Hz, if we look at measured motion of individual points on the heart during normal beating, there is significant energy in the motion to frequencies up to 20 Hz. The coronary arteries that are operated on during CABG surgery range from 2mm in diameter down to smaller than 0.5mm, which means the system needs to have a tracking precision in the order of 100 $\mu$m. This corresponds to a less than 1% dynamic tracking error up to a bandwidth of 20 Hz.

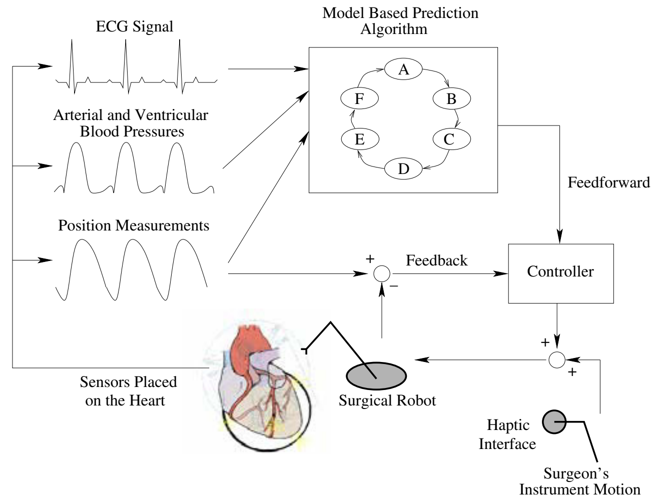


Fig. 2. The proposed control architecture for Active Relative Motion Cancellation

The specifications for tracking heart motion are very demanding. These stringent requirements could not be achieved using traditional algorithms in earlier attempts reported in the literature [11], [16], [6], [7]. Traditional algorithms rely purely on feedback signal from measurement of heart motion using external sensors, and do not use any model of heart motion. Using a basic model of heart motion can significantly improve tracking performance since heart motion is quasi-periodic [6]. It is also possible to use the information from the biological signals, such as EKG activity, and arterial and ventricular blood pressures, to control the robotic tools tracking the heart motion. The control architecture we are proposing in this research project is shown in Fig. 2. In this architecture, the control algorithm utilizes the biological signals in a model based predictive control fashion. Using biological signals in the control algorithm will improve the performance of the system since these signals are results of physiological processes which causally precede the heart motion. For example, electrical signals which stimulate the contraction of the heart muscles precede the actual contraction by about 200 msec, and this signal can be observed in the EKG measurements. Because of this, EKG signal is very suitable for period-to-period synchronization with sufficient lead time for feedforward control, and identification of arrhythmias. Similarly, the aortic, atrial and ventricular blood pressures are significant indicatives of the heart motion as they can be used to predict when the heart valves will be opening and closing, identifying the distinct phases of the heart cycle. These distinct phases correspond to qualitatively different mechanical properties of the heart tissue, changing the local deformation model. The blood pressure signals also

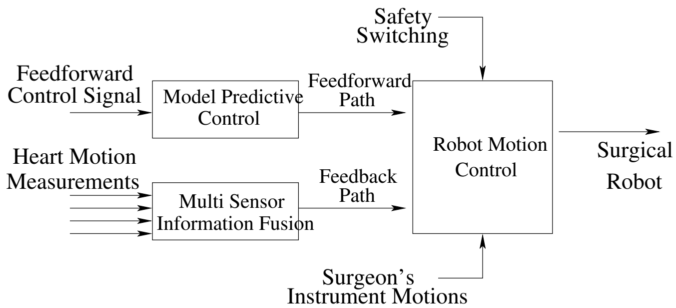


Fig. 3. Intelligent control algorithms for Active Relative Motion Cancellation. The feedforward motion and the safety switching signals come from the heart motion model.

give additional independent information, which can be used in conjunction with EKG signal to improve noise robustness and to reliably detect unexpected rhythm abnormalities and arrhythmias.

### *A. Intelligent Control Algorithms for Model-Based ARMC*

The goal of our research is the development of intelligent control algorithms that utilize the biological signals in a model-based predictive control fashion. The control algorithms need to fuse information from multiple sources: mechanical motion sensors which measure the heart motion and sensors measuring biological signals. The control algorithm also needs to be able to handle changes in the heart motion, including adapting to slow variations in heart rhythm during the course of the surgery, as well as handling occasional arrhythmias which may have natural causes or may be due to the manipulation of the heart during surgery.

In the architecture proposed (Fig. 3, 2), the robot motion control signal will be computed by combining the feedforward signal provided by the heart motion model and the feedback signal measured from direct heart motion measurements. Analysis of heart motion data presented in the next section characterizes the properties of the quasi-periodic nature of the heart motion and the associated biological signals. This aims to determine the best strategies for feedforward motion control. The feedforward controller will be designed using the model predictive control [5] and optimal control [1], [2] methodology of modern control theory, as described in IV.

The confidence level reported by the heart motion model will be used to adaptively weigh the amount of feedforward and feedback components used in the final control signal. This confidence level will also be used as a safety switching signal to turn off the feedforward component of the controller if an arrhythmia is detected, and switch to a further fail-safe mode if necessary. These research on safety algorithms will be an important component of our research.

Although, the system concepts of Nakamura et al. [11] and Ginhoux et al. [6] are similar to ours at the most basic level, there are significant differences including the lack of intelligent model based predictive control using biological signals, and multi sensor fusion with complementary and redundant sensors, which form the core of our proposed architecture. The system by Nakamura et al. uses purely position feedback obtained from a two-camera computer vision system. Neither biological signals are used in the system, nor is a feedforward control component present. The system by Ginhoux et al. utilizes a feedforward control algorithm, based on model predictive control and adaptive observers, however, it does not utilize any biological signals.

## III. Analysis of Heart Motion Data

### *A. Experimental Setup for Measurement of Heart Motion*

We used a sonomicrometry system manufactured by Sonometrics Inc. (London, Ontario, Canada) for measuring heart motion. Sonomicrometry system measures distances within soft tissue by using ultrasound signals. A set of small piezoelectric crystals embedded, sutured, or otherwise fixed to the tissue are used to transmit and receive short pulses of ultrasound signal, and the "time of flight" of the sound wave as it travels between the transmitting and receiving crystals are measured. From this distance map, the 3-D configuration of all the crystals is calculated [14]. The sonomicrometry system has an important advantage over using a vision system, which is the sensor of choice in the earlier works in the literature, for measuring heart motion for robotic ARMC. A vision system is not suitable for use during surgical manipulation because the surgical instruments (including the robotic tools) will occlude the POI rendering the vision system practically useless, whereas the sonomicrometry system does not have this shortcoming.

The heart motion data was collected on an animal model (an adult porcine). In the experimental set-up one crystal of the sonomicrometric system was sutured next to the Left Anterior Descending Artery (LAD) located on the front surface of the left ventricle of the heart, at a point one third of the way from the starting point of the LAD. Six other crystals were asymmetrically mounted on a rigid plastic base of diameter 56 mm, on a circle of diameter 50 mm, forming a reference coordinate frame. This rigid plastic sensor base was inserted behind the heart, inside the pericardial sack, and the motion of the POI on the LAD was measured relative to this coordinate frame. For proper operation of the sonomicrometric sensor system, the sensors must always be in contact with the heart. To accomplish this, the pericardial sack has been filled with a saline solution, completely immersing the sensor base. Data was collected at a sampling rate of 257 Hz, and processed off-line using the proprietary software provided with the system to calculate the 3D motion of the POI. Only filtering performed on the data produced by the sonomicrometry system was the (very-limited) removal of the outliers, which occasionally occur as a result of ultrasound echoing effects.

### *B. Analysis of Data*

The average heart rate of the animal model during the 60 sec duration of data collection was 120 beats-per-minute, as calculated from the EKG signal recorded simultaneously with the motion data. The peak displacement of the POI from its mean location was 12.1 mm, with a root-mean-square (RMS)

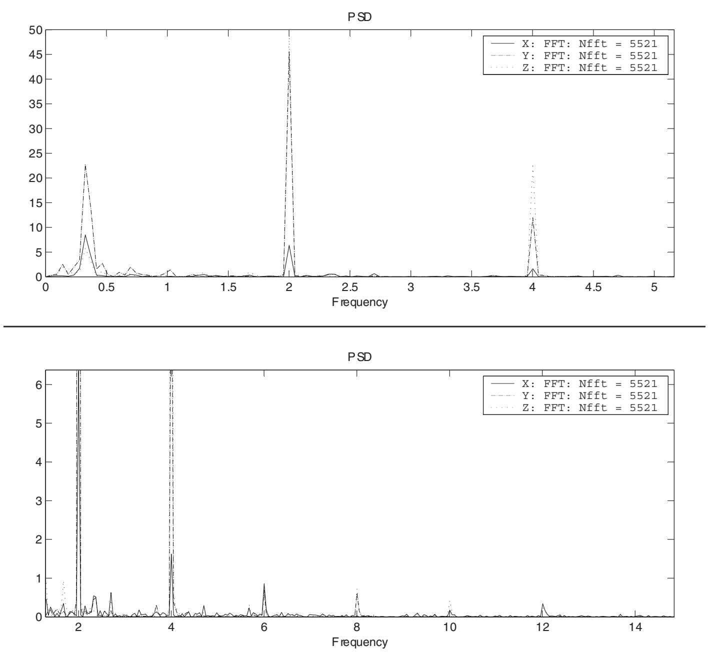


Fig. 4. Power spectral density (PSD) of the motion of the point-of-interest. The x, y, and z components of the motion are superimposed to better show the dominant modes, which are at 0.37 Hz and 2.0 Hz. Note the change in scales between the low frequency range (top), and the moderate-to-high frequency range (bottom).

value of 5.1 mm. Fig. 4 shows the Power Spectral Density (PSD) of the motion of the POI. Two observable dominant modes of motion are revealed by this figure. The first mode is at 0.37 Hz and corresponds to the breathing motion. The second dominant mode is at 2.0 Hz and corresponds to the main mode of motion due to heart beating, as it matches the frequency observed from the EKG signal. The component of motion corresponding to breathing motion, which is estimated by filtering the motion data using a low-pass filter of cut-off frequency 0.8 Hz, has a RMS magnitude of 2.86 mm. The remainder of motion, which is due to the beating of the heart, has a RMS magnitude of 4.18 mm. The POI motion can be approximated with an error less than 140 $\mu$m RMS with frequency components up to 26 Hz. This gives the specifications for the robotic mechanism and ARMC control algorithm design. These results are consistent with the heart motion measurements reported by Groeger in [8]. The data in that study was collected using a stereo vision system. The results of our study confirm the reported results using an experimental setup using an alternate sensory modality, i.e. the sonomicrometry system.

The control algorithm proposed in Section II is based on the premise that the heart motion is quasi-periodic and the motion during the previous beats can be used, to some extent, as a feedforward signal during the control of the robotic tool for ARMC. Here, our main concern is with the moderate-to-high frequency components of the motion since they are the most demanding for the mechanism and the ARMC control algorithm. As described above, the low frequency components of motion typically results from breathing (bandwidth of 0.8 Hz including the first harmonic of the breathing frequency), and can easily be cancelled using a feedback controller. The feedforward controller is needed to cancel the high frequency components of motion. After the breathing motion is filtered out using a high-pass filter with a rather low cut-off frequency of 0.8 Hz, the PSD of the motion signal is composed of very narrow peaks at the harmonics of the heart beat frequency. This shows that the moderate-to-high frequency component of the motion signal is quasi-periodic, with frequency equal to heart beat rate, supporting the feasibility of the ARMC algorithm.

## IV. ARMC Control Algorithm Design

### A. Control Algorithms

The key challenge in the design of the ARMC control algorithms is to satisfy the very demanding requirements on tracking error (more than 97% motion cancellation as described in the previous section). We have studied three different control algorithms for their feasibility, Proportional-Derivative (PD) control, Pole Placement (PP) control, and Model Predictive Control (MPC). The results of the linear quadratic regulator (LQR) output tracking controller was used as the baseline performance. As the LQR output tracking controller non-causally uses the actual heart motion data as the desired trajectory, and is an optimal controller, it provides the practical limit of tracking performance achievable for a mechanism using a linear controller.

The PD and PP controllers are the commonly used feedback based control algorithms. They have been included in the comparison mainly to demonstrate the best achievable performance without using any estimation of the heart motion.

The MPC based output tracking controller we have used combines the LQR optimal control strategy with prediction [4], [5], [1], [2]. The plant model and the given desired trajectory, which extends into the future, provides the prediction. At each time step, the control action is calculated by solving a finite horizon linear quadratic optimal control problem, which compares the predicted plant signals to the provided desired trajectory and the control objectives during a given time horizon. The prediction horizon recedes as time progresses.

*Heart Motion Estimation for the MPC controller:* A key component of the MPC controller for the ARMC algorithm is the estimated motion of the heart which is provided to the controller. Ginhoux et al. [6], [7] use an adaptive observer, which identifies the Fourier components of the past motion at the base heart rate frequency and its several harmonics, to estimate the future motion. This approach assumes that the heart rate stays constant. In this study, we used a simpler estimation which uses the motion of the heart from the previous cycle as a prediction of the next cycle. In figure 5, the actual and the estimated motions can be seen as the control executes. The current time for which the control is being executed, is noted by the circle in the plot, and the asterisk shows the final horizon value that is being used for the MPC controller. Although this approach yields large errors

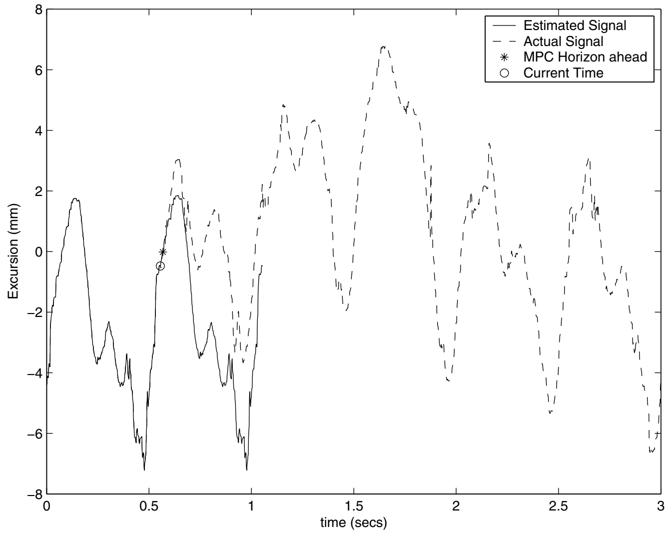


Fig. 5. Estimated and actual heart motion.

in extended estimates (Fig. 5), this should not become a determining issue as the horizons used in the MPC algorithm are relative short compared to the heart cycle.

### B. Experimental Setup

The control algorithms described above were implemented on two 1-DOF experimental test-beds, a subwoofer speaker and the first axis (base rotation) of the PHANToM$^{TM}$ Premium version 1.5 3-DOF haptic interface. The subwoofer speaker is an intrinsically stable device and possesses a highly repeatable nature. Though smaller speakers generally do not move with great amplitudes, subwoofers have excursions of several inches, and are typically designed to move at the lower end of audio frequency range. This combination of high bandwidth and large excursions make a subwoofer speaker an ideal initial test bed for algorithm development. The PHANToM robot possesses different characteristics from those of the subwoofer speaker and will provide more insight into the effectiveness of the algorithms as it is a realistic test-bed set-up. The PHANToM's lightweight, low-inertia, high-bandwidth mechanism, with sufficiently high force output capabilities to be able to carry out the manipulations required for the CABG surgery, embodies the desired design characteristics of the next generation robotic system for beating heart surgery.

The subwoofer setup was made up of a MTX Audio T8124A speaker (4Ω, 400W, 24.4mm peak-to-peak excursion), an ultrasonic sensor (Cleveland Motion Controls Pulsonic Sensor, with the configured range of 6.35-25.4cm, repeatability of 0.0127 cm, gain of 2.54 cm/V gain, and an update rate of 800 Hz), a generic PWM based current amplifier (15A, 3kHz bandwidth, 25 kHz switching rate), and a Pentium 3 based PC running QNX operating system as the control computer. The PHANToM setup was made up of a PHANToM Premium version 1.5 haptic interface with custom drive electronics (as described in [3]) and a Pentium 4 based PC with QNX operating system as the control computer.

A third-order system transfer function model, which include the inertia of the speaker and the amplifier roll-off, identified using basic system identification[1], was used to design the controllers for the subwoofer test-bed :

$$G_1(s) = \frac{5.533 \times 10^5}{s^3 + 96.24s^2 + 1.339 \times 10^4 s + 6.313 \times 10^5}[mm/V]. \tag{1}$$

System identification performed on the first axis (base rotation) of the PHANToM setup revealed a sixth order transfer function model with a small second order resonance effect. A fourth order transfer function model obtained from this sixth order model by balanced model reduction (which effectively ignored the resonance effect) was used for the design of the control algorithms:

$$G_2(s) = \frac{983.6s^2 + 1.784 \times 10^4 s + 8.691 \times 10^7}{s^4 + 200.2s^3 + 3.234 \times 10^5 s^2}[rad/Nm]. \tag{2}$$

The system identification also revealed Coulomb friction value of $0.045$ Nm. With the exception of PD control, all control algorithms were implemented using state-space realizations and utilized state feedback. As only positions were directly sensed, an observer was implemented for each of the plant models to obtain the full state vector for state feedback.

The experiments utilized pre-recorded real heart motion data (described in Section III) rather than an on-line measurement of the target motion (i.e. heart motion) as the input to the control algorithms. Rather than picking one of the principal axes, the motion along the axis of largest displacement was used as the heart trajectory to achieve the most demanding test case. It should be noted that the test data did not include any noticeable rhythm or breathing abnormalities beyond physiologically normal variations.

### C. Experimental Results

The results of the tracking experiments are summarized in Table I. The reported values are the RMS error and the RMS control action values. The error values for the PHANToM set-up include both the angular error (in mrad) and corresponding displacement error (in mm) for the 215mm arm length of the PHANToM. The tracking results for the MPC controller with the PHANToM set-up is shown in Fig. 6.

TABLE I

SUMMARY OF THE EXPERIMENTAL RESULTS FOR THE SUBWOOFER AND PHANTOM SET-UPS.

| | Speaker | | PHANToM | |
|---|---|---|---|---|
| | Error mm | Control Action V | Error mrad (mm) | Control Action Nm |
| LQR | 0.28 | 0.33 | 0.683 (0.147) | 0.0526 |
| PD | 1.4 | 0.23 | 1.22 (0.262) | 0.327 |
| PP | 0.82 | 0.37 | 1.37 (0.295) | 0.304 |
| MPC | 0.46 | 0.33 | 1.09 (0.234) | 0.196 |

[1]The subwoofer set-up also had several nonlinear effects which were compensated. The details are outside the scope of this paper and can be found in [15]

### D. Discussion of the Experimental Results

The MPC based controller, which used the estimation of the heart motion, was able to outperform the feedback based controllers, both in terms of the RMS error and in terms of the control action used. It was able to maintain a reasonable control effort while showing accuracy very close to the desired specification. However, a comparison with the baseline performances demonstrated by the LQR controller for both of the set-ups reveal that there is still room for improvement with using better motion estimation algorithms.

## V. Conclusion and Future Work

As a result of the experiment and analysis presented above, two important pieces of information is obtained for the design of the intelligent robotic tools for off-pump CABG surgery. First, this study revealed one of the most important requirements on the mechanism and control design for the robotic ARMC: the required bandwidth and precision of the system for proper ARMC. Second, we observed that the moderate-to-high frequency component of the heart motion is quasi-periodic, with frequency equal to heart rate. This means that the control algorithm for ARMC proposed in Section II (Fig. 2) is valid.

The results also demonstrated the feasibility of developing a robotic system for performing off-pump CABG surgery with active relative motion cancelling, using the control architecture for ARMC proposed in Section II (Fig. 2). The reported experimental tracking results (of 234$\mu$m RMS error), which were collected on a realistic hardware test-bed, are significantly better than the earlier results reported in the literature with about 10 times smaller tracking errors. The next steps of the research will be the development of model based estimation of the heart motion using biological signals, and extending the algorithms to 3-DOF tracking case.

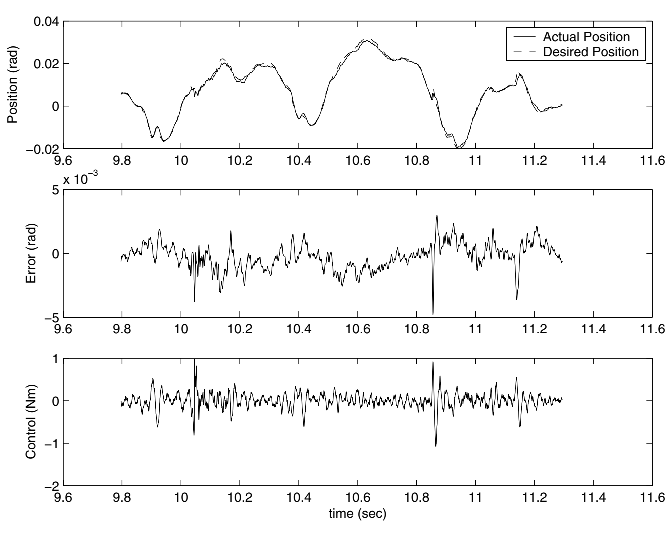


Fig. 6. PHANToM MPC tracking results.

## VI. Acknowledgements

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