Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Model Based Control Algorithms for Robotic Assisted Beating Heart Surgery

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Abstract— **Robotics technology promises an enhanced way of performing off-pump coronary artery bypass graft (CABG) surgery. In the robotic-assisted CABG surgery, surgeon performs the operation with intelligent robotic instruments controlled through teleoperation that replace conventional surgical tools. 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. This algorithm is called Active Relative Motion Canceling (ARMC). In this paper, the use of biological signals to achieve better motion canceling in the model-based intelligent ARMC algorithm is presented. Also, integration of arrythmia detection and handling with the ARMC algorithm is proposed in order to provide safety over the system. Finally, tracking results of combined respiratory motion and heartbeat motion on a 3-DOF robotic test-bed system are reported.**

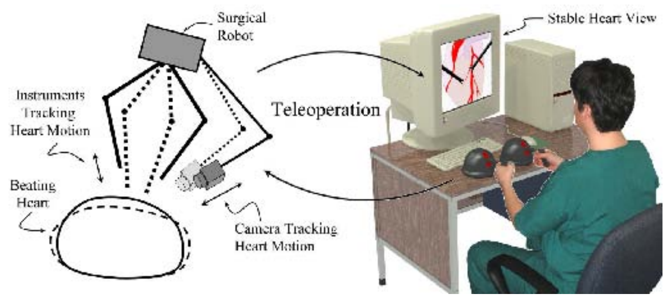

Fig. 1. System concept for Robotic Telesurgical System for Off-Pump CABG Surgery with Active Relative Motion Canceling (ARMC). Left: Surgical instruments and camera mounted on a robot actively tracing heart motion. Right: Surgeon operating on a stabilized view of the heart, and teleoperatively controlling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

I. INTRODUCTION

Off-pump Coronary Artery Bypass Graft (CABG) surgery is preferred over the on-pump CABG surgery because of the complications resulting from the use of the cardio-pulmonary bypass machine, which include long term cognitive loss [1], and increased hospitalization time and cost [2]. 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 surgeries, 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 Canceling (ARMC) algorithms, allowing CABG surgeries to be performed on a beating heart with technical perfection equal to traditional on-pump procedures.

In the proposed robotic assisted surgery concept, conventional surgical tools are replaced with robotic instruments which are under direct control of the surgeon through teleoperation (Figure 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, canceling 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 surgery where the heart is passively constrained to dampen the beating motion. We call the proposed control algorithm "Active Relative Motion Canceling (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.

This paper discusses the design and implementation of intelligent control algorithms for telerobotic systems, utilizing biological signals in a model-based predictive control fashion. In the robotic assisted heart surgery, detection of unexpected rhythm abnormalities and arrhythmias is a problem that has not been adequately addressed. Proposed ARMC algorithm uses a heart model utilizing biological signals to detect and handle any irregularities during the robotic assisted operation.

Section II reviews the literature of related work in the field. Details on the ARMC algorithm is provided in Section III of the paper. Section IV describes the control algorithms used in the tracking problem. In Section V, simulation and experimental results are presented. Finally, the conclusions are presented.

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II. Related Work in the Literature

The earlier studies in the literature on canceling biological motion in robotic assisted medical interventions are focused on cancelation of respiratory motion. Schweikard *et al.* and Sharma *et al.* studied the compensation of the breathing motion in order to reduce the applied radiation dose to irradiate tumors [3], [4]. Both studies concluded that motion compensation was achievable. In [5], Riviere *et al.* looked at the cancelation of respiratory motion during percutaneous needle insertion. Results showed that an adaptive controller was able to model and predict the breathing motion. Trejos *et al.* conducted a feasibility study on the ability to perform tasks on motion-canceled targets, and demonstrated that tasks could be performed better using motion canceling [6].

In [7], Nakamura *et al.* performed experiments to track the heart motion with a 4-DOF robot using a vision system to measure heart motion. The tracking error due to the camera feedback system was relatively large (error in the order of few millimeters in the normal direction) to perform beating heart surgery. 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 rat's heart [8]. Groeger *et al.* used a two-camera computer vision system to measure local motion of heart and performed analysis of measured trajectories [9], and Koransky *et al.* studied the stabilization of coronary artery motion afforded by passive cardiac stabilizers using 3-D digital sonomicrometry [10].

Ortmaier *et al.* [11] reported significant correlations between heart surface trajectory and Electrocardiogram (ECG) signals, which implies these inputs can be used interchangeably. ECG signal was utilized in visual measurement of heart motion using a camera system. It was employed in estimation of the motion when the surgical tools occluded the view. Heart motion estimation was not based on a heart motion model and completely depended on the early recorded heart position data. Actual tracking of the heart motion using a robotic system was aimed as a future work.

More recently, in a pair of independent parallel studies by Ginhoux *et al.* [12] and Rotella [13], motion canceling through prediction of future signals was demonstrated. In both studies, model predictive controllers were used to get higher precision tracking. In the former, a high-speed camera was used to measure heart motion. 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 [12]) in each of the directions in a 3-DOF tracking task. Although it yielded better results than earlier studies using vision systems, the error was still very large to perform heart surgery, as operation targets to be manipulated using the robotic systems in a CABG surgery are blood vessels with 2 mm or less diameter. In [13] accuracy very close to the desired error specifications for heart surgery were achieved on a 1-DOF test bed system, and Rotella concluded that there still was a need for better signal prediction.

The initial part of this study was presented in [14] and [15]. In [14], Cavusoglu *et al.* showed the feasibility of a robotic system performing off-pump CABG surgery with the proposed ARMC algorithm. In [15], Bebek and Cavusoglu demonstrated that using ECG signal in the motion estimation improved tracking results. Heart motion tracking results on a 3-DOF test bed system were 2.5 times better than the best results reported in the literature [12]. This paper extends the work presented in [14] and [15] by combining respiratory motion tracking and heartbeat motion tracking, and also by integrating arrythmia detection and handling with the heart model used in the ARMC algorithm.

III. Intelligent Control Algorithms for Model Based ARMC

The control architecture proposed in this research project is shown in Figure 2. In this architecture, the control algorithm fuses information from multiple sources: mechanical motion sensors which measure the heart motion and sensors measuring biological signals. The control algorithm identifies the salient features of the biological signals and merge these information to predict the feedforward reference signal. This improves the performance of the system since these signals are results of physiological processes which causally precede the heart motion.

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.

Motion of the point of interest (POI) has two dominant modes of motion: heartbeat motion and respiratory motion (details on the heart data and ECG data can be found at [14], [15]). These two modes are separated by using a pair of complementary filters as shown in the algorithm architecture (see Figure 2). The control path for tracking of the heartbeat component of the motion has significantly more demanding requirements in terms of the bandwidth of the motion that needs to be tracked. That is why a more sophisticated feedforward algorithm is employed for this part. Breathing motion has a significantly lower frequency and it is canceled by a purely feedback based controller. The robot motion control signal is computed by combining these two parts. The feedforward part is calculated with the signal provided by the heart motion model and the feedback signal is calculated with the direct measurements of heartbeat and respiratory motions. The feedforward controller is designed using model predictive control [16] and optimal control [17], [18] methodology of modern control theory, as described in Section IV.

The confidence level reported by the heart motion model is 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. This confidence level will also be used to adaptively weigh the amount of feedforward and feedback components used in

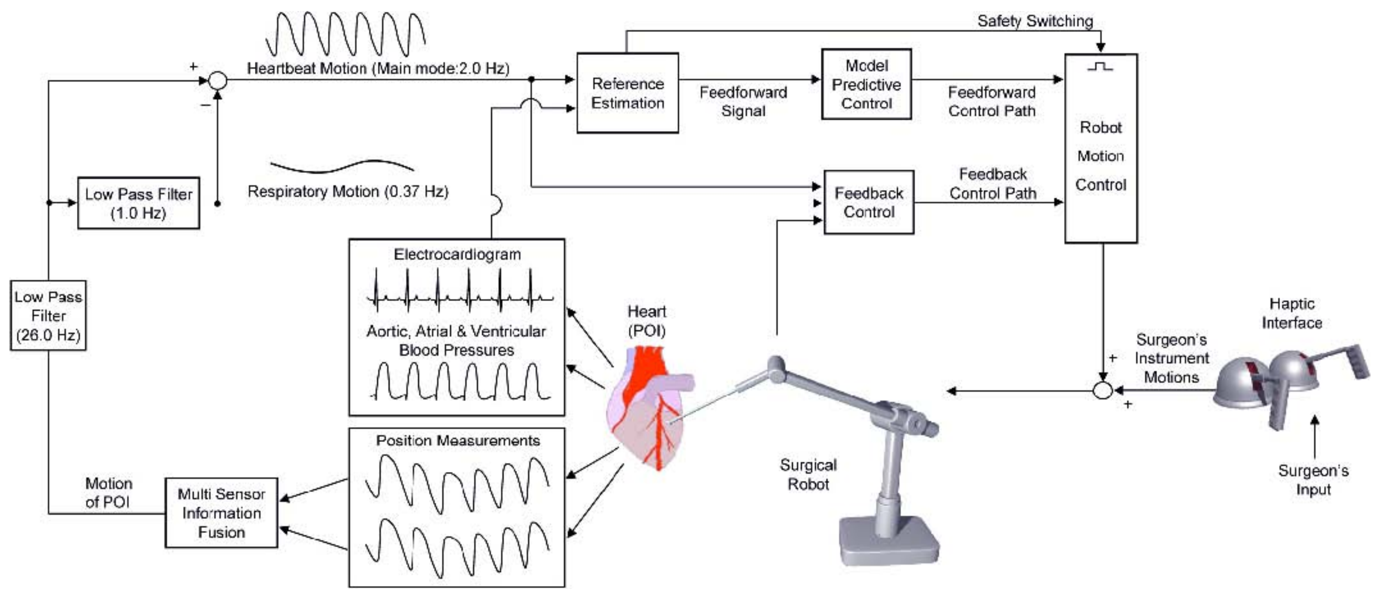

Fig. 2. Proposed control architecture for designing Intelligent Control Algorithms for Active Relative Motion Canceling on the beating heart surgery.

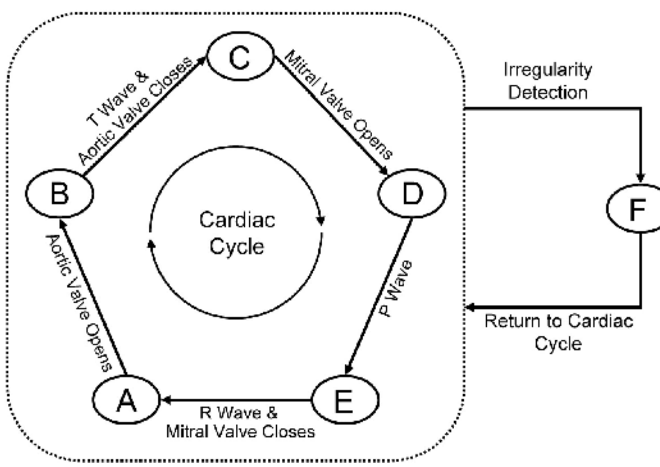

Fig. 3. A state model of the beating heart. Transition between the states are depicted using ECG waves and the motion of the heart valves, which can be inferred from blood pressure measurements. States forming the cardiac cycle are: **A**-Isovolumic contraction. **B**-Ejection. **C**-Isovolumic relaxation. **D**-Ventricular filling. **E**-Atrial Systole. **F**-Irregularity in the Cardiac Cycle.

the final control signal. These safety features will be an important component of the final system.

With the architecture proposed in this paper, system's awareness will be increased by utilizing a heart motion model in reference signal estimation. Inclusion of biological signals in a model-based predictive control algorithm increases the estimation quality, and such a scheme provides better safety with more precise detection of anomalies and switching to a safer mode of tracking.

ECG contains records for the electrical activity of the heart. Each of these electrical stimulations results in a mechanical muscle twitch. Thus, the identification of ECG waves and complexes would help determine the heart activities since these are the physiological processes which causally precede the heart motion. Therefore, ECG signal is very suitable for period-to-period synchronization with sufficient lead time for feedforward control, and identification of arrhythmias. Biological signals other than ECG that can be used to assist the tracking of heart motion are aortic, atrial and ventricular blood pressures. Similar to ECG signal, these 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, which in turn helps us determine 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 give additional independent information, which can be used in conjunction with ECG signal to improve noise robustness and to reliably detect unexpected rhythm abnormalities and arrhythmias.

In Figure 3, a state model for the cardiac cycle is shown. The model involves primary states of the heart's physiological activity. Transitions between the states are depicted using the states of the mitral and aortic valves of heart and P, R and T waves of the ECG. During the ECG wave form detection process, QRS complex is detected and used in substitute to R wave. Any out of sequence or abnormal states in the cycle can be identified as irregularity. Using this model, rhythm abnormalities and arrhythmias can be spotted and system can be switched to a safer mode of operation.

IV. Control Algorithms

The control algorithm is the core of the robotic tools for tracking heart motion during CABG surgery. The robotic tools should have high precision to satisfy the tracking requirements. 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.

A key component of the ARMC algorithm is the reference motion estimation of the heart which is provided to the feedforward path. If the feedforward controller has high enough precision to perform the necessary tracking then the tracking problem can be reduced to predicting the estimated reference signal effectively.

Reference Signal Estimation

Heartbeat is a quasi-periodic motion with small variations in every beating cycle. If the past heartbeat motion cycle is known, it can be used as an estimate reference signal for the future cycle. Any measured heart position value can be approximated forward one cycle as long as the heartbeat period for that cycle is known. In this case, a constant heartbeat period was used to store one period length of the heartbeat signal and that was used as a prediction of the next cycle. The stored beating cycle was used as the approximate future reference beating signal in the ARMC algorithm.

Any position offset between the heart position and reference estimate was compensated using a polynomial error correction function, such that the error was gradually subtracted from the estimate up to some point ahead.

Reference Signal Estimation Using Biological Signals

Although the position offset between the last and future beating cycles can be eliminated gradually using the technique above, the error due to changes in heartbeat period remains. Because heartbeat is a quasi-periodic motion with small period variations in every beating cycle, these period changes could result in large offsets in the estimated signal, resulting jumps during the tracking.

We therefore introduced a second technique for estimating the reference signal to handle period variations using biological signals. QRS, T, and P wave forms of the ECG were used as check points for detecting current heartbeat period. These wave forms were detected in hard-real-time by an algorithm adapted from [19]. Bahoura *et al.* evaluated the original algorithm in real-time with the MIT-BIH Arrythmia Database [20]. This database contains 48 half-hour excerpts of two-channel ambulatory ECG recordings. They reported a 0.26% false detection rate (126 false positive beats and 180 false negative beats out of 116,137 beats), showing the algorithms capability in detecting QRS complexes. We used constant detection parameters instead of adaptive ones, and obtained a 1.49% false detection rate using the same database (408 false positive beats and 709 false negative beats out of 75,010 healthy beats).

With this method, QRS-T-P waves were detected in real time for the collected 56 s ECG data with 100% QRS complex and T wave detection rates, and 97.3% P wave detection rate. In this reference estimation technique, rather than using a constant heartbeat period, a variable period calculated using ECG was used. This period was calculated by averaging the periods of the three ECG wave forms. The period was updated continuously as new wave forms were detected.

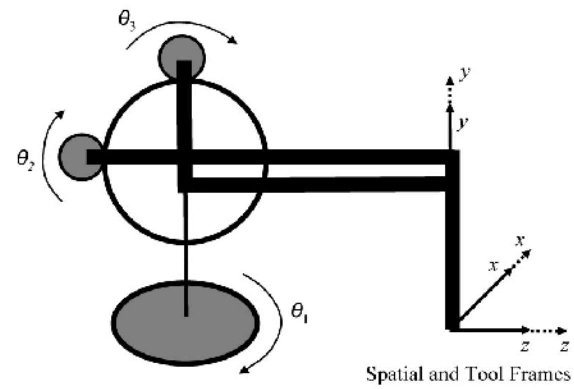

Fig. 4. Zero Configuration of the PHANToM manipulator, also showing the axes movements and spatial and tool frames.

Receding Horizon Model Predictive Control

Having the estimated future trajectory in hand, the following control problem arises: "Tracking of heart motion where there is some knowledge of the future motion." This can be achieved using a model based optimal controller. In this case, a Receding Horizon Model Predictive Control (RHMPC) algorithm was used [17]. In RHMPC the optimal gains are calculated for a receding horizon at every control step. With every control cycle, a new point on the desired signal is used and an old point is dropped in the gain calculation. The calculation is then repeated at every control cycle. The prediction horizon recedes as time progresses such that furthermost point ahead is considered to be moving one step for every control cycle.

V. Simulation and Experimental Results

In order to find the performance of the estimation algorithms, a RHMPC with known future reference signal was also tested. Knowing the future reference signal for the RHMPC algorithm is close to perfect tracking. However using the future reference signal in heart tracking is not feasible as this makes the algorithm acasual. In this case, it was used to show the base line performance.

Test Bed System

PHANToM® Premium 1.5A robot was used as a hardware test-bed system for the development of the algorithms. In Figure 4, the degrees of freedom and the zero configuration of the manipulator is shown. For detailed derivation of the mathematical model of the PHANToM robot, see [21]. The PHANToM robot possesses similar characteristics of an actual surgery robot. Its lightweight links, low inertial axes and drive system allows sufficient motion and speed abilities for tracking the heartbeat signal.

In the experiments, prerecorded heart motion signal and ECG signal were used. The robot was made to follow the combined motion of heartbeat and breathing as described in Section III. Separating the respiratory motion enabled better heart motion estimation. In terms of control performance, controlling the respiratory motion separately did not affect the heart tracking accuracy when we compare the results of

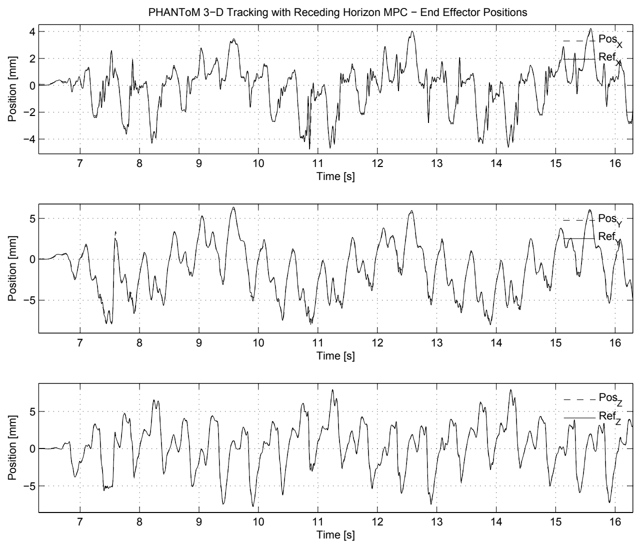

Fig. 5. PHANToM End-effector results for Receding Horizon MPC with Exact Reference Information. Reference and Position signals of the x-y-z axes are shown.

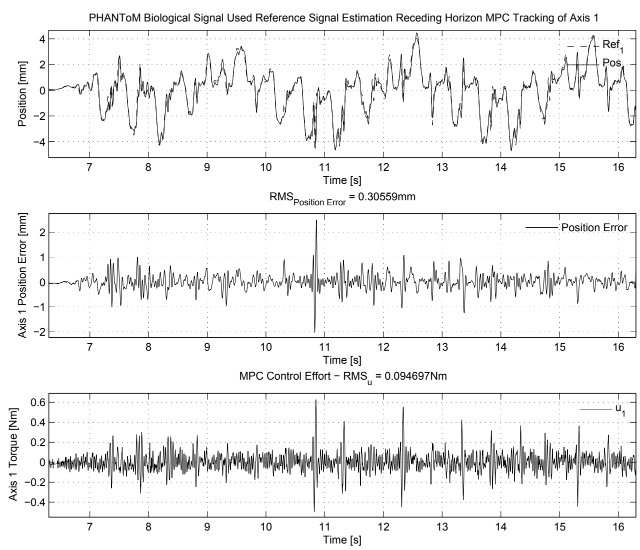

Fig. 6. PHANToM 1^{st} axis results for Receding Horizon MPC with Reference Estimation using ECG Signal. Reference and Position, Position Error, and Control Effort signals are shown.

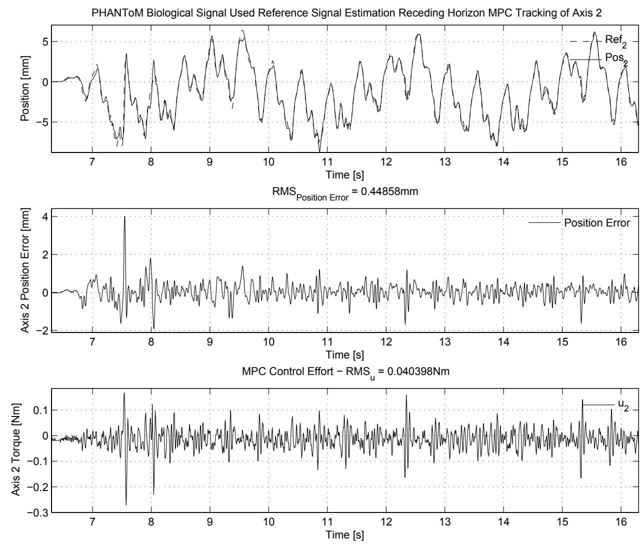

Fig. 7. PHANToM 2^{nd} axis results for Receding Horizon MPC with Reference Estimation using ECG Signal. Reference and Position, Position Error, and Control Effort signals are shown.

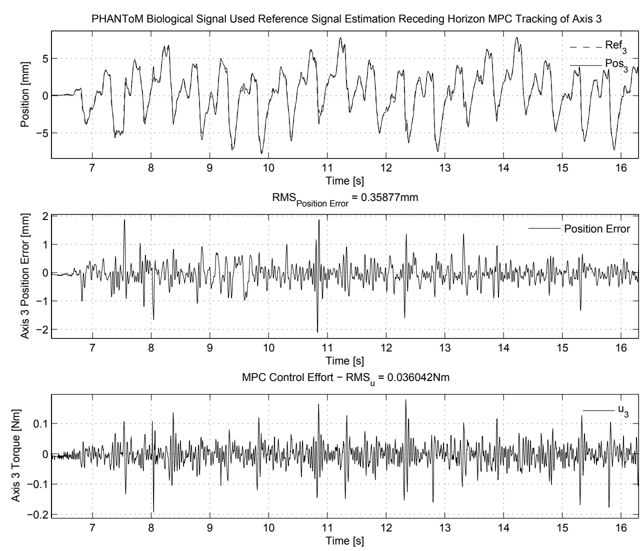

Fig. 8. PHANToM 3^{rd} axis results for Receding Horizon MPC with Reference Estimation using ECG Signal. Reference and Position, Position Error, and Control Effort signals are shown.

the combined motion tracking with the pure heartbeat motion tracking results of [15]. This validates our earlier observation that heartbeat motion tracking will be the bottleneck in motion tracking and the breathing motion can be easily tracked using a pure feedback controller.

Experimental Results

For each case, experiments on PHANToM robot were repeated 10 times. Among these results, the maximum values for the End-effector RMS Position Error and RMS Control Effort are summarized in Table I to project the worst cases. It was noted that the deviation between the trials are relatively small. Tracking results of the end-effector of the PHANToM for Receding Horizon Model Predictive Control with Exact Reference Information is shown in Figure 5. Low frequency respiratory motion is clearly visible in the y-direction. Receding Horizon Model Predictive Control with Reference Signal Estimation using ECG signal results for each axis are shown in Figures 6, 7, and 8. All three axes of the PHANToM demonstrated similar performance. Peaks in the position error are due to the noisy data collected by sonomicrometric sensor. Although high frequency parts of the raw data are filtered out, relatively low "high frequency" components stayed intact. It is unlikely that POI on the heart is capable of moving 5 mm in milliseconds time.

If we compare the results of the algorithms with each other, as predicted, the RHMPC with Reference Signal

TABLE I

END-EFFECTOR SIMULATION AND EXPERIMENTAL RESULTS: *Summary of the maximum end-effector RMS position error and RMS control effort values for the control algorithms used.*

End-effector Tracking Results	*RMS Position Error*		*RMS Control Effort*	
	Simulation	PHANToM	Simulation	PHANToM
Units	mm		Nm	
Receding Horizon MPC with Exact Reference Information	0.2948	0.2839	0.0145	0.0485
Receding Horizon MPC with Reference Signal Estimation	0.5477	0.6738	0.0151	0.0477
Receding Horizon MPC with Reference Signal Estimation using ECG Signal	0.4909	0.6535	0.0163	0.0570

Estimation Using Biological Signals algorithm outperformed the RHMPC with Reference Signal Estimation algorithm. Results proved that by using ECG signal in the motion estimation, heart position tracking was not only improved but also became more robust. The tracking results are 2.5 times better than the best results reported in the literature [12]. Comparing the predictive algorithms' results with the baseline performance results shows that, there is still room for improving the estimation algorithm.

CONCLUSIONS

In this paper, the use of biological signals in the model-based intelligent ARMC algorithm to achieve better motion canceling was presented. Experimental results showed that using ECG signal in ARMC algorithm improved the reference signal estimation. Use of ECG and blood pressure signals was proposed to enhance the tracking performance, and to detect unexpected rhythm abnormalities and arrhythmias.

Separating the respiratory motion and heartbeat motion enabled better heartbeat motion estimation. In terms of performance, controlling the respiratory motion separately did not affect the overall tracking accuracy.

ACKNOWLEDGMENT

This work was supported in part by NSF under grants CISE IIS-0222743, EIA-0329811, and CNS-0423253. We would also like to thank Dr. Mark Ratcliffe for his help during collection of the experimental data.

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