Smith Predictor Based Robot Control for Ultrasound-guided Teleoperated Beating-heart Surgery

Meaghan Bowthorpe, *Student Member, IEEE*, Mahdi Tavakoli, *Member, IEEE*, Harald Becher, and Robert Howe, *Member, IEEE*,

***Abstract*—Performing surgery on fast-moving heart structures while the heart is freely beating is next to impossible. Nevertheless, the ability to do this would greatly benefit patients. By controlling a *teleoperated* robot to continuously follow the heart's motion, the heart can be made to appear stationary. The surgeon will then be able to operate on a seemingly stationary heart when in reality it is freely beating. The heart's motion is measured from ultrasound images and thus involves a non-negligible delay due to image acquisition and processing, estimated to be 150 ms that, if not compensated for, can cause the teleoperated robot's end-effector (i.e., the surgical tool) to collide with and puncture the heart. This research proposes the use of a Smith predictor to compensate for this time delay in calculating the reference position for the teleoperated robot. The results suggest that heart motion tracking is improved as the introduction of the Smith predictor significantly decreases the mean absolute error, which is the error in making the distance between the robot's end-effector and the heart follow the surgeon's motion, and the mean integrated square error.**

***Index Terms*—Beating-heart surgery, Robotic assistance, Ultrasound image guidance**

NOMENCLATURE

$\bar{C}$	A controller in a time delayed system
$\bar{H}$	A transfer function of a time delayed system
$\hat{P}_H, \hat{p}_H$	Estimated position of the heart in the frequency and time domains, respectively
C	A controller in a system without a time delay
D_{RH}, d_{RH}	Distance between the robot and the heart tissue in the frequency and time domains, respectively
e	Command following error ($p_S - d_{RH}$)
G	The plant, i.e., the robot
H	A transfer function of a system without a time-delay
P_H, p_H	Position of the heart in the frequency and time domains, respectively
P_S, p_S	Position of the surgeon in the frequency and time domains, respectively
R	Input signal to a control system
Y	Output signal of a control system
CI	Cubic Interpolation
EKF	Extended Kalman filter
POI	Point of interest
SP	Smith predictor
ZOH	Zero order hold

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Meaghan Bowthorpe is with Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB T6G 2R3, Canada (e-mail: meaghan.bowthorpe@ualberta.ca)

Mahdi Tavakoli, PhD, PEng, is with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB T6G 2R3, Canada (e-mail: mahdi.tavakoli@ualberta.ca)

Harald Becher, MD, PhD, FRCP, is with the Faculty of Medicine and Mazankowski Heart Institute, University of Alberta, Edmonton, AB T6G 2R3, Canada (e-mail: haraldbecher@med.ualberta.ca)

Robert Howe, PhD, is with the School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, 02138, USA (e-mail: howe@seas.harvard.edu)

I. INTRODUCTION

The heart is a quick-moving organ with velocities and accelerations up to 210 mm/s and 3800 mm/s^2, respectively [1] making it an extremely difficult organ to perform a surgical procedure on while it is freely beating. One would require superhuman skills to manually compensate for the heart's fast motion and simultaneously perform a surgical procedure. Hence, most surgical procedures are performed on an arrested heart or on a mechanically-stabilized heart [2].

Arresting the heart may have undesirable side effects. During arrested-heart surgery, the heart is stopped and the patient is connected to a heart-lung machine, which circulates the blood and ventilates the lungs. After the procedure, the heart is massaged and the surgeon attempts to restart it. However, complications such as irregular heartbeats may occur. Other drawbacks include an increased risk of stroke [3] and/or long-term cognitive loss [4]. On the other hand, mechanically-stabilized-heart surgery avoids the dangers of arrested-heart surgery but cannot completely cancel all of the heart's motion and is only effective for surgeries performed on the surface of the heart.

These side effects and limitations can be eliminated if the heart is allowed to beat freely during the surgical procedure. This would be feasible if a robot could follow the heart's beating motion, allowing the surgeon, who is teleoperating the surgical robot, to operate on a seemingly stationary heart. In addition, normal heart beating motion during the surgery would allow for *intra-operative* evaluation of the effectiveness of reconstructive procedures on dynamic heart structures (e.g., mitral valve repair), which is impossible when the heart is arrested. Such a surgical system can use techniques inspired by the somewhat similar problem of motion compensation for hand tremor reduction [5].

The ability to track the location of the point of interest (POI) on the heart is essential for the development of the proposed motion-compensating, beating-heart, robot-assisted surgical system. Various types of sensors can be used to gather this information. For example, the heart's position can be measured by direct contact using a force sensor, by sonomicrometry crystals, by high frame rate cameras, or by medical scanners. Force sensors have been applied in catheter-based cardiac procedures [6], and sonomicrometry crystals have been used to prevent occlusions caused by surgical tools in visual data [7]. Some researchers mechanically stabilized the heart first and then tracked the residual motion with a camera [8]. High-frame-rate video cameras provide rich visual data, but can only be used for extracardiac procedures [9]; whereas, medical (mainly ultrasound) scanners provide images of the tissue and can be used for both intracardiac and extracardiac procedures [10]. However, medical scanners have low frame rates. For instance, the frame rate of a 3D ultrasound scanner can be as low as 28 Hz [11]. The location of the POI must be found in each image frame, which introduces a delay. This time delay and the low image acquisition rate must be compensated for. Otherwise, the teleoperated robot end-effector (i.e., the surgical tool) may collide with and puncture the fast-moving heart. Despite these drawbacks, ultrasound images are used for this research as they have the ability to visualize the entire heart, even through the opaque blood pool. This is important as the goal is to have a robot simultaneously follow a POI regardless of whether it is on the interior or exterior surface of the heart.

Once the location of the POI on the heart has been tracked, the robot-assisted surgical system can be made to follow the heart's motion. In addition, the surgeon must also be able to control the surgical robot-assisted system in order to perform a surgical procedure. Different techniques have been employed to allow the surgeon to control the surgical robot-assisted system. For example, the surgeon could use a motion compensating hand-held tool [10] and [11]. Another possibility is to attach the surgeon's arm to a platform which is moving in the same manner as the beating heart [12]. Many, including the proposed research, involve a user interface for the surgeon as part of a teleoperated robot-assisted surgical system. Finally, although beyond the scope of this paper, giving the surgeon a stabilized view of the heart will make performing the surgical task much more intuitive [13].

A. Representative Image-guided Procedures

While image-based heart position tracking can be procedure-specific, the Smith predictor based robot control methods developed in this paper apply to any teleoperated surgery on the beating heart that is performed under medical image guidance. As a specific example, we describe pericardiocentesis and annuloplasty as well as the related image processing method for tracking a POI on the heart under ultrasound image guidance.

1) Pericardiocentesis: Pericardiocentesis is a surgical procedure that is performed when there is a build-up of excess fluid in the pericardial sac that must be drained. The extra fluid puts increased pressure on the heart and does not allow it to beat properly. The fluid is drained by inserting a needle through the chest wall and into the pericardial sac as shown in Fig. 1. Currently, the surgeon inserts the needle (while the heart is beating and the patient is conscious) with little to no intra-operative image guidance [15]. As a precaution and to limit the chest motion, the patient is instructed to hold his/her breath as the needle is inserted. However, if the needle punctures a coronary artery, immediate surgery may be required to stop the bleeding, making this emergency procedure highly stressful. To reduce the risks associated with this procedure, the general framework of beating-heart surgery using a heart motion-synchronized needle can be applied. This will allow the surgeon to insert the needle as if the heart wall is stationary, making the operation safer for the patient and less stressful for the surgeon.

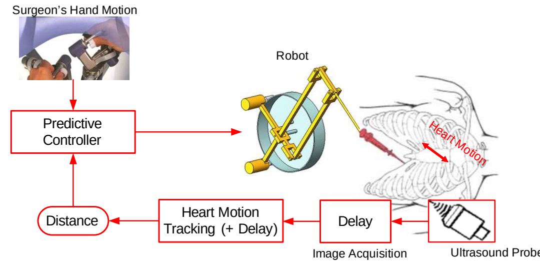

Fig. 1: The teleoperated image-guided beating-heart surgical setup for pericardiocentesis. The needle is inserted through the chest wall and into the pericardial sac but should stop short of the heart tissue [14].

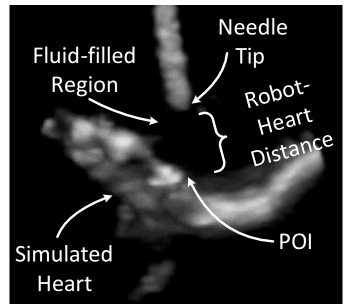

Fig. 2: A 3D ultrasound of the experimental setup. The bright areas of the image are simulated tissue and the needle and the dark areas are fluid-filled regions.

2) Annuloplasty: Annuloplasty is a surgical procedure that is performed when the mitral valve is not closing properly, thus a lower volume of blood is pumped during each heart beat due to regurgitation. To correct this, an annuloplasty ring is stapled around the mitral valve to reshape it. The ability to perform this procedure while the heart is beating would allow the surgeon to evaluate the function of the reshaped mitral valve on the fly. The surgeon would then be able to readjust the shape of the mitral valve as necessary during the procedure. Currently, the result of the procedure is only known after the heart is restarted when it is too late to make adjustments. If a surgical tool could be made to follow the mitral valve's one dimensional motion [1], it would offer a better outcome of the procedure for the patient.

B. Image-based tissue tracking

For this work we use three-dimensional ultrasound images from SONOS 7500 (Phillips Medical, Andover, MA) as they are non-invasive and can image the exterior and interior of the heart. A two-dimensional ultrasound image could also have been used if a needle guide [16] properly oriented the needle to ensure it is visible in the ultrasound plane. To virtually stabilize the heart via proper control of the robot, the distance between the heart tissue and the needle tip must be measured in each image frame. This distance is calculated using the flashlight method developed by Novotny et al. [17], where the axis of the needle is found using a Radon transform. This axis is then extended towards the heart tissue. The POI (the heart wall) is the closest change from a dark area (the fluid-filled region) to a light area (the tissue) beyond the needle tip along this axis, and is marked as POI in Fig. 2. The distance between this tissue location and the needle tip is recorded as the robot-heart distance.

II. Prior Art

Prior art has attempted different and sometimes intertwined methods of controlling robots to follow the heart's quasi-periodic motion. Here, we will first distinguish at a high level between two approaches to delay compensation: *prediction algorithms*, which *feed-forward the predicted* POI's position as the reference position for the teleoperated robot, and *predictive controllers*, which account for the POI measurement time delays in a *feedback* structure and are thus informed by the dynamic characteristics of the robot. Given that the reference position for the robot includes the measurement of the fast-varying heart position, it is important to take into account the dynamics of the robot. Table I summarizes the above and states if the heart's position is determined from medical images (thus introducing delays), and if the surgical robot's dynamics have been considered. Throughout the rest of the paper, heart position measurement delay is simply referred to as delay.

A. Feedforward compensation of delay through prediction

Most past research involving prediction and feed-forward delay compensation neglects the surgical robot's dynamics and does not involve feedback control. Instead, the focus is solely on predicting the heart's position.

Yuen et al. compare the performance of three heart position estimation methods: an extended Kalman filter and two autoregressive models, one with a least-squares estimator and one with a fading memory estimator [11]. The heart position data is collected from ultrasound images. This predictor is then used to control a *hand-held* one-dimensional motion compensation tool for mitral valve repair [1]. Interestingly, as the surgical tool is hand-held, there is no dynamic effect intervening between the surgeon's position and the rigid tool's position, and the intervening dynamics between the reference position and the actual position, which is that of a voice coil linear actuator, is neglected.

TABLE I: The previous research has been divided into different categories based on whether medical images were used to track the heart position and whether the robot dynamics were considered in the surgical robot control method.

	Prediction or Predictive Control	Image-Based	Robot Dynamics
[1]	Prediction	No	No
[7]	Prediction	No	Yes
[11]	Prediction	Yes	No
[18]	Prediction	No	Yes
[19]	Predictive Control	No	Yes
[20]	Predictive Control	No	Yes
Proposed Method	Predictive Control	Yes	Yes

Other prediction methods address heart rate variability through the use of adaptive filters, which slowly change the length of the predicted heart beat to make it coincide with the length of the actual heartbeat. In [18], the heart's position was captured with sonomicrometry crystals, not with medical images.

Bebek and Cavusoglu employ an electrocardiogram-triggered feed-forward prediction approach [7]. The heart position from the past heartbeat is used to predict the heart position in the current heartbeat and the patient's electrocardiogram is used to ensure that the beginning of the actual and predicted heartbeats are synchronized. Again the heart position is captured with sonomicrometry crystals.

B. Feedback compensation of delay through predictive control

Past research also considers the robot dynamics in a feedback structure. Predictive controllers use the dynamic model of the robot in a feedback structure to account for the delay inherent in the measurement of the heart position.

Ginhoux et al. consider the respiratory- and the heartbeat-induced motions of the heart and compensate for them separately [19], [20]. A repetitive ARIMAX model with periodic noise is used to model the respiratory component of the heart motion. The heartbeat-induced motion is the remaining motion which is modeled by a Fourier series containing the base frequency (the heart rate) and the first five harmonics. A very high-frame-rate (500 Hz) camera is used to obtain images of the heart surface for extracardiac tissue tracking but, time delay compensation is not addressed.

The proposed research takes the next logical step and introduces a model that considers *both the time delay due to the image-based heart motion tracking and the teleoperated robot's dynamics in a feedback control structure*. While a variety of methods are used to estimate the current heart position, we augment the feedback control system with a modified Smith predictor to ensure that the teleoperated robot remains at a set distance from the heart as commanded by the surgeon's hand position despite the time delays caused by image acquisition and operations needed for calculating the heart position.

This paper is organized as follows. Section III discusses the Smith predictor principles. The research problem is formulated in Section IV and the implementation of the Smith predictor in a teleoperated beating-heart surgical system is described in Section V. Sections VI and VII highlight simulation and experimental results, respectively. Finally, concluding remarks are given in Section VIII. Throughout the remainder of this paper, the following abbreviations will be used. The end-effector of the teleoperated surgical robot will henceforth be referred to as the robot. The time delay in measuring the heart's position due to ultrasound image acquisition and processing will simply be the delay.

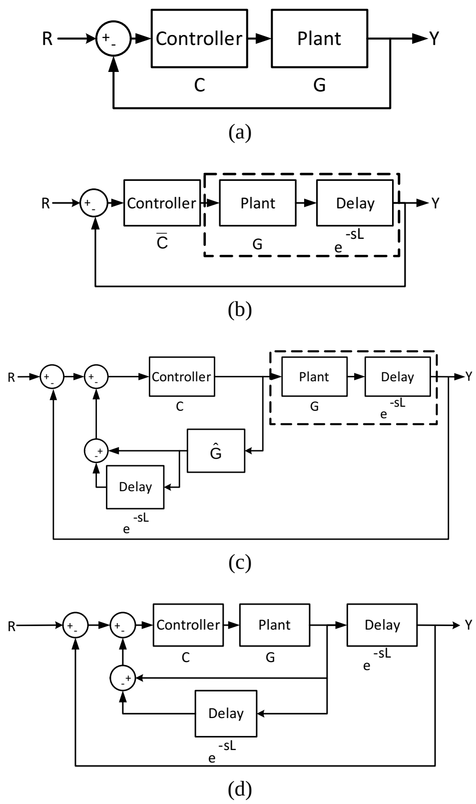

Fig. 3: (a): A standard feedback controller and plant that does not include time delay. (b): A standard feedback controller and plant with time delay. (c): The Smith predictor is added to the feedback loop where the plant's model must be estimated. (d): The Smith predictor is added to the feedback loop where the plant's model does not need to be estimated.

III. Preliminaries: Smith Predictor

A Smith predictor is a predictive feedback controller used to ensure that a closed-loop control system retains its stability and good performance in the presence of a known, fixed time delay within the loop [21]. Consider the generic feedback loops in Figs. 3a and 3b. To begin, as shown in Fig. 3a, the controller C is designed in the no delay closed-loop system H where

$$H = \frac{Y}{R} = \frac{CG}{1+CG}. \quad (1)$$

G is the plant transfer function, R is the Laplace transform of the input, and Y is the Laplace transform of the plant's output. For the delayed case in Fig. 3b, the controller C is replaced by $\bar{C}$ and the closed-loop transfer function

$$\bar{H} = \frac{Y}{R} = \frac{\bar{C}Ge^{-sL}}{1+\bar{C}Ge^{-sL}}. \quad (2)$$

To retain the same performance as the no delayed system, we need $\bar{H} = He^{-sL}$. Therefore, $\bar{C}$ is calculated to be

$$\bar{C} = \frac{C}{1+CG(1-e^{-sL})}. \quad (3)$$

The Smith predictor $\bar{C}$ as shown in Fig. 3c requires an estimate of the plant, $\hat{G}$. However, if the plant can be separated from the delay, we do not need the estimate of the plant's model; rather, the output of the plant can be used directly – see Fig. 3d.

IV. Problem Formulation

The goal of beating-heart surgery is to have a teleoperated robot follow the heart at a set distance as commanded by the surgeon's hand position. To accomplish this, a feedback control system must be designed to track the surgeon's position while compensating for the heart's repetitive beating motion. This paper focuses on the heart's beating motion and not the translational motion caused by respiration. A provision for including this translational motion has been included in [19], where the control effort coming from two controllers, one to make the surgical robot follow the heart's motion and another to make the surgical robot follow the respiratory motion, were added together.

The inputs to the robot control system are the surgeon's position p_S and an estimate of the heart's current position $\hat{p}_H$. The measured variable, which experiences delays due to image acquisition and processing, is the distance between the robot and the heart d_{RH}. *The set-point for this distance is the surgeon's position*. Because this distance, the robot-heart distance, is measured from ultrasound images, the robot and the heart tissue must both be visible in each ultrasound image.

A simple feedback loop representing this system is shown in Fig. 4a, where the system has been separated into a part that we can design, "Performed via Software", and a part that we cannot change, "Physical System". In fact, we cannot predict or alter the surgeon's position nor can we change the robot's dynamics or the heart's motion, hence these blocks form the physical system. In contrast, we can design the controller and chose how to calculate the tissue/robot distance from the ultrasound images as these blocks are performed in the software. Note that the configuration in Fig. 4a has no provision for compensating for the heart's motion.

Before commencing the robot control design process, let us make the following observations:

- The heart motion is quasi-periodic,
- The time delay is constant (or can be made constant),
- We are able to extract the last heart beat from the heart motion trajectory.

Next, we will make the following assumptions:

- The robot is a linear time-invariant system and has one degree of freedom,
- The surgeon is capable of performing a surgical procedure in the presence of the above time delay if the heart motion is compensated for.

We have limited the robot to one degree of freedom because both pericardiocentesis and mitral valve annuloplasty only require the surgical tool to be inserted into the patient along a line. Secondly, although it is more difficult, surgeons have the ability to perform a surgical procedure with a teleoperation system with delays of up to 300 ms [22].

As it stands, a shortcoming of the system in Fig. 4a is that, due to the delay present in the feedback loop, it is unstable and/or has poor performance. To tackle this problem, we will use a modified Smith predictor to compensate for the delay to ensure that the system remains stable and performs well.

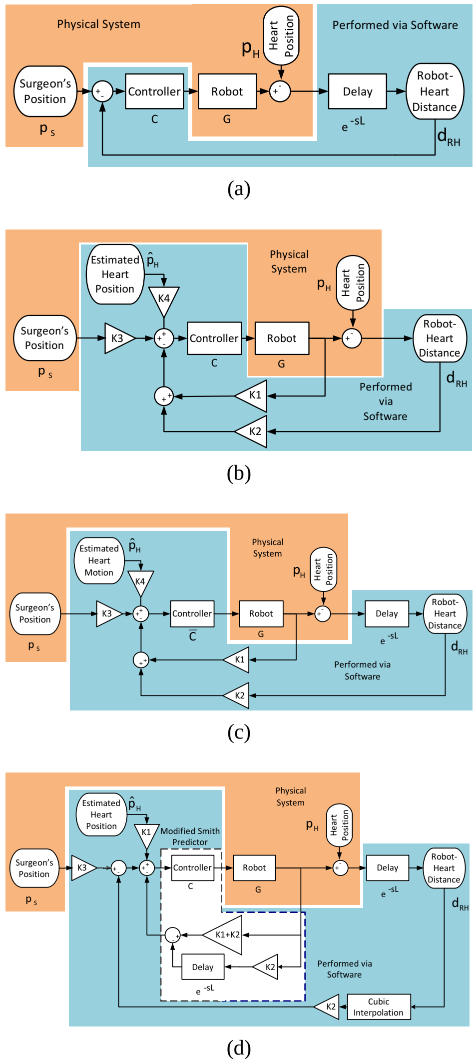

Fig. 4: (a): The initial representation of the components of the feedback controller. (b): The feedback controller designed to make the robot-heart distance follow the surgeon's position. Four gain blocks are added (K_1-K_4), which increase the number of design parameters. (c): The initial controller C is then replaced by a Smith predictor. (d): The complete control loop including the Smith predictor.

V. Proposed Smith Predictor Based Design

In the negative feedback control loop in Fig. 4a, the robot-heart distance only follows the surgeon's position and there is no provision concerning following the heart's motion. Consequently, a prediction or an estimation of the heart's position must be added to the control system – see Fig. 4b. The feedback loop incorporates this estimate as an additional position set-point for the robot-heart distance. Since the heart's motion is quasi-periodic, the measured positions from the previous heart beat is deemed useful in estimating the heart's position in the current beat. This feedback loop helps the robot follow the heart's (outdated) position as well as the surgeon's (current) position. To add more design parameters, four gain blocks, K_1, K_2, K_3, and K_4, have been added: one for each feedback loop and one to scale the surgeon's position.

A. Controller Design in the Absence of Delay

In order to design a control system that will perform well under delay, it must first perform well under no delay. Therefore, the control system is first analysed without any time delay in Fig. 4b. First, the transfer function between the three inputs, the estimated heart's position $\hat{P}_H$, the heart's actual position P_H, and the surgeon's position P_S, and the output, the robot-heart distance D_{RH}, is calculated.

$$D_{RH} = \frac{(K_4CG)\hat{P}_H - (1 + CGK_1)P_H + (CGK_3)P_S}{1 + CG(K_1 + K_2)} \quad (4)$$

The controller C was chosen to be a proportional controller $C = k$ and the y axis of the Phantom Premium 1.5A robot (Sensable/Geomagic, Wilmington, MA) was chosen as the robot with the following transfer function [23]:

$$G = \frac{s^4 + 30.25s^3 + 2.923 \times 10^5 s^2 + 5.741 \times 10^5 s + 1.784 \times 10^{10}}{1.526s^4 + 233s^3 + 2.848 \times 10^5 s^2} \quad (5)$$

The goal is to make the robot-heart distance D_{RH} follow the surgeon's hand position P_S. For this reason, the steady-state value of D_{RH} is calculated when each of the inputs is a step function using the following equation.

$$d(\infty) = \lim_{s \to 0} sD_{RH}(s) \quad (6)$$

$$= \lim_{s \to 0} s \left(\frac{K_4CG\frac{\hat{P}_H}{s} - (1 + CGK_1)\frac{P_H}{s} + CGK_3\frac{P_S}{s}}{1 + CG(K_1 + K_2)} \right)$$
$$\approx \frac{K_4\hat{P}_H - K_1P_H + K_3P_S}{K_1 + K_2}. \quad (7)$$

assuming $CG >> 1$, $K_1 \geq 1$, and $K_2 \geq 0$.

The distance, $d(\infty)$, given in (7), needs to be equal to the surgeon's position P_S, therefore the heart's position P_H and the estimated heart's position $\hat{P}_H$ need to cancel each other. Hence, we need $K_1 = K_4$ as the heart's past position, $\hat{P}_H$, should be approximately equal to the heart's current position P_H. Next, for the steady-state value D_{RH} to approach P_S, $K_3 = K_1 + K_2$.

B. Smith Predictor Design

Once the controller has been designed for the no delay case, it is redesigned to preserve its performance when the delay is present. Hence, the new controller $\bar{C}$ is designed to preserve the transfer function between the surgeon's position P_S and the distance D_{RH} when the time delay is present – see Fig. 4c. The transfer function between the surgeon's position P_S and the robot-heart distance D_{RH} for the time-delayed case, where the first two terms of (4) have been cancelled by equating K_1 and K_4 is

$$D_{RH} = \frac{\bar{C}GK_3e^{-sL}}{1 + \bar{C}G(K_1 + K_2e^{-sL})}P_S, \quad (8)$$

where L is the length of the time delay. By equating the third term of the original transfer function in (4) multiplied by e^{-sL} to (8) and substituting in the gain values found previously ($K_1 = K_4$ and $K_3 = K_1 + K_2$), the controller $\bar{C}$ is calculated as

$$\bar{C} = \frac{C\hat{G}}{1 + C\hat{G}K_2(1 - e^{-sL})}, \quad (9)$$

which is a modified version of the original Smith predictor given in (3). The final control system is shown in Fig. 4d where $\bar{C}$ has been replaced by (9), resulting in the reappearance of the original controller C. An estimate of the robot's model is not needed as the robot and the delay are separate entities, giving us access to the output from the robot before the time delay. Hence, we do not need to estimate the robot's model. Because the ultrasound images are acquired at a slower rate than the robot's update rate, a method for upsampling the slow data is needed. The heart's principle motion has a frequency of 1 Hz and it is shown in [11] that the heart's motion can be approximated by this base frequency and the next 7 harmonics up to a frequency of 8 Hz. Because the ultrasound images are acquired at a rate of 28 Hz, the heart's motion is not aliased and the signal can be reconstructed using interpolation. In the simulation and experimental sections, two methods will be compared: zero order hold and cubic interpolation.

A minor disadvantage of using a Smith predictor is that the robot will follow the surgeon's position after a delay equal to that caused by the image acquisition and processing. However, past research has demonstrated that a surgeon is capable of operating when there are delays up to 300 ms in the transmission of position commands to the teleoperated robot [22], thus a delay of around 100 ms to 150 ms in the beating-heart surgery application is within the acceptable range for the surgeons. It is very important to note that, as is shown in the next section, the Smith predictor has been modified to ensure that the robot-heart distance follows the surgeon's hand motion.

C. Heart Motion Estimation

In order for the robot-heart distance to follow the surgeon's motion, an estimate of the current heart position $\hat{p}_H$ must be added to the system. Three different estimation methods are used in this paper. The first method takes advantage of the heart's quasi-periodic motion. The delay in the system is approximately 100 ms to 150 ms and is much smaller than the length of an actual heartbeat - 667 ms to 1 s for heart rates ranging from 60 bpm to 90 bpm. Therefore, the heart position in the previous heartbeat is known and is used as an estimation of the current heart position. The estimated and actual positions are temporally aligned using the average heart rate, which is assumed to be constant and known. This method is referred to as "Fixed". The second method uses an extended Kalman filter (EKF) to directly estimate the heart position. The trajectory of the heart motion is modeled by an m-order Fourier series with a DC offset as in [11]

$$y(t) = c + \sum_{i=1}^{m} r_i \sin(iwt + \phi_i) \tag{10}$$

where m is the number of harmonics, c is the DC offset, w is the heart rate, and r_i and ϕ_i are the harmonic amplitudes and phases, respectively. This method is referred to as "EKF Estimate". The third estimation method is a combination of the previous two. The heart motion from the previous heartbeat is used to estimate the current heart position, but the estimated and current heart positions are temporally aligned according to the current heart rate, which is estimated by w from the EKF. The estimated current heart rate is allowed to vary with time. This method is referred to as "EKF Period".

VI. Simulation Results

The proposed Smith predictor based controller is simulated in Simulink. The simulated heart signal is created by measuring the distance between the heart and the robot in each frame throughout multiple heartbeats. A single simulated heart beat is found by averaging the corresponding distances from the heartbeats. The period of this averaged heart beat is matched to the period of a clinical ECG signal from the MITBIH database [24] to create simulated heart motion (see Fig. 5a). A time delay of 100 ms and an acquisition rate of 25 Hz is used to simulate the delay and down sampling caused by the ultrasound image acquisition and processing. The gain parameters K_1 and K_2 are chosen to be 9 and 1, respectively. Following the guidelines set Sec. V-A, K_3 and K_4 are then 10, and 9, respectively. The robot-heart distance should follow the surgeon's hand motion. The performance of this system is evaluated by calculating the mean of the command following error, $e = |p_S - d_{RH}|$ and the integrated squared error $ISE = \frac{1}{n}\sum_{i=1}^{n} e^2$, where n is the number of data points.

To begin, the need for delay compensation is proven by simulating the system without the Smith predictor or the estimate of the heart motion. The robot-heart distance steadily increases as is shown in Fig. 5b, proving this is not a suitable control method.

Next, three trials are performed to characterize the system's performance as compared to the best possible case when the delay equals zero. The results are presented in Table II. First, to have a baseline for performance comparison, the delay is removed from the system and so is the Smith predictor. The result is shown as line ND in Fig. 5c and line ND NSP NSM of Table II. Next, the delay and the Smith predictor are returned to the system. The surgeon's position is set to zero, the slow data was upsampled using cubic interpolation, and the heart position is estimated using the method "EKF Period". The result is shown as line SP in Fig. 5c and line D SP NSM of Table II. Then, a chirp signal with an amplitude of 2 mm and a frequency ranging from 0.1 Hz to 2.3 Hz - see line p_S in Fig. 5d - is used to represent the surgeon's position as a surgeon can track motion up to 1 Hz and has voluntary motion as fast as 4 Hz to 7 Hz [25]. The robot's position p_R and the command following error e are shown in Fig. 5d and line D SP SM of Table II. The mean command following error e and ISE match those of the case when the surgeon's position is set to zero. This suggests that the surgeon's position has little if any adverse effect on the performance of the predictive control loop.

To improve the performance of the control system, the slowly obtained robot-heart distance must be upsampled and an estimate of the heart's current motion is needed. Two methods are used to upsample the robot-heart distance in each set of trials. A zero order hold (ZOH) increases the number of measurements but does not estimate the value

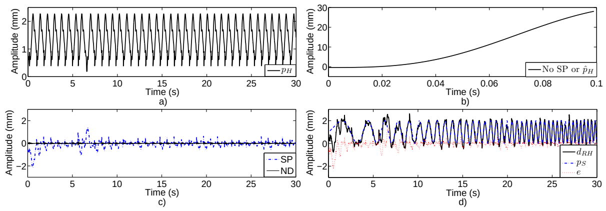

Fig. 5: (a): The simulated heart motion p_H. (b): The command following error e when only a proportional controller is used, i.e., no Smith predictor or estimation of the heart's position are used even though the delay is present in the system. (c) The command following error e for the best case scenario where the delay is removed (ND) and when the Smith predictor and delay are present (SP). In both cases the surgeon's motion is set to zero. (d): The surgeon's motion p_S is a chirp signal, the robot-heart distance d_{RH} follows p_S.

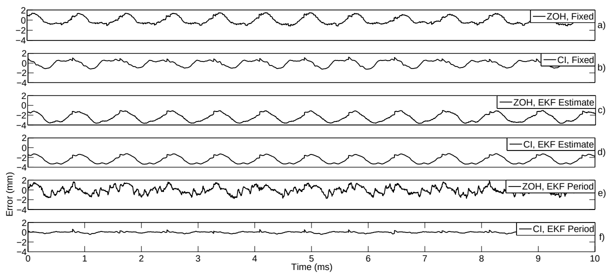

Fig. 6: The error e is measured for each simulation. (a), (b): The current heart motion is estimated by the previous heart cycle when the heart rate is assumed to be fixed. A ZOH (a) and CI (b) are used to upsample the data. (c), (d): The current heart motion is estimated by the EKF. A ZOH (c) and CI (d) are used to upsample the data. (e), (f): The current heart motion is estimated by the previous heart cycle motion where the period has been changed to match the current heart period as estimated by the EKF. A ZOH (e) and CI (f) are used to upsample the data.

of the robot-heart distance between samples, whereas cubic interpolation (CI) does estimate the value of the robot-heart distance between samples. The three methods described above are used to estimate the current heart position: "Fixed", "EKF Estimate", and "EKF Period". The chirp signal described above is included as the surgeon's position in each of the following trials. This computer-generated signal was used in the experiments in order to simulate the same user and keep the effect of the surgeon's motion on the error the same throughout all of the remaining trials.

The effect of these upsampling and heart motion estimation methods are studied by testing each combination. The results are given in Fig. 6 and Table III. For the first two trials the "Fixed" estimation method is used and the length of the heart beat is set to 803 ms, the average heart beat length. The results are shown in Figs. 6a and 6b and line A of Table III. In the next two trials, the estimated heart rate is the value predicted by the EKF, "EKF Estimate". The results are shown in Figs. 6c and 6d and line B of Table III. In the last two trials, the estimated heart motion is the same as the past heart beat but its period has been matched to the current heart rate, which is estimated by the EKF, "EKF Period". The results are shown in Figs. 6e and 6f and line C of Table III. The cases where cubic interpolation is used to increase the sampling time (Figs. 6b, 6d, and 6f) have a smaller mean command following error because the position of the heart is estimated between measurements. This is important as the heart continues to move between sample times. The actual heart rate –see Fig. 5a – changes throughout the trial. This is why directly using the previous heart motion

TABLE II: Command following errors found in the preliminary simulations. D: Delay, ND: No Delay, SP: Smith Predictor, NSP: No Smith Predictor, NSM: No Surgeon Motion, SM: Surgeon Motion

	Mean e (mm)	ISE (mm^2)
ND NSP NSM	0.45	0.033
D SP NSM	0.77	0.089
D SP SM	0.77	0.088

TABLE III: A summary of the simulation results. A: Heart position estimated from the previous heartbeat where the heart rate is assumed fixed. B: Heart position estimated from the EKF. C: Heart position estimated from the previous heartbeat but is period matched based on the the current heart rate estimated by the EKF.

	ZOH		CI	
	Mean e (mm)	ISE (mm^2)	Mean e (mm)	ISE (mm^2)
A	0.95	1.12	0.57	0.42
B	2.44	6.63	2.44	6.46
C	0.82	0.98	0.15	0.07

did not have good performance. However, the amplitude of the heartbeat remains fairly constant, hence there is value in using the shape of the past heartbeat. Estimating the current heart rate and then period matching the motion from the past heart beat along with upsampling the slow data with cubic interpolation gives the best result.

VII. Experimental Results

Following the successful simulation of the system, preliminary experiments are performed with a teleoperated 1-DOF surgical tool under ultrasound guidance. The experimental setup (Fig. 7) includes a mechanical heart simulator and a 1-DOF surgical robot. The robot is actuated by a NCC20-18-02-1X linear voice coil motor (H2W Technologies Inc, Valencia CA). The heart simulator has a 12 mm stroke. The position of the robot is measured by a A-MAC-B62 linear potentiometer position sensor (Midori America Corp, Fullerton CA). Three dimensional ultrasound images are acquired from a SONOS 7500 (Phillips Medical, Andover, MA), which has a sampling rate of 28 Hz. The image acquisition and processing delay is 136 ms and the use of cubic interpolation further

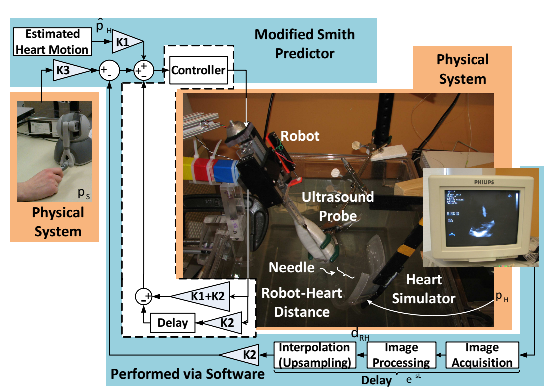

Fig. 7: The experimental setup. A linear voice coil actuates a needle which follows the mechanical heart simulator and the surgeon's motion based on ultrasound image guidance.

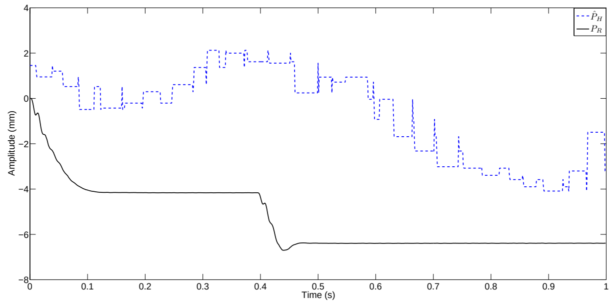

Fig. 8: The necessity of the Smith predictor is shown by removing it from the system. An estimate of the heart motion is not included. The position of the robot p_R is the solid black line. It is evident that the robot moves once it is actuated, but quickly reaches the limit of it's range of motion. It does not follow the heart's motion p_H.

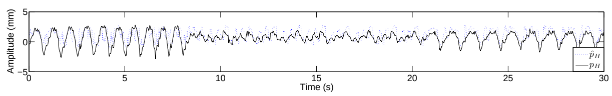

Fig. 9: The EKF's ability to handle a variable heart rate is tested. The dotted blue line shows the estimated heart motion and the black line shows the actual heart motion. In this case, the prediction from the EKF was used as the estimated heart motion. Cubic interpolation was used to increase the sampling rate.

increases this delay by 71 ms. A more detailed description of the experimental setup can be found in [26].

First the need for delay compensation (Smith predictor) and the estimation of the heart position is proven. Fig. 8 shows the result when both the Smith predictor and the heart position estimation have been removed from the system i.e., as in Fig. 4a. The robot position clearly does not follow the heart's trajectory. Rather, it quickly moves to the end of its range of motion and remains there.

Next, The EKF's ability to follow a changing heart beat is tested in Fig. 9. The heart's motion was predicted by the EKF and cubic interpolation was used to increase the sampling rate. The estimated heart motion does, in fact, change to reflect the changing heart rate.

Finally, six trials evaluating the different upsampling and heart position estimation methods are performed. The results are given in Fig. 10 and Table IV. First, the past-cycle heart position is directly used as the estimated heart position, "Fixed". The results are given in Figs. 10a and 10b and line A of Table IV. Then, the EKF is used to estimate the heart position, "EKF Estimate". The results are given in Figs. 10c and 10d and line B of Table IV. Finally, the estimated heart position is obtained by delaying the previous heart beat by the length of the current heart beat, which is calculated by the EKF, "EKF Period". The results are given in Figs. 10e and 10f and line C of Table IV.

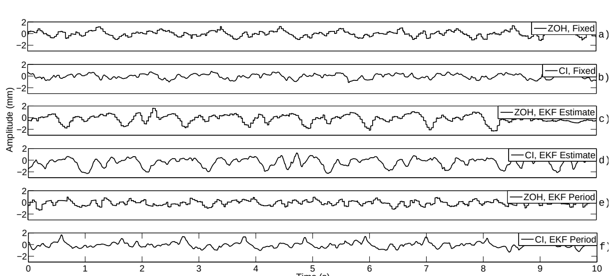

Fig. 10: The command following error e is measured for each experimental trial. (a), (b): The current heart motion is estimated by the previous heart cycle when the heart rate is assumed to be equal to the average heart rate and remains fixed. A ZOH (a) and CI (b) are used to upsample the data. (c), (d): The current heart motion is estimated by the EKF. A ZOH (c) and CI (d) are used to upsample the data. (e), (f): The current heart motion is estimated by the previous heart cycle motion where the period has been changed to match the current heart period as estimated by the EKF. A ZOH (e) and CI (f) are used to upsample the data.

It is shown in Fig. 10 that the Smith predictor based control method is able to keep the system stable. Some estimation and upsampling methods provide better performance. Using cubic interpolation helps to reduce the average absolute error as it corrects for the loss of data caused by the downsampling during image acquisition. From the simulation results we expect that using the past heart beat but matching its period to the current period, which is estimated by the EKF, to have the best performance. However, as the heart rate remained fairly constant throughout the trials, both the case when the heart motion is estimated by directly delaying the previous heart motion and the case where this estimate was period matched to the current heart rate as estimated by the EKF have similar performance. Using the estimate of the EKF directly did not perform as well because the estimate from the EKF has a smaller amplitude than the actual heart motion.

The magnitude of the tracking error in the proposed method is similar to those reported by others. It is difficult to make an accurate comparison between the proposed method and others as they use different approaches to measure the heart's motion and some methods simply ignore the surgical robot's dynamics. Kettler et al. asked human participants to draw a circle between two concentric circles that were attached to a platform that moved in a manner similar to the mitral valve [1]. This study used a hand-held tool and, therefore, the robot's dynamics were not considered. It was shown that when the motion-compensating tool was used, participants were able to draw 80% of a circle between the two concentric circles as opposed to less than 60% when a solid tool was used. Bebek et al. made a surgical robot follow the heart's motion [7], but the heart's position was measured by sonomicrometry crystals, which means that they did not have to consider the delay caused by ultrasound image acquisition and processing that is inherent to the system architecture considered in this paper. They reported root mean squared (RMS) errors in the range of 0.68 mm. Yuen et al. made a hand-held surgical tool follow the heart's motion under ultrasound guidance [11]. The delay was considered but the surgical robot's dynamics were not. They reported RMS errors of 1.43 mm. Frank et al. used adaptive filters to follow pre-recorded heart motion [18]. This study reported RMS errors of 0.5 mm. Ginhoux et al. followed the heart's motion with a mean tracking error of 0.08 mm and a maximum tracking error of 0.256 mm [19]. This study considered the surgical robot's dynamics but a 500 Hz video camera was used to capture the heart's motion and hence the image acquisition and processing delays were negligible. The largest mean error reported in the proposed research was 0.61 mm, which is comparable to the mean errors reported by other groups. This is while the proposed method deals with both delays and robot dynamics at the same time, which is more challenging compared to past work.

TABLE IV: A summary of the experimental results. A: Heart position estimated from the previous heartbeat where the heart rate is assumed fixed. B: Heart position estimated from the EKF. C: Heart position estimated from the previous heartbeat but is period matched based on the the current heart rate estimated by the EKF.

	ZOH		CI	
	Mean e (mm)	ISE (mm^2)	Mean e (mm)	ISE (mm^2)
A	0.45	0.32	0.37	0.20
B	0.59	0.57	0.61	0.70
C	0.41	0.26	0.42	0.29

VIII. Concluding Remarks

This paper proposes a predictive feedback control scheme for image-guided teleoperated beating-heart surgery. This predictive control system makes sure that the distance between the heart wall and the robot's end-effector (i.e., surgical instrument) is commanded by the surgeon's position that is input via a user interface. For estimating the heart's position, ultrasound images are used because they are inexpensive to obtain, minimally invasive, and can visualize through blood as required for intracardiac surgery. Because the ultrasound images must be acquired and processed, time delays are introduced into the control system. If this delay is not compensated for, the system may become unstable in the worst case or show unacceptable tracking errors in the mild case.

In this paper, a Smith predictor is added to the feedback control system to compensate for the above-mentioned delay. A slight disadvantage of this approach is that while the robot will follow the heart's position on the fly, it will follow the surgeon's position (in the ultrasound images) only after a delay. In future work, the performance of this system will be evaluated by having multiple human users perform a task.

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