This chapter appears in:
Frederick T. Hawthorne (Ed.), Minimally Invasive Surgery:
Evolution of Operative Techniques, Safety & Effectiveness and
Long-Term Clinical Outcomes, Nova Science Publishers, ISBN
978-1-62948-839-4, 2014.

Chapter

ADVANCES TOWARDS BEATING HEART SURGERY

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Abstract

Cardiovascular disease affects many patients each year, some of whom will require surgery. The advent of minimally invasive surgery has greatly reduced the amount of trauma a patient undergoes when a surgical procedure is performed on the heart. However, current interventional practices leave much to be desired. Currently, surgeons have two options when operating on a heart: either the heart is mechanically stabilized or it is arrested and the patient is connected to a heart-lung bypass machine. In fact, due to the heart's fast motion, it is extremely difficult for a surgeon to operate on a freely beating heart. The effectiveness of mechanically stabilizing the heart is limited to areas on the outer surface of the heart that are accessible from the chest cavity. As for arresting the heart, this approach does not allow the surgeon to evaluate the outcome of the procedure intra-operatively when the heart is drained and not beating. To accurately evaluate the effectiveness of most corrective cardiac surgeries and perform further adjustments to improve the outcome, the heart must be freely and normally beating during the procedure.

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A new operative technique with increased safety and effectiveness that does not require the heart to be arrested or stabilized is robot-assisted beating-heart surgery. A surgical robot (holding a surgical tool) is computer controlled to automatically follow the beating motion of the heart such that the heart appears stationary with respect to the surgical tool. A surgeon can then, through a user interface, control the surgical robot in order to operate on a seemingly stationary heart even though the heart is actually beating freely.

Beating-heart surgical systems, although designed differently for different procedures, contain common components. The two main components are a motion-capture module that will measure the position of the heart and the surgical tool and a control system that will use the information gathered by the motion-capture module to automatically make the surgical tool follow the heart's motion. The design of these two components is based on the target surgical site and procedure. For example, a fast video camera or an endoscope could capture the heart's motion for surgical procedures performed on the outside of the heart. However, a different method that can visualize through the blood pool within the heart must be used for a procedure performed inside the heart. For instance, ultrasound imaging or even a force sensor could be used for motion capture depending on the requirements of the procedure. This chapter will discuss the many different heart motion-capture modules and control systems that have been proposed as well as the advantages and disadvantages of each method. In addition, a discussion of which types of surgical procedures can benefit from a beating-heart surgical system is included.

PACS 05.45-a.

Keywords: Beating-heart Surgery, Image Guidance, Robotic Assistance, Feedback Control, Feedforward Control, and Predictive Control

AMS Subject Classification: 93C, 94A

1. Introduction

Cardiovascular disease is one of the leading causes of death worldwide [1]. Any advancements that will make the surgical procedure safer for patients and shorten the recovery time has the potential to greatly benefit society. The advent of minimally invasive surgery has reduced the amount of trauma a patient undergoes when a surgical procedure is performed. However, current interventional practices for heart surgery leave much to be desired. Currently, surgeons have two options when operating on a heart. The first is to mechanically stabilize the heart using a mechanical stabilizer that either applies pressure or suction to stabilize a small localized area on the surface of the heart. This device can only be used on localized areas of the surface of the heart accessible from the chest cavity. Also, this method cannot keep the localized area completely still; there will inevitably be some residual motion [25]. The second is to arrest the heart and connect the patient to a heart-lung bypass machine, which circulates the blood and ventilates the lungs. After the procedure, the heart is massaged and restarted. However, complications such as irregular heartbeats may occur. As well, the patient is at an increased risk of having a stroke [26] and may suffer from long-term cognitive loss [23].

These risks could be removed if a surgeon could operate on a freely beating heart. However, due to the heart's fast motion – with velocities and accelerations up to 210 mm/s and 3800 mm/s^2, respectively [19] – normal operation on the beating heart is extremely difficult for a surgeon as it would require superhuman skill to follow the heart's motion and simultaneously perform a surgical procedure. Letting the heart beat freely during the procedure would be feasible if the surgical robot could make the surgical tool, which is attached to it, follow the heart's beating motion. This would mean that there would be no relative motion between the surgical procedure's point of interest (POI) on the heart and the tip of the surgical tool. Then, the surgeon is given "remote" control over the surgical robot as well as a stabilized view of the heart. The surgeon's motions are simply added via the software to the surgical robot's heart-tracking motions, allowing the surgeon to operate on a seemingly stationary but actually beating heart.

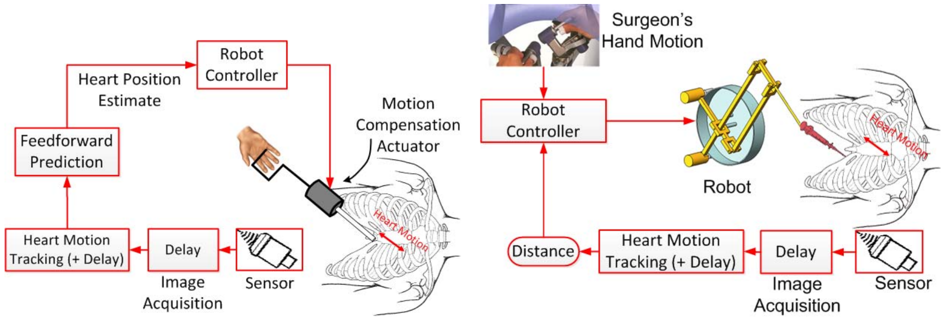
Beating-heart surgery promises many benefits for surgeons and patients. It would eliminate the adverse side effects associated with mechanically stabilizing or arresting the heart. In addition, normal heart beating motion during the surgery would allow for intra-operative evaluation of the effectiveness of reconstructive procedures on dynamic heart structures (e.g., mitral valve repair), which is impossible when the heart is arrested.

Different surgical procedures can benefit from robot-assisted beating-heart surgical systems, and hence, the surgical systems are designed differently, but have similar components. The two main components are a motion-capture module that measures the position of the heart and the surgical tool and a control system that uses the information gathered by the motion-capture module to automatically make the surgical tool follow the heart's motion. The entire surgical system is described in more detail in Section 2. More specifically, the choice of the surgical tool and the surgeon's user interface is discussed. Next, the motion-capture module, which can look quite different for procedures performed inside and outside the heart is discussed in Section 3. Finally, the controller, which makes the surgical tool follow the heart's motion is discussed in Section 4. The concluding remarks are given in Section 5.

2. Surgical System Development

The goal of a robot-assisted beating-heart surgical system is to enable a surgeon to operate on a beating heart. There are several ways to develop the various components of this system as the chosen design depends on the intended surgical procedure. These design possibilities are the focus of this chapter. Despite the differences in design, a robot-assisted beating-heart surgical system consists of specific components. These components include a robot which holds the surgical tool, a sensor to measure the heart's motion, a user interface that allows the surgeon to control the robot's motion, and a controller to make the robot follow the summation of the heart's motion and the surgeon's motion. Therefore, relative to the heart, the surgical tool will follow the surgeon's motion. With this and a stabilized view of the heart, the surgeon will be able to operate on the beating heart.

To begin, two block diagrams of two different possible systems are shown in Figures 1(a) and 1(b) [5], [31]. The first, in Figure 1(a) is designed for a hand-held tool that is controlled to track the heart's motion. The second, in Figure 1(b) is designed for a teleoperated system, where the surgeon's console is physically separate from the surgical robot, that is controlled to track the heart's motion *and* the surgeon's motion. Even though the surgeon will interact differently with these two systems, they have many elements in common. The first is a method of capturing the heart's and the surgical tool's motion. This is the "Sensor" in Figures 1(a) and 1(b). Many different ways of measuring the heart's motion and the surgical tool's motion have been proposed in the literature, each with their own benefits and limitations. Section 3 includes a description of these methods. Once the heart's and the surgical tool's motion is known, a control system should be developed that will take the heart's motions (and the surgeon's motions) into account and move the surgical robot accordingly. This is the "Robot Controller" in Figure 1(a) and 1(b). Section 4 discusses the various control methods that have been proposed. The difference



(a) (b)

Figure 1. Two block diagrams of a robot-assisted beating-heart surgical system. (a) A system designed for a hand-held robot [31]. (b) A system designed for a teleoperated robot. ©2013 IEEE. Reprinted, with permission, from [5].

between these systems is how the elements interact with each other. For example, the surgeon's motion is added before the controller in Figure 1(b) and after that in Figure 1(a).

The surgeon interacts with the surgical system through the surgeon's user interface. This may be the surgical tool itself in the case of a hand-held surgical tool or a physically separate console in the case of a teleoperated surgical tool or a catheter-based system. In both cases, the surgical tools are controlled to follow the heart's motion, but the inputs to the control system will be different. The different surgical tools and their corresponding user interfaces are discussed below.

2.1. Hand-held Surgical Tools

Hand-held surgical tools are similar to laparoscopic tools where the surgeon holds the long rod-like tool in his or her hand. Such tools can be modified for robot-assisted beating-heart surgery by attaching an actuator, that moves the surgical tool tip with respect to the surgical tool's handle, between the rod of the surgical tool and the handle. A hand-held surgical tool has been designed at the Harvard BioRobotics Lab [19]. A picture of the prototype is shown in Figure 2 [31]. The surgeon is able to directly affect the distance between the tool tip and the heart because the surgical tool tip is moving in synchrony with

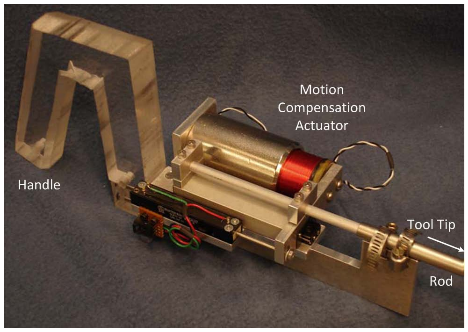


Figure 2. A prototype of a hand-held tool for robot-assisted beating-heart surgery. ©2008 IEEE. Reprinted, with permission, from [31].

the heart. If the surgeon does not move, the distance remains constant while the heart is beating. The usefulness of such a tool was tested under multiple conditions resembling surgical tasks by multiple users. The users were asked to draw a circle between two concentric circles attached to a platform moving in the same manner as a point on the edge of the mitral valve leaflets. The first trial did not include motion compensation between the tool tip and the platform, while the second was under complete motion tracking and the remainder were under varying degrees of positional errors and asynchronous errors [19]. This study showed that the use of heart motion compensation greatly improved the user's ability to draw the circle.

This above tool has been designed for procedures that require heart motion compensation in one direction only. This is sufficient, e.g., for stapling an annuloplasty ring in place to reshape a mitral valve [19]. This surgical tool can also only offer the dexterity that a current laparoscopic tool has.

2.2. Teleoperated Surgical Tools

Another method is to use a teleoperated surgical tool where the surgical robot and the surgeon's console (user interface) are physically separated. The surgical tools are similar to those used in laparoscopy except that they are held by a surgical robot instead. The surgeon loses physical contact with the surgical tools and a sense of touch with this method. The surgeon must rely on visual cues to determine the forces with which he or she is interacting with the tissue. The benefit is that the surgeon can now sit behind a console comfortably and does not need to attempt to operate with hand-held tools at an awkward angle above the patient. Unlike a hand-held tool, the dynamics of the robot are now important. In this case, the surgeon's motions are recorded and transmitted to the surgical robot. The benefit of using a teleoperated surgical tool is that a multi-degree of freedom wrist can be added to the tool tip. This gives the surgeon added dexterity that is not possible with current laparoscopic tools. Teleoperated surgical tools can be used for many procedures including annuloplasty [5] and coronary artery bypass graft (CABG) [13], [29].

2.3. Catheter-based Surgical Tools

Catheter-based surgical tools offer a less invasive method of performing beating-heart surgery as compared to teleoperated surgical tools. The catheter is a long and thin flexible tool that reaches the heart via the vascular system. This is beneficial for patients, but the catheters are difficult to steer and control at the fast rate required by beating-heart surgery. The target procedure for catheter-based surgical tools is ablation [17] or discriminating tissue stiffness [16]. Kesner et al. have found that moving the catheter within its sheath is difficult due to friction and backlash and appropriate compensation is required [18]. Loschak et al. have extended the work done by Kesner et al. in order to automatically move the catheter tip to a desired location in three-dimensional space [21]. Catheter-based surgical tools can be considered a special case of teleoperated surgical tools because the surgeon controls the catheter from a user interface. The main difference is that with teleoperated tools we must consider the inertial contributions due to the weight of the robot, whereas with catheter-based tools we must consider friction and backlash within the sheath.

3. Heart Motion Measurement Methods

The ability to track the location of the POI on the heart is essential for the development of the proposed robot-assisted beating-heart surgical system. One cannot control the surgical robot to follow the POI if its location is unknown. This is one of the greatest challenges in developing a beating-heart surgical system. Before these motion-capture methods are described, it is important to understand how the heart moves. The heart's complete motion is caused by two different sources: the actual contraction and expansion of the heart muscles as it beats and the motion of the lungs during respiration. The complete robot-assisted surgical system will need to track both types of motion. Respiratory motion is slow and can be made quite periodic when the patient is connected to a ventilator. This type of motion is much easier to track than the heart's beating motion, which can be three-dimensional and can have large accelerations, especially for tissue inside the heart.

Various types of sensors can be used to gather information about the POI's motion. For example, the heart's position can be measured by 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 [34], and sonomicrometry crystals have been used to prevent occlusions caused by surgical tools in visual data [3]. High-frame-rate video cameras provide rich visual data, but can only be used for extracardiac procedures [12], whereas medical (mainly ultrasound) scanners provide images of the tissue deep inside the body and can be used for both intracardiac and extracardiac procedures [30].

Many different methods have been presented to track the heart's motion; however, not all are feasible in an operative setting. Some methods focus both on respiratory- and heart beat-induced motion whereas others only focus on heart beat motion. A discussion of the different tracking methods is facilitated by breaking them into two categories: image-based methods and non-image-based methods. There are advantages and disadvantages to each method as will be discussed later in greater detail. The image-based methods can be used only if the motion of the POI remains within the field of view of the image. Surgical tools may briefly block the POI and inhibit a measurement from being taken. Other non-image-based methods do not have these requirements.

3.1. Image-based Motion Tracking Methods

Images are an effective way to provide the surgeon with information about the heart's motion as a large section of the heart is visible in each image. Many different types of image-based tracking methods can be used to track the motion of the heart. These include high-speed cameras and medical scanners. All image-based tracking methods require a certain amount of time to acquire each image and then process it in order to find the location of the heart. This may or may not introduce a non-negligible time delay into the system. The image-based tracking methods will be further separated into two categories: camera-based methods and medical scanner-based methods.

3.1.1. Camera-based Methods

Camera-based methods provide colour images of the heart that are rich with detail. This aids in tracking a specific point on the heart. However, this method is limited to tracking points on the surface of the heart because cameras cannot visualize through the opaque blood pool. The advantage of camera-based methods is that these images often have better resolution, show more detail, and are obtained faster than medical scanner images such as ultrasound and MRI. In addition, if the camera is held motionless, both the respiratory-induced motion and the heart beat-induced motion of the heart are captured. The target surgical procedure that uses camera-based methods is a CABG.

High-speed video cameras are used by [12], [13], and [22] – a 500 Hz in the case of [12] and [13] and a 955 Hz monochrome camera in the case of [22]– to capture the heart's motion. Because the images are acquired quickly, neither method needs to consider the minimal image acquisition delay. The next step is to process the images in order to identify the location of the POI. Three markers on the simulated heart, an LED marking the surgical tool's tip, and a laser shining onto the simulated heart along the axis of the surgical tool allow Ginhoux et al. to quickly identify the simulated heart's position with respect to the surgical tool tip [12], [13]. The image processing required to find these markers is described in [20]. When this method is used in vivo, optical markers must be attached to the heart. Nakamura et al. do not place markers on the heart, instead they identify a POI in the image and then track this same structure in subsequent images [22]. Others are trying to identify how the entire heart (and not simply the POI) moves in each image [4] and how to stabilize it [27].

3.1.2. Medical Scanner-based Methods

Ultrasound images are the most common medical images used for heart motion capture. These images are relatively inexpensive and simple to obtain. MRI images could be used, however it is challenging to operate within the large magnetic field and the confines of the MRI scanner itself. Also, obtaining images from an MRI scanner in real-time is still very difficult. The advantage of using ultrasound images is that they can visualize the interior heart tissue through the opaque blood pool in real-time. However, ultrasound scanners have low frame rates. For instance, the frame rate of a 3D ultrasound scanner can be as low as 18 Hz [9]. The location of the POI must then be found in each image frame, which can introduce a delay. This time delay and the low image acquisition rate must be compensated for by the control system (Section 4). Otherwise, the teleoperated robot end-effector (i.e., the surgical tool) may collide with and puncture the fast-moving heart.

The aforementioned hand-held tool relies on data from ultrasound images in [33]. The image processing method used to locate the POI on the heart and the surgical tool in each image frame is the flashlight approach described in [24] and used in [5]. This method identifies the surgical tool by finding the longest straight line in the image through the Radon Transform [24]. This line is then extended until the nearest bright point (the closest heart tissue) is found. This is the location of the POI - the tissue directly in front of the surgical tool tip. This information is used by the controller to make the surgical tool follow the motion of the POI, as will be discussed in Section 4.

The catheter-based systems also use ultrasound images. However, instead of an external probe, a catheter mounted intracardiac echocardiography probe is used [7], [21]. Some preliminary work about creating a larger field of view from the indivudial ultrasound images has been performed by Brittain et al. [7]. Later, these images will be used to track a POI on the interior surface of the heart.

The target procedures for medical scanner-based motion measurement methods are procedures performed inside the heart such as annuloplasty for mitral valve correction or ablation to treat arrhythmia. The image resolution is much worse than that of a camera-based system, and hence research about procedures performed on the exterior surface of the heart does not use ultrasound images. However, if the resolution of a medical scanner image is sufficient for a procedure performed on the surface of the heart, a medical scanner-based method could be used for this procedure.

3.2. Non-image-based Motion Tracking Methods

Different groups have also proposed tracking methods that do not require images of the heart. Some of these methods are feasible for surgical procedures such as the use of force sensors [8], [15], and [17] or a fiber optic probe [28], while others such as the use of sonomicrometry crystals are not [3], [14], [29].

One possible method is to use a force sensor [34]. The goal is to keep the contact force between the heart tissue and the surgical tool the same. The difficulty is that the rapid back and forth motion of the surgical tool creates vibrations at the tip. This can lead to instability and tracking errors. Nevertheless, if the vibrations can be controlled, this method is feasible for performing a surgical procedure such as tissue ablation, where the surgical tool can be in constant contact with the heart tissue. The main advantage is that it would give the surgeon a sense of touch, which is not currently available in most teleoperated robotic surgical systems. The surgeons must use visual cues to determine the forces they are applying when they are grasping the tissue.

Bebek et al. [3], Tuna et al. [29] , and Horiuchi et al. [14] use sonomicrometry crystals to track the position of the heart. Sonomicrometry crystals are small piezoelectric crystals that transmit and receive ultrasound signals. In order to measure the motion of the POI on the heart, a base of six asymmetrically mounted crystals is set under the heart and another crystal is sutured onto the POI [3]. The "time of flight" data is used to calculate the distances between the crystals. This is a complex calculation and is currently not done in real time. In this approach, both the heart's beating motion and respiratory-induced motion can be measured [29]. Inserting the crystal base and suturing another crystal to the POI is not feasible for a surgical procedure. However, it does provide an excellent method for accurately measuring the heart's position. The accuracy of other methods that are feasible for surgery can be tested with respect to this one. This method does suffer from noise caused by ultrasound echoes. Horiuchi et al. are using various filters to increase the accuracy and reduce the effect of noise in this system [14]. Tuna et al. are continuing the work by Bebek et al. by modeling the heart's motion as a weighted sum of previously collected heart motion data points.

4. Control Methods

The controller is an essential part of the targeted surgical system. It takes data about the heart's position (and about the surgeon's position in the teleoperated and catheter-based case) and calculates a signal such as a torque or current that will be fed to the robot, causing it to move in the desired direction. Interestingly, the choice of a control method is tied closely to the choice of the heart motion measurement method. Some motion-capture methods collect data quickly, with a negligible time delay as is the case with a video camera or a force sensor. Others, such as ultrasound imaging, take time to capture an image and introduce a non-negligible time delay into the system. Then, the collected data must be processed. This may or may not increase the time delay further. If a non-negligible time delay is present in measuring the heart's position, then the heart's latest

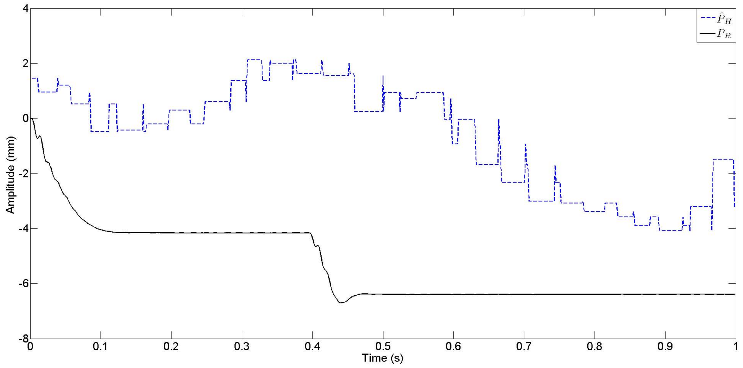


Figure 3. This diagram shows the position of the simulated heart, $\hat{P}_H$, (blue dotted line) and the position of the surgical tool, P_R, (solid black line) when ultrasound images are used to capture the heart's and the surgical tool's position but the time delay is not compensated for. The surgical tool does not follow the heart's position, even though it should as the surgeon's motion was set to zero. This demonstrates the need for time delay compensation. ©2013 IEEE. Reprinted, with permission, from [5].

position at any instant in time is unknown. This adds a challenge in designing a controller that must now make the surgical tool follow the heart's unknown motion with high accuracy. If this non-negligible delay is ignored and the surgical tool is made to track heart data which is inevitably "old", there is a great risk that the surgical tool will collide with and possibly damage the heart tissue. Figure 3 shows such a system's poor performance [5]. To address this issue, the heart's current position needs to be estimated either by a predictive controller or a separate estimator. Different estimation techniques can be used but they all rely on the fact that the heart's motion is quasi-periodic. This means, previously collected data can give us some insight about the heart's current position. If the delay is in fact negligible and the heart's position does not move significantly between the point in time when the measurement was taken and when the heart's position is calculated from that measurement, a heart motion estimator and/or a predictive controller is not necessary. However, at least fast motions of the heart make the delay compensation necessary in most practical cases, even if the delay is not too large.

As was discussed in Section 3, the heart's complete motion is composed of respiratory-induced motion and heart beat-induced motion. The final robot-assisted surgical system must take both sources of motion into account. As a first step, some past research has ignored the respiratory-induced motion in favour of studying how to compensate for the heart beat-induced motion, and vice versa. When the patient is in the operating room, his or her breathing is controlled by a ventilator which makes the respiratory-induced motion almost completely periodic, much more periodic than the heart beat-induced motion. For this reason more emphasis has been put on tracking the heart beat-induced motion as this is more challenging.

For further analysis, these predictive controllers can be separated into two categories: predictive feedforward controllers and predictive feedback controllers. Predictive feedforward controllers estimate the heart's current position and use this as the set point to move the surgical tools to. Predictive feedback controllers also estimate the heart's current position but they take the tracking error into account.

4.1. Predictive Feedforward Controllers

Predictive feedforward controllers estimate the heart's current position merely based on past heart motion. This is meant to compensate for the delay in measuring the heart's current position. Because the motion of the heart can change slightly from beat to beat, most research does not directly use the previous heart beat as an estimate of the current beat. Rather, data from one or more previous heartbeats are analysed and used to create a more accurate prediction of the current heart motion. Much work has been done on developing accurate mathematical models of the heart's motion [10], [12], [13], [33] . An overview of these methods is given in [2].

To begin, Bebek et al. use the motion from the previous heart beat as an estimate of the current postion, but they time-shift the data to ensure that the beginning and end of the actual and estimated heart beat motion profiles are synchronized [3]. They do this by first identifying the different sections of a heart beat in the electrocardiogram (ECG) signal. Next they either expand or shrink the previous heart beat with respect to time in order to match each section of the current heart beat to the corresponding section of the previous heart beat. This ensures that the estimated heart beat will be temporally aligned with the actual heart beat even if the heart rate is changing. This is shown in Figure 4, where heart motion from the previous heart beat (dotted line in the top right corner) is temporally aligned to match the actual heart motion (solid line in the bottom left corner).

Others have fit an equation to the heart's motion by exploiting its quasi-periodic nature. Yuen et al. [33] and Tuna et al. [29] modeled the heart's motion as a weighted sum of previously recorded heart motion data points. It is interesting to note that using higher order models of the heart (i.e., using more previous data points) and predicting only a few samples into the future instead of many gave the lowest prediction error [29]. The heart's motion has also been modeled as a weighted sum of sinusoids where both the amplitude and frequency are allowed to change [28], [32], [33].

The drawback of a feedforward controller is that it does not compensate for tracking errors caused by noisy measurements and disturbances. Figure 5 shows a block diagram of such a system for controlling a hand-held tool. In this figure, the heart's position is the measured variable and this value is given to a predictive filter to estimate the heart's current position. However, in this figure, the surgeon's motion is added when the surgeon *physically* moves the hand-held tool. Therefore, there is no error in tracking the surgeon's motion. As well, it is important to note that only the heart's position is measured and given to the predictive filter, not the surgical tool's position. Figure 6 shows the result of a feedforward estimation system.

4.2. Predictive Feedback Controllers

Teleoperated systems generally use feedback controllers because they can correct for measurement errors and tracking errors. Predictive feedback controllers, unlike predictive feedforward controllers, do compensate for a tracking error. The error is subtracted from the reference signal and results in a smaller or larger control signal. A diagram of a typical feedback control loop is given in Figure 7. Here, the heart's position is added as a noise disturbance. The effectiveness of using a feedback controller is shown in Figure 8 where B is the feedforward response and C is the feedback response. When noise disturbances are present as in Figure 8 feedback provides a better result. Certain feedback controllers can also account for the delay that may be inherent to the heart motion measurement method such as ultrasound imaging.

Ginhoux et al. describe a two part controller to follow the respiratory-induced motion in [13]. It uses the knowledge of the surgical robot's dynamics as well as the period of the respiratory-induced motion to make the surgical tool move in the same manner as the lungs. Then, a separate controller is intro-

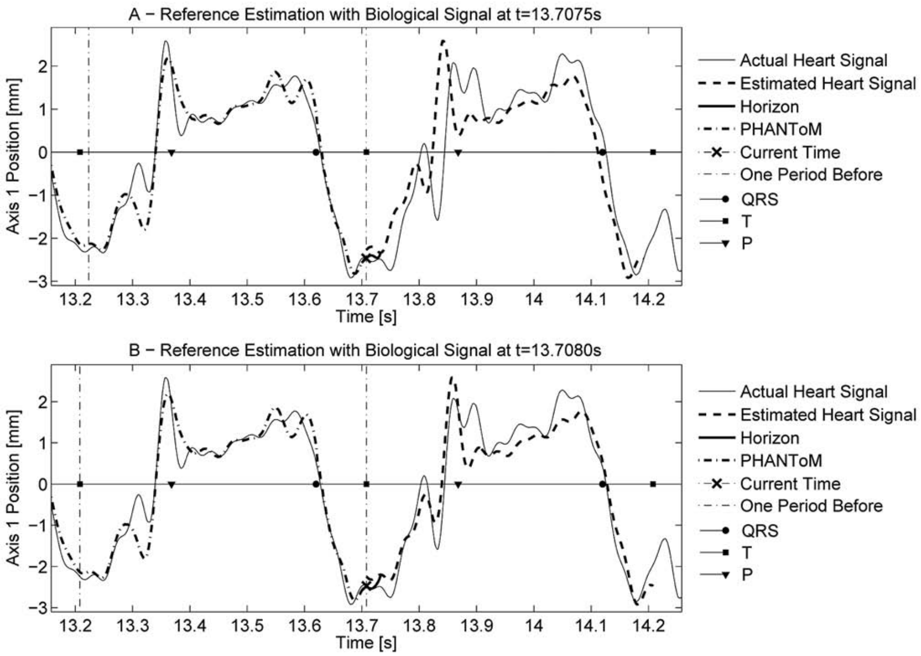


Figure 4. This is the estimation of the current heart beat by temporally aligning the previous heart beat introduced by Bebek et al. [3]. The heart beat is given by the solid line in each diagram. The circle, square, and triangle represent the different components of the ECG signal (QRS, T, and P waves respectively). (A) The shape of the past heart beat (dotted line) estimates the current heart beat (solid line). These two beats are not very well aligned temporally. (B) The shape of the past heart (dotted line) beat has been altered temporally to better match the current heart beat (solid line). ©2007 IEEE. Reprinted, with permission, from [3].

duced in [12] that follows the heart's beating motion. As a high speed camera is used to capture the heart's motion, time delay is negligible. Dominici et al. also consider both the heart beat-induced motion and respiratory-induced motion, but the heart's complete motion is measured by the force the surgical tool exerts on the heart tissue [11]. These systems use a teleoperated surgical robot and, for this reason, the controller must take the robot's dynamics into account so that the surgeon's motion is properly transmitted to the surgical tool. Any errors in tracking the surgeon's and the robot's motions are taken care of by a

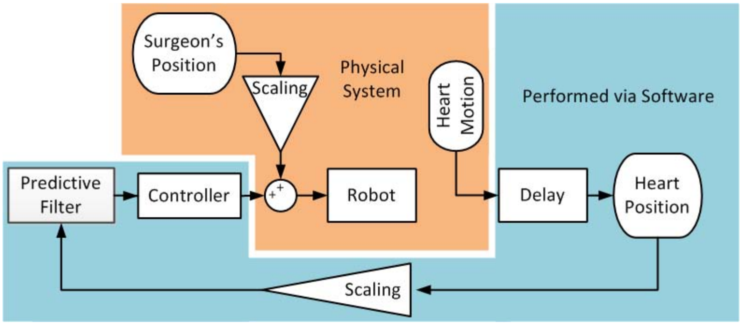


Figure 5. A feedforward control loop containing delay compensation for a hand-held tool.

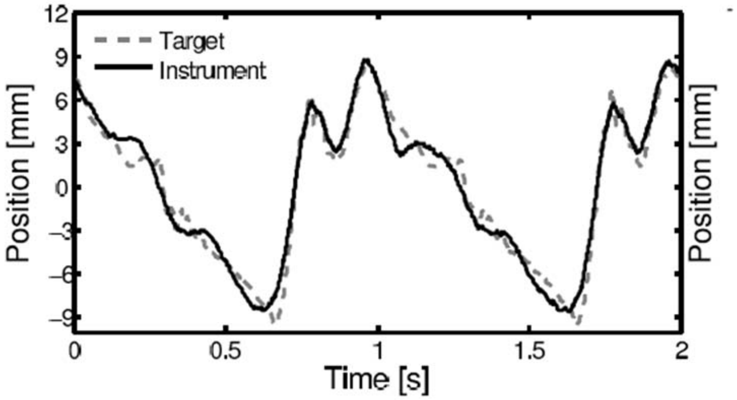


Figure 6. The result of a feedforward control loop, where the gray dotted line is the heart's position and the solid black line is the surgical tool's position. ©2008 IEEE. Reprinted, with permission, from [33].

feedback control loop. What is rather unique about these controllers is that they compensate for both the respiratory-induced motion and the heart beat-induced motion.

Some force-controlled systems use similar feedback controllers. Joinie-Maurin et al. use force feedback for situations when the surgical tool is in constant contact with the heart tissue and position-based disturbance rejection is not easy to perform [15]. A predictive feedback controller that includes a model of the surgical robot's dynamics and a model of the heart's motion is

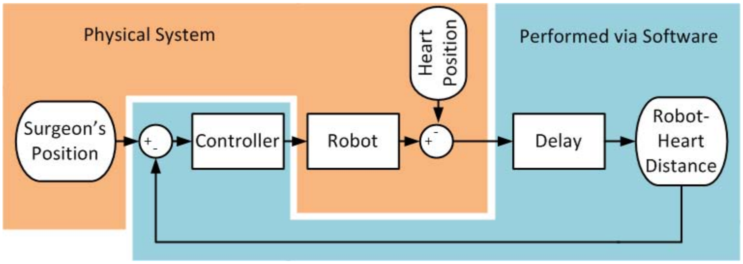


Figure 7. A feedback control loop.©2013 IEEE. Reprinted, with permission, from [6].

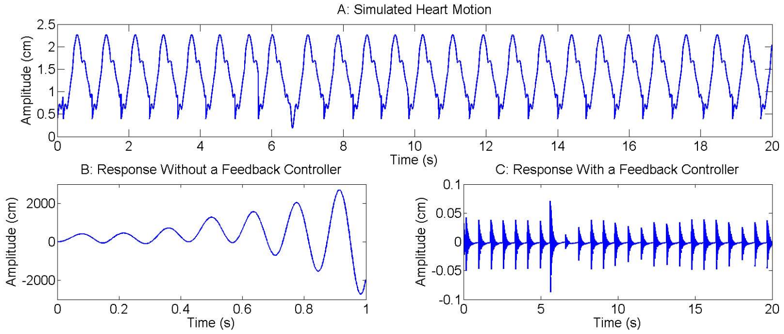


Figure 8. This figure demonstrates how feedback controllers perform in the presence of noise disturbances. (A) shows the simulated heart motion that was added as a disturbance. (B) shows the response when a feedback controller was not used. This represents the error and ideally should be zero. (C) shows the response of a feedback control system. The response signal is very small and is close to its ideal value of zero.

used to determine the optimal signal to send to the robot. This controller is also split into two sections: one to follow the heart's motion and one to follow the surgeon's motion. A similar method is used for position tracking in [12] and [13]. Cagneau et al. use a technique where the controller learns from previous tracking errors to continually reduce the tracking error between the heart and the surgical tool [8]. Because the heart's motion is quasi-periodic, the system can "learn" its motion over time. This method would not work if the heart moved completely randomly. Due to this continual learning, the controller can still

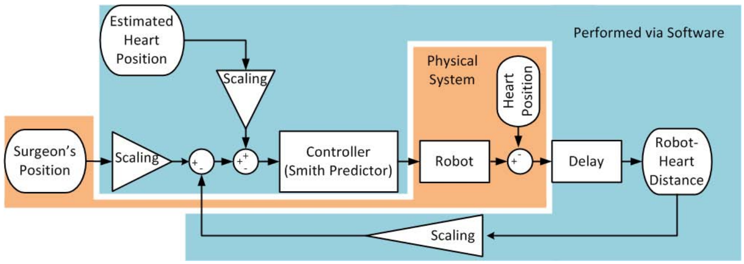


Figure 9. A feedback control loop containing delay compensation. ©2013 IEEE. Reprinted, with permission, from [6].

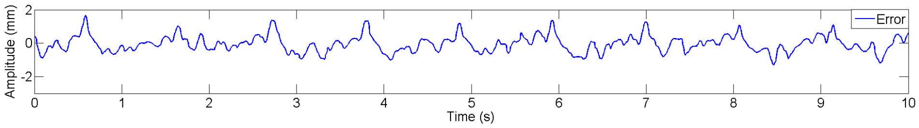


Figure 10. The result of a feedback control loop compensating for the delay caused by ultrasound image acquisition and processing. ©2013 IEEE. Reprinted, with permission, from [6].

follow the heart's motion even if the heart rate is changing.

Bowthorpe et al. describe a controller that follows only the heart beat-induced motion, but also compensates for the large time delay introduced by the use of ultrasound images to capture the motion of the heart [5], [6]. The time delay is compensated for by estimating the distance between the heart and the surgical tool. This value is fed back to the controller in delayed form. This system is shown in Figure 9 and the result is given in Figure 10. Unlike in Figure 5, the tracking error – the difference between the surgeon's position and the robot-heart distance – is given to the controller.

A brief overview of the literature is presented in Table 1. The literature is categorized based on which method was used to measure the heart's motion, whether a feedforward or feedback controller was used, and which type of surgical tool was used.

Table 1. This is a summary of the literature. It is categorized based on which method was used to measure the heart's motion, whether a feedforward or feedback controller was used, and which type of surgical tool was used.

Measurement	Feed Forward			Feedback	
	Catheter	Hand-held	Teleoperated	Catheter	Teleoperated
Camera			[10]		[13], [12], [22]
Ultrasound	[18], [7]	[31], [32], [34], [30], [33], [24]			[5]
Fiber Optic Probe			[28]		
Force Sensor				[17]	[15], [8]
Position Sensor	[21]				
Pre-recorded		[19]			
Sonomicrometry			[29], [14]		[3]

5. Conclusion

A robot-assisted beating-heart surgical system has the potential to improve the outcome of many surgical procedures performed on the heart. There are different ways to design such a system as each surgical procedure has different requirements. For example, the procedure could be performed on the outside surface of the heart or within the heart, which would affect the choice of the motion-capture module. This motion-capture system, in turn, affects the choice of a controller because there may or may not be a non-negligible time delay in acquiring the heart motion data. In addition, whether the surgeon prefers to use a teleoperated device or whether a hand-held device will suffice also affects the choice of the controller. Furthermore, the speed of the motion of the POI on the heart may mean that the robot control loop will need to have fast dynamics (large bandwidth of error tracking).

Once the requirements for a specific surgical procedure have been determined, the robot-assisted beating-heart surgical system can be designed. This will include a controller that can compensate for both the respiratory-induced motion and the heart beat-induced motion while still following the surgeon's motion. A motion capture system is needed to collect data about the heart's position and the surgical tool's position. Next, a user interface for the surgeon is required. Finally, a stabilized view of the target site on the heart must be given to the surgeon in order for him or her to operate.

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