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Heartbeat Synchronization for Robotic Cardiac Surgery

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Abstract

Minimally Invasive Direct Coronary Artery Bypass (MIDCAB) requires surgeons the precision of hand skill and the mental concentration, since it needs to work on beating hearts. We propose a surgical robot system that compensates motions of organs during operations. The motion canceling robot system consists of three technologies; visual synchronization, motion synchronization and master-slave control. The visual stabilization provides the surgeon with the image of stabilized target point on the video monitor. The surgeon operates the master robot referring to the stabilized image. The motion stabilization, on the other hand, controls the slave robot being synchronized with the heart beat, which is the function of the master-slave control. Master-slave transforms the master motion and controls the slave robot. In this paper, we verify the effectiveness of the prototype system by invivo experiment.

Key Words:
Medical Robot, Minimally Invasive Surgery, High Speed Camera

1 Introduction

Minimally Invasive Direct Coronary Artery Bypass (MIDCAB) is paid an attention to as minimally invasive procedure of the cardiovascular surgery region. This was introduced by Dr. Benetti of Argentina in 1994. The procedure was executed in Japan for the first time in March, 1996. In most cases, the patients are released from hospitals within a week.

Conventional procedures of the coronary artery bypass surgery incise most of the thorax, and use a heart-lung machine. The MIDCAB was developed to make the incision minimum like Fig.1, and not to damage the respiratory function. In addition, the chance of complications such as cerebral infarction and aorta dissociation is reduced, since the extra corporeal circulation using heart-lung machine is not adopted. Also note that there is an advantage of there is no degradation of erythrocyte by extracorporeal circulation[1][2].

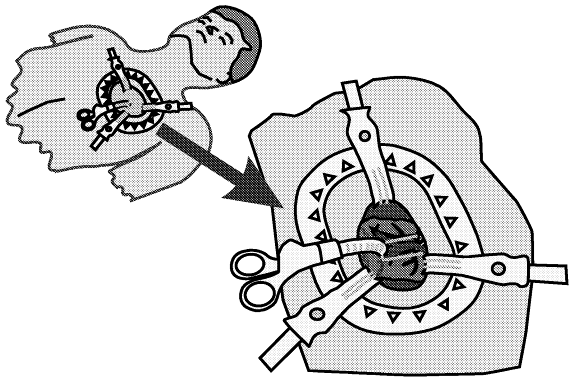

Fig. 1: Minimally invasive direct coronary artery bypass

Minimally invasive cardiac surgery such as direct coronary artery bypass or endoscopic coronary artery bypass requires surgeons of the precision of hand skill and the mental concentration. The request becomes even harder if it is to be done on beating hearts in order to minimize patients' damage. Recently, though the master-slave robotic surgical system such as da Vinci (Intuitive Surgical Inc.) and Zeus (Computer Motion Inc.) is developed for the practical use[3][4], the difficulty of the surgery on the beating heart has not been solved. Then, we propose a master-slave robotic surgical environment for surgeons that compensates the motion of organs during operations, especially that of beating hearts.

A high-speed camera tracks the movement of target points on the heart. Using the data, the slave robotic device synchronizes itself with the movement of the target points. The synchronization maintains the slave robotic device relatively stational to the target point on the heart. In the meantime, the surgeons observe the image on the monitor screen, that is also synchronized by the image processing technology such that the target points remain stational. The surgeons manipulate the master robotic device, which is then added to the synchronized motion of the slave robotic device and changes the relative position.

The proposed system will relieve the stress of the cardiac surgeons operating on the beating hearts, and assist them to pay more attention to the decision-making and precise manipulation in surgery.

We built the prototype system of robotic synchronization and verified it by in-vivo experiments.

2 Robotic Heartbeat Synchronization

A source of disturbance in endoscopic surgery is the movement of organs due to the respiration and heartbeat of patients. The surgeons must overcome the difficulty by their skill and mental concentration.

The movement of the organ is even more serious in cardiac surgery operations. The movement of the heart is not only faster than that of respiration, but also more complex and unpredictable. The following procedures may be selected in the MIDCAB to ease the difficulty:

(1) Heartbeat reduction using "β-blocker".
(2) Cardiac arrest for short time induced by the adenosine injection.
(3) Heartbeat reduction by the vagal stimulation.
(4) Mechanical restraint using heart locking device called "stabilizer".

However, (1) (2) and (3) are unsuitable for long time operation, since the medicine must be delivered every short time period. Mechanical equipments as locking devices in (4) would become obstacles in operations and limit free work-space for instruments. Even with any and all of these procedures, the small residual motion is still disturbing in anastomosis of small blood vessels on the beating heart. The motion compensation technology is, therefore, demanded to resolve the problem.

We would like to propose the motion compensation technology with which a surgeon sees the stational image of the point of interest on a monitor screen and, relying on the image, manipulates the master device reaching the slave robotic device for the point of interest, though, in reality, the point of interest is on the beating heart. The slave robotic device, in the meantime, moves in synchronization with the heartbeat and changes its relative position to the point of interest according to the motion of the manipulated master device.

We call the motion compensation technology the "Heartbeat Synchronization" which consists of three technical elements: Visual Synchronization, Motion Synchronization, and Master-Slave control. Visual synchronization provides the stationary image of the point of reference, while motion synchronization moves the slave robotic device and keeps it relatively stationary to the point.

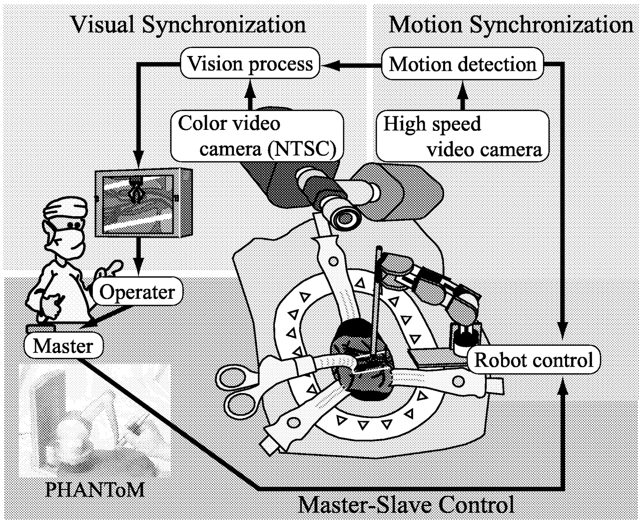

Fig. 2: Heartbeart Synchronization

The motion of the master device is transferred to the slave robotic device and controls the relative position of the slave robotic device to the point of interest. The overall system is illustrated in Figure 2.

3 Components

3.1 Master-Slave Robotic Devices

3.1.1 Slave device

The current design of slave robotic device has four degrees of freedom being driven by small integrated actuators (YASUKAWA Electric), each consisting of a brashless AC motors, a harmonic drive reducer, and an optical rotary encoder.

The slave robotic device has the kinematic design as shown in Figure 3 and Table 1, which is intended to be used being fixed on the oval frame (approximately 20cm $\times$ 15cm) that is commonly used in the MIDCAB (see Figure 1) to maintain the access window and to fix devices such as mechanical stabilizers.

Installing the slave robotic device and the other devices on a common base fixture or frame would simplify the calibration of the system. A slave robotic device would need at least 6 DOF for dexterity and ease-of-use of surgeons. Although the current proto-

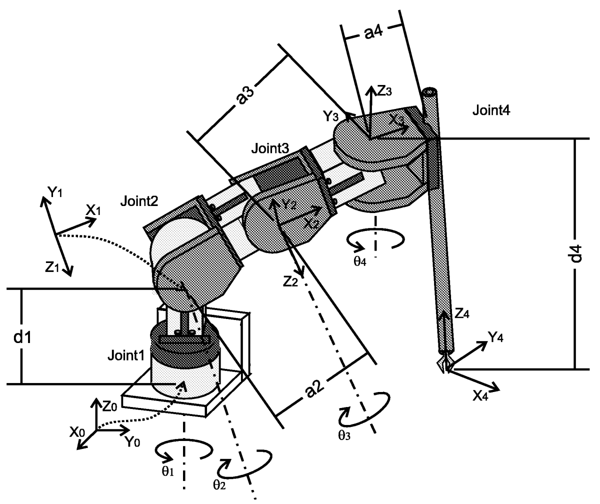

Fig. 3: Slave Robotic Device

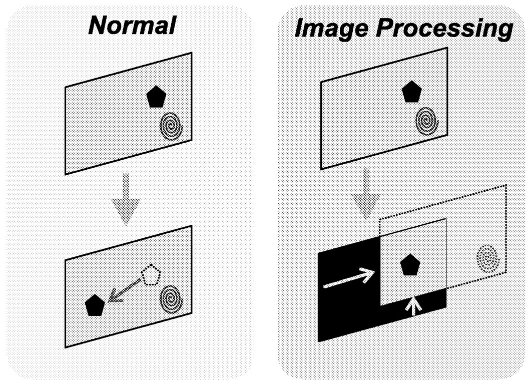

Fig. 4: Tracking and image rendering for visual synchronization

Table 1: Denavit-Hartenbrg Slave Robotic Device

Link	Variable	α_i	$a_i(mm)$	$d_i(mm)$
1	θ_1	$\frac{\pi}{2}$	0	62
2	θ_2	0	46	0
3	θ_3	$-\frac{\pi}{2}$	46	0
4	θ_4	0	30	-150

type has only 4 DOF, it is designed to experimentally verify the fundamental functionality of the heartbeat synchronization with the realistic size that can be installed on the oval frame. Three degree of freedom are used for the positioning of the tip, and the fourth degree of freedom is for controlling the angle about the Z_0-axis of the X_0-Y_0-Z_0 coordinate frame in Figure 3. The 4×4 Jacobian matrix is computed and used to solve the differential kinematics.

3.1.2 Master device

As the master device, we adopted the Phantom Desktop (SensAble Technologies, Inc.), which has six-axes joint measurements and three axes of haptic force feedback. The force feedback function is not currently used in our system. The haptic sensation could be used to feedback the force interaction at the end-point of the slave robotic device, or to establish haptic communication between the surgeon and the assisting surgical navigation system.

3.2 Visual Synchronization

Visual synchronization implies to provide surgeons with the stationary image of the moving point of reference on the beating heart. The image processing system tracks the point of reference and continuously obtains its position on the image. The image is cut out from the image memory and relocated so that the point of reference always remains in the same position on the monitor screen. The similar function was used in the camcorder to reduce image disturbances due to hand vibration using gyro sensors or by simple digital image processing. Combining the function with the image tracking, the tracking reliability and time of computation are the critical issues to challenge. The scheme is illustrated in Figure 4.

We previously used a single color NTSC camera for tracking and image rendering using image processing boards such as Tacking Vision (Fujitsu) and IP5000 (Hitachi) [5] . It worked fine for visual synchronization though the stability of motion detection was not excellent and the update rate of motion is limited by the NTSC standard (the flame rate of 30Hz, the field rate of 60Hz), which resulted in the low accuracy of motion synchronization which we discuss in the next subsection.

In the new prototype system, we adopt two different CCD video cameras; a color NTSC camera and a monochrome high-speed camera (Dalsa: model CA-D6, 955 fps, 512×512 pixels). The motion of the point of reference is tracked and measured using the high speed camera and an image capture/processing board (Coreco: Viper-Digital), while the image of the NTSC camera is used for rendering. The color image is cut from the image memory according to the position measured using the high speed camera. This image processing is done by IP5000 (Hitachi).

The two cameras were integrated using a half-mirror prism into a dual-head video camera as shown in Figure 5. The two cameras share a single zoom lens for 35 mm MF single lens reflex camera, which was selected because of its long flange-back length.

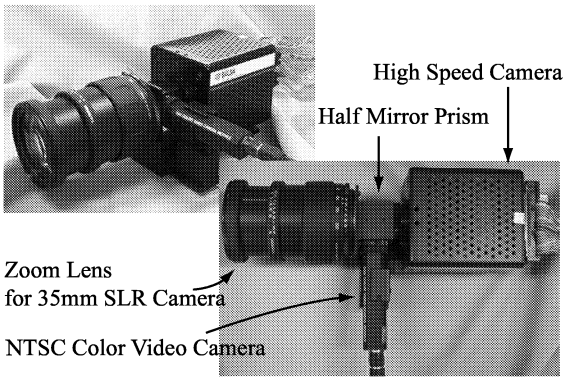

Fig. 5: A dual-head video camera for visual synchronization

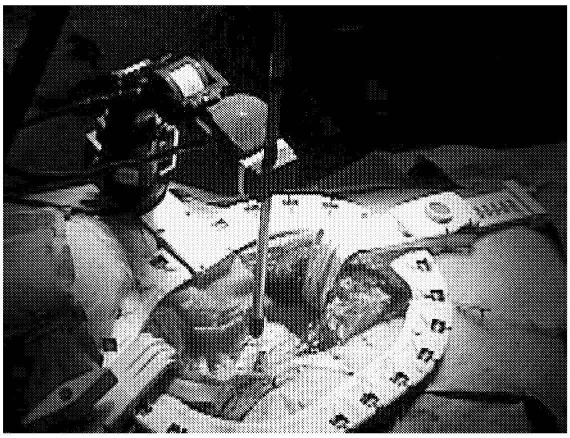

Fig. 6: In-vivo experiments for motion synchronization

3.3 Motion Synchronization

The measured position of the point of reference on the beating heart is now used as feedback signal to control the endeffector of slave robotic device relatively to the point of reference. We established near 1ms visual feedback control system using the high speed camera. The slave robotic devise moves with the motion of reference point. Therefore, the slave robotic devise is seen stationary in the rendered monitor image as well as the point of reference. We call this technology the motion synchronization.

The experimental verification of motion synchronization was successfully conducted in-vivo for a pig as seen in Figure 6. Figure 7 shows the data of experiment, where the X and Y axes are those in the image plane of the camera. The small and almost constant error remained in X axis, since it was a direction that the gravity effect appeared. The error was afterward removed with a simple gravity compensation algorithm implemented in the controller. For the reference of readers, the data of similar experiments, that was previously done using a NTSC camera only, is shown in Figure 8. The comparison of Figures 7 and 8 clearly shows that the near 1 ms visual feedback control is surprisingly effective to synchronize the slave robot motion with the heartbeat, while the synchronization is unsuccessful with visual feedback control using NTSC standard cameras.

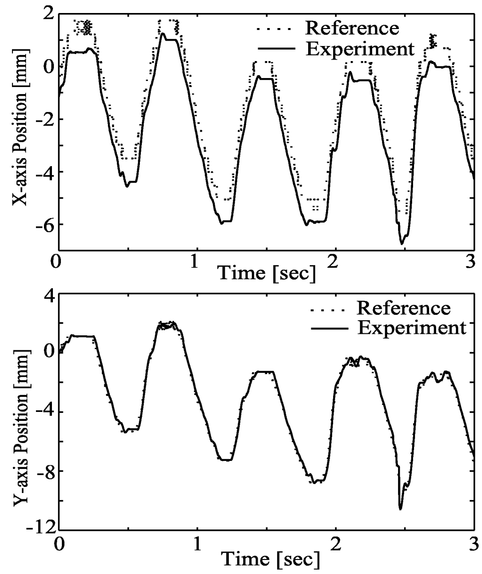

Fig. 7: Motion Stabilization System Response

3.4 Dominant Frequencies of Heartbeat

We have made frequency analysis of the heartbeat in order to understand the dominant frequencies and to discuss the requirements for the speed of image processing. In an in-vivo experiment, we placed a yellow sphere bead of 2 mm in diameter on the beating heart of a pig. The image was captured through a NTSC camera and processed in the field rate (60 Hz) online using Tracking Vision (Fujitsu). Figure 9 shows the results of measurements, which are clearly consisting of two different dominant frequencies. The lower frequency is the effect of respiration of lung, and the higher one is due to the heartbeat. Note that the wave of higher frequency is not ideally cyclic and involves random or chaotic nature.

We identified the frequencies with the help of autoregressive (AR) model[6]. Using the p-th AR model as shown in EQ.1 we have computed the coefficients a_k by the least squares method minimizing the vari-

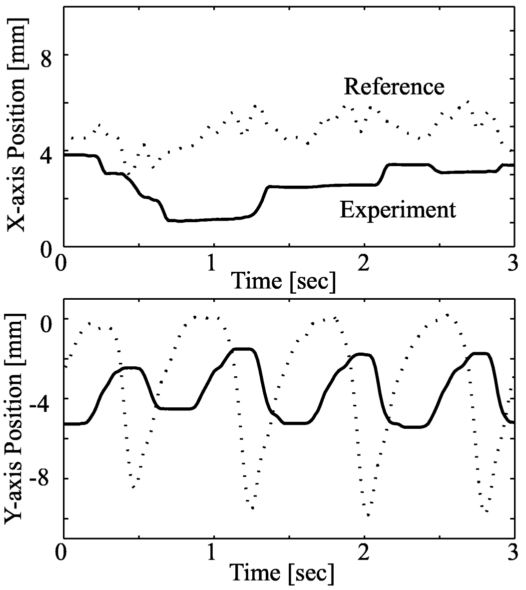

Fig. 8: Responses of motion synchronization with a NTSC camera

ance of prediction error $e[k]$.

$$x[n] = -\sum_{k=1}^{p} a_k x[n-k] + e[n] \qquad (1)$$

First we determined p, the order of AR model, to be six, which was computed using 512 points of data that are taken every eight points from the whole 4096 points of data. The computed spectral density is shown in Figure 10, which indicates that we have three dominant frequencies. Namely, 0.18 Hz, 1.5 Hz, and 3.0 Hz respectively. The lowest one is of respiratory movement of the heart. The heartbeat turned out to have the other two frequencies, among which the first dominant heartbeat frequency is 1.5 Hz. When we measure the heartbeat using an NTSC camera of flame rate, it implies that we have only ten measurements in a wavelength of the second frequency of the heartbeat. Knowing the fact that the heartbeat involves random or chaotic nature, only ten points are insufficient to predict the heartbeat and to use as feedback signal for the slave robotic device.

4 Experiments of Heartbeat Synchronization

Integrating the visual synchronization and the motion synchronization into the master-slave robotic devices, we set up the prototype system for the heartbeat synchronization. At the present, we completed the laboratory experiments in an artificial environment, and have not yet finished the animal experiments.

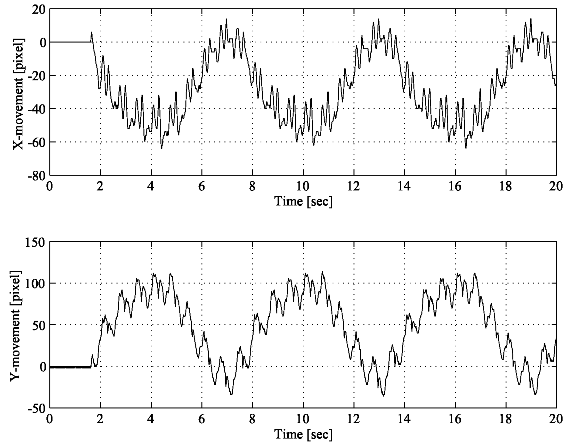

Fig. 9: Heartbeat measurements for frequency analysis

As seen in Figure 11, a laser point was projected on a paper underneath the oval frame window to which the slave robot was fixed. The laser point was projected from a laser pointer oscillating under the paper at the frequency of approximately 1.5Hz. The measured motion of the laser point was used for the visual and motion synchronizations. At the same time, an operator manipulated the master device (Phantom desktop) while watching the synchronized image. The command signal was transmitted from the master to the slave robotic device and additively combined with the vibrating laser point measurement. We would see the slave robot vibrating fairly complex, if we were directly seeing it. On the contrary, we saw on the monitor screen the slave robot quietly moving toward the stationary point of reference.

The results of experiments are graphically shown in Figure 12. The bottom two graphs are those of the motion of master device. The middle two graphs show the vibration of laser point measured using the high speed camera. The top two graphs are of the combined motion of the slave robotic device, where the solid line shows the real motion of the slave device, while the broken line indicates the combined reference signal. The difference is hard to read in the graphs and approximately 0.5 mm at the maximum. The motion was smooth and there were no visible effect of time delay.

5 Conclusions

The results of this paper is summarized in the following four points:

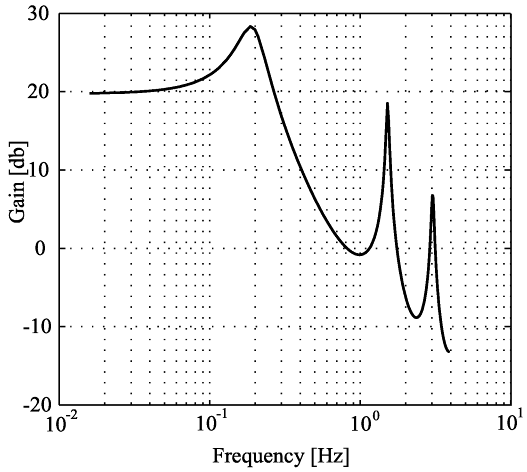

Fig. 10: Spectrum analysis of heartbeat based on a sixth order AR model

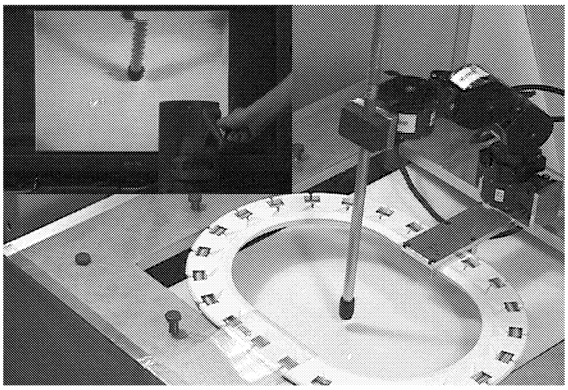

Fig. 11: Oscillating laser point and the synchronization system

1. We introduced the concept of the heartbeat synchronization for minimally invasive cardiac surgery.
2. We developed the visual and motion synchronization technologies, which were made possible by adopting a 955 fps high speed camera.
3. Through in-vivo experiments, we confirmed the visual and motion synchronization.
4. The heartbeat synchronization system was prototyped integrating the visual and motion synchronization technologies into the master-slave robot system. Experiments in an artificial environment clearly verified the effectiveness of the system.

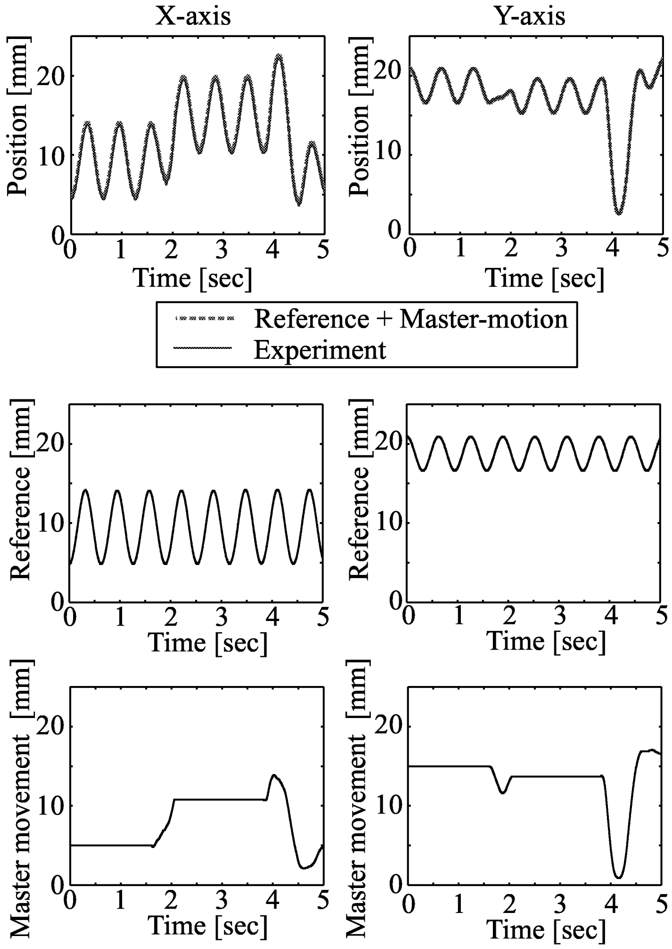

Fig. 12: Experiment of heartbeat synchronization (artificial environments)

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