On the Feasibility of a Moving Support for Surgery on the Beating Heart

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Abstract. In this paper the use of a heart-tracking hand support is proposed to allow coronary artery bypass grafting surgery to take place on the beating heart. This method eliminates the tissue damage associated with the use of physical heart stabilizers.
To evaluate whether tasks can be performed on a moving target while the operator's hands are moved with it, a moving platform was designed. Twenty six subjects performed a task that simulates suture placement, using different vision systems. Accuracy and task completion time were measured. The experimental results demonstrate that it is possible to perform accurate tasks while the hand is moving in synchrony with the workspace. The decrease in accuracy that results from a moving target was reduced up to 40% when using the support. With the use of the support, the task completion time increased 50% less than when the support was not used. The use of mono or stereo vision systems to provide a steady image of the workspace reduced the increase in task completion time. However, accuracy results are inconclusive due to problems with the vision systems used.

1 Introduction

The use of the heart and lung machine during coronary artery bypass grafting (CABG) surgery allows the heart to be stopped while it performs the circulation and filtration of the blood. This provides a motionless surgical area needed to perform complex grafts. However, there is a series of damaging effects on the blood that arise due to its use, as well as an increase in the surgery cost and the patient's recovery time [1].

CABG surgery can be performed without the use of the heart and lung machine since the chambers of the heart are not opened. The only technical requirement for suturing is to have a bloodless anastomotic field. This can be achieved by a temporary coronary occlusion [2].

However, there is a great difficulty in performing the grafts on the heart surface while it is in motion. Previous studies have been made to allow CABG surgery to be performed on the beating heart. The proposed methods work by stabilizing the surgical area on the surface of the heart, either by pressure on the tissue [3, 4] or by attaching an apparatus using suction [5, 6]. The use of stabilizers that work by pressure have the disadvantage of allowing grafts to

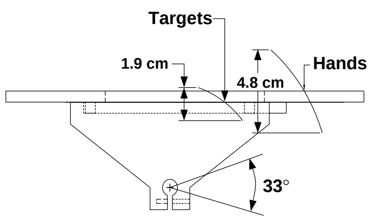


Fig. 1. Platform Motion

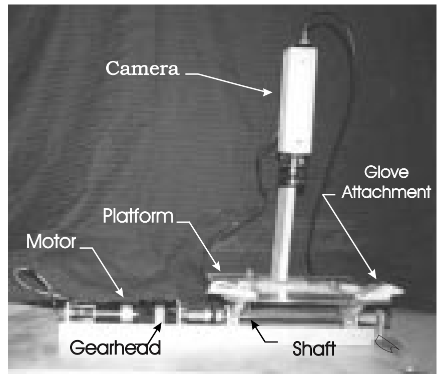


Fig. 2. Moving Platform

be performed only on the top surface of the heart. Stabilizers that work using suction have the disadvantage of damaging the heart tissue, even when used for short periods of time [7].

A moving hand support that moves in synchrony with the heart was independently proposed recently in [8]. The relative displacement between the moving platform and the surgical site is controlled by a pacer that controls the motion of the heart so that it follows the platform. Pacing the heart motion insead of following it has the disadvantage of having to control the heart rate to minimize errors between the surgical site and the platform.

Other work includes a system developed by [9], which is comprised of three interactive robotic arms that position the endoscope and manipulate the surgical instruments. The surgeon views the surgical site and controls the instruments while seated at an ergonomically enhanced console. A similar device developed by [10] was recently used for Minimally Invasive CABG surgery with cardiopulmonary bypass.

This paper examines the possibility of performing CABG surgery on the beating heart by moving the hands of the surgeon in synchrony with the heart motion. This would allow the surgery to take place without the use of the heart and lung machine and without exerting any stress on the heart tissue.

The objective of the experiment performed was to determine the possibility of performing a task that requires a high degree of accuracy while the hand is in motion. In addition, it was desired to determine the need for a vision system that provides a stable view of the hands, tools and workspace.

2 Experimental setup

2.1 Moving Platform

To test the ability of a human to perform a task on a moving target while the hands are being moved with it, an experimental platform was built. The motion of the platform roughly imitates the heart motion through an oscillatory rotation around a shaft. Figure 1 shows the vertical displacement in centimeters of the hand and the targets caused by a 33° rotation of the shaft.

Equipment	Brand \Model	Characteristics
Motor	Maxon \RE035-071-34EAB200A	90 Watt DC, Stall Torque 1.1 Nm
Gearhead	Sterling Inst. \ S9117A-PG010	Planetary, Ratio 10:1, single stage
Camera	Philips \VC72505T	Color CCD
Cameras	Pulnix \TM-545	Monocrome CCD, 510 x 492 pixels
Stereo Goggles	Keiser Electro-optics \ VIM 500	Color, 180000 pixels, 4:3 ratio

Table 1. Equipment details

The hand of the subject can be attached to the platform by means of a glove fixed to it, so that it tracks the platform. This simulates perfect tracking of the surgical site by the hand. It is possible to attach one or two cameras to the platform so that the workspace can be seen either on a TV screen (1 camera, mono vision) or on a pair of goggles (2 cameras, stereo vision). To provide a guide for the task to be performed, a piece of paper having a suture target pattern (see section 2.2) can be inserted and fixed at a desired position.

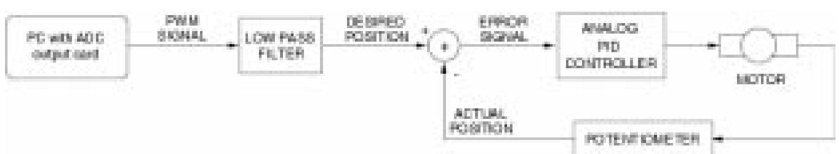


Fig. 3. Functional Components of the System

Figure 2 shows a picture of the platform with one camera mounted on it. Table 1 shows the details of the equipment used in the system.

Figure 3 shows a diagram of the functional components of the system. The desired platform angle was generated by a PC as a pulse width modulated (PWM) signal. This was converted to a reference voltage for a standard PID motor controller loop.

The original waveform used by the program was determined by measuring the motion of the medial coronary artery of a pig's heart which was then scaled to a human heart. A simple exponential rise and fall waveform was created based on the maximum measured motion [6]. Figure 4 shows a typical plot of the actual motion of the targets as a function of time.

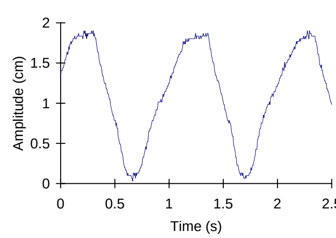


Fig. 4. Typical motion plot

2.2 Task and Test design

The task performed simulates a simple suturing process. It consists of marking with a pen one single dot inside each of the circles of a pattern as seen in Figure 5, in the order shown by the numbers. The diameters of the circles, the grid spacing and the respective target size assigned for the four different sizes used is shown in Table 2.

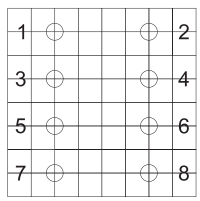


Fig. 5. Test pattern

Target Size	Diameter (mm)	Grid Spacing (mm)
1	3.43	4.76
2	2.29	3.18
3	1.73	2.38
4	1.14	1.59

Table 2. Test pattern dimensions

It was determined that a total of seven different tests should be performed. The tests and the reasons for each of them are as follows:

1. Steady platform and direct visualization of the workspace. This situation simulates suturing on a stable heart, which is generally achieved by means of the heart and lung machine.
2. Steady platform and visualization of the workspace on a TV screen. This test was added as a reference to Test 6.
3. Steady platform and visualization of the workspace through stereo goggles. This test was added as a reference to Test 7.
4. Platform in motion and no attachment of the hand. This test simulates suturing on the beating heart without any stabilization help.
5. Platform in motion, hand attached to it and direct visualization of the workspace. This test simulates suturing on the surface of the beating heart and the hands are being moved to track the surgical site.
6. Platform in motion, hand attached to it and visualization of the workspace on a TV screen. This situation simulates suturing while the heart and the hands are seen as a steady, two dimensional image.
7. Platform in motion, hand attached to it and visualization of the workspace through stereo goggles. To provide depth perception, two cameras and a pair of stereo goggles were used to produce a three dimensional image.

The hand that was attached to the platform during tests 5 to 7, depended on whether the subject was left or right handed.

2.3 Testing

A total of twenty six subjects tested the platform. The test population was comprised of three cardiac surgeons, one professor and twenty two graduate students. The age of the subjects ranged from 22 to 49 years of age. Seven were older than 30 years of age and nineteen were younger. There was a total of

Moving Platform Testing

Subject's Information

Name: ____________

Age: ____________

Sex: ____________

Occupation: ____________

Subject's Evaluation on Moving Platform

After performing each task, score each according to the following scale:

4-Very High 3-High 2-Average 1-Low 0-None

Please feel free to add comments and suggestions. The numbers from one to seven correspond to each of the tests made, which are:

1. Steady platform and direct vision.
2. Steady platform and use of the image from the camera (mono vision).
3. Steady platform and use of the image from the camera (stereo vision).
4. Moving platform and no attachment of the hand.
5. Moving platform, hand attached and direct vision.
6. Moving platform, hand attached and steady image (mono vision).
7. Moving platform, hand attached and steady image (stereo vision).

Discomfort	1 __	2 __	3 __	4 __	5 __	6 __	7 __
Fatigue	1 __	2 __	3 __	4 __	5 __	6 __	7 __
Concentration	1 __	2 __	3 __	4 __	5 __	6 __	7 __
Difficulty	1 __	2 __	3 __	4 __	5 __	6 __	7 __

Comments and suggestions: ____________

Fig. 6. Questionnaire

Score	Characterisitcs of the mark
6	A neat dot inside the target
5	A smear inside the target or one neat dot in contact with the circle
4	A smear in contact with the circle
3	A neat dot outside the circle but inside the four quadrants surrounding the target
2	A smear outside the circle but inside the four quadrants surrounding the target
1	A smear or a dot that is outside the four surrounding quadrants

Table 3. Scoring scale

seven female subjects and nineteen male subjects. Two of the subjects were left handed.

Although surgeons perform training exercises similar to the task performed, none of the other subjects had any experience in performing such tasks. For this reason they were allowed to practice as much as they felt was necessary. Each subject was told to perform the task as accurately and quickly as possible, giving greater importance to the accuracy than to the speed. Each of the subjects performed the seven tests in a random order.

After each test, subjects were asked to fill out the subjective questionnaire shown in Fig. 6.

Three of the subjects were asked to perform the test set an additional two times with the goal of determining whether there was a learning process involved when performing the task.

Target Size	Accuracy Score	Completion Time (s)
1	46.6 $\pm$ 2.4	6.52 $\pm$ 2.6
2	47.2 $\pm$ 1.3	6.04 $\pm$ 2.0
3	47.3 $\pm$ 1.4	6.08 $\pm$ 2.1
4	45.5 $\pm$ 2.5	6.31 $\pm$ 2.2

Table 4. Average results for test 1

4	Very High
3	High
2	Average
1	Low
0	None

Table 5.

2.4 Quantification of Performance

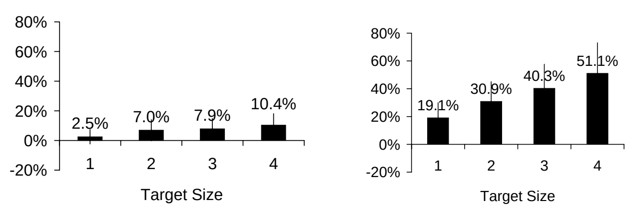
The two factors measured to judge performance were task completion time and the accuracy and neatness of the mark made with the pen. To measure accuracy the scoring scale shown in Table 3 was used. If two marks were made, the one further away from the target was considered for scoring purposes.

3 Experimental Results

Table 4 shows the measured values for task completion time and accuracy for Test 1. These values are averaged over the 26 subjects. The standard deviations are indicated.

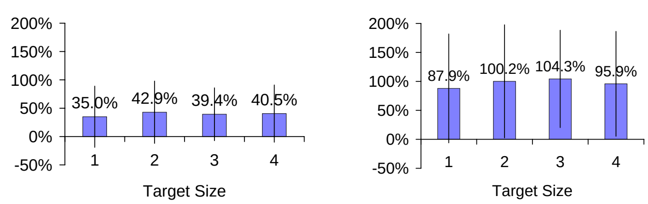
For each subject, all measured values were normalized with respect to the test where the platform was stable and the same vision system was used. The graphs show the average results obtained by the twenty six subjects. The error bars show the standard deviation of the measurements from the average.

3.1 Results obtained from tests with direct vision.



(a) Hand attached (b) Hand not attached

Fig. 7. Decrease in accuracy



(a) Hand attached (b) Hand not attached

Fig. 8. Increase in task completion time

Figure 7 shows the decrease in accuracy that results from a moving platform compared to a steady platform for the four different target sizes (see Table 2).

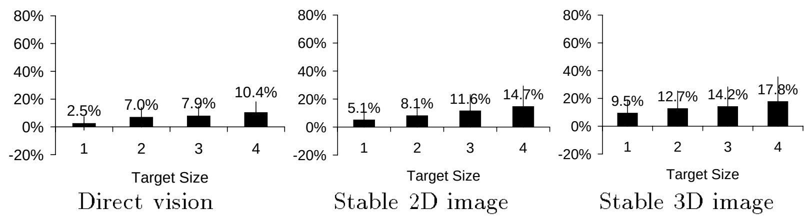


Fig. 9. Decrease in accuracy when using different vision systems

Similarly, Figure 8 shows the increase in the task completion time in comparison to when the platform was stable.

The results show that without the hand support, the accuracy decreases by more than 50% when performing the task on the smallest pattern size. When the hand is attached to the platform this reduction is less than 11%, even for the smallest targets.

When the hand is attached and the platform is in motion, the average task completion time is increased by around 40% with respect to when the platform is stable, independent of the target size. This shows a considerable improvement over unattached hand, where the increase in task completion time is doubled.

3.2 Results from the use of different vision systems

Further analysis was made to determine the advantages or disadvantages of using different vision systems to provide a steady image of the workspace. The results are compared to the test with direct vision in Figures 9 and 10.

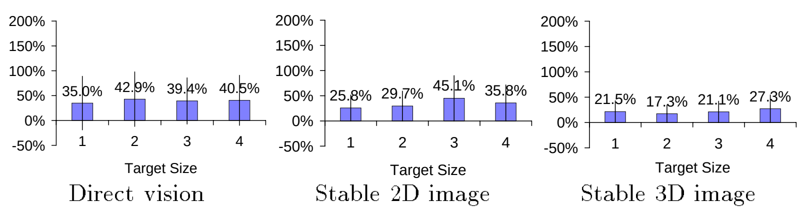
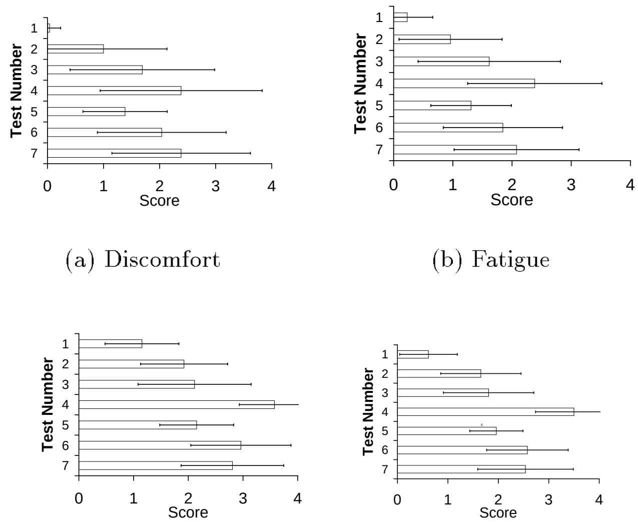


Fig. 10. Increase in completion time when using different vision

These graphs show how the accuracy is reduced by approximately 15% for the smallest target using mono vision and 18% using stereo vision. These values are both greater than for direct vision. On the other hand, the stereo vision system produces the least increase in task completion time - less than 30% for all the target sizes.

3.3 Questionnaire Results

The graphs in Figure 11 show the results of the subjective evaluation made by each test subject. The scale used by the subjects for scoring purposes is shown in Table 5. The test number shown corresponds to the list given in Section 2.2.



(a) Discomfort (b) Fatigue

(c) Concentration (d) Difficulty

Fig. 11. Questionnaire results

As can be seen from the graphs, subjects found the test with no hand support and the platform in motion (Test 4) to be the most uncomfortable, fatiguing and difficult one, as well as the one that required the most concentration. When the platform was not in motion, the test with direct vision (Test 1) was perceived to be the easiest and simplest to perform. Looking at the image on the TV screen (Test 2) in 2D or with the goggles (Test 3) in 3D caused the task to be more difficult and to require higher concentration. In addition, the use of the goggles produced the greatest discomfort and fatigue.

These results are consistent with the results obtained when the platform was in motion (Tests 5, 6 and 7), although there is a general increase in all the factors due to the motion.

3.4 Results of the Learning Process

The results obtained when three of the subjects repeated the test two more times show that there is no general tendency for an increase in accuracy or decrease in task completion time for the second or third performances. In some cases there is improvement, but not in all the tests.

4 Discussion

The direct vision results demonstrate that when the hand moves in synchrony with the task space, there is a significant improvement in the accuracy achieved. Using a vision system to provide a steady image of the workspace and the hand did not further improve the accuracy of results; however, there are several factors that have to be taken into account when analyzing these results. The TV screen used in the 2D system is located in front of the subject, causing the workspace to be seen as a vertical surface instead of a horizontal one. In addition, there is lack of depth perception. When using the stereo goggles, although the 3D image provided depth perception, problems arose due to the low resolution of the image (17 pixels across smallest target) and the fact that the image was located at the edge of the depth of field of the camera.

Due to the nature of the surgical task, magnification of the workspace is a necessity. Without the use of a vision system, capable of following the motion of the heart, the surgical area would likely pass out of the field of view of the magnification apparatus. It is believed that if a clear and magnified stereo image is provided, the results obtained can be as good or better than those obtained when looking at the surgical area directly.

When analyzing the results obtained for task completion time, it was noticed that there was a high degree of variability among the subjects, as seen from the large standard deviations shown in the graphs. This variability was noticeable in all of the tests, including those where the platform was stable (Table 4). The main cause of this variability is the random order in which the tests were performed — it was common for subjects to decrease completion time from the first tests to the last. This makes it difficult to obtain conclusive results from the graphs; however, the analysis was made based on the general tendency, showed by the average value obtained from all the subjects.

There was an increase in the task completion time when performing the task with the platform in motion regardless of the vision system used. This increase in time is considered to be much less than that required for the use of the heart and lung machine (approximately 80 minutes); therefore, the approach is still viable.

The increase in task completion time when using the stereo vision system was slightly less than when using the 2D system or direct vision. By offering a stable, 3D image of the workspace, the motion of the platform did not degrade performance as much as with the other vision systems. This agrees with the results of the questionnaire which indicate that the 3D image reduced the concentration requirements and perceived difficulty of the task.

The results from the questionnaire also indicate that there is a need to improve the design of the apparatus. The levels of discomfort, fatigue, concentration and difficulty experienced by the subjects when the platform was in motion can be reduced by a better design of the support and the vision system.

It is worth noting that there is no significant performance improvement to be realized by repeating the tests several times. This is demonstrated by the tests used to evaluate the learning process. Also, the ability to perform the tests was not influenced by surgical skill, as the performance of the three surgeons was very similar to the other, unskilled subjects.

5 Conclusions and Future Work

A method based on a moving hand and/or tool support that tracks the motion of the heart creates a new alternative for performing coronary artery bypass grafting surgery while the heart itself is circulating and filtrating the blood. This reduces the overall invasiveness of the surgery, the recovery time and the secondary effects.

Twenty six subjects evaluated the moving hand support with the goal of determining the feasibility of the approach. The experimental results show that it is possible to perform accurate tasks while the hands are being moved in synchrony with the workspace.

The results obtained when using the support are clearly improved as compared to those when it was not used. The average accuracy of the tasks was nearly unaffected (more than 90%). Average task completion time was increased by approximately 40%. No improvement was realized by providing a stationary image due to the lack of a high resolution stereo vision system.

The need for a magnified image justifies the need for a vision system that follows the motion of the workspace. The vision system used should provide a stable stereo image with very good resolution and clarity.

Potential improvements to the apparatus include an ergonomically designed support that guides and supports the hand comfortably. Adjustments to allow the tool that is being used to also be attached and moved in synchrony with the heart would be beneficial. The main future work will involve tracking the heart motion in real time and designing a mechanism that produces the required platform motion.

6 Acknowledgments

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