Evaluation of Image Stabilization Methods in Robotic Beating Heart Surgery

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Abstract:
In cardiopulmonary bypass surgery, it is beneficial to avoid the use of a heart-lung machine and perform beating heart surgery instead. This is a difficult task even for the most skilled surgeons. To eliminate the risks associated with cardiopulmonary bypass on a beating heart, a motion compensation system can be used. We place markers on the heart surface, which we can use to track the complex heart motion and to produce still footage of the heart surface by applying one of several stabilization algorithms to eliminate the motion. We compare six different stabilization algorithms, affine, B-spline, piecewise linear and three types of radial basis functions. In this paper, we evaluate the results using three evaluation methods, pixel intensity average difference, optical flow, and stabilized marker tracking. All of these show a significant reduction in motion after stabilization, especially for interpolation-based stabilization methods as opposed to the affine approximation. We discuss advantages and disadvantages of the different evaluation methods.

Keywords: *absolute difference, optical flow, marker tracking*

1 Problem Formulation

Worldwide, the majority of coronary artery bypass graft surgeries (CABG) are performed on arrested hearts due to the demanding task of operating on a beating heart. In this case, however, additional risks are incurred by cardiopulmonary bypass and the use of heart-lung machine [1]. Robot-assisted surgery would consist of presenting a stabilized view of the operated surface to the surgeon, allowing him to perform surgery as if working on a still surface. While changes to the texture of the heart surface remain visible, its movement is removed. The surgeon's motion is then synchronized to the actual motion from the heart surface by a remote-controlled robot [2].

Several steps need to be performed, namely image acquisition, tracking of landmarks on the heart surface, and image stabilization. Several works have been published regarding the topic of tracking multiple targets, which are the landmarks in the considered scenario [3]. Stabilization evaluation has been somewhat disregarded in literature. Amongst research teams working on motion compensation for beating heart surgery, few seem to quantitatively evaluate heart surface stabilization results. We have previously proposed the use of absolute image differences [4], and Gröger et al. [5] have considered optical flow as an evaluation method. In the research area of camera motion stabilization, other measures such as fidelity, minimum image displacement, and maximum image displacement have been used [6].

This paper includes two main contributions. First, we apply the image stabilization methods introduced in [7] to new experimental footage of a heart without a mechanical stabilizer, whereas our previous work only considered a mechanically stabilized heart. Second, we compare the results based on three different evaluation methods and discuss the advantages and disadvantages of the different ways to evaluation stabilization quality.

2 Materials and Methods

The footage used for our experiments was captured during porcine open heart surgery performed at the Department of Cardiac Surgery, University of Heidelberg using a Pike F210-C camera with a resolution of 1920 by 1080 pixels. No mechanical stabilizer was used. About 20 artificial landmarks, which we refer to as markers, were placed on the heart surface. The task of tracking landmarks involves identifying individual markers throughout the video sequence and estimating their position. For the purpose of this paper we implemented a basic marker tracking algorithm based on color segmentation and a nearest neighbor approach. We have recently proposed a more sophisticated approach based on the so-called Kernel-SME algorithm in [8]. Based on these target tracks, we apply a number of stabilization algorithms, which we discuss in detail in [7]. We compare a basic affine transformation with interpolation schemes based on B-Splines, piecewise linear interpolation based on the Delaunay triangulation (similar to [5]), and radial basis functions with a Gaussian, a locally supported, and a thin-plate-spline as the basis function. The sequences resulting from stabilization were evaluated using all detected markers as well as with a subset of markers, omitting one marker for evaluation purposes. Stabilization evaluation was carried out using three different testing methods, "pixel intensity average difference", "optical flow", and "2D tracking of stabilized markers".

Pixel Intensity Average Difference

The pixel intensity average difference was previously used by Kurz and Hanebeck [4], [7] during experiments on a heart phantom and footage of a mechanically stabilized porcine heart. To determine residual motion, each frame belonging to the sequence is compared to a reference frame of the same sequence. The intensity error is the difference in intensity between pixels in the reference frame and corresponding pixels in the current frame for all frames. The overall error is the average error over all pixels and color channels.

Optical Flow

Since the goal of stabilization is to eliminate all motion from the sequence, the residual motion in the sequence can be used to describe the quality of the stabilization. We used the optical flow algorithm [9] to compute the velocity in the stabilized video sequence. The velocity magnitude was extracted to describe the residual motion in the sequence. A similar method has been applied by Gröger et al. [5].

Stabilized 2D Marker Tracking

The marker tracking algorithm was applied to the stabilized sequences in order to assess the reduction in inter-frame marker motion (in pixels) after stabilization. This evaluation method is somewhat biased since it only applies to the markers, which were the starting point for stabilizing the images. Thus, it is expected that the stabilization at these points would be more accurate than at other points in the image. To measure the effect of this bias, the video footage was also stabilized omitting one marker, which was then tracked after stabilization.

3 Results

Marker tracks obtained with the 2D marker tracking algorithm illustrate tracking quality for the different types of sequences processed. The tracking algorithm successfully distinguishes and tracks each marker (Figure 1, Figure 2).

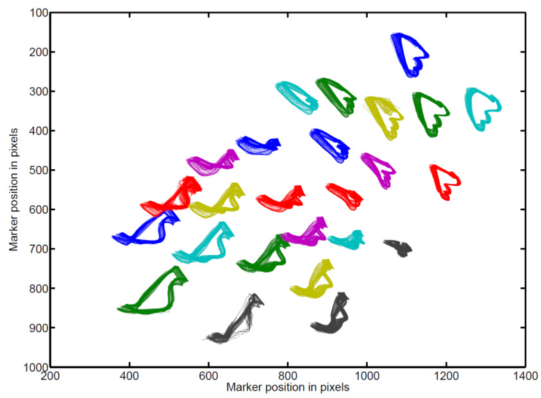


Figure 1: Tracks for all markers.

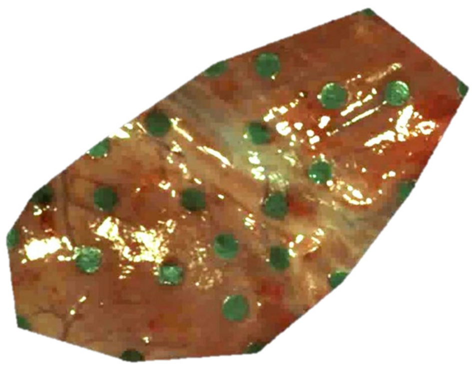


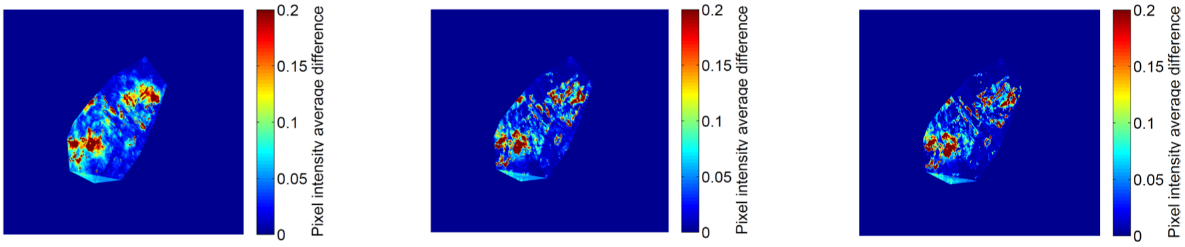
Figure 2: Region of interest on the heart surface.

Pixel Intensity Average Difference

Evaluation of stabilized footage with the pixel intensity average difference method confirms stabilization has reduced the inter-frame difference between pixel intensities (see table below). The affine approximation yields worse results than the interpolation techniques. The results of the latter are very similar. Comparison of results from stabilization using all markers versus a subset reveals only a small variation between the two cases, confirming that the stabilization is not sensitive to changes in individual markers.

	Markers	Unstablilized	Affine	B-Spline	Delaunay	Gauss	Local RBF	Thin plate spline
Mean	All	0.336	0.256	0.240	0.240	0.240	0.246	0.240
Std. Dev.	All	0.171	0.140	0.137	0.136	0.137	0.138	0.138
Median	All	0.332	0.273	0.254	0.254	0.253	0.262	0.252
Mean	All but one	0.333	0.249	0.235	0.234	0.235	0.240	0.234
Std. Dev.	All but one	0.174	0.145	0.142	0.141	0.142	0.143	0.143
Median	All but one	0.325	0.260	0.243	0.242	0.242	0.250	0.240

In the example in Figure 3, the average difference is reduced by all stabilization methods in comparison with the unstabilized control. Interpolation yielded only slightly lower average differences from the affine approximation. The effect of specular reflections on the stabilization is clear when comparing the regions of highest pixel intensity average difference with the regions where specular reflections are most intense (Figure 2). Generally, the specular reflections will affect different regions in the image as the heart surface moves and deforms. As the motion of the specular reflections is not corrected by the stabilization algorithm, evaluation methods will consider reflections as part of the residual motion.



a) Unstabilized   b) Affine   c) B-spline

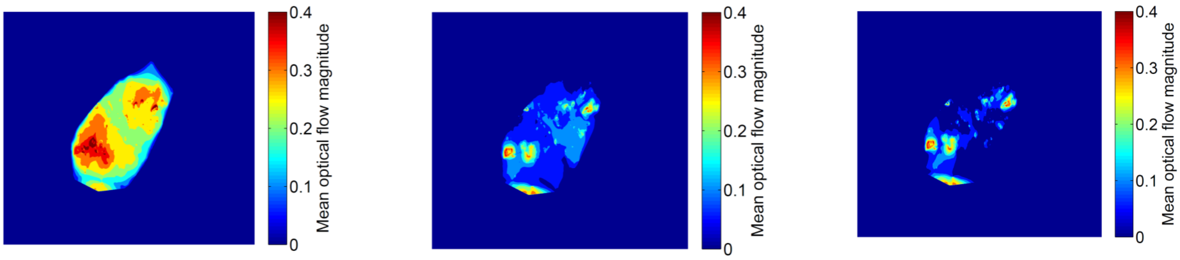
Figure 3: Results from pixel intensity average difference.

Optical Flow

Optical flow results clearly show the success of the stabilization techniques when comparing the magnitude images to the control (see table below). This evaluation method highlights the lower residual motion resulting from stabilization using interpolation methods versus the affine approximation. Only slight variations in performance are observed between footage stabilized with all markers versus the subset, indicating once again the stabilization algorithm's robustness.

	Markers	Unstablilized	Affine	B-Spline	Delaunay	Gauss	Local RBF	Thin plate spline
Mean	All	0.302	0.114	0.086	0.084	0.084	0.093	0.086
Std. Dev.	All	0.128	0.075	0.082	0.081	0.081	0.078	0.081
Median	All	0.286	0.098	0.055	0.055	0.055	0.071	0.055
Mean	All but one	0.303	0.113	0.086	0.083	0.084	0.094	0.086
Std. Dev.	All but one	0.129	0.075	0.082	0.081	0.081	0.078	0.082
Median	All but one	0.286	0.098	0.055	0.051	0.055	0.071	0.055

Optical flow magnitude variations are illustrated in Figure 4 for one experiment. When compared to the stabilized footage, the residual motion magnitude appears to be highest in regions with important specular reflections as with the average difference method. Optical flow results were found to be nondeterministic by testing the same video sequence twice. In the table above, results for the unstabilized footage illustrate this flaw of the algorithm.



a) Unstabilized   b) Affine   c) B-spline

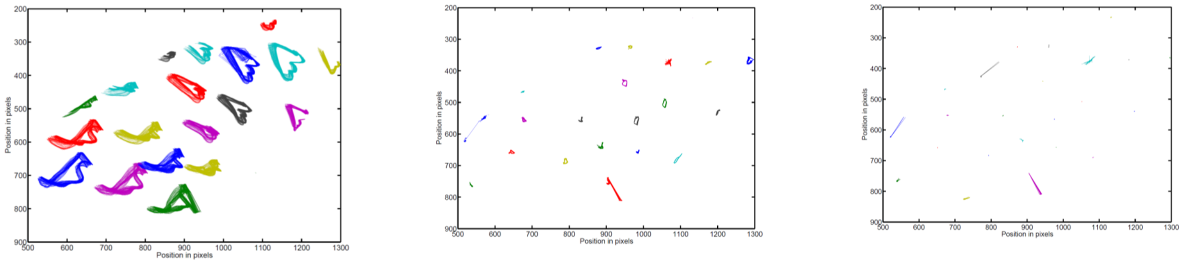
Figure 4: Results from optical flow.

Stabilized 2D Marker Tracking

The effect of stabilization can be easily viewed with the marker tracking algorithm (Figure 1). These results illustrate the success of all stabilization methods. The resulting tracks (Figure 5) for affine stabilization are significantly less spatially compact than those of the interpolation methods. There occur a few outliers in this evaluation approach as a result of imperfect tracking, but this is not a significant problem. Quantitative results indicate sub-pixel stabilization results for all interpolation methods (see table below). One pixel corresponds to approximately 0.05 mm on the heart surface.

	Markers	Unstablilized	Affine	B-Spline	Delaunay	Gauss	Local RBF	Thin plate spline
Mean	All	14,89	2,27	0,30	0,40	0,29	0,38	0,31
Std. Dev.	All	11,06	1,89	0,20	0,24	0,20	0,24	0,21
Median	All	11,78	1,69	0,27	0,37	0,26	0,34	0,28
Mean	All but one	14,89	2,37	1,47	1,44	1,49	2,31	1,38
Std. Dev.	All but one	11,06	1,98	1,00	1,18	1,12	1,91	0,90
Median	All but one	11,78	1,77	1,21	1,09	1,17	1,72	1,15

Since the markers are used in the stabilization algorithm as points where motion is known, it is expected that their tracks after stabilization would only show very little motion. To eliminate this bias from the stabilization evaluation, one marker was eliminated from the dataset before stabilization. As expected, markers omitted from the initial marker tracking preceding stabilization were less accurately tracked than when these same markers were included in the stabilization step.



a) Unstabilized b) Affine c) B-spline

Figure 5: Results from stabilized 2D marker tracking.

4 Discussion and Summary

Specular reflections reported to be a problem in heart stabilization did not prove to be an important issue in marker tracking. There is some visible drift in marker motion, which can be attributed to breathing motion. Such additive motion should not be neglected in model-based stabilization algorithms.

All three evaluation methods lead to similar conclusions. Pixel intensity average difference and optical flow methods have the advantage of evaluating the entire image as opposed to the tracking algorithm. Both global methods have the drawback of being susceptible to specular reflections. Despite this downside, both methods indicated an improvement in stabilization with the interpolation methods. Direct comparison shows that the optical flow algorithm produces more significant differences between the different stabilization algorithms. As opposed to the first two methods, marker tracking is not susceptible to specular reflections and allows quantification of motion in distance units, but has the downside of only evaluating specific points in the image.

5 Acknowledgments

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6 References

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