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Tracking heart surface features to determine myocardial contrast agent enrichment

Abstract: Fluorescent cardiac imaging can be applied for intraoperative quality control after a coronary bypass grafting surgery to ensure the myocardial perfusion by evaluating the increasing contrast agent enrichment in the heart. The motion due to the beating heart impedes the interpretation of the contrast agent enrichment in the vessels and leads to noisy enrichment curves. We propose tracking of the heart surface features to compensate for the motion of the beating heart and thereby improve the analysis of the contrast agent enrichment. Furthermore, we propose a vessel segmentation pipeline for a local evaluation of contrast agent enrichment directly in the vessels.

Keywords: Object tracking, heart motion, surface features

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1 Introduction

A coronary artery bypass grafting (CABG) is a surgical procedure to treat coronary heart disease. The cause for this can e.g. be atherosclerosis which arises due to unhealthy lifestyle or medical reasons. Following, plaque can be build up in the arteries and impair the blood supply to the heart which makes CABG an important medical procedure. During an immediate postoperative period, the grafts can fail due to different reasons, e.g. poor bypass conduit or vessel quality [1]. These failures can already be detected during surgery to avoid postoperative complications. Different technologies for intraoperative graft quality control have been proposed, but have several limitations such as a subjective evaluation of the results or invasiveness [2]. Detter et al. [2, 3] propose fluorescent cardiac imaging (FCI) for intraoperative quality control of the grafts. FCI is a noninvasive technique for visualization of the coronary vessels and allows for generating contrast agent enrichment curves for an objective evaluation of myocardial perfusion. Even though FCI can detect graft occlusion and support in intraoperative graft patency assessment, the data is recorded under controlled conditions in open-chest pigs and limited due to several factors. Changes concerning heart rate, blood pressure as well as the scattering properties of the heart and motion due to the beating heart, influence the measurements. The motion results in noisy enrichment curves which impedes the interpretation.

Object tracking is an active area of research and also widely applicable in medical scenarios. The tracking methods have to be precise, robust and fast to allow for a real time processing of image sequences. Furthermore, the algorithms have to cope with changes in appearance, such as illumination, rotation of the object and occlusions. Tracking based on correlation filters is computationally efficient and different real time capable algorithms have been proposed [4]. The Kernelized Correlation Filter (KCF) [5] and its extensions have successively been applied to different data sets [6, 7] for a robust tracking.

In this paper, we evaluate the KCF for tracking of the heart surface features to compensate the motion during graft quality assessment and to generate smooth contrast agent enrichment curves. We consider the KCF for a markerless tracking of the heart surface features and investigate the influence of the template size and initial tracking position on the heart surface. Additionally, we propose a segmentation pipeline to determine the location of the vessels in the frames and propagate the position throughout the sequences. This approach allows for a local evaluation of the contrast agent enrichment in a vessel. We evaluate the two approaches amongst others by using the Forward-Backward-Error (FBE) [8], as no ground-truth data is available. Furthermore, we consider the enrichment curves

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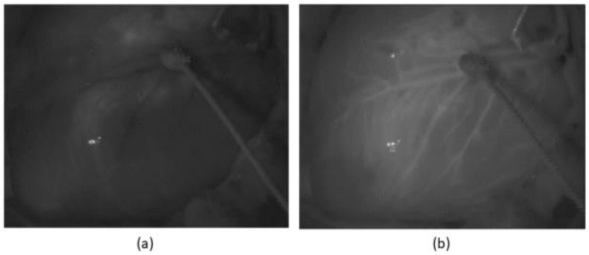

Figure 1: Frame at the beginning of the recording with very low contrast (a) and frame in the middle of the recording, showing the vessels due to the enrichment of the contrast agent (b).

of the contrast agent for an indirect evaluation of our approaches. We can show that tracking of the heart surface features improves the generation of smooth contrast agent enrichment curves and allows for real time processing of the image sequences.

2 Data

The dataset comprises 14 videos of FCI recorded from different pig hearts. The pigs were narcotized and a median sternotomy followed by coronary revascularization were performed on the beating heart. Afterwards, a contrast agent, indocyanine green, was injected intravenously and the heart was illuminated with near-infrared light (785 nm) from laser diodes. An infrared-enhanced camera was used to record the emitted fluorescence signal and band pass filters were placed in front of the camera to transmit the emitted light at 830 nm without the excitation light. The videos were recorded with 25 fps for about 60 sec with 768x576 pixels. Exemplary frames from the videos are shown in Figure 1.

In the beginning of the video sequence, the image contrast in the frames is low. Due to the enrichment of the contrast agent over time, the image contrast increases and the vessels are visualized more clearly. The camera is positioned 25 cm above the hearts but the orientation differs regarding the rotation of the hearts. Also artifacts, such as reflections from the surface and the catheters are visible in the frames. As we extract the templates automatically at certain positions, we exclude one video from evaluation where the heart's position differs significantly from the others due to rotation of the camera.

3 Method

We evaluate the contrast agent enrichment curves with and without tracking and propose a segmentation pipeline evaluating local areas at the vessels.

3.1 Kernelized Correlation Filter

The KCF [5] allows for discriminant feature channels, such as histogram of oriented gradients (HOG) at high frame rates. The tracking is split into the training of the tracker based on the initial template and updating during the tracking process. The tracker is trained on the frame sequences and updated with a combination of the previous and current state. The KCF operates in Fourier domain and makes use of circulant matrices to speed up the tracking process.

3.2 Evaluation

There was no ground-truth data available for the heart motion. Therefore, we rely on the FBE as proposed by Kalal et al. [8] for evaluation of our tracking precision. Initially, a point $\mathbf{p}_t$ at time t is tracked for j steps in an image sequence $S = (I_t, I_{t+1}, \dots, I_{t+j})$ and results in trajectory $T_f^j = (\boldsymbol{p}_t, \boldsymbol{p}_{t+1}, \dots, \boldsymbol{p}_{t+j})$. Tracking backwards results in the trajectory $T_b^j = (\boldsymbol{p}'_{t+j}, \dots, \boldsymbol{p}'_{t+1}, \boldsymbol{p}'_t)$. The FBE is then defined as the Euclidean distance between the points at time t

$$\mathbf{FBE} = \| \mathbf{p_t} - \mathbf{p'_t} \|. \quad (1)$$

If the tracker loses the template the resulting trajectory is somewhat random for the forward and the backward path, resulting in a high FBE. In some cases the tracker drifts off on the forward and backward path due to the periodic beating of the heart. Therefore, we count the number of total tracking failures where the tracker fails to make an update for the succeeding frame and determine if drifting occurs based on the initial and last positions in the tracking trajectory. Additionally, we consider the processing speed in fps and the total variation (TV)

$$\mathbf{TV} = \sum_{\mathbf{n}} | \mathbf{x_{n+1}} - \mathbf{x_n} | \quad (2)$$

of the generated enrichment curves for evaluation. The curves are generated by evaluating the mean gray value in an area of 50x50 pixels in the center of the template. A successful tracking would generate a smooth gray value curve with a low TV.

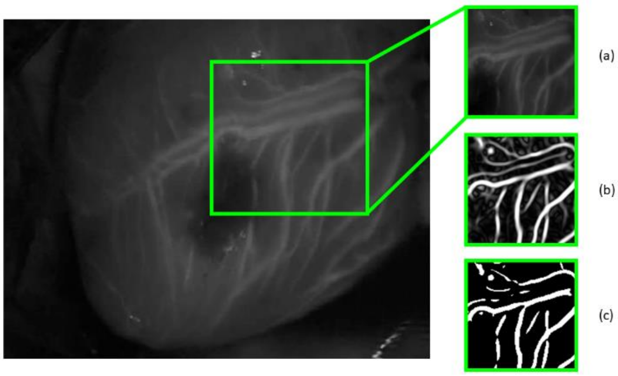

Figure 2: Examples from the segmentation pipeline. A cropped template from the original image (a) is processed with the ridge detector to detect the vessels (b) and a segmentation mask (c) is generated.

3.3 Segmentation

To receive information about the gray values and thereby the contrast agent enrichment directly at a vessel, we perform a segmentation on the forward tracking path and propagate the information to the backward tracking path to extract the gray value at the detected point at the vessel. After the initial frames the contrast agent enriches in the vessels. In this state, the image contrast between the vessels and the background is high but lowers once the contrast agent spreads into the surrounding tissue. We therefore perform a segmentation in the frames where the contrast is high, to detect the vessels position in the tracked template. The contrast of the tracking area in each frame is computed as the standard deviation $\sigma = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \mu)^2$ of the gray values of pixels $\mathbf{x}_i$ with mean μ. Firstly, we apply a ridge detector [9] which is based on the eigenvalues λ_1 and λ_2 of a hessian matrix of the image I

$$\mathbf{H} = \begin{bmatrix} \frac{\delta^2 I}{\delta x^2} & \frac{\delta^2 I}{\delta x \delta y} \\ \frac{\delta^2 I}{\delta x \delta y} & \frac{\delta^2 I}{\delta y^2} \end{bmatrix} \quad (3)$$

to detect the vessels. Secondly, we perform a window leveling and binarization. Thirdly, we detect the center point of the largest segmented vessel. The different steps of the approach are visualized in Figure 2. A smaller area of 25x25 pixels around this point is used for a more local evaluation of the gray values during the backward tracking path.

4 Results

We distinguish between evaluation of the contrast agent enrichment in a static region (*static*), in a region with motion tracking (*tracking*) and evaluation of gray values with tracking

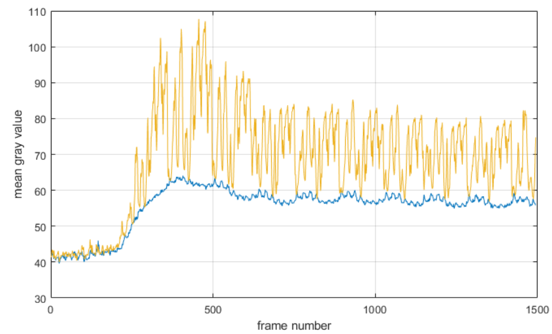

Figure 3: The enrichment curve in a static template (yellow curve) compared to a template tracked with KCF (blue curve).

and segmentation (*segmentation*). Initially, we evaluated different template sizes between 50x50 to 200x200 pixels regarding the FBE, drifting and tracking fails for the KCF tracker. The smaller template sizes led to immediate tracking fails. As the occurring motion is not purely rigid, we decided to use the smallest template size which did not result in a high amount of tracking failures, to obtain a local assessment for the motion. We therefore applied a template size of 150x150 pixels.

Next, we evaluate the different tracking regions on the heart surface in all videos. We separate the heart into nine minimally overlapping regions based on the heart's anatomy. The regions and results for the KCF tracker can be taken from Table 1. We consider the regions where no drifting occurs and the number of tracking failures, the FBE and the TV from the mean gray values are low. The results indicate that the tracking is most successful when the tracker is placed in the bottom right or middle right section of the heart. In most regions where drifting occurs during tracking, the number of total tracking failures is also high. Overall, the FBE is between 12 and 28 pixels but does not reflect the drifting or tracking failures. The

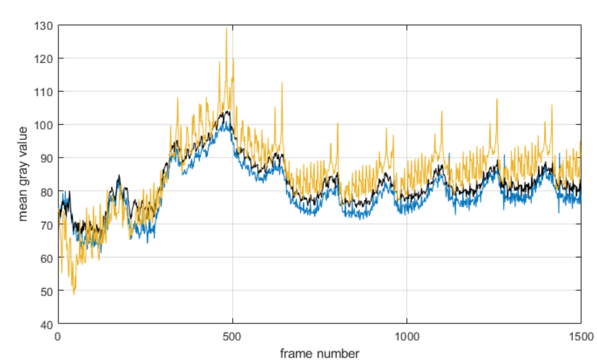

Figure 4: Enrichment curve in a static region (yellow curve), a region tracked with KCF (blue curve) and a region tracked with KCF and additional segmentation (black curve).

tracking failed for the top right region. Figure 3 shows an exemplary contrast agent enrichment curve with and without tracking. The curve generated with tracking is smoother than the static approach but follows a similar course.

Table 1: Nine different regions (bottom left, bottom middle, bottom right, middle left, middle middle, middle right, top left, top middle, top right) on the beating heart evaluated with the KCF tracker. The mean value over 13 video sequences are shown.

position	FBE in pixel	number of failures	TV	drifting
BL	27.6	477.7	2007.7	1
BM	19.4	269.4	2157.2	0
BR	25.4	46.4	1511.5	0
ML	18.1	266.8	2043.5	1
MM	12.9	517.2	2328.6	1
MR	14.7	7.4	1281.6	0
TL	17.2	71.9	1390.1	1
TM	17.7	151.7	1232.8	1
TR	/	/	/	1

Table 2: Results obtained with tracking the template with KCF compared to the static template and the segmentation (segm) approach for the bottom right (BR) and middle right (MR) region.

tracker	FBE in pixel	number of failures	TV	drifting	fps
KCF BR	25.4	46.4	1511.5	0	114.7
KCF MR	14.7	7.4	1281.6	0	111.4
static BR	/	/	1978.1	/	/
static MR	/	/	2338.3	/	/
segm BR	/	/	3137.0	/	/
segm MR	/	/	3103.6	/	/

We evaluate the KCF tracker for the two selected regions, bottom right and middle right, in all videos regarding speed, precision and indirectly by evaluating the smoothness of the contrast agent enrichment curve and compare it to the TV of the static and the segmentation approach. The results are shown in Table 2. The results obtained with the KCF tracker are the best concerning the TV for both regions. The TV is 1511.5 with tracking and 1978.1 with the static approach and 1281.6 with tracking and 2383.3 with the static approach for the bottom right and the middle right region, respectively. The number of total tracking failures is low for both regions and the fps high, thus enabling real time tracking of the heart surface features.

Furthermore, we examine if evaluating the gray values at a vessel can improve the smoothness of the enrichment curve. We perform a segmentation and evaluate a small region around a detected point at the vessel. An exemplary enrichment curve where the segmentation performs better than a static approach is shown in Figure 4. The results in Table 2 and the evaluation of further enrichment curves show, that the segmentation performs in general worse than a static and tracking approach. The enrichment curves show a high TV which is due to additional small motion when the template slips of the vessel.

5 Discussion and Conclusion

The results show that the tracking of the heart surface with the KCF performs well for the bottom right and middle right regions on the heart and improves the smoothness of the contrast agent enrichment curves. The KCF enables real time processing faster than the video frame rate. The tracking could be integrated into the system for an online evaluation of the contrast agent enrichment with tracking during surgery. The low number of tracking failures account for a robust motion estimation. The segmentation works well to determine a point for evaluation at the vessel, but additional motion and contraction due to the pulsating heart lead to motion that the tracker cannot resolve. The succeeding evaluation with segmentation shows a higher TV than the static evaluation in most cases. A more accurate evaluation of the motion of the vessels could help overcome these limitations. Overall, the performance of the tracker relies heavily on the initial template size and position due to drifting effects on the surface of the beating heart. When placing the template at a suitable position, our tracking improves the enrichment curve analysis and leads to smoother curves than with a static approach. Further work will consider using multiple templates for tracking and also considers unsupervised convolutional neural networks for the tracking of the heart surface features.

Author Statement
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has been approved by the authors' institutional review board or equivalent committee.

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