Structure Tensor Based Substitution of Specular Reflections for Improved Heart Surface Tracking

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Abstract. Specular reflections pose a particular challenge to intensity-based tracking approaches. The proposed scheme substitutes specular areas with respect to local image structures, extracted by the structure tensor. It can be applied to images of the beating heart prior to tracking and is shown to improve the estimation of local motion by natural landmarks significantly.

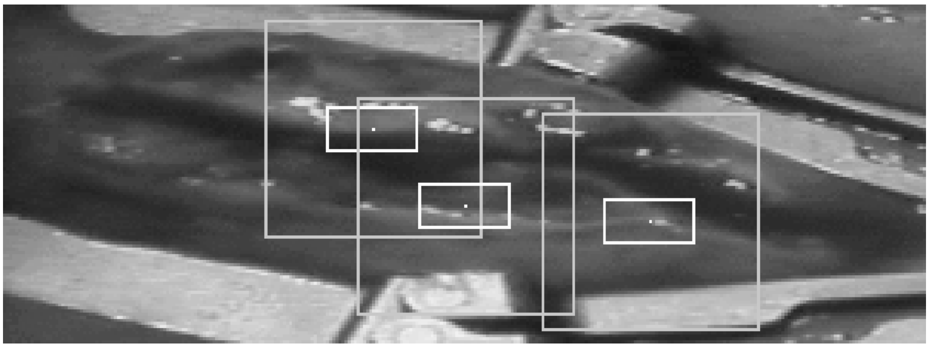
1 Introduction

Intraoperative organ motion, induced by heart beat and respiration poses special requirements to robot-assisted surgery. Motion compensation is a highly desired issue, particularly in minimally invasive beating heart surgery [1]. Recognition of this motion is required for compensation by robotic systems. While in beating heart surgery the motion of the heart is mechanically stabilised, significant residual motion still remains. Estimating the motion of the heart by natural landmarks instead of artificial markers [2, 3] is especially attractive since no further markers need to be introduced into the field of surgery. Moreover, the nature of block matching yields a particular texture unique for each landmark, which easily enables the tracking of several landmarks concurrently, whereas identical artifical landmarks bear the danger of ambiguities.

However, specular reflections of the light source on the surface of the beating heart (Fig. 1) can disturb tracking of natural landmarks considerably, which makes their appropriate treatment a prerequisite. Previous work mainly investigates specular, together with diffuse, reflections [4, 5]. Specular reflections on the heart surface, however, are totally reflecting, which means that information about the original texture is not available any more. More recent strategies to remove specular reflections from endoscopic image sequences use light fields [6]; the approach, however, is very time-consuming and thus not applicable on a frame per frame basis in realtime as required for motion tracking.

The proposed approach eliminates totally reflecting specularities on the heart surface taking into account local structure information only taken from the current image. It is designed to be used as a preprocessing step to tracking to increase robustness in presence of specular reflections.

Fig. 1. Stabilised heart with landmarks and tracking areas (left to right: LM2/8/1).



2 Methods

Substitution of specular reflections. Methods dealing with specular reflections were introduced in [7]. The approach using local structure orientation to interpolate between boundary pixels proved as most promising. Specular areas are characterised by maximum brightness values in the image and can be segmented by thresholding followed by morphological image operations.

The locally dominant structure orientation at a particular pixel in the segmented specular area is extracted from the structure tensor, which provides a reliable measure of the orientation of structures derived from local gradient information [8]. For an image f with Gaussian smoothed gradient $\nabla f_\sigma \stackrel{\text{def}}{=} \nabla(g_\sigma * f)$ the *structure tensor* is defined as

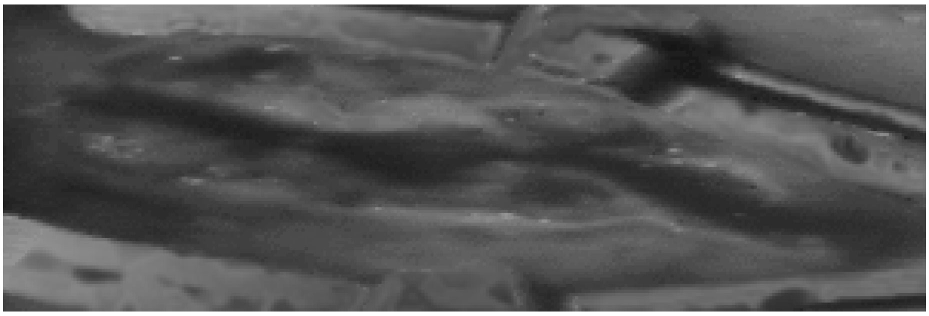
$$J_\rho(\nabla f_\sigma) \stackrel{\text{def}}{=} g_\rho * [\nabla f_\sigma \otimes \nabla f_\sigma] = g_\rho * \begin{bmatrix} (\frac{\partial f_\sigma}{\partial x})^2 & \frac{\partial f_\sigma}{\partial x}\frac{\partial f_\sigma}{\partial y} \\ \frac{\partial f_\sigma}{\partial x}\frac{\partial f_\sigma}{\partial y} & (\frac{\partial f_\sigma}{\partial y})^2 \end{bmatrix}, \quad (1)$$

where g_ρ is a Gaussian kernel of standard deviation $\rho \geq 0$, separately convolved with the components of the matrix resulting from the tensor product $\otimes$. The *noise scale* σ reduces image noise before the gradient operator is applied, while the *integration scale* ρ adjusts J_ρ to the size of structures to be detected. For the given heart images, appropriate values for noise and integration scale are $\sigma = 1$ and $\rho = 2.8$, corresponding to a catchment area of about 9×9 pixels. The eigenvector of the structure tensor J_ρ corresponding to the minor eigenvalue provides the preferred local orientation, the *coherence direction* [8].

To reconstruct specular areas, the new intensity for each pixel is calculated by linear interpolation between the intensities of the boundary points along the main local orientation. Final low-pass filtering ensures sufficient smoothness in the reconstructed area.

The specular area is substituted by intensity texture likely to correspond to the original area on condition that surface structures possess some continuity. Specular areas should not be large compared to local structures, since otherwise local structure orientation is distorted and small details cannot be reconstructed.

Fig. 2. Heart surface with structure based substitution of specular reflections.



Motion tracking. The scheme to substitute specular reflections is applied to images of the beating heart prior to tracking and assessed by its effect on the trajectories. Natural landmarks are used to track local motion on the beating heart as described in [9]. These landmarks are selected image patterns of a given size and offer a particular characteristic arising from their texture. Tracking is performed by intensity based pattern matching of a given reference landmark in a particular search area. The sum of squared differences (SSD) error measure is used to find the position of the best matching pattern. The nonlinear distortions of the heart surface can be approximated in the 2D image plane by an affine motion model, in which often only the translational components are dominant and thus sufficient for tracking in the mechanically stabilised area on the beating heart [9]. Tracking for the examples below was performed in the translational search space, searched exhaustively for the best matching pattern. Three example landmarks together with their translational search areas are shown in Fig. 1.

3 Results

Substitution of specular reflections is considered with specular reflections on the heart surface for the area of interest within the mechanical stabiliser in Fig. 1. As investigated in more detail in [7], the result in Fig. 2 shows good reconstruction for local specular reflections, based on robust orientation information by the structure tensor. Structures are continued, and sufficient smoothness is provided at the boundaries, and within reconstructed areas by final low-pass filtering. Runtime complexity analysis of the algorithm shows that the substitution scheme enables efficient implementation and preprocessing for motion tracking [7].

Motion tracking. The effect of substitution of specular reflections on tracking is evaluated in the following. The trajectories of particular landmarks on the original heart surface (Fig. 1) are compared to those with substituted specular reflections (Fig. 2).

Fig. 3. Tracking trajectory t_x of LM2 (dark) on original images disturbed by specular reflections and filtered version $\bar{t}_x$ (light); squared distances between t and $\bar{t}_x$ (bottom).

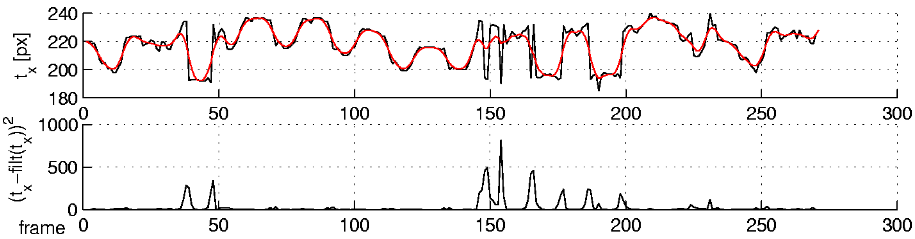


Table 1. Outlier measures $o(t)$ for tracking in original and reconstructed heart images.

landmark / parameter	original	reconstructed
LM2 t_x, t_y	29.3639, 22.5509	3.9102, 1.0354
LM8 t_x, t_y	6.5710, 0.6397	2.3038, 0.6592

The *outlier measure*, used to assess tracking trajectories, is defined as the mean squared distance between a given trajectory t and its smoothed version $\bar{t}$

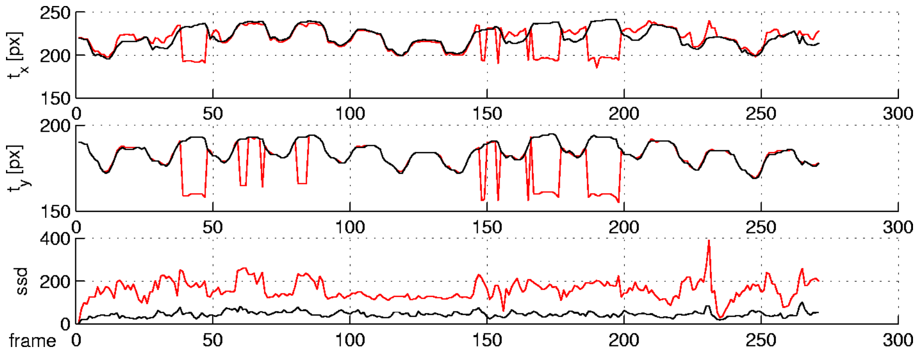
$$\mathrm{o}(t) \stackrel{\mathrm{def}}{=} \frac{1}{|\mathrm{dom}(t)|} \sum_{i \in \mathrm{dom}(t)} (t(i) - \bar{t}(i))^2 . \tag{2}$$

It quantifies the deviation of t from $\bar{t}$ and deteriorates by the number of outliers occurring. The smoothed trajectory $\bar{t}$ is gained by zero-phase forward and reverse filtering, such that dominant frequencies of the trajectory are preserved. Figure 3 provides an example of t and $\bar{t}$ and their squared distances, which shows that outliers, caused by tracking failures, are weighted dominantly in $o(t)$. Therefore, the outlier measure is regarded as suitable to assess the quality of tracking.

Outlier measures (Table 1) are worse (i.e. higher) for horizontal translation t_x than for t_y. This reflects the horizontal orientation of local structures, on which the landmarks are located. Therefore, more robust tracking is possible vertically, which has more local contrast.

Whereas tracking results are very similar for landmark LM1, which caused no outliers with and without substitution, the trajectories of the two other landmarks LM2 and LM8, subject to frequent specular reflections, show differences. Their outlier measures are significantly lower after substitution of specular reflections and indicate a substantial improvement on outlier behaviour: The plot of the corresponding trajectories in Fig. 4 shows strong outliers in both translational parameters t_x and t_y for tracking of LM2 in the original image sequence, as specular reflections cause a different edge somewhere else in the tracking area to be more similar to the edge in the reference pattern. The significantly lower SSD measure (Fig. 4) of tracking in images without specular reflections confirms the superior performance of tracking based on the proposed substitution.

Fig. 4. Structure tensor reconstruction (dark) versus original image (light) at LM2.



4 Conclusion

The substitution method shows good results at removing specular reflections on the heart surface in the given images. Smooth transition at the boundaries of the reconstructed area and inside ensure that no artefacts are introduced, while local image structures are continued through the reconstructed area. The method is applied to heart images prior to tracking. Results are shown for example landmarks and the quality of tracking is assessed by a special measure. Most outliers in the motion trajectories, caused by specular reflections, disappear if the substitution scheme is applied. This improves tracking performance significantly and proves as a key step for robust motion estimation of the beating heart.

References

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