Removing Specular Reflection Components for Robotic Assisted Laparoscopic Surgery

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Abstract—In this paper, we propose a practical method for removing specular artifacts on the epicardial surface of the heart in robotic laparoscopic surgery while preserving the underlying image structure. We use freeform temporal registration of the non-rigid surface motion to recover chromatic information saturated by highlights. The diffuse and specular image components are then separated by shifting pixel intensities with respect to chromacity gathered from the spatio-temporal volume. Results on in vivo data and reconstructions of 3D structure from the diffuse images show the potential value of the technique.

Keywords—robotic assisted minimally invasive surgery; specular reflection; chromacity; multiresolution image registration;

I. INTRODUCTION

In minimally invasive surgery (MIS), the introduction of surgical robots has allowed enhanced manual dexterity through the use of microprocessor controlled mechanical wrists. They permit the use of motion scaling for reducing gross hand movements and the performance of micro-scale tasks that are otherwise not possible. Key applications of robotic assisted MIS include the performance of cardiothoracic surgery on a beating heart so as to minimize patient trauma and avoid certain side effects of cardiopulmonary bypass. One of the significant challenges of beating heart surgery, however, is the complex rhythmic movement of the operating field introduced by cardiac and respiratory motion. Determining the 3D surface structure of the soft tissue is important for providing the surgeon with intra-operative guidance, motion stabilization, and applying image guided active constraints to avoid critical anatomical structures such as nerves and blood vessels. Previous work by Stoyanov et al. [1] has introduced a dense 3D depth recovery technique that can be used for this purpose. The method, however, has also identified the importance of handling specular reflection of the epicardial surface. Whilst specular reflections convey valuable information on the imaging geometry, computationally they can introduce significant errors to image based depth recovery techniques.

For laparoscopic images, Gröger et al. [2] proposed a method for removing highlights on the epicardial surface with a structural tensor based interpolation and diffusion scheme. Specular highlights were detected by thresholding a normalized intensity image, and subsequently removed by filling in information from the surrounding area. In practice, the technique can result in a loss of the underlying image data in the thresholded region and it is adversely affected by the paucity of information in the structure tensor and the dynamic properties of the highlights. More recently, Tan et al. [3] proposed a method based on image chromacity for separating the diffuse and specular reflectance components of multicolored surfaces. In an iterative framework without color segmentation, specular intensity was reduced from a single image subject to the chromacity of neighboring diffuse pixels. When applied to laparoscopic images with achromatic pixels, which are common due to the proximity of the light source, the method cannot reduce a significant part of the specular component. Furthermore, the sensitive color boundary between small vessels can be obscured in the iterative framework. In a different approach, Criminisi et al. [4] studied the movement of specularities in the epipolar plane image (EPI) volume and characterized their motion by looking at the disparity and epipolar deviations. Specular and diffuse components were separated from the EPI volume for linear camera motions in static and rigid scenes. For the deforming epicardial surface, however, the epipolar constraint does not apply temporally and the camera motion is heavily restricted by the trocar. In the literature, there are many other algorithms that have been developed for decomposing diffuse and specular reflection based on varying lighting conditions [5], polarizing filters [6] and color segmentation [7]. However, they are not applicable to the confined environment of the operating theatre in MIS or to the practical characteristics of laparoscopic images.

The purpose of this paper is to propose a method that can retain as much of the underlying image information as possible by extending the chromacity based algorithm proposed by Tan et al. [3]. This is achieved by introducing a spatio-temporal framework such that in areas where the chroma information has been lost due to intensive highlights, temporal non-rigid registration is used to obtain the correct chromacity value. For the rhythmically deforming epicardial surface, this allows the building of a diffuse chromacity map of the surface, which can be used to filter out specular components. The practical value of the technique is assessed with in vivo data for recovering the 3D shape of the surface based on binocular stereo.
II. REFLECTION MODEL

With the dichromatic reflection model, the image intensity can be expressed as the linear sum of diffuse and specular reflection components [8]. By ignoring camera noise and gain, and undertaking the neutral interface reflection (NIR) assumption, the image intensity can be written as [3]:

\[
I_c = m_d(x)\Lambda_c(x) + m_s(x)\Gamma_c
\]  

(1)

where the index \(c\) is representative of the different sensors of the RGB color space, and the terms \(\Lambda_c(x)\) and \(\Gamma_c\) are the diffuse and specular chromacities respectively, normalized such that \(\Sigma \Lambda_c = \Sigma \Gamma_c = 1\). Under NIR, specular chromacity is independent of the pixel position \(x = (x, y)\) by assuming that the color of illumination is constant and uniform. Different expressions modeling the form of the weighing coefficients for the diffuse \(m_d(x)\) and specular \(m_s(x)\) reflectance terms can be derived based upon the physical and optical properties of reflectance [9]. In general, they are dependent on the geometric surface structure and independent of the CCD sensor sensitivity.

If the illumination color is known, the image data can be normalized to make the specular chromacity component equal to pure white color [3]. This results in the simplification of (1) to:

\[
\hat{I}_c = m_d(x)\hat{\Lambda}_c(x) + m_s(x)
\]  

(2)

The color of illumination can itself be estimated from the specular reflections by using color constancy [10], or alternatively, using a white reference calibration.

III. SPECULAR TO DIFFUSE MECHANISM

Pixel chromacity or normalized RGB can be directly computed from the pixel data (as we are working per pixel, position parameters are omitted for clarity):

\[
\sigma_c = \frac{\hat{I}_c}{\Sigma I_i}
\]  

(3)

From the assumed reflection model and (3), it is clear that for a uniformly colored surface the maximum chromacity \(\sigma = \max(\sigma_d, \sigma_s, \sigma_p)\) of diffuse pixels will always be higher than that of specular pixels. By making use of the distribution of image pixels projected into a 2D space of maximum chromacity \(\hat{\sigma}\) against the maximum intensity \(\hat{I} = \max(\hat{I}_d, \hat{I}_s, \hat{I}_p)\), it is possible to infer the diffuse reflectance component of image pixels [3]:

\[
I_c^{\text{diff}} = \hat{I}_c - \frac{\Sigma I_i}{3} + \frac{\hat{I}(3\hat{\sigma} - 1)}{\hat{\sigma}(3\hat{\Lambda} - 1)}
\]  

(4)

where \(I_c^{\text{diff}}\) is the diffuse component of reflectance, and the term \(\hat{\Lambda} = \max(\Lambda_d, \Lambda_s, \Lambda_p)\) represents the maximum diffuse chromacity. In general, \(\hat{\Lambda}\) is not known and it is difficult to estimate its true value for all pixels in images of multicolored textured surfaces. An arbitrary value of \(\hat{\Lambda}\) can be used in order to recover the diffuse geometric profile of the image, which within an iterative logarithmic differentiation scheme can discriminate between chromatic specular and diffuse pixels.

Figure 1. A spatio-temporal volume with two time image slices showing the specular movement along the epicardial surface.

For a surface deforming over time as in MIS, achromatic specular highlights will move and reveal diffuse areas for which \(\hat{\Lambda}\) can be determined. In Fig. 1, we show the specular highlights at two time slices within the spatio-temporal volume. With the rhythmic deformation of the epicardial surface the chromacity information for saturated regions will be known when the highlights return at a subsequent deformation cycle. Therefore if the positional parameters for a pixel are known throughout the spatio-temporal volume, it is possible to derive the pixel’s diffuse component at any time slice by shifting the image intensity with respect to the most diffuse pixel chromacity in the volume. In order to infer the diffuse chromacity, it is necessary to determine a dense temporal motion map of the epicardial surface.

IV. TEMPORAL REGISTRATION

The epicardial surface in robotic assisted MIS is generally smooth and continuous therefore occlusion and discontinuity may be assumed as negligible. The difficulty of dense temporal motion registration is usually due to the paucity of identifiable landmarks and the view dependent reflection characteristics of the wet tissue. Explicit geometrical constraints of the deformation model are therefore required for ensuring the overall reliability of the algorithm. In this study, the free-form registration framework proposed by Veseer et al. [11] was used as it provides a robust, fully encapsulated multi-resolution approach based on piece wise bilinear maps (PBM). The lattice of PBM easily lends itself to a hierarchical implementation and it permits non-linear image transitions, which are appropriate for temporally deforming surfaces as observed in MIS. Within this framework, the surface motion obtained at low-resolution levels is propagated to higher levels and used as starting points for the optimization process.

To cater for surfaces in laparoscopic images that have complex reflectance properties dependent on the viewing position, normalized cross correlation (NCC) was used as a
similarity measure. The NCC of two image regions $M$ and $N$ both of dimensions $(u,v)$ is defined as:

$$NCC = \frac{\sum_{u,v} (M(u,v) - \bar{M})(N(u,v) - \bar{N})}{(\sum_{u,v} (M(u,v) - \bar{M})^2)(\sum_{u,v} (N(u,v) - \bar{N})^2)^{1/2}}$$  

(5)

The first order derivative of the given metric can be computed directly which permits the use of fast optimization algorithms. For this study, the Broyden-Fletcher-Goldberg-Shano (BFGS) method can be used. This is a quasi-Newton technique, which uses an estimate of the Hessian to speed up the iterative process. Fig. 2, shows several levels of the hierarchical evolution of the registration algorithm.

Figure 2. Images showing the warped source image at three resolution levels and corresponding images showing the evolution of the PBM lattice.

Figure 3. Several slices and corresponding warped image indicating the direction of building the maximum chromacity image map.

By registering time slices in the spatio-temporal volume, we are able to apply the PBM warping to images prior to the current slice and infer chromatic information in the current image. For improving robustness, the framework can be employed iteratively with diffuse images being input back into the registration process until it reaches a stable solution. A simple algorithm for reducing the effects of large highlights in the initial iteration was used, which involved the following steps: i) detecting the highlight by thresholding the intensity and saturation, ii) identification of the control points in the PBM lattice which have been affected, iii) interpolating from the surrounding control points to remove errors.

V. RESULTS

Fig. 4 shows two time frames from an in vivo laparoscopic image sequence of the beating epicardial surface between a mechanical stabilizer. The corresponding images show the diffuse heart surface after specular removal using the proposed method, demonstrating the recovered image data in saturated regions. It is evident that the underlying structure is not lost or interpolated. Some artifacts do remain, which are mainly caused by errors in the registration process, as in the current framework we have not explicitly handled error propagation. It is worth noting some of the residual artifacts remain in the specular reflection regions. These are left due to deviations of the image from the chosen reflectance model caused by inter-reflections and image noise.

Figure 4. (a) and (c) show in vivo images of the epicardial surface, (b) and (d) show the corresponding images with removed specular reflection components.

To assess the effect of removing specular highlights on the performance of a structure recovery algorithm we applied the method proposed in [1] to both the normal and the generated diffuse images. Renditions of the recovered epicardial surface are shown in the Fig. 5, where visibly the diffuse images generate more stable results.

Figure 5. Renditions of 3D reconstructions using from the (a) normal images and (b) the diffuse images.

As ground truth for the 3D structure of the operating field is not available, we analyzed the temporal 3D motion of the disparity map for consecutive time slices. In Fig. 5 we show the histograms of the inter disparity motion components. It is evident that the presence of specular reflections causes
perturbations in the recovered structure, which are removed by using the proposed method. In the histogram depicting results for the proposed technique, motion is smoothly distributed about a central point as one would expect for the epicardial surface.

![Histograms of inter-disparity motion for the images with specular reflectance shown in blue and the images processed by the proposed technique shown in red.](image)

**Figure 5.** Histograms of inter-disparity motion for the images with specular reflectance shown in blue and the images processed by the proposed technique shown in red.

**IV. CONCLUSIONS**

In this paper, we have developed a practical strategy for removing complex specular reflectance components from laparoscopic images of a rhythmically deforming surface. The proposed algorithm makes use of chromatic and temporal constraint to recover diffuse images in scenes with complex reflective properties. Image structure lost due to the intensity of the light source is recovered by applying the temporal constraints to the surface. Our results have shown that the diffuse component of the reflectance is deduced from the chromacity information in the spatio-temporal volume and the *in vivo* data demonstrate the effectiveness of the technique. It is worth noting that in the current paper we have not considered noise and complex reflectance components due to inter-reflections. The current result suggests that further attention in these areas is necessary to ensure improved modeling accuracy.

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**REFERENCES**


