ROBUST REGISTRATION OF MULTISPECTRAL IMAGES OF THE CORTICAL SURFACE IN NEUROSURGERY

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ABSTRACT

Optical multispectral imaging during open neurosurgery can provide functional information equivalent to fMRI as well as information about blood flow and oxygenation dynamics. To perform multispectral analysis images acquired sequentially under different illumination wavelengths must be coregistered such that information about the same surface region can be obtained throughout the imaging time period. In this paper, we present a feature driven registration technique that can register multispectral images and is robust to specular reflections and to the variable appearance of the brain's surface under different illumination conditions. We present preliminary results on data from two patients.

Index Terms— multispectral imaging, feature-based registration, deformable surface tracking

1. INTRODUCTION

Functional magnetic resonance imaging (fMRI) is increasingly being used for pre-operative planning for neurosurgery, however, intra-operative MRI is expensive, obtrusive and unavailable in most operating theatres. We have previously demonstrated that exposed-cortex optical imaging in rodents can provide dynamic information that is equivalent to fMRI measures, and additionally provides information about blood flow and oxygenation dynamics that fMRI cannot [1]. Optical imaging of the exposed cortex allows changes in the concentration of oxy and deoxy-hemoglobin (HbO and HbR) as well as changes in vessel tone to be mapped at high frame rates [2]. It can be performed with lightweight equipment that is easily integrated in the operating theatre as shown in Fig 1 and does not require contact with the exposed tissue and does not interfere with the surgical instruments.

The major challenge of intrasurgical multispectral optical imaging is the correction of motion artifacts. The brain moves significantly during open-cortex procedures both with breathing and heart rate pulsations. The motion is both translational and distorting. Previous open-cortex optical imaging attempts have utilized a glass block in contact with the brain to restrict motion [3], but this approach proved unpopular in the sterile environment of the operating room. Gated approaches synchronizing image acquisition to the respiratory and cardiac rates have also been reported but inherently suffer from bounded temporal resolutions [4]. Alternative techniques using non-rigid image registration to compensate for motion artifacts have also been developed but mostly for post-operative analysis due to high computational complexity limiting real-time implementation [5].

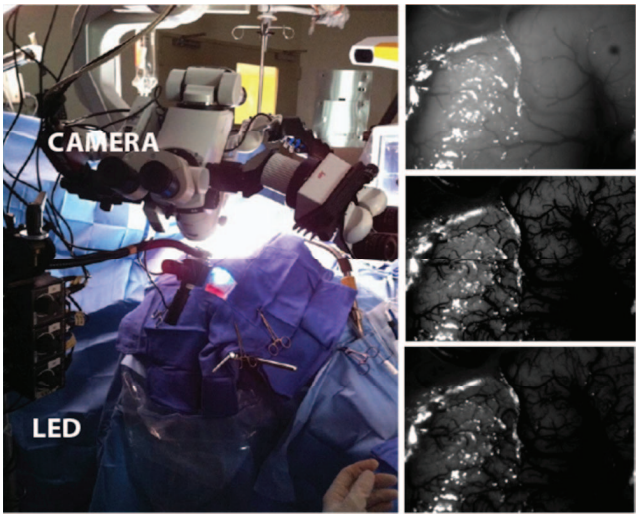


Fig. 1 Optical imaging system used to obtain multispectral images of the exposed cortical surface during surgery and example images obtained using red, green and blue illumination (625nm, 530nm and 470nm respectively, top to bottom).

More recently, fast techniques for the recognition and tracking of deformable surface using feature correspondences have been investigated [6]. The advantage of these methods is that any sparse matching strategy can be used to achieve robust performance in the presence of large deformations. The effectiveness of the approach has been demonstrated for tracking the cardiac surface in endoscopic images [7]. In this paper, we apply this technique for registering multispectral images of the exposed cortical surface acquired during invasive neurosurgery. The method is potentially suitable for real-time implementation to enable *in vivo* data analysis. We report preliminary results on patient data.

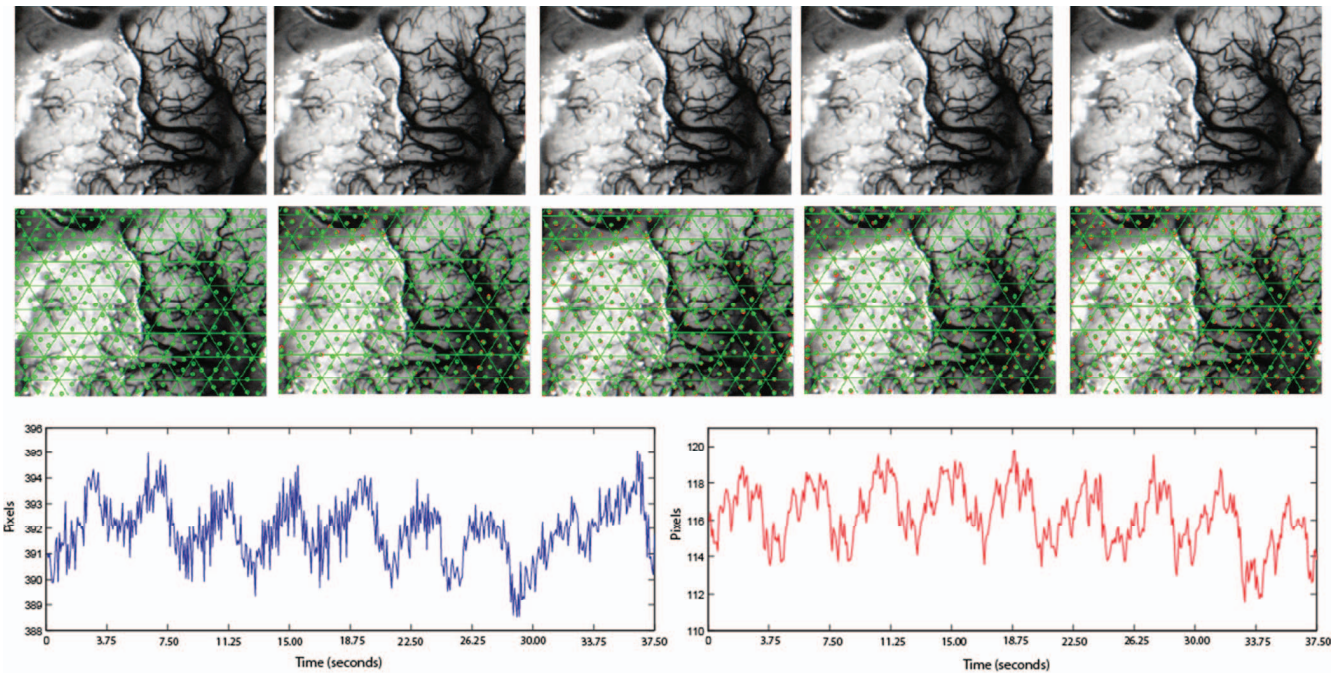


Fig. 2. A series of example images of the exposed cortical surface with the corresponding images overlaid with the deformable mesh showing the motion and deformation of the surface. The line plots show the 2D motion (X – blue, Y – red) of a specified point within the mesh over time illustrating the periodic cardiac component of the cortical surface motion.

2. METHODS

2.1. Optical imaging system

Optical imaging was carried out using our recently developed 'ultrafast multispectral' implementation of intrinsic optical signal imaging. Images were acquired using sequentially strobed light emitting diode (LED) illumination synchronized with high-speed camera acquisition at a frame rate of 40 Hz, yielding a net 3-wavelength frame rate of 13.3Hz. LED wavelengths are selected for quantification of oxy- and deoxy-hemoglobin concentration dynamics at the cortical surface. Imaging is non-contact, with images acquired using a monochrome Firewire camera (AVT Pike F-032B) mounted onto a surgical microscope allowing rapid set-up. For image recording we used our opensource SPLASSH optical imaging software [8]. A craniotomy was performed and the dura reflected prior to imaging.

2.2. Preprocessing and initial correspondence

The 16-bit images delivered by the camera system were initially preprocessed using histogram equalization and then converted to 8-bit images to allow faster image processing. Salient image features were detected in the template image using the Shi and Tomasi operator [9] but any feature detection algorithm that operates on the intensity gradients is suitable for the detection procedure. Correspondence for the detected features was then established between the template image and subsequent images using the efficient pyramidal Lucas-Kanade method implemented in the OpenCV vision library (http://opencv.willowgarage.com). Examples of detected and tracked salient points are shown in Fig 2 which also illustrates the periodic motion of the brain during surgery due to the cardiac cycle.

More complex features and matching strategies can be used to obtain correspondences in situations where the camera moves or there is more significant cortical surface deformation. This does not influence the registration framework described below.

2.3. Surface model

We represent the exposed brain surface model S as a triangulated mesh consisting of hexagonal elements as illustrated in Fig 2. Each vertex v_i of the mesh is specified by its image coordinates (x_i, y_i) and the collection of all vertices defines a state vector S which controls the shape and position of M. Any point p_i within the mesh can be described by its barycentric coordinates $B_i(p)$ and the vertices of the triangle facet that it occupies (v_1, v_2, v_3). When the brain surface undergoes motion or deformation due to the cardiac cycle or respiration, the new position of the point p_i can be computed using the mapping $T_S(p)$ defined as:

$$T_S(p) = \sum_{i=1}^{3} B_i(p) \begin{bmatrix} x_i \\ y_i \end{bmatrix} \qquad (1)$$

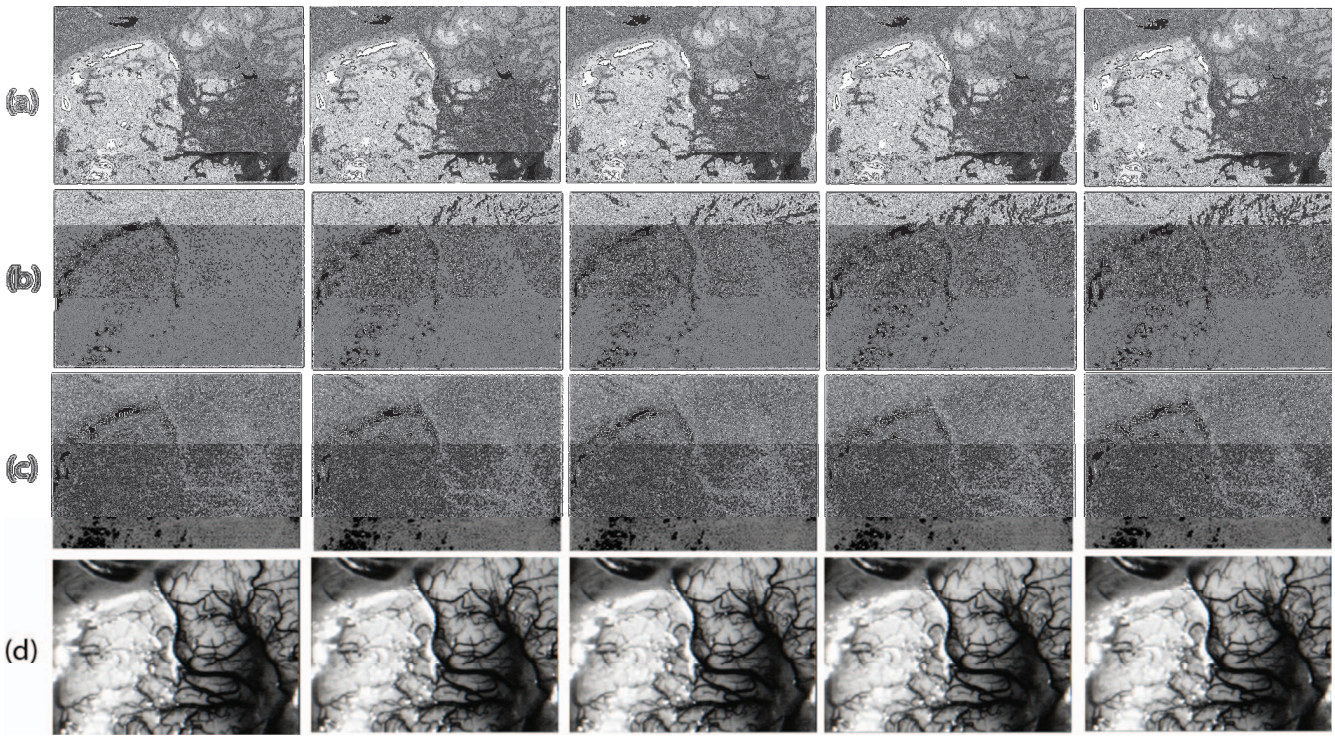


Fig. 3. (a) Example images from the green channel of the multispectral source taken at different time points during a cardiac cycle; (b) absolute difference between the template image and the shown images where black represents large difference and they gray values show no difference; (c) absolute different between the template image and the registered images showing the improved alignment after registration; (d) the warped registered images representative to the original data shown in (a).

The goal of the registration framework is to determine the deformation and movement of S such that an observed set of points within the surface mesh of the reference image aligns correctly according to the corresponding points in the destination image according to (1).

2.4. Energy function

The mesh registration is posed as an energy minimization problem as proposed in [6] using the following objective function $\varepsilon(S)$ subject to the parameters of S:

$$\varepsilon(S) = \lambda\varepsilon_D(S) + \varepsilon_C(S) \qquad (2)$$

The term $\varepsilon_D(S)$ defines a deformation energy which regularizes the position of the vertices and $\varepsilon_C(S)$ defines the correspondence error measured as the Euclidian 2D image distance in pixels between the measured and transformed feature coordinates.

Regularization is calculated as proposed in [6] to maintain spatial coherency of the triangles in the mesh by penalizing non-uniform movements. For border vertices that are not constrained by surrounding points we use all the available surrounding constraints and set the rest to zero. The weight term λ is used to determine the influence of regularization on the overall minimization energy. By using high values of λ it is possible to control the rigidity of the surface model. In this study we set λ equal to 0.5.

Both $\varepsilon_D(S)$ and $\varepsilon_C(S)$ can be formulated as squared Euclidian distance measures and therefore the minimization of $\varepsilon(S)$ can be performed via iterative non-linear least squares techniques such as the Levenberg-Marquardt algorithm. The effect of tracking the deformation of M is illustrated in Fig 2 where a reference image is registered over subsequent frames using the deformable mesh. The motion of a specific point within the mesh is shown in the graphs of Fig 2 illustrating the period component of the physiological movements.

3. RESULTS

The method was implemented in C++ using the OpenCV library (http://opencv.willowgarage.com) for feature detection and pyramid Lucas-Kanade tracking and the VXL library for Levenberg-Marquardt optimization of the triangular mesh (http://vxl.sourceforge.net/). The performance of the implementation is highly dependent on the resolution of the mesh. For a mesh resolution of 100 control vertices registration takes approximately 300ms on an Intel i7 2.67 GHz CPU. This can be greatly improved by

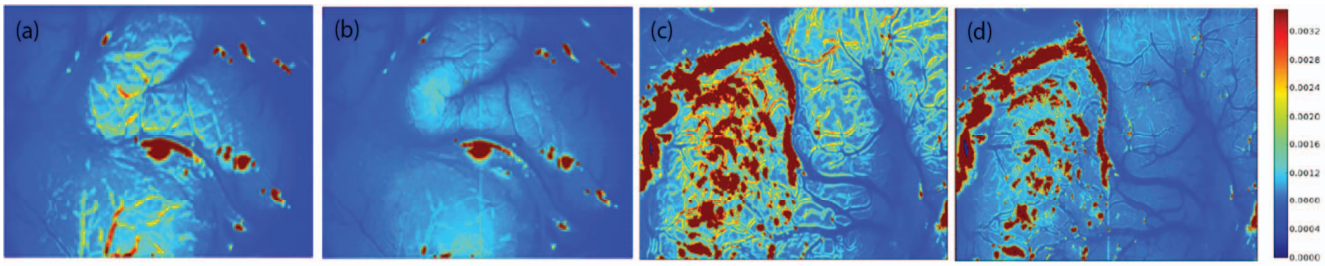


Fig. 4. The images represent the variance of each pixel over the length of each dataset. They were created by calculating the standard deviation and dividing by the mean of the time course for each pixel over a 30 second dataset. (a) variance map for the unregistered dataset for patient 1 with the registered data shown in (b); (c) variance map for the unregistered dataset for patient 2 with the registered data shown in (d).

code optimization and parallelization. Furthermore for analyzing only specific regions of the image it is possible to use small mesh resolutions that can operate in real-time.

Preliminary results are reported on the performance of the registration algorithm and the multispectral analysis on data recorded from surgical procedures on two patients. Fig 3 shows some example images of the raw and registered data for one example patient. The difference images between the template and images acquired at other points during the cardiac cycle show how registration reduces the difference error by aligning the images. The black regions in the difference images represent large intensity misalignment, which is clearly reduced by the proposed method. The remaining difference in pixel intensities after registration is largely due to the motion of specular highlights which varies independently of the motion of the cortical surface.

Fig 4 shows the reduction in the coefficient of variance of data over a 30 second time period before and after image registration. While specular reflections remain, regions of true signal exhibit much lower variance suggesting successful registration. We will use this data to obtain functional information of the brain surface during surgery.

4. DISCUSSION

In this study, we have presented a method for tissue deformation tracking of the cortical surface during open neurosurgery. The method can achieve performance comparable to discrete feature tracking techniques but covering the entire visible surface even in regions without textural information. Experimental results indicate that the technique is efficient and will be suitable for real-time *in vivo* tissue tracking with further optimization as has been demonstrated in other applications of surgical vision [10].

Future directions we are pursuing include the use of probabilistic prediction for rhythmic motions and implementing the method in a hierarchical framework to enhance computational performance. The method can potentially be incorporated with algorithms for cortical surface tracking using the stereo-microscope images [11] and we are also in the process of comparing our work to intensity based techniques available online [12].

5. AKNOWLEDGEMENTS

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8. REFERENCES

[1] Chen BR, Bouchard MB, McCaslin AFH, Burgess SA, Hillman EMC, "High-speed vascular dynamics of the hemodynamic response", *Neuroimage*, 54 (2), 1021-1030, 2011.

[2] Bouchard MB*, Chen BR*, Burgess SA, Hillman EMC, "Ultra-fast multispectral optical imaging of cortical oxygenation, blood flow and intracellular calcium dynamics", *Optics Express*, 17 (18), 15670-15678, 2009.

[3] Haglund MM, Ojemann GA, Hochman DW, "Optical imaging of epileptiformand functional activity in human cerebral cortex", *Nature* 358:668-671, 1992.

[4] Mayhew J, Johnston D, Berwick J, Jones M, Coffey P, Zheng Y, "Spectroscopic analysis of neural activity in brain: increased oxygen consumption following activation of barrel cortex", *Neuroimage*, 12:664–675, 2000.

[5] Ma H, Geneslaw A, Zhao M, Suh M, Perry C, Schwartz TH, "The importance of latency in the focality of perfusion and oxygenation changes associated with triggered afterdischarges in human cortex", *J Cereb Blood Flow Metab*, 29(5):1003–1014, 2009.

[6] Pilet J, Lepetit V, Fua P, "Real-time Non-Rigid Surface Detection," in *IEEE CVPR*, 822-828, 2005.

[7] Stoyanov D, Yang GZ, "Soft tissue deformation tracking for robotic assisted minimally invasive surgery," in *IEEE EMBC*, 254-257, 2009.

[8] Sun R, Bouchard MB, Hillman EMC, "SPLASSH: Open source software for camera-based high-speed, multispectral in-vivo optical image acquisition," *Biomed Opt Expr*, 1 (2), 385-397, 2010.

[9] Shi, J., Tomasi, C. "Good features to track," in *IEEE CVPR*, 593 - 600, 1994.

[10] DeLorenzo C, Papademetris X, Staib LH, Vives KP, Spencer DD, Duncan JS "Nonrigid Intraoperative Cortical Surface Tracking Using Game Theory," in *IEEE ICCV*, 1 – 8, 2007.

[11] Klein S, Staring M., Murphy K, Viergever M.A, Pluim JPW, "elastix: a toolbox for intensity based medical image registration," *IEEE Trans Med Imag*, 29 (1), 196 - 205, 2010.

[12] Stoyanov D, "Surgical Vision," *Ann Biomed Eng*, 1-14, 2012.