A variational framework integrating distortion correction, segmentation and cortical parcellation on diffusion MRI

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***Abstract*—In whole-brain connectivity analysis of diffusion MRI (dMRI) data, an accurate delineation of the white-matter and grey-matter surfaces is required. While high-standard segmentation is readily available for anatomical MRI, such as T1-weighted, dMRI typically have lower resolution and severe geometrical distortions. We propose a dMRI segmentation-registration framework that exploits the detailed anatomy extracted from anatomical MRI as shape-prior. We use an "active contours without edges"-like model to look for a deformation field that optimally maps the shape prior on the multivariate features in diffusion space. This joint approach reflects the intrinsic coupling of segmentation and distortion correction. Complementary, a precise and consistent cortical parcellation on dMRI is straightforward by projection from T1 space. Thus, we expect to improve the reliability and robustness of the resulting connectivity networks and their comparability within and across subjects. First results on synthetic datasets and simulated dMRI confirm the effectiveness of our approach.**

***Index Terms*—diffusion MRI, susceptibility distortion, segmentation, registration, parcellation, shape-prior.**

I. Introduction

DIFFUSION MRI (dMRI) is a widely used family of magnetic resonance (MR) techniques [**?**] which recently has accounted for a growing interest in its application to whole-brain structural connectivity analysis. This emerging field, coined in 2005 as *MR Connectomics* [**? ?**], currently includes a large amount of imaging techniques for acquisition, processing, and analysis specifically tuned for diffusion MRI (dMRI) data.

The whole-brain connectivity analysis has given rise to some challenges towards reliable structural information about the neuronal tracts from dMRI [**? ?**]. Here, we shall address brain tissue segmentation on diffusion space and correction of geometrical distortions inherent to the acquisition sequence [**?**].

In this work, we will refer as brain tissue segmentation to the precise delineation of the cerebrospinal fluid (CSF)-grey matter (GM) and GM-white matter (WM) interface surfaces. An accurate brain tissue segmentation is required to filter the fiber bundles obtained with dMRI tractography. This requirement is usually solved in practice by plainly thresholding the fractional anisotropy (FA), a well-known scalar map derived from dMRI which depicts the isotropy of water diffusion inside the brain. Also, it is necessary to locate the intersections of fiber bundles and GM. Moreover, a precise location of the GM-WM surface is also essential to finally achieve a consistent parcellisation of the cortex to represent the nodes of the output network. This parcellisation is generally defined in a high-resolution and better understood structural magnetic resonance imaging (MRI) of the same subject (e.g. T1-weighted (T1) and/or T2-weighted (T2) weighted acquisitions). Even though some efforts have addressed the study of the robustness of tractography with respect to intra-subject variability [**? ?**], these results are restricted to certain regions of the brain, only. Therefore, robust and precise segmentation methods are required in the whole-brain application. The problem is challenging due to the much lower resolution of dMRI (typically around $2.5 \times 2.5 \times 2.5 mm^3$) compared to structural MRI, and the existence of geometrical distortions.

dMRI data are usually acquired with echo-planar imaging (EPI) sequences as they allow for very fast acquisitions, but they are known to suffer from geometrical distortions due to local field inhomogeneities. These artifacts happen along the phase-encoding direction, and are most appreciable in the front part of the brain for the strong air/tissue interface around the frontal sinuses. A number of methodologies have been developed to correct for the distortion, and are generically named as *EPI-unwarp* techniques [**? ? ? ?**]. These methods usually require the extra acquisition of the magnitude and phase of the field ("field-mapping"), a condition which is not always met. Some other methodologies do not make use of the field-mapping, compensating the distortion with non-linear

Manuscript received XXX XX, 2013; revised XXX XX, 2013. This study is supported by: the Spain's Ministry of Science and Innovation (projects TEC2010-21619- C04-03, TEC2011-28972-C02-02, CDTI-CENIT AMIT and INNPACTO PRECISION), Comunidad de Madrid (ARTEMIS) and European Regional Development Funds; the Center for Biomedical Imaging (CIBM) of the Geneva and Lausanne Universities and the EPFL, as well as the Leenaards and Louis Jeantet foundations. *Asterisk indicates corresponding author*.

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registration from structural MRI or other means [**?**]. To our knowledge, there exists no study on the impact of the EPI distortion on the variability of tractography results.

Therefore, the problems of precise segmentation in dMRI-space and the spatial mapping between these contours and the corresponding surfaces in anatomical images bear significant redundancy. Once the spatial relationship between T1 and dMRI space is established, the contours which are readily available in T1 space can simply be projected on to the dMRI-data. Conversely, if a precise delineation in dMRI-space was achieved, the spatial mapping with T1-space could be derived from one-to-one correspondences on the contours. However, neither segmentation nor registration can be performed flawlessly, if considered independently. The significant benefits of exploiting the anatomical MRI when segmenting the dMRI data have been demonstrated [**?**], justifying the use of the shape prior information.

We suggest clustering the current methodologies of template-based segmentation methods into three groups. The first group typically adds a shape prior term to the energy functional of an evolving active contour [**? ? ? ? ? ? ? ?**]. These methods generally have a explicit description of the expected relative boundary locations of the object to be delineated, and some even model the statistical deviations from this average shape. Closely related to this group are atlas-based segmentation methods [**? ? ? ? ?**], where the prior imposes consistent voxel-based classification of contiguous regions. Here, the presence of more structures than one unique region of interest (ROI) helps aligning the target image with the atlas in a hierarchical fashion. Finally, the third group generalizes the atlas to actual images, and the contour is to segment simultaneously two different target images, related by a spatial transform to be co-estimated [**? ?**].

In this paper we propose a novel registration framework to simultaneously solving the segmentation and distortion challenges, by exploiting as strong shape-prior the detailed morphology extracted from high-resolution anatomical MRI. Indeed, hereafter we assume this segmentation problem in anatomical images as a solved by widely used available procedures. Moreover, the shape prior is of very "strong" nature, since it is specific to the particular subject. Also, after global alignment using existing approaches, the remaining spatial deformation between anatomical and diffusion space is due to EPI distortions. Finally, we need to establish precise spatial correspondence between the surfaces in both spaces, including the tangential direction for parcellation. Therefore, we can reduce the problem to finding the differences of spatial distortion in between anatomical and diffusion weighted (DW) space. We thus reformulate the segmentation problem as an inverse problem, where we seek for an underlying deformation field (the distortion) mapping from the structural space into the diffusion space, such that the structural contours segment optimally the dMRI data. In the process, the one-to-one correspondence between the contours in both spaces is guaranteed, and projection of parcellisation to DW space is implicit and consistent.

We test our proposed joint segmentation-registration model on two different synthetic examples. The first example is a scalar sulcus model, where the CSF-GM boundary particularly suffers from partial volume effect (PVE) and can only be segmented correctly thanks to the shape prior and its coupling with the inner, GM-WM boundary through the imposed deformation field regularity. The second case deals with more realistic dMRI data stemming from phantom simulations of a simplistic brain data. Again, we show that the proposed model successfully segments the dMRI data based on two derived scalar features, namely FA and mean diffusivity (MD), while establishing an estimate of the dense distortion field.

The rest of this paper is organized as follows. First, in **??** we introduce our proposed model for joint multivariate segmentation-registration. Then we provide a more detailed description of the data and experimental setup in **??**. We present results in **??** and conclude in **??**.

II. Conclusion

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Appendix A
Proof of the First Zonklar Equation

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Appendix B

Appendix two text goes here.

Acknowledgment

The authors gratefully acknowledge V. Estellers for critical discussions at early stages of this project and L. Vese for her generous support.

References

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Oscar Esteban Biography text here.