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Dealing with uncertainty and imprecision in image segmentation using belief function theory

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ABSTRACT

In imaging, physical phenomena and the acquisition system are responsible for noise and the partial volume effect, respectively, which affect the uncertainty and the imprecision. To address these different imperfections, we propose a method that is based on information fusion and that uses belief function theory for image segmentation in the presence of multiple image sources (multi-modal images). First, the method takes advantage of neighbourhood information from mono-modal images and information from an acquisition system to reduce uncertainty from noise and imprecision due to the partial volume effect. Then, it uses information that arises from each modality of the image to reduce the imprecision that is inherent in the nature of the images, to achieve a final segmentation. The results obtained on simulated images using various signal-to-noise ratios and medical images show its ability to segment correctly multi-modal images in the presence of noise and the partial volume effect.

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1. Introduction

In imaging, information is imperfect. The imperfections can be separated into two main categories: uncertainty and imprecision. Both of these categories have a negative effect on image processing. They respectively correspond to a qualitative and quantitative defect in the knowledge. Noise, which originates from the inaccuracy of the image acquisition system with respect to reality, leads to the presence of uncertainty. Another problem in medical image processing is the presence of the partial volume effect. Originating from the limited spatial resolution of images and the sampling, the partial volume effect leads to the presence of imprecision. This effect results in a mixing of the intensities of neighbouring voxels, which is observed at the transition between regions. Moreover, in the medical image reconstruction process, a Gaussian filtering is applied, which increases the partial volume effect. The Gaussian filter is characterised by its Full Width at Half Maximum (FWHM), which is a measure that is proportional to the standard deviation of the Gaussian filter.

Belief Function Theory (BFT) [1–3] is especially well suited to representing information from partial and unreliable knowledge. BFT has the advantage of manipulating not only singletons but also disjunctions, which correspond, respectively, to simple and compound hypotheses. If manipulating singletons allows us to represent uncertainty as in probability theory, the manipulation of disjunctions allows us to represent imprecision. By assigning the Basic Belief Assignment (BBA) to singletons and disjunctions, both the uncertainty and the imprecision can be explicitly modelled. Using disjunctions, this approach makes it possible to account for the lack of knowledge. However, one of the difficulties resides in the modelling of

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the disjunctions. Although many methods for probability estimation on singletons are proposed in the literature, few methods use disjunctions. In [2,4,5], a modification of probabilistic models is proposed. This approach consists in transferring a part of a belief about disjunctions from a probabilistic distribution. Some methods are based on prior knowledge [6,7]. The disjunctions to be considered are determined in a supervised way. In [6], for example, trapezoidal functions are used for estimating the BBA on both singletons and disjunctions. Applied to multi-modal images, it is interesting to note that the image fusion, using Dempster's rule, allows them to model imprecision that corresponds to voxels that are subject to the partial volume effect. Indeed, their belief remains represented in disjunctions after the fusion. In [8], a modification of the k-nearest neighbour distance model is proposed. In this model, BBAs are estimated by combining, using Dempster's rule, the nearest neighbours, which are represented by two focal elements, the singleton that the neighbour belongs to and Ω, which is weighted by a distance function. Data for which all of the neighbours are, respectively, close and distant will be represented on singletons and disjunctions. Indeed, uncertainty and imprecision are modelled according to the neighbourhood in the feature space. This model appears to be more efficient for segmenting medical images compared to a probabilistic model [9]. More recently, the Fuzzy C-Means (FCM [10]) distance-based algorithm has been generalised into the Evidential C-Means algorithm (ECM) [11], which allows to represent ambiguous information in the feature space on disjunctions in an unsupervised way. This algorithm has been modified, in [12], to add some constraints between clusters, and it has also been modified to account for proximity data [13], as initially proposed in [14]. Because these methods have not been introduced for modelling knowledge in image processing, the spatial relationships between voxels are not used.

Some methods that use belief function theory have been proposed specifically for image processing. In [15], the authors propose to use the histogram of the images for estimating the consonant mass distribution. The voxels for which a grey level has many occurrences, which are near a peak on the histogram, are mainly represented by the corresponding singleton. In contrast, the voxels for which the grey level has few occurrences, at the transitions between peaks, are mainly represented by disjunctions. The interest in this method arises from the use of the histogram to model the imprecision. However, this method does not consider the spatial relationship between voxels. In [16], the authors propose to use belief function theory in the Markov field context, which aims at benefiting from neighbourhood information for removing noise. The more general framework that is brought by the belief function allows us to account for the imprecision that is brought by the sources of the images. This Markov field extension is interesting for removing noise, but it has not been introduced for addressing the problem of the partial volume effect. A method for image fusion that presents occlusions is proposed in [17]. This method consists in using the neighbourhood information for addressing imperfections. First, imprecision due to occlusions is modelled with disjunctions on each image. Then, the fusion of each voxel with a mass function, which represents the neighbourhood and uses a normalised sum operator, is conducted to model the uncertainty. The authors make the assumption that this compromise rule is well adapted at first, before combining multiple images. Finally, an iterative regularisation process, which is similar to a Markov field, is performed to improve the decision. Despite uncertainty due to noise, the imprecision due to occlusions is managed, and the imprecision due to the partial volume effect is not considered. In [18], an approach that performs a conjunctive combination of neighbouring voxels has been proposed. On the one hand, this approach allows for each voxel to reduce the uncertainty due to noise and imprecision due to the partial volume effect by transferring part of the belief on singletons according to its neighbourhood. On the other hand, it allows us to consider very ambiguous voxels that correspond to transitions between regions in which the partial volume effect occurs on the empty set. Some authors have investigated this method for the segmentation of medical images [9,19,20]. In [20], the approach is especially interesting because the fusion of neighbourhood information is integrated into the ECM algorithm [11]. This process updates cluster centres from data whose noise and partial volume effect are reduced. Currently, this approach has not been introduced for modelling the imperfections on disjunctions. In [21], the author proposes to use fuzzy morphological operators for modelling imperfection from initial BBAs. This goal is achieved by transferring, for each voxel, a part of the belief on disjunctions according to its neighbourhood either in feature space or in the image. This method allows us to consider both the uncertainty and the imprecision in the disjunctions. By combining multiple complementary images to model imperfections, uncertainty due to noise can be reduced, whereas imprecision due to the partial volume effect remains represented in the disjunctions. Because BFT can model differentially these two imperfections and because neighbourhood information is sufficient for reducing the uncertainty, it could be interesting to reduce the uncertainty and model the imprecision on mono-modal images and then use multiple pieces of information to remove the imprecision.

Our aim is two-fold: first, to reduce the uncertainty due to noise, and then, to reduce the imprecision due to the partial volume effect, which corresponds to the lack of knowledge at the transitions between areas. For this purpose, BFT is used. We call our method Evidential Voxel-based Estimation of Imperfect Information (EVEII). First, our method operates a disjunctive combination followed by a conjunctive combination of neighbouring information on mono-modal images. The disjunctive combination allows us to transfer both uncertain and imprecise information on disjunctions. Then, the conjunctive combination is applied to reduce the uncertainty due to noise while maintaining a representation of imprecise information at the boundaries between the areas on the disjunctions. To remove the imprecise information that is considered on the disjunctions, fusion with an a priori contextual knowledge that is represented by a simple mass function related to the acquisition system is proposed. Finally, a multi-modal image fusion is proposed. We benefit from the complementarity of images to reduce the imprecisions that are inherent in the nature of these images.

The method is applied to the fusion of multi-tracer PET (Positron Emission Tomography) medical images of the same patient. Three radiotracers are used to provide information on tumour glucose metabolism, cell proliferation, and hypoxia

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