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Bilateral filter regularized accelerated Demons for improved discontinuity preserving registration

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ABSTRACT

The classical accelerated Demons algorithm uses Gaussian smoothing to penalize oscillatory motion in the displacement fields during registration. This well known method uses the L2 norm for regularization. Whereas the L2 norm is known for producing well behaving smooth deformation fields it cannot properly deal with discontinuities often seen in the deformation field as the regularizer cannot differentiate between discontinuities and smooth part of motion field.

In this paper we propose replacement the Gaussian filter of the accelerated Demons with a bilateral filter. In contrast the bilateral filter not only uses information from displacement field but also from the image intensities. In this way we can smooth the motion field depending on image content as opposed to the classical Gaussian filtering. By proper adjustment of two tunable parameters one can obtain more realistic deformations in a case of discontinuity. The proposed approach was tested on 2D and 3D datasets and showed significant improvements in the Target Registration Error (TRE) for the well known POPI dataset.

Despite the increased computational complexity, the improved registration result is justified in particular abdominal data sets where discontinuities often appear due to sliding organ motion.

1. Introduction

In medical image processing, a lot of research has and still is devoted to image registration [1].[1] The non-rigid image registration methods play an important role in today's modern medical diagnostics and Image-Guided Therapy (IGT) systems. Medical image registration seeks geometrical transformations which map one of the images into the spatial domain of the other image. In general, image registration is not restricted to the same modality but can also handle multi-modal image pairs.

During the last decade, imaging techniques capable of acquiring four-dimensional (4D) organ motion (3D+time), for example 4D MRI [3] became available. With the introduction of these imaging principles also the need for image registration approaches able to handle the discontinuities in the motion field, e.g., due organs sliding along the chest wall, grew [9].

Discontinuities preserving regularization methods can be based on local and global support, or with or without prior segmentation of region of interest. In Ruan et al. [5] the authors propose a regularization energy that encodes a discriminative treatment of different types of motion discontinuities, by using Helmholtz-Hodge decomposition. Heinrich et al. [6] presented a framework using a variational formulation of the optical flow model for 3D medical image registration, using robust discontinuity preserving non-quadratic regularization. This allows globally smooth deformations with local discontinuities, such as seen in sliding motion of the abdominal organs during respiration.

Applying discontinuities preserving regularization across the entire volume domain, i.e., globally, does not distinguish between different structures producing unrealistic motion fields.

On the other hand, in Staring et al. [2] the locally adapted, tissue-dependent filtering technique were developed. The degree of filtering is related to tissue stiffness. The tissue-dependent filter is incorporated in registration algorithm which uses mutual information as a similarity measure and cubic B-splines to model the deformation field.

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In Werner et al. [10] authors apply Thirions Demons registration with masked and unmasked force calculation, and the most accurate approach is then applied to local lung motion analysis. Ding et al. [11] proposed a method to evaluate the sliding motion of the lobar surfaces during respiration using lobe-by-lobe mass-preserving non-rigid image registration. They, however, segmented the lobes during preprocessing in the three parts. In Schmidt-Richberg et al. [7] a diffusion-based model for incorporating physiological knowledge in image registration is presented. They estimate slipping motion at the organ borders by decoupling normal- and tangential- directed smoothing for the estimation of respiratory lung motion. A different approach based on anisotropic diffusion to accommodate the deformation field discontinuities seen during sliding motion is shown in Pace et al. [8]. In [4] for example Kiriyanthan et al. proposed a unified variational approach that simultaneously segments and registers the images.

With the state-of-the-art registration methods this problem can only be handled when manual segmentations of the different tissues are provided. This, however, implies significant manual work. On the other side, the assumption about the type of the tissues, or decomposition to basic components that are regularized separately, sliding motion detection are some of the disadvantage of the state-of-the art implementations. In contrast we propose in this paper an automatic bilateral filter based Demons registration approach that can handle discontinuous motion fields intuitively.

Our contribution is mainly inspired by the work proposed in [2] and also Manduchi et al. [18] and Xiao et al. [14]. The proposed regularization of deformation fields is a spatially adaptive, and it is able to produce more realistic deformations. Proposed regularization use two controllable parameters for detection local changes: spatial and intensity smoothness. Proposed method does not need prior information. The quantitative analysis shows improved Target Registration Error (TRE) when compared to original Gaussian smoothing.

2. Methods

The goal of image registration can in general be described as finding a displacement field T that warps each pixel of the moving image M onto the static fixed image S in an optimal sense. The optimality criterion is defined by the similarity measure and can change depending on the nature and modality of the input images. The optimization of the similarity measure is an ill-posed problem that needs further physically inspired constraints which reduce oscillations and guide the registration process.

In this paper a modification to the accelerated Demons registration algorithm [13] is presented. This modification replaces the Gaussian filter regularization of the deformation field with a bilateral filter. Inspiration for this modification stems from the work of optical flow discontinuity handling from [14] where the flow vectors are smoothed with a modified version of bilateral filter.

Proposed method does not need any manual segmentation prior to registration. This modification improves the deformation fields around discontinuities and forms the basis for further research in this direction.

2.1. Deformation discontinuities

Organ motion represents a significant problem in medical image analysis. Movement in medical images is associated with tissue deformation, which should be fairly smooth except at the sliding regions, where edge is located. Due to a sliding motion at different types of tissues, discontinuities in the deformation field are formed (Fig. 1). Elastic registration algorithms tend to find the deformation based only on a similarity measure, which leads to an ill-posed problem. Therefore, regularization of the displacement field is necessary. We can introduce the regularization term $S(u)$ to smooth deformation field u, so the problem of registration is defined as minimizing the following energy functional

$$C(u) := D(I_S, T_u(I_M)) + S(u) \tag{1}$$

where I_S and I_M are static and moving images respectively, and T represents elastic transformation which iteratively transforms the moving image I_M to better align the I_F.

In Eq. (1) the term $D(I_S, T_u(I_M))$ represents the similarity measure, usually the sum of squared differences (SSD), and $S(u)$ is regularization, usually with Gaussian smoothing. This leads to smooth deformations, as in Thirions Demons approach [15].

Typically, common image registration methods tend to isotropically smooth all components of the motion field, which is not appropriate when dealing with sliding organ motion with discontinuity in the deformation field.

Isotropically smoothed motion field enforced upon the sliding object, which slides along the stationary object, will be incorrectly applied to the stationary tissue, making it appear to move (Fig. 1a). The key part in discontinuity preserving registration is to preserve discontinuities in this affected regions, and also differentiate among different types of tissues and regularize them accordingly.

2.2. Demons accelerated algorithm

The Demons algorithm as proposed by Thirion [15] draws an analogy to thermodynamical principles found by Maxwell in the 19th century when describing a thermodynamical paradox. The aim of the Demons algorithm is to find a displacement field T that maps all pixels m of the moving image M onto the corresponding pixels s of the static image S. The algorithm is iterative and new *forces* are calculated at each step by evaluating an optical flow-like equation. Different modifications with additional forces have been proposed to speed-up convergence of the basic Demon algorithm. To improve convergence of the algorithm, Wang combined his active force approach with the normalization factor α proposed in [13]. The factor α functions as a step size that can be adaptively changed after each iteration. They proposed to reduce the step size when the algorithm approaches convergence. Eq. (2) shows how the tunable normalization factor α is integrated into Wang's Demon force calculation:

$$\vec{v}_i = (m-s)\frac{\vec{\nabla} s}{(\vec{\nabla} s)^2 + \alpha_1 (m-s)^2} + (m-s)\frac{\vec{\nabla} m}{(\vec{\nabla} m)^2 + \alpha_2 (s-m)^2} \tag{2}$$

As image registration is an ill-posed problem and the displacement field is calculated only from local information, regularization is essential. Thus, the current displacement field requires a regularization after each iteration with a Gaussian filter. Wang's integration of the moving image gradient and Cachier's α factor [16] significantly improved convergence in comparison to Thirion's Demon implementation. Another well known strategy to reduce computational complexity is the multiresolution approach in which image resolution of the images is increased from coarse to fine.

A starting point for this research is Thirions Demons algorithm, a well-known and widely used algorithm for image registration tasks, due its simplicity and fast convergence. Furthermore, the Thirions Demons can be expressed in similar terms like the well known optical flow algorithm. The both algorithms use isotropic smoothing of the deformation fields.