Consistent Landmark and Intensity-Based Image Registration

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***Abstract*—Two new consistent image registration algorithms are presented: one is based on matching corresponding landmarks and the other is based on matching both landmark and intensity information. The consistent landmark and intensity registration algorithm produces good correspondences between images near landmark locations by matching corresponding landmarks and away from landmark locations by matching the image intensities. In contrast to similar unidirectional algorithms, these new consistent algorithms jointly estimate the forward and reverse transformation between two images while minimizing the inverse consistency error—the error between the forward (reverse) transformation and the inverse of the the reverse (forward) transformation. This reduces the ambiguous correspondence between the forward and reverse transformations associated with large inverse consistency errors. In both algorithms a thin-plate spline (TPS) model is used to regularize the estimated transformations. Two-dimensional (2-D) examples are presented that show the inverse consistency error produced by the traditional unidirectional landmark TPS algorithm can be relatively large and that this error is minimized using the consistent landmark algorithm. Results using 2-D magnetic resonance imaging data are presented that demonstrate that using landmark and intensity information together produce better correspondence between medical images than using either landmarks or intensity information alone.**

***Index Terms*—Correspondence, deformable templates, image registration, inverse transformation, landmark registration.**

I. INTRODUCTION

IMAGE registration algorithms are used to define correspondences between sets of images. Various characteristics of image data are exploited to drive image registration algorithms. The characteristics exploited range from designated landmark positions [1]–[4], to contours [5]–[7] or surfaces [8]–[11], and to volumetric functions of voxel intensities [6], [12]–[21].

There are many image registration algorithms based on the exact matching of corresponding landmarks in two images [22]. The unidirectional landmark thin-plate spline (UL-TPS) image registration technique pioneered by F. Bookstein [1], [2], [23] is the most commonly used landmark driven nonrigid image registration algorithm. Generalizations of UL-TPS procedure include kriging methods [24], [25] that use regularization models other than the TPS model, anisotropic landmark interactions [4] and directed landmarks [26].

Most landmark-based registration algorithms, including the ones described in this paper, assume that a small deformation is sufficient to register a set of images. In cases where the small deformation assumption holds, registration algorithms may efficiently estimate diffeomorphic transformations in a solution space that contain nondiffeomorphic transformations. The small deformation limitation is not universally applicable, and work by Joshi and Miller *et al.* [27]–[29] estimates large deformation transformations in a solution space of diffeomorphisms by constraining the transformations to obey diffeomorphic fluid properties.

The UL-TPS algorithm (see Section II-B) defines a unique smooth registration from a template image to a target image based on registering corresponding landmarks. Correspondence away from the landmark points is defined by interpolating the transformation with a TPS model. Although TPS interpolation produces a smooth transformation from one image to another, it does not define a consistent correspondence between the two images except at the landmark points. This can be seen by comparing the transformation generated by matching a set of template landmarks to a set of target landmarks with the transformation generated by matching the target landmarks to the template landmarks. If the correspondence is consistent then the forward and reverse transformations will be inverses of one another. This is not the case as shown by the examples in Section III. Consistency of the forward and reverse transformations is a necessary condition to define a unique correspondence between two images since it insures that the correspondence defined by the forward transformation is consistent with the correspondence defined by the reverse transformation. Without consistency, the forward transformation would define one correspondence between the images while the reverse transformation would define a different correspondence.

The consistent registration methods presented in this paper builds on the unidirectional landmark and intensity methods described in [30] which used a Fourier series basis to parameterize the transformation and the method developed by Kybic [31] that used B-splines.

In this paper, the idea of consistent image registration [32]–[34], [38] is combined with the UL-TPS algorithm [1]–[4], [23] to overcome the problem that the forward and reverse transformations generated by the UL-TPS algorithm are not inverses of one another. In the consistent image registration approach, the forward and reverse transformations between two images are jointly estimated subject to the constraints that they minimize the TPS bending energy and that they are inverses

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