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Rapid surface registration of 3D volumes using a neural network approach

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Abstract

An automatic surface-based rigid registration system using a neural network representation is proposed. The system has been applied to register human bone structures for image-guided surgery. A multilayer perceptron neural network is used to construct a patient-specific surface model from pre-operative images. A surface representation function derived from the resultant neural network model is then employed for intra-operative registration. The optimal transformation parameters are obtained via an optimization process. This segmentation/registration system achieves sub-voxel accuracy comparable to that of conventional techniques, and is significantly faster. These advantages are demonstrated using image datasets of the calcaneus and vertebrae.

Keywords: Surface registration; Neural network; Surface modelling; Medical images

1. Introduction

Medical imaging is increasingly used for surgical training, diagnosis, planning, guided surgery, post surgical assessment, monitoring disease progression, and many more. Often, multiple images are acquired of the subject at different times or using different modalities. A physical point in the subject will then have different coordinates in these separately acquired images. Spatial alignment or registration of these images is crucial in order to fuse, compare, and visualize the different image datasets. To date, high-resolution medical images are available in a variety of modalities and can be acquired at an extremely rapid rate. It is important that the registration process is able to handle huge multi-modality datasets quickly and accurately.

Current methods to perform registration can be categorized as marker-based methods [1,2], intensity-based methods [3,4], and feature-based methods [3,5]. Hybrid approaches have also been reported [6,7]. Due to the lack of distinctive objects in some medical images, registration is occasionally performed by introducing extrinsic features such as skin markers, screw markers, and dental adapters. They are rigidly positioned with respect to the human or animal subject during scanning [1,2]. Jan et al. [1] proposed an automated method for registering PET, CT, and SPECT images of small animals. They obtained a predetermined transformation matrix among different modalities using a calibration phantom and a holder. The spatial transformation matrix remains unchanged with the holder, which was arranged in fixed positions on the scanner couches. When different objects were scanned together with the holder, the acquired tomograms of different modalities can be registered with the predetermined transformation

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matrix. Intensity-based methods are preferred when the images do not have many prominent details. The distinctive information is provided by gray levels or colors instead of local shape and structure. Feature-based matching methods are typically applied when local structural information is more significant compared to the information based on image intensity. In hybrid approaches [6,7], intensity-based and feature-based methods are used together to optimize speed, accuracy, and robustness of registration.

Surface-based registration is commonly used for the following reasons: (1) it is less computationally intensive compared to volume-based registration since it has fewer points; (2) it can be used to perform multi-modality registration provided that the surfaces can be extracted precisely from different image modalities, which is typically not easy; (3) the surface is a feature that is relatively invariant over time, which is useful, for example, in monitoring progression of bone disease. Surface-based registration techniques differ in the elaboration of surface representation, similarity criterion matching and global optimization. Besl and McKay [5] has proposed the iterative closest-point (ICP) method [3,8,9] to determine the closest-point pairs, followed by computing the transformation from these pairs with a quaternion technique. A least-squares minimization technique then determines the rigid-body transformation that minimizes a cost function related to the distance between the two surfaces. However, these methods incur heavy computational cost in searching for point correspondences. Though techniques [8,9] have been proposed to accelerate the process, computational speed remains an issue for interactive applications. Chamfer matching (CM) [10] is another method for finding the best fit of edge points from two different images by minimizing a generalized distance between them. Variants that improve on the basic idea have been described [11,12]. Ghaffor [12] improved the speed, at the cost of increasing memory load, to store the pre-created distance map. Curvature-based surface features are well suited for use in multimodal medical image registration. Francis [13] proposed a method of obtaining a parametric surface representation from volumetric data. Surfaces were extracted using active contour models. A mongé basis for each surface patch was estimated and used to transform the patch into local, or parametric, coordinates. As stated, this method works well with simple surfaces but produced more errors when the complexity of the surface increased. Both accuracy and speed are important for the clinical application of a registration method [22]. Nevertheless, existing surface-based registration methods are not able to satisfy the concurrent requirements of accuracy and speed that are essential for clinical applications.

We propose to use a neural network (NN) representation of the surface in our surface-based registration system. The NN is used here to create a distance function that maps a 3D input point to the distance of that point from the object surface. A NN can efficiently model the spatial distance function with sufficient training data and time. The main advantage of NN modelling is that once trained, the computational effort needed to compute the function is extremely small. Thus, our system can achieve extremely fast and accurate 3D registration. An NN approach has been used by Srikanchana et al. [17] to model a non-linear transformation and has been used for principal direction computation by Shang et al. [19]. To the best of our knowledge, there is no surface-based registration method that uses a NN approach to model a surface with the aim of reducing the computational load.

An overview of the registration system is presented in Section 2. A detailed discussion of the registration method is provided in Section 3. The experiments are described in Section 4 and presented in Section 5. Section 6 concludes the paper.

2. Overview of registration system

Fig. 1 shows the architecture of the proposed registration system and its interfaces with external entities. The registration system comprises two main processes: semi-automatic segmentation for both pre-operative and intra-operative scans, and automatic real-time registration for intra-operative scans. This paper focuses on the latter.

Segmentation is first performed to separate the bone of interest from its surroundings. From this, we identify the bone surface that will be used in the registration procedure. Since CT imaging is a high-resolution modality, the set of 2D contours extracted slice by slice constitutes the 3D bone surface model. The pre-operative and intra-operative image volumes are then aligned or registered into the same geometric space. The registration algorithm comprises two steps: 3D surface modelling with a NN, and an optimization procedure to determine the transformation that best aligns the bone surfaces from the pre-operative and intra-operative scans. The suitably registered datasets can then be employed for image-guided surgery [14].

Since bone structures are of high intensities in CT images, they can usually be separated from soft tissue using thresholding methods. However, global thresholding would fail due to bone heterogeneity and imaging artifacts. We resort to a local adaptive thresholding scheme [15] that is robust to these conditions. An example of the final segmentation result (obtained with some manual assistance) is shown in Fig. 2.

The proposed NN-based registration algorithm (NNM) consists of two steps: coarse registration to obtain an initial estimate of the transformation followed by fine registration to achieve sub-pixel accuracy. The fine registration step achieves fast computation by reducing the computational requirement of the cost function (the distance measurement between the new and the reference surface points) and by using an efficient optimization routine. Current registration techniques focus mainly on fast optimization routines to reduce the overall time for surface-based registration. The cost function used in traditional surface-based registration is highly computationally intensive. Method using the