

3D and 4D Medical Image Registration Combined with Image Segmentation and Visualization

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INTRODUCTION

Image registration, segmentation, and visualization are three major components of medical image processing. Three-dimensional (3D) digital medical images are three dimensionally reconstructed, often with minor artifacts, and with limited spatial resolution and gray scale, unlike common digital pictures. Because of these limitations, image filtering is often performed before the images are viewed and further processed (Behrenbruch, Petroudi, Bond, et al., 2004). Different 3D imaging modalities usually provide complementary medical information about patient anatomy or physiology. Four-dimensional (4D) medical imaging is an emerging technology that aims to represent patient motions over time. Image registration has become increasingly important in combining these 3D/4D images and providing comprehensive patient information for radiological diagnosis and treatment.

3D images have been utilized clinically since computed tomography (CT) was invented (Hounsfield, 1973). Later on, magnetic resonance imaging (MRI), positron emission tomography (PET), and single photon emission computed tomography (SPECT) have been developed, providing 3D imaging modalities that complement CT. Among the most recent advances in clinical imaging, helical multislice CT provides improved image resolution and capacity of 4D imaging (Pan, Lee, Rietzel, & Chen, 2004; Ueda, Mori, Minami et al., 2006). Other advances include mega-voltage CT (MVCT), cone-beam CT (CBCT), functional MRI, open field MRI, time-of-flight PET, motion-corrected PET, various angiography, and combined modality imaging, such as PET/CT (Beyer, Townsend, Brun et al., 2000), and SPECT/CT (O'Connor & Kemp, 2006). Some preclinical imaging techniques have also been developed, including parallel multichannel MRI (Bohurka, 2004), Overhauser enhanced MRI (Krishna, English, Yamada et al., 2002), and electron

paramagnetic resonance imaging (EPRI) (Matsunoto, Subramanian, Devasahayam et al., 2006).

Postimaging analysis (image processing) is required in many clinical applications. Image processing includes image filtering, segmentation, registration, and visualization, which play a crucial role in medical diagnosis/treatment, especially in the presence of patient motion and/or physical changes. In this article, we will provide a state-of-the-art review on 3D/4D image registration, combined with image segmentation and visualization, and its role in image-guided radiotherapy (Xing, Thorndyke, Schreibmann et al., 2006).

BACKGROUND

3D/4D Medical Imaging

A 3D medical image contains a sequence of parallel two-dimensional (2D) images representing anatomic or physiologic information in 3D space. The smallest element of a 3D image is a cubic volume called voxel. A 4D medical image contains a temporal series of 3D images. With a subsecond time resolution, it can be used for monitoring respiratory/cardiac motion (Keall, Mageras, Malter et al., 2006).

Patient motion is always expected: faster motion relative to imaging speed causes a blurring artifact; whereas slower motion may not affect image quality. A multislice CT scanner provides improved spatial and temporal resolution (Ueda et al., 2006), which can be employed for 4D imaging (Pan et al., 2004). Progresses in MRI imaging have also been reported, including parallel multichannel MRI (Bodurka, Ledden, van Gelderen et al., 2004).

Because PET resolution and speed are limited by the physics and biology behind the imaging technique, some motion suppression techniques have been developed clinically, including patient immobilization (Beyer, Tellmann, Nickel, & Pietrzyk, 2005), respiratory gating (Hehmeh, Erdi, Pan et al., 2004), and motion tracking (Montgomery, Thielemans, Mehta et al., 2006). Motion tracking data can be used to filter the imaging signals prior to PET image reconstruction for reliable motion correction. Motion blurring, if uncorrected, can reduce registration accuracy. Visual-based volumetric registration technique provides blurring correction (filtering) before registration, by defining the PET volume with reference to the CT volume, causing blurred PET

surface voxels to be rendered invisible (Li, Xie, Ning et al., 2007).

Image Segmentation and Visualization

Medical image segmentation defines regions of interest used to adapt image changes, study image deformation, and assist image registration. Many methods for segmentation have been developed including thresholding, region growing, clustering, as well as atlas-guided and level sets (Pham, Xu, & Prince, 2000; Suri, Liu, & Singh et al., 2002). Atlas-guided methods are based on a standard anatomical atlas, which serves as an initial point for adapting to any specific image. Level sets, also called active contours, are geometrically deformable models, used for fast shape recovery. Atlas-based level sets have been applied clinically for treatment planning (Lu, Olivera, Chen et al., 2006a; Ragan, Starkschall, McNutt et al., 2005;) and are closely related to image registration (Vemuri, Ye, & Chen, et al., 2003). Figure 1 shows automatic contours. Depending on how the 3D image is segmented, it can be either 2D-based or 3D-based (Suri, Liu, Reden, & Laxminarayan, 2002).

3D medical image visualization has been increasingly applied in diagnosis and treatment (Salgado, Mulkens, Bellinck, & Termote, 2003), whereas 2D-based visualization is predominantly applied clinically. Because of the demand on computing power, real-time 3D image visualization is supported by specialized graphics hardware (Terarecon, Inc.) (Xie, Li, Ning et al., 2004) or high-end consumer graphics processors (Levin, Aladl, Germanos, & Slomak, 2005). 3D image visualization has been applied to registration of four imaging modalities with improved spatial accuracy (Li, Xie, Ning et al., 2005; Li et al., 2007). Figure 2 shows 3D volumetric image registration using external and internal anatomical landmarks.

Rigid Image Registration

Rigid image registration assumes a motionless patient such that the underlying anatomy is identical in different imaging modalities for alignment. Three approaches to rigid registration are: coordinate-based, extrinsic-based, and intrinsic-based (Maintz & Viergever, 1998). Coordinate-based registration is performed by calibrating the coordinate system to produce “co-registered” images. Multimodality scanners, such as PET/CT and SPECT/CT, are typical examples.

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