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Volume Registration Based on 3-D Phase Correlation for Tumor Motion Estimation in 4-D CT

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Abstract— **This paper presents a three-dimensional (3-D) volume registration method that uses 3-D phase correlation to estimate the respiration-induced tumor motion in four-dimensional (4-D) thorax computed tomography (CT) for radiation therapy. The proposed method is an extension of 2-D phase correlation method to 3-D volume registration. Given two CT volumes obtained from different respiration stages, the tumor motion is modeled as a translational shift between the volumes. The 3-D phase correlation is obtained from the 3-D inverse Fourier transform of a normalized cross power spectrum of the volumes. The tumor motion along three directions is estimated by locating the highest peak in the 3-D phase correlation. In order to improve the estimation accuracy, we extend the 3-D phase correlation to sub-voxel accuracy. Experimental results demonstrate the effectiveness of the proposed method relative to a conventional 2-D phase correlation-based method.**

I. Introduction

In radiation therapy, respiration-induced tumor motion not only significantly limits the efficiency of the radiation delivery, but also causes complications due to over-irradiation of normal tissues [4]. In recent years, to improve the efficiency of the radiation delivery, 4-D CT scanner, which takes 3-D volumes with an additional dimension of time, has been developed to observe the tumor motion in the treatment planning [4], [1], [5].

The 4-D CT consists of a series of 3-D CT volumes acquired at different respiratory stages. It provides dynamical anatomical information of the patient's body during a respiratory cycle. Combined with image or volume registration techniques [3], clinicians can estimate the tumor motion along three directions (lateral, antero-posterior, and cephalo-caudal), and subsequently delineate several planning target volumes (PTVs) corresponding to each of the respiration stage for dynamical radiation delivery.

Conventional image registration can be applied to estimate the tumor motion by using a series of cross-section image pairs in the 4-D CT. A serious problem to be considered here is that specifying the appropriate cross-section images for the registration is quite exhausting and imprecise since the tumor's location always changes with the respiratory stages. On the other hand, 3-D volume registrations, which directly perform on the 3-D volumes, can also been utilized to estimate the tumor motion in the 4-D CT, but most of them need the prior knowledges and are computationally excessive [3].

In this paper, we present a 3-D phase correlation-based method to estimate the tumor motion in the 4-D CT. The proposed method is an extension of the phase correlation-based method from the 2-D image registration to 3-D volume data for application of radiation therapy. The proposed method utilizes the 3-D fast Fourier transforms (FFTs) to calculate a 3-D phase correlation of two given volumes. Then, the tumor motion along three directions are simultaneously estimated by locating the the maximum of a 3-D sinc function fitting to the 3-D phase correlation. Experimental results demonstrate the proposed method is capable of archiving a higher accuracy relative to a conventional 2-D image registration method [2].

II. 3-D Phase Correlation for Tumor Motion

Let $V_1(x,y,z)$ and $V_2(x,y,z)$ be two CT volumes of size $(N_1 \times N_2 \times N_3)$ acquired at different respiratory stages, where V_1 and V_2 stand for the voxel intensities, and (x,y,z) are the coordinates along the lateral, antero-posterior, and cephalo-caudal axes, respectively. Supposing that $V_1(x,y,z)$ and $V_2(x,y,z)$ cover the tumor area, the tumor motion between two respiratory stages can be modeled as a translational shift as follows:

$$V_1(x,y,z) = V_2(x-\Delta x, y-\Delta y, z-\Delta z) \tag{1}$$

where $(\Delta x, \Delta y, \Delta z)$ stand for the motion values along the three directions. Figures 1(a) and 1(b) show a tumor in two CT volumes acquired at the end-exhale and end-inhale stages, respectively. We can see that the tumor's location is changed due to the respiration.

The phase correlation-based method for the motion estimation is based on the Fourier shift theorem. Specifically, a volumetric shift in the spatial domain can be expressed as a linear phase difference between two 3-D Fourier spectra in the frequency domain. Therefore, the translation model in the spatial domain Eq. (1) can be rewritten in the frequency domain, given as

$$F_1(u,v,w) = F_2(u,v,w) e^{-j2\pi\left(\frac{u\Delta x}{N_1}+\frac{v\Delta y}{N_2}+\frac{w\Delta z}{N_3}\right)} \tag{2}$$

where $F_1(u,v,w)$ and $F_2(u,v,w)$ are the 3-D discrete Fourier transforms (DFTs) of $V_1(x,y,z)$ and $V_2(x,y,z)$, respectively,

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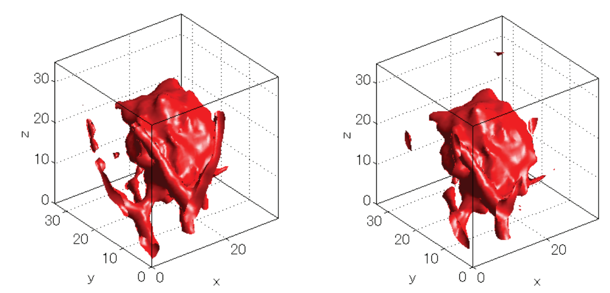
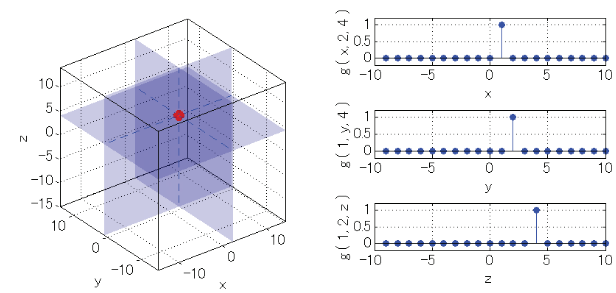


(a) (b)

Fig. 1. Tumor motion in the 4-D CT. (a) Tumor at the end-exhale stage. (b) Tumor at the end-inhale stage.



(a) (b)

Fig. 2. Example of the 3-D phase correlation when translation values are integers. (a) The 3-D phase correlation reaches its maximum at $(1,2,4)$ when $(\Delta x,\Delta y,\Delta z)=(-1,-2,-4)$. (b) The phase correlation crossing the maximum of the phase correlation along three axes.

and (u,v,w) are the discrete variables in the frequency domain.

The 3-D normalized cross power spectrum of two volumes, denoted by $G(u,v,w)$, is given by

$$G(u,v,w) = \frac{F_1(u,v,w)}{|F_1(u,v,w)|}\frac{F_2^*(u,v,w)}{|F_2^*(u,v,w)|} = e^{j2\pi\left(\frac{u\Delta x}{N_1}+\frac{v\Delta y}{N_2}+\frac{w\Delta z}{N_3}\right)} \tag{3}$$

where the asterisk denotes the complex conjugate.

The 3-D phase correlation $g(x,y,z)$ of two volumes can be obtained from the inverse discrete Fourier transform (IDFT) of the normalized cross power spectrum as follows:

$$g(x,y,z) = \text{IDFT}\left[e^{j2\pi\left(\frac{u\Delta x}{N_1}+\frac{v\Delta y}{N_2}+\frac{w\Delta z}{N_3}\right)}\right] \tag{4}$$

If $(\Delta x,\Delta y,\Delta z)$ are integers, the 3-D phase correlation $g(x,y,z)$ is a shifted delta function

$$g(x,y,z) = \begin{cases} 1, & (x,y,z)=(-\Delta x,-\Delta y,-\Delta z) \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

whose peak is located at the coordinates $(-\Delta x,-\Delta y,-\Delta z)$. Therefore, the translation between two volumes can be estimated by locating the highest peak in the phase correlation as follows:

$$(\Delta x,\Delta y,\Delta z) = -\left[\underset{(x,y,z)}{\arg\max}\ g(x,y,z)\right] \tag{6}$$

Figure 2(a) shows a 3-D phase correlation of two volumes when the translation $(\Delta x,\Delta y,\Delta z)=(-1,-2,-4)$. The 3-D phase correlation reaches its maximum at $(1,2,4)$. Figure 2(b) plots the phase correlation along three axes crossing the maximum of the phase correlation. The highest peak of the 3-D phase correlation is located at $(1,2,4)$, which indicates that the translation along three directions are $(\Delta x,\Delta y,\Delta z) = (-1,-2,-4)$.

III. Sub-Voxel Tumor Motion Estimation

Although the 4-D CT is represented by voxel, sub-voxel translation between two volumes always occurs during sampling the analog signal into digital signal. When the translation values are fractions, the 3-D phase correlation is not a shift delta function. Figure 3 shows such example of the 3-D phase correlation when $(\Delta x,\Delta y,\Delta z)=(-1.3,-2.4,-4.6)$. The coordinates of the highest peak are $(1,2,5)$, even though the actual translation values are $(-1.3,-2.4,-4.6)$.

When the translation values are fractions, the 3-D phase correlation $g(x,y,z)$ can be derived as follows:

$$g(x,y,z) = \frac{1}{N_1N_2N_3}\frac{\sin(\pi(x+\Delta x))}{\sin\left(\frac{\pi}{N_1}(x+\Delta x)\right)} \times\frac{\sin(\pi(y+\Delta y))}{\sin\left(\frac{\pi}{N_2}(y+\Delta y)\right)}\frac{\sin(\pi(z+\Delta z))}{\sin\left(\frac{\pi}{N_2}(z+\Delta z)\right)} \tag{7}$$

If $\pi(x+\Delta x)/N_1$, $\pi(y+\Delta y)/N_2$, and $\pi(z+\Delta z)/N_3$ are sufficiently small, the discrete phase correlation $g(x,y,z)$ can be approximated as a sampled 3-D sinc function, given by

$$g(x,y,z) \approx \frac{\sin(\pi(x+\Delta x))}{\pi(x+\Delta x)}\frac{\sin(\pi(y+\Delta y))}{\pi(y+\Delta y)} \times\frac{\sin(\pi(z+\Delta z))}{\pi(z+\Delta z)} = \text{sinc}(x+\Delta x)\text{sinc}(y+\Delta y)\text{sinc}(z+\Delta z) \tag{8}$$

where the sinc function is defined by

$$\text{sinc}(x) = \frac{\sin(\pi x)}{\pi x} \tag{9}$$

Figures 3(b), 3(c), and 3(d) plot three continuous sinc functions fitting to the discrete phase correlation. Accordingly, the translation between two volumes can be estimated with sub-voxel accuracy by finding the location of the maximum of the sinc function. In this paper, we adopt a non-interpolation method [2] that uses the highest peak of the discrete 3-D phase correlation and its three neighboring points to estimate the sub-voxel translation values. The detail of this method can be found in [2].

Figure 4 summarizes the computational process of the 3-D phase correlation method for the tumor motion estimation in which the 3-D DFTs are performed by the 3-D FFTs. Given two volumes $V_1(x,y,z)$ and $V_2(x,y,z)$ covering the tumor area in the 4-D CT, we firstly truncate the volumes using 3-D Hann windows prior to the 3-D DFTs for preventing the edge

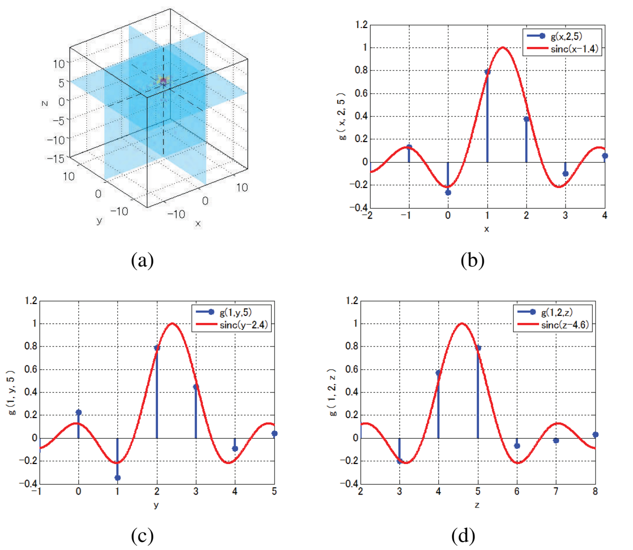


Fig. 3. Example of 3-D phase correlation when translation values are fractions. (a) The 3-D phase correlation reaches its maximum at $(1,2,5)$ when $(\Delta x, \Delta y, \Delta z) = (-1.3, -2.4, -4.6)$. (b), (c), (d) Three sinc functions fitting to the discrete phase correlation along three axes crossing the highest peak of the phase correlation. The sub-voxel translations can be estimated by locating the maxima of the sinc functions.

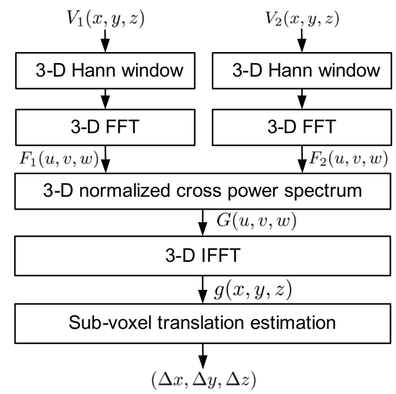


Fig. 4. Computational process of the 3-D phase correlation for tumor motion estimation.

TABLE I

ERRORS IN DISPLACEMENT ESTIMATION.

	2-D method [2]	3-D method
RMSE (Δx)	0.17	0.09
RMSE (Δy)	0.21	0.18
RMSE (Δz)	0.36	0.21

* Values are in voxel.

effects in the 3-D DFTs. The 3-D Hann window is defined as

$$H(x,y,z) = \frac{1+\cos(\frac{2\pi x}{N_1})}{2} \frac{1+\cos(\frac{2\pi y}{N_2})}{2} \frac{1+\cos(\frac{2\pi z}{N_3})}{2} \quad (10)$$

The 3-D phase correlation of two volumes is then calculated by using the 3-D IDFT of the normalized cross power spectrum of the two volumes. Finally, the translation $(\Delta x, \Delta y, \Delta z)$ is estimated by finding the location of the maximum of a 3-D sinc function fitting to the discrete 3-D POC.

IV. EXPERIMENTAL RESULTS

In this section, a set of experiments is conducted to evaluate the performance of the proposed method compared with a 2-D phase correlation-based method [2]. The experimental data consists of an artificial 4-D CT and a clinical 4-D CT.

We generate an artificial 4-D CT, which consists of an original CT volume and 9 sub-voxel translated volumes, to simulate the respiration-induced tumor motion. The sub-voxel translation is generated by using following method. Firstly, an original CT volume is magnified 10 times by a bicubic interpolation. Then, the magnified volume is shifted in three directions with integers. The sub-voxel translated volumes are obtained by down-sampling the shifted volumes with factor 1/10.

In the original CT volume, we specified a sub-volume covering the tumor area as a reference volume V_1. In the artificially translated volumes, we also specified 9 sub-volumes at the same location as V_2. Figures 5(a), 5(b), and 5(c) show the axial (x-y plane), coronal (x-z plane), and sagittal (y-z plane) cross-section images of the original CT volume, in which the squares specify the sub-volume for tumor motion estimation. Figure 5(d) shows the tumor surface in the sub-volume.

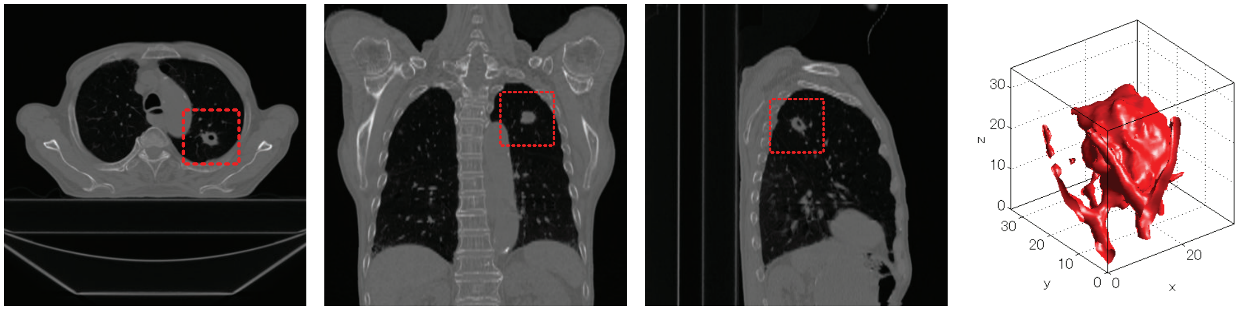
We also implement the 2-D phase correlation-based method [2] for comparison. In order to obtain the translation along three directions, the 2-D phase correlation-based method must be performed on the coronal and sagittal cross-section images specified by clinicians.

Figures 6(a), 6(b), and 6(c) plot the actual tumor motion values and the estimated results obtained from two methods. Table I summarizes the root of mean square errors (RMSEs) in the experiments. The experimental results on the artificial 4-D CT demonstrate that the proposed method is capable of achieving a higher accuracy than the 2-D phase correlation-based method.

We also conduct a experiment on an actual clinical CT volume sequence which consists of nine 3-D CT volumes acquired from different stages in a respiratory cycle. Figure 7(a) shows a coronal images in the clinical 4-D CT. The tumor motion trajectory estimated by the proposed method is plotted in Figure 7(b). The estimated results which are confirmed by radiologists' sight suggestion also showed the efficiency of the proposed method.

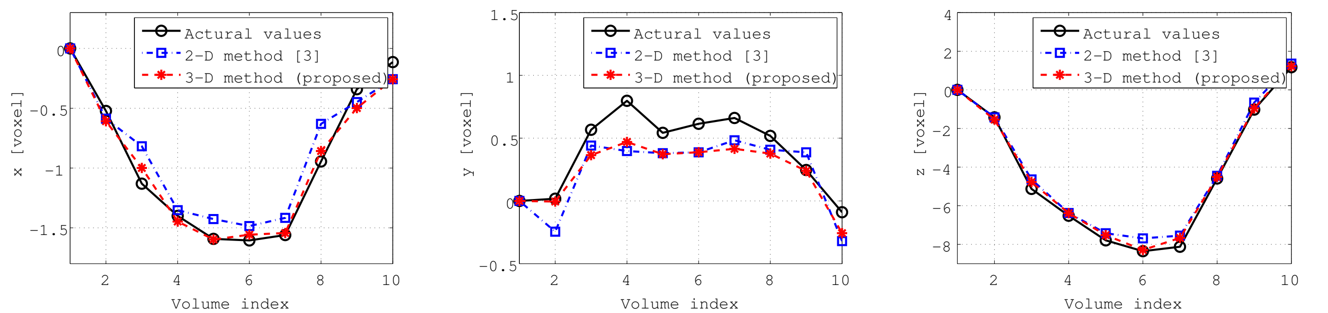
V. CONCLUSIONS

We have proposed a 3-D phase correlation-based volume registration method for tumor motion estimation in 4-D CT volumes. Compared with conventional 2-D image registration method, the proposed method directly performs on 3-D CT volumes, instead of 2-D cross-section images manually specified by clinicians. Experimental results clearly demonstrated the efficiency of the proposed method. As a future work, we will extend the the proposed method from



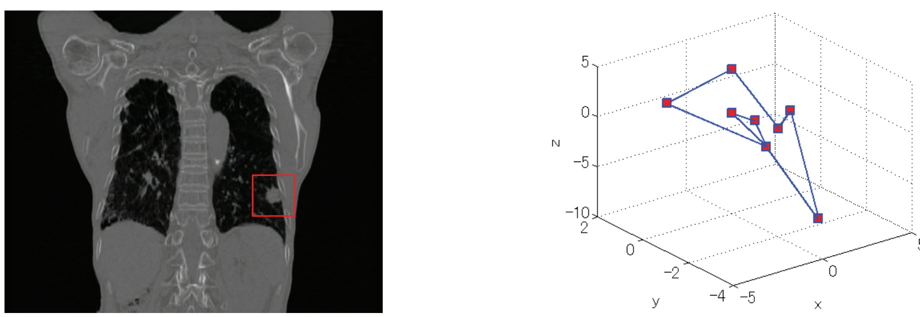
(a) (b) (c) (d)

Fig. 5. An original CT volume for generating sub-volume tumor motion. (a) Axial (x-y plane) image. (b) Coronal (z-y plane) image. (c) Sagittal (y-z plane) image. (d) Tumor surface in the 3-D volume.



(a) (b) (c)

Fig. 6. Actual displacement values and estimated results obtained from the 2-D phase correlation-based method [2] and proposed method. (a) Displacement along x axis. (b) Displacement along y axis. (c) Displacement along z axis.



(a) (b)

Fig. 7. Clinical 4-D CT and the estimated tumor motion trajectory. (a) A coronal image in clinical 4-D CT. (b) Tumor motion trajectory estimated by the proposed method.

3-D translation estimation to rotation and scaling estimations and compare the performance of the 3-D phase correlation-based method with some state-of-art registration methods.

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