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The Study of Fiducial Localization Error of Image in Point-based Registration

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Abstract—**Image Guided Surgery (IGS) has been widely used in neurosurgical procedures to minimize invasion and to improve surgical accuracy. Registration is a key step of IGS, while Fiducial Localization Error (FLE) is an important factor affecting registration accuracy. FLE can be caused in both image domain (I-FLE) and physical domain (P-FLE). In this study, we design experiments to measure and compare the affecting factors on image FLE of point-based registration with special designed phantom. The results show that two factors affecting I-FLE are artificial picking and image voxel size. The artificial picking may cause the I-FLE average from 0.43 ± 0.14mm to 0.74 ± 0.26mm, and the voxel size may cause from 0.43 ± 0.14 mm to 0.77 ± 0.23 mm. The artificial picking error can be reduced by improving the picking person's experience, and we strongly recommend using smallest pixel spacing images for the registration. As for the selection of slice thickness, we find that the situation of Over-Sampling and Under-Sampling may occur, which would cause the thinner slice group of the image to get a higher I-FLE.**

I. Introduction

Image guided surgery (IGS) has been widely used in neurosurgical procedures to minimize invasion and to improve surgical accuracy. In image-guided surgery, there are three key steps: Identifying anatomical tissue in the images (segmentation), and mentally establish the spatial relationship between the imagery and the patient (registration). Additionally, the procedure's execution accuracy should be comparable or better than that achieved by the traditional approach (navigation) [1].

The key step affecting IGS system's accuracy is registration, which is the procedure of point-pair matching with the purpose to get the accurate alignment of the image and the physical anatomy targets locations. Maurer et al. [2] suggested three error sources of measures for analyzing the accuracy of point-based registration methods. a) FLE, the error in locating the fiducial points, b) FRE, the distance between corresponding fiducial points after registration, and c) TRE, the distance between corresponding points other than the fiducial points after registration. The assessment method is calculation of the length of the FLE, FRE, TRE vectors, such as the root mean square (RMS) of the vector.

FLE could be caused in both image domain (I-FLE) and physical domain (P-FLE). Shamir et al. [3] observed that different anatomical landmarks are associated with different FLE distributions spanning the range of 0.5±0.5mm to 2.0±2.1mm on the MRI image and the range of 1.9±1.0mm to 3.2±1.6mm on the physical domain.

In this study, we notice that I-FLE is an important factor of the registration error in the IGS system we developed. With the improvement of tracking systems, P-FLE has been reduced greatly to an average of 0.200 ± 0.141mm, as measured with Optotrak(NDI) system. Since the average and the standard deviation of I-FLE could be even greater than P-FLE in our research, so we focus on the influence of I-FLE on the whole system error. We consider two factors that contribute to Image FLE (I-FLE), one is the subjective factors, and the other is the voxel size. We measure and compare the data of different people picking the landmarks of the images with different voxel sizes. Specifically, our study aims at discussing three questions: (1) How does subjective factors influence I-FLE? (2) How does image voxel size influence I-FLE? (3) How great is I-FLE's influence on the Target Registration Error (TRE)?

II. Methods

A. Mathematical Definition

Fiducial Localization Error (FLE)

FLE is estimated by calculating the average of the measured distance value between repeated position picking of one fiducial point. Take I-FLE as an example:

$$\mathrm{I-FLE} = \frac{1}{n-1}\sum_{i=1}^{n-1}\|f_{i+1}^{I} - f_{i}^{I}\| \qquad (1)$$

Where f_i^I is the fiducial point image coordinate scalar value, n is the number of the repeated picking times.

Transformation Matrix ($T^{W\text{-}I}$) Calculation

The rigid transformation matrix T^{W-I} is calculated to minimize the RMS distance between the landmark sets.

$$T^{W-I} = \arg\min_{\mathrm{T}}\left(\sqrt{\frac{1}{\mathrm{N}}\sum_{i=1}^{N}\|f^{W}\cdot T - f^{I}\|^{2}}\right) \qquad (2)$$

Where f^W is the fiducial point world coordinate scalar value.

Target Registration Error (TRE)

TRE is the distance after registration between

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corresponding points not used in calculating the registration transforms:

$$\mathrm{TRE} = \|t^W \cdot T^{W-I} - t^I\| \quad (3)$$

Where t^W and t^I are corresponding to the target point position in world coordinate and image coordinate.

B. Experiment Design

1. Phantom preparation

To solve the questions mentioned above, we make a series of experiments with the phantom designed by ourselves. The phantom has two features: 1) To simulate the clinical situation, we designe the phantom with the size of the level from the real head of the patient. 2) We make some small pits on the phantom for different purpose, some of them stand for fiducial points, others for target points. Figure 1 shows the phantom and the landmarks designing position.

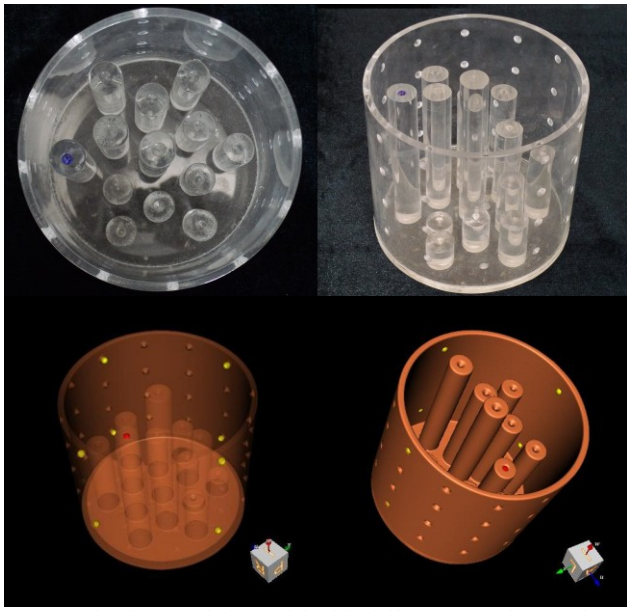

Fig. 1 The phantom design and the fiducial/target point design. The landmarks are shown as yellow point, and the target points are shown with the red color.

2. Image Acquirement and Experiment Devices

The phantom's image is acquired through the Siemens CT scanner. The image resolutions are 512*512 and 256*256, with the pixel spacing 0.32*0.32 and 0.65*0.65mm. Slice numbers are 232, 125, 96, 86, with the slice thickness 0.7, 1.3, 1.7, 1.9mm.

The position tracking system is Optotrak (Northern Digital, CAN). The camera can locate the tip of probe with an accuracy of 0.15 mm.

The image locating software is developed by ourselves. With it we can locate the landmarks not only in 3D view, but also in 2D orthogonal views. First we pick a landmark in the 3D view generally, and the 2D slices will change automatically corresponding to the coordinate of the point. And then we can adjust accurately in 2D views. So the doctor can locate the landmarks more easily and accurately with our IGS system, which is shown as the red cross in Figure 2.

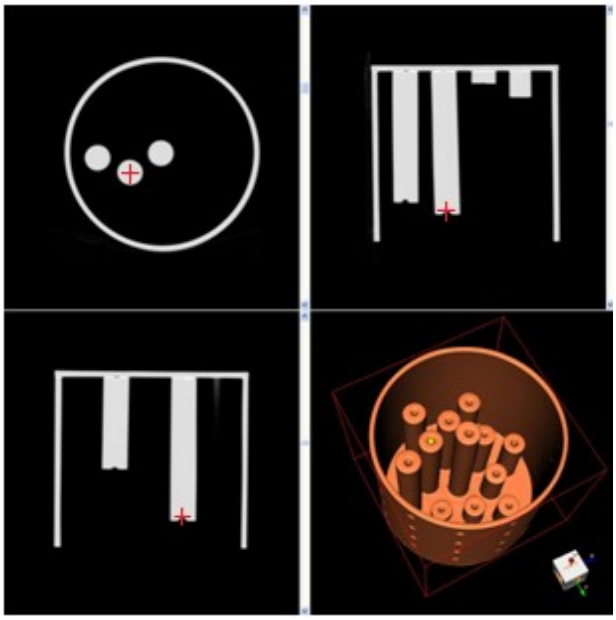

Fig. 2 The IGS software developed by ourselves. The right bottom view is the 3D view, and the other three views are 2D views.

3. Inspection of Image Fiducial Localization Error

In the experiment design, we considered two factors that contribute to Image FLE (I-FLE), which are the subjective factors and the voxel size. So we planned to design experiments in order to make the two factors independent. And calculate the average of the measured distance value between repeated picking position of one fiducial point to get the distribution and average value of the I-FLE.

1) Acquirement of the influence of artificial picking:

To measure the influence of the artificial picking, we considered to minimize the influence of the voxel size, so we take the experiment image with a fixed voxel size, which is the smallest of our images. And we designed two sub-experiments:

a. In order to study a person's landmark locating stability, he is required to pick the landmarks from the image for several times. Then we calculate the average and standard deviation (STD) of the data.
b. In order to study different people's landmark locating error, three people are required to pick the landmarks from the same image, and each one picked one landmark for several times

2) Influence of voxel size:

To measure the influence of the voxel size, we considered to minimize the influence of the artificial picking, so we choose an experienced person to pick the landmarks with different voxel size.

We hope to discuss the voxel size's influence in two parts, one is the influence of different pixel spacing, and the other is the influence of different slice thickness. So we locate the landmarks from several groups of different voxel size images, which have different pixel spacing or different slice thickness.

4. Inspection of Target Registration Error

In this part, our purpose is to find out different I-FLE's

influence to TRE. We considered three factors that contribute to TRE: 1) Number of fiducial points; 2) Position of the fiducial points; 3) FLE. Fitzpatrick [4] replaced $\langle \text{I-FLE}^2 \rangle + \langle \text{P-FLE}^2 \rangle$ by $\langle \text{FLE}^2 \rangle$.

In order to achieve our purpose, we considered to minimize the influence of P-FLE, the position and number of fiducial points.

With this consideration, 1) we measured P-FLE with the Optotrak system, resulting in an average of 0.200mm, and a standard deviation of 0.141mm, far less than the I-FLE. 2) Bai Jing et al. [5] have reported the relationship between number of landmarks and TRE, which shows that TRE will not change obviously when they take more than 8 landmarks. So we use 8 landmarks for registration. 3) As J. B. West's research [6], to reduce the TRE, the target points should be close to the center of the landmarks, and the placement of landmarks should be as far as possible from each other. Based on this, we choose the landmarks' position as far as possible on our phantom as Figure 1.

After the preparation, for registration, we choose the different voxel size images, and one group of world coordinate position which is acquired as the average of several times landmarks selecting through Optotrak. Then we choose the target point most close to the center of the landmarks to calculate the TRE.

5. Experiment Data Processing

For I-FLE data acquirement, we calculate the corresponding landmarks' distance in adjacent groups, as shown in Expression (1). And then calculate the average and STD values of them.

For TRE data acquirement, first we calculate the transform matrix T^{W-I} with Expression (2). And then transform the target point's position from world coordinate to image coordinate. Then calculate TRE according to Expression (3). Also calculate the average and STD values of them.

III. Results

A. The factors' influence on I-FLE

1) Influence of artificial picking:

Three people picked 8 landmarks from the image with the voxel size 0.32*0.32*0.7 for 15 times of 8 landmarks. And calculate the distance between adjacent two groups, getting 14*8 distance value. Then calculate the average and STD for the influence of artificial picking. The observed I-FLE's average and STD is shown as Table I.

TABLE I
Influence of artificial picking on I-FLE

	Average(mm)	STD(mm)
Person A	0.43	0.14
Person B	0.74	0.26
Person C	0.57	0.19

2) Influence of voxel size:

Table II shows the results of an experienced person picking the landmarks from five groups of different voxel size images, 8 landmarks for 15 times for each group.

Figure 3 shows the I-FLE distribution by probability density with different voxel sizes. A-E shows the distribution of the five group images, and F shows the distribution compare between the two different pixel size groups, which is 0.32*0.32*1.3 and 0.65*0.65*1.3.

TABLE II
Influence of voxel size on I-FLE

	Voxel Size	Average(mm)	STD(mm)
A	0.32*0.32*0.7	0.43	0.14
B	0.32*0.32*1.3	0.49	0.16
C	0.32*0.32*1.7	0.48	0.15
D	0.32*0.32*1.9	0.46	0.10
E	0.65*0.65*1.3	0.77	0.23

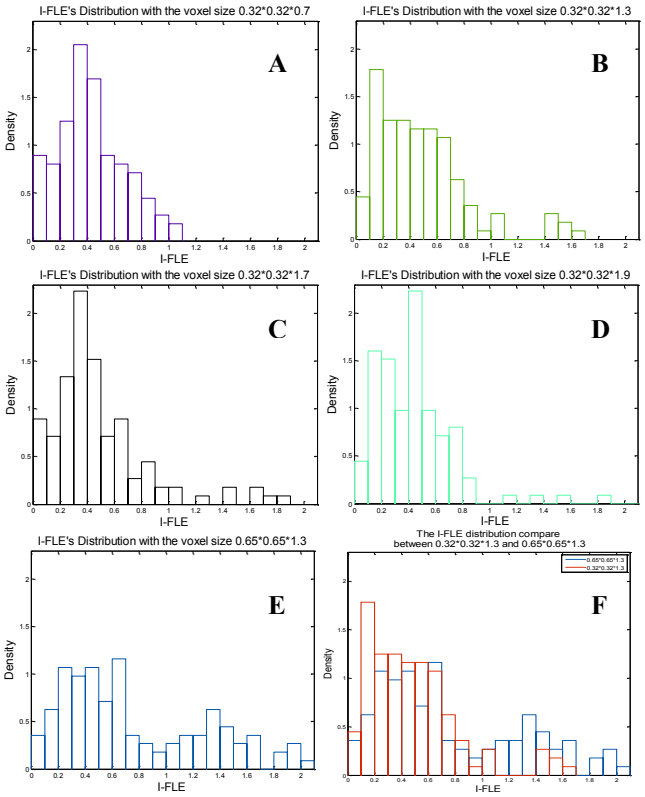

Fig. 3 I-FLE's distribution with different voxel sizes, x axis stands for I-FLE, y axis stands for the probability density.

B. I-FLE's influence on TRE

In the registration step, we take the five groups of different voxel size images as the data of image space. And to get the data in world space, we calculate the average of 15 times landmarks selected through Optotrak. The result is shown in Table III.

TABLE III
I-FLE's influence on TRE

	Voxel Size	I-FLE(mm)	TRE(mm)
A	0.32*0.32*0.7	0.43 ± 0.14	0.53 ± 0.11
B	0.32*0.32*1.3	0.49 ± 0.16	0.86 ± 0.15
C	0.32*0.32*1.7	0.48 ± 0.15	0.87 ± 0.10
D	0.32*0.32*1.9	0.46 ± 0.10	0.71 ± 0.11
E	0.65*0.65*1.3	0.77 ± 0.23	1.06 ± 0.17

IV. Discussion

In this study, we observe that the subjective factors and the voxel size may influence the I-FLE, and different I-FLE may cause different TRE, and we have found some of their correlation.

A. Affecting factors on I-FLE

1) Influence of artificial picking

As Table I shows, different people make different I-FLE, the average range is from 0.43 ± 0.14mm to 0.74 ± 0.26 mm. The most important factor of the artificial picking is experience. Repeated training would improve the picking skill which is the experience from Person A, who gets the best results.

2) Influence of voxel size

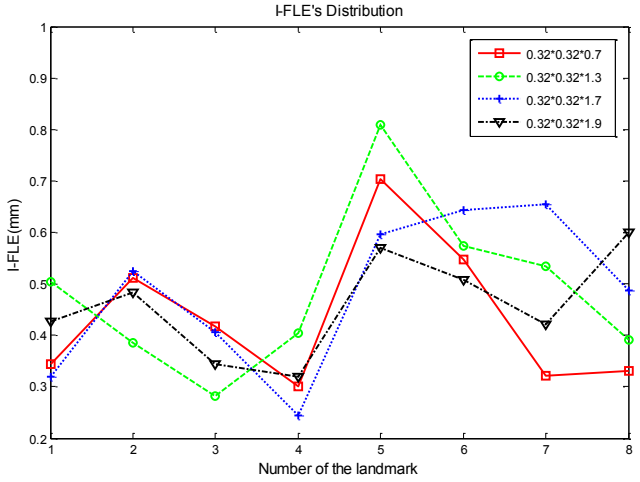

Fig. 4 I-FLE's distribution of the influence of voxel size at each landmark, x axis stands for 8 landmarks, and y axis stands for the average of I-FLE at corresponding landmarks.

Through Table II, we could see that different voxel size may cause different I-FLE. In first four groups, we change only the slice distance from 0.7mm to 1.9mm, and the average is 0.43-0.49mm, and when we transform the pixel spacing into 0.65(with the resolution 256*256 as group 5, The average come to 0.77mm, the pixel spacing influent I-FLE obviously. So for the fiducial based registration, we suggest the image resolution as high as possible.

Within the first four groups, we observe that I-FLE is at a relatively low level in group A, and the other three groups have similar averages. Figure 4 shows the I-FLE's distribution of the four groups at each landmark. Through the figure we can find that at each landmark, the order of the I-FLE is random and unpredictable. Even though in group one, the I-FLE have been the lowest only at two landmarks. This is different from our common sense. *I-FLE does not follow the slice thickness strictly, sometimes the thinner slice image may have higher I-FLE.* We consider this as influence of Over-Sampling and Under-Sampling. In Over-Sampling situation, people could not locate the landmark's position steadily, so the I-FLE may be caused from three orthogonal directions; in Under-Sampling situation, although the slice could not reflect the real position of the tip of the landmark, people can identify the landmark tip's slice steadily because of the thick slice. So the I-FLE may be caused mainly from the direction of x and y. But this is only our inference, and we still need to design experiments to prove it in our further work.

B. Affecting factors on TRE

In this part, our results shows the TRE's average is 0.53-1.06mm, STD is 0.10-0.17mm, less than most other studies. That is because we fixed the landmarks' position value in the physical domain, so that minimize the P-FLE. And the target point's position and the number of landmarks we chose are almost the best performance to minimize the influence of registration algorithm. And by minimizing all of these factors' influence, we can see the I-FLE's influence on TRE clearly. Through Table III, we find qualitatively that the average of TRE is following I-FLE. And the maximum average of TRE is almost double to the minimum. So in order to lower the TRE, lower the I-FLE is a very important factor. Thereby it is important to improve the voxel size, and let experienced doctor to locate the landmarks.

V. Conclusion

In this study, we analyze affecting factors on Image FLE(I-FLE) and design experiments to measure I-FLE. The results shows that artificial picking may cause the I-FLE average from 0.43 ± 0.14mm to 0.74 ± 0.26mm, and the voxel size may shift from 0.43 ± 0.14mm to 0.77 ± 0.23 mm in our study. The subjective picking error can be reduced by improving the picking person's experience. And we strongly recommend using smallest pixel spacing images for the registration. As for the selection of slice thickness, we find that there is the situation that the thinner slice group of the image getting a higher I-FLE. For this non-common-sense situation, we infer that it may be caused by Over-Sampling and Under-Sampling.

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