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A novel registration method for image-guided neurosurgery system based on stereo vision

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Abstract. This study presents a novel spatial registration method of Image-guided neurosurgery system (IGNS) based on stereo-vision. Images of the patient's head are captured by a video camera, which is calibrated and tracked by an optical tracking system. Then, a set of sparse facial data points are reconstructed from them by stereo vision in the patient space. Surface matching method is utilized to register the reconstructed sparse points and the facial surface reconstructed from preoperative images of the patient. Simulation experiments verified the feasibility of the proposed method. The proposed method it is a new low-cost and easy-to-use spatial registration method for IGNS, with good prospects for clinical application.

Keywords: Image-guided neurosurgery system, stereo vision, spatial registration, iterative closest point

1. Introduction

Image-Guided Neurosurgery Systems (IGNS) are widely used in neurosurgery and have been shown to improve surgical visualization and navigation as well as reduce the postoperative tumor residual [1-4].

Spatial registration is the procedure of determining a spatial transformation in image space and patient space, which is the key technology in the IGNS. Currently, IGNS usually uses point-matching registration method, and the points can be bone mounted screws, skin adhesive markers or anatomical landmarks [5-7]. In point-matching registration, at least three non-colinear points are localized in both the image space and the patient space, and a spatial transformation is calculated by matching the corresponding points. However, a pre-operative preparation step is needed for point matching based on skin markers, which includes planning and adhering the markers and CT/MRI scanning after attaching the skin markers. It is time-consuming, makes the patient uncomfortable, and the skin

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markers might slip on the skin or even fall off, which certainly affects the registration accuracy. In addition, a dedicated CT/MRI scanning has to be done after attaching the markers, which means additional cost and even radiation exposure for the patient.

Another approach is to utilize the facial structure for image-to-patient registration using laser range scanners (LRS) [8-12]. In surface registration there are two large sets of points representing the same anatomical structure in the patient space and the image space. Using a surface-matching algorithm, a transformation between the two point sets, which is also the transformation between the two spaces, could be calculated. This method has many problems in robustness and accuracy [13]. Therefore, LRS based surface matching approach is not commonly used in clinic.

In addition, Jiann-Der Lee [14] presented a new method which implemented the spatial registration based on the facial feature, and this system consisted of two stereo vision cameras and one image captured camera. So far, this method is not suitable for clinical applications.

In this paper, we present a new spatial registration method of IGNS based on video images processing. A calibrated camera is utilized to capture the images of the entire head. Meanwhile, it can be tracked by an optical tracking system. Then, a set of sparse facial points are reconstructed from video images by stereo vision in the patient space. We used Iterative Closest Point (ICP) to register the sparse points in the patient space and the facial surface reconstructed from CT/MRI images of patient. The framework of the proposed registration method and the methodology are described in Section 2. Section 3 implements a simulation experiment and discusses the results and Section 4 concludes the paper.

2. Materials and methods

2.1. Flowchart

Figure 1 shows the flowchart of the proposed spatial registration method of IGNS based on video images processing. A calibrated video camera is utilized to capture a series of head images of the patient. Meanwhile, the optical tracking system is used in order to provide real-time tracking of each

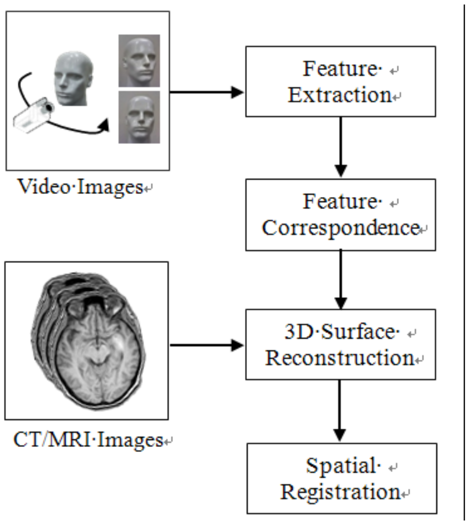

Fig. 1. Flowchart of the proposed spatial registration method.

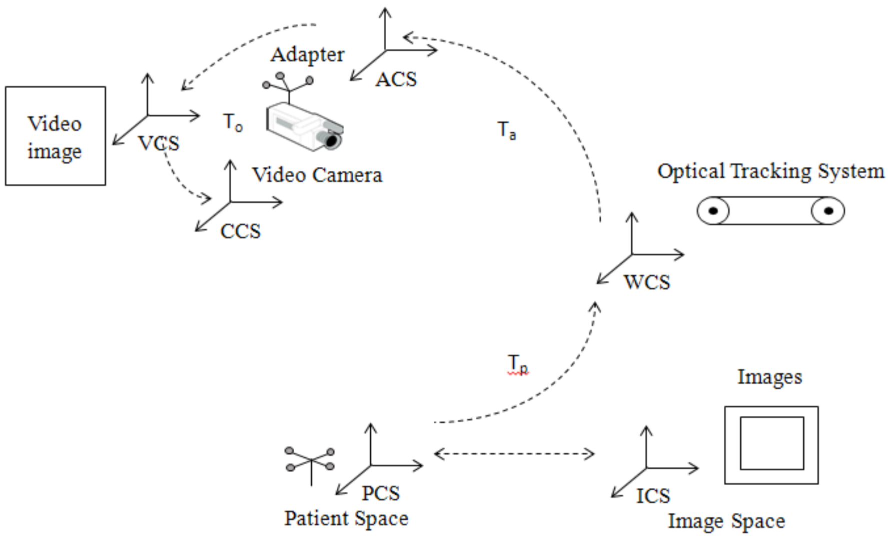

Fig. 2. Transformation between coordinates.

video frame to calculate the intrinsic and extrinsic parameters. After the images are captured, we detect the feature points using Speeded Up Robust Features (SURF) [15] on all images, and find their corresponding points on every two adjacent images by comparing the distance of the closest neighbor to that of the second-closest neighbor under the epipolar constraint. The spatial position of each pair of corresponding points can be estimated by stereo vision. Meanwhile, a facial data set is also extracted from preoperative images. Finally, the ICP is used to calculate a transformation from the image space to the patient space for the image-to-patient registration.

2.2. Coordinate transformation

In the proposed method, there are five coordinate systems. They are the coordinate of a video image (VCS), the coordinate of a video camera (CCS), the coordinate of an adapter (ACS) which is fixed on the video camera, the coordinate of the optical tracking system (WCS), and the coordinate of the patient space (PCS). Figure 2 shows the transformation between these coordinates. The reference frame is rigidly attached to the patient's head to establish the patient coordinate system (PCS). An adapter, which consists of 3 reflective spheres tracked by the optical tracking system, is fixed on the camera to define a camera coordinate system (CCS). In ACS, the intrinsic parameter (T_i) and the extrinsic parameter (T_o) can be obtained in calibration. In the procedure of image capturing, T_i and T_o both keep invariant. The transformations from WCS to ACS (T_a) and from WCS to PCS (T_p) can be achieved from that the adapter and the reference are tracked by the optical tracking system. Therefore, the extrinsic parameter of each image can be calculated by T_p, T_a and T_o.

2.3. Sparse facial data sets reconstruction

In this method, two surface data point sets are needed. One is extracted from the CT/MRI images of the patient, and the other is reconstructed from the patient space by stereo vision. To reconstruct the patient space facial point cloud, feature points are detected by SURF on all images captured by the video camera. To find their corresponding points on every two adjacent images by comparing the distance of the closest neighbor to that of the second-closest neighbor under the epipolar constraint. Then, the sparse physical space point of each pair of corresponding points can be estimated by stereo vision.

Wrong correspondences are unavoidable, and we eliminate them by epipolar constraint. According to the principle of pinhole imaging model, if p and $p^{'}$ in two different images are the projection of the same point P in the world coordinate system, their relationship is as below:

$$p^T F p' = 0 \tag{1}$$

Where the matrix F is called fundamental matrix, and it can readily be computed from intrinsic and extrinsic parameters. So, according to Eq. (1), if p and $p^{'}$ are a pair of correspondence points, the point $p^{'}$ must lie on the epipolar line associated with the point p. After that, the patient space point P can readily be estimated.

2.4. Spatial registration

After the patient space point data is reconstructed, ICP is utilized to match the two point sets. Before surface matching, a coarse registration is performed. The coarse registration error is used to remove the spatial points which are high error, and it can improve the registration accuracy. Finally, ICP algorithm is used to register image space data set and physical space data set.

3. Experiment and results

To verify the feasibility of the proposed method, we design an experiment. An entire head point cloud with texture was obtained using LRS. We simulated the procedure of capturing the images. A series of images were generated using the perspective projection theory at different angles, which comprises ±15°, ±30°, ±45°, ±60°, and ±90°. Meanwhile, the intrinsic and extrinsic parameters of each image used to generate the image were preserved. Figure 3 shows the head point cloud and several projection images.

Then, with a rotation and translation transformation, a new point cloud is generated as data set of image space.

After obtaining the projection images and the point cloud in the image space, we use a four-step registration algorithm to execute the image-to-patient registration.

In the first step, the feature points are extracted from the projection images. We use SURF algorithm to do the feature extraction. Figure 4 shows the feature points extracted by using SURF algorithm. The reason that we use SURF algorithm is that it is a scale- and rotation-invariant, repeatable, distinctive

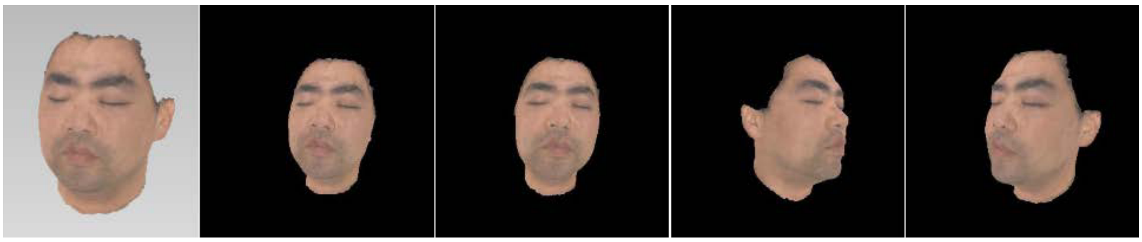

Fig. 3. Head point cloud and several projection images.

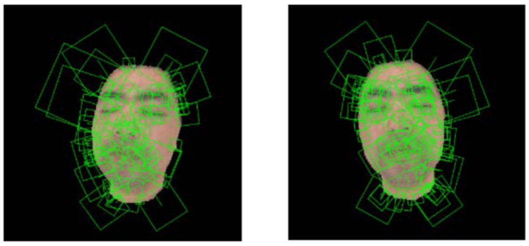

Fig. 4. Feature extraction using SURF.

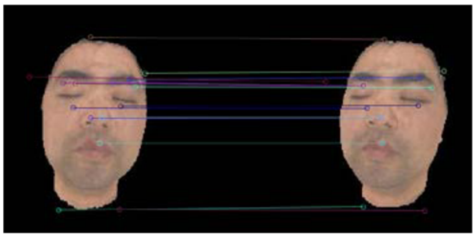

Fig. 5. Correspondence points.

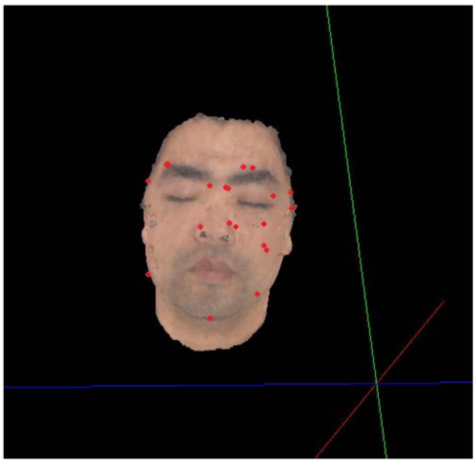

Fig. 6. Registration result: Red points are spatial points in the patient space.

and robust.

In the second step, we find the correspondence points on every two adjacent images by comparing the distance of the closest neighbor to that of the second-closest neighbor. And then, wrong matches are removed by epipolar constraint. Figure 5 shows the results of correspondence points.

In the third step, the spatial points in the patient space are reconstructed by stereo vision. We use an initial registration to compute a transformation as the starting point for the fine registration. Then, we utilized the initial registration error to remove the outliers. After finishing the initial coarse registration, we transformed the spatial points into the image space and then set a threshold value which is twice the initial registration error. For each point, if the distance to its nearest neighbor in the point cloud from the image space is larger than the threshold, it is treated as an outlier and removed.

In the last step, the ICP algorithm is used to perform the patient-to-image registration between the sparse spatial point set in the patient space and the point set in the image space. Figure 6 shows the registration result. We calculated the target registration error (TRE) of four points to evaluate the accuracy of registration. TRE was defined as

$$TRE = T(p) - q \tag{2}$$

Where T is a rigid transformation from the patient space to the image space, and p and q denote the i-th marker point in the patient space and the image space, respectively. The TRE is used to reflect the registration accuracy at an arbitrary position in the two spaces. Table 1 shows the TREs of seven targets. The average TRE is 2.71 mm.

Table 1

The TREs of seven targets

	Target 1	Target 2	Target 3	Target 4	Target 5	Target 6	Target 7	Average
TRE	1.59	2.19	2.85	3.62	2.78	3.16	2.80	2.71

Table 2

The SREs of five different data sets registration

	1	2	3	4	5	Average
SRE	3.24	4.51	2.36	3.62	4.14	3.57

In point cloud surface-matching, the surface registration error (SRE) is usually used to reflect whether two surfaces are accurately matched. The SRE is the average distance of the two surfaces and is defined as

$$SRE = \sqrt{\sum_{i=1}^{N} \frac{|T(p)-q|^2}{N}} \quad (3)$$

Where N is the number of point pairs after registration, p denotes the i-th point of the point cloud from the patient space, and q is its nearest neighbor in the point cloud from the image space after registration. Table 2 shows the SREs of five different data sets registration. The average SRE is 3.57 mm.

4. Conclusion

In this study, we propose a new surface-matching method for spatial registration of IGNS using 3D reconstruction based on video image processing. Initial simulation experiment showed the feasibility of this method. In future work, the entire head dense surface data will be reconstructed and registered with the image space. And then we will test the method on real person an in clinical experiments in future.

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References

[1] G. Anslandt, S. Behari, et al., Neuronavigation: Concept, techniques and applications, Neurology India **50** (2002), 244-255.
[2] F.A. Jolesz, Image-guided procedures and the operating room of the future, Radiology **204** (1997), 601-612.
[3] C. Nimsky, O. Ganslandt, et al., Intraoperative compensation for brain shift, Surgical Neurology **56** (2001), 357-364.

[4] M.M. Wang and Z.J. Song, Classification and analysis of the errors in neuronavigation, Neurosurgery **68** (2011), 1131-1143.
[5] G. Eggers, J, Muhling and R. Marmulla, Image-to-patient registration techniques in head surgery, International Journal of Oral and Maxillofacial Surgery **35** (2006), 1081-1095.
[6] H. Dang, Y. Otake, S. Schafer, et al., Robust methods for automatic image-to-world registration in cone-beam CT interventional guidance, Medical Physics **39** (2012), 6484-6498.
[7] A.I. Omara, M.N. Wang, Y.F. Fan and Z.J. Song, Anatomical landmarks for point-matching registration in image-guided neurosurgery, The International Journal of Medical Robotics and Computer Assisted Surgery **10** (2014), 55-64.
[8] P.J. Besl and N.D. McKay, A method for registration of 3D shapes, IEEE Transaction on Pattern Analysis and Machine Intelligence **14** (1992), 239-256.
[9] J. Schlaier, J. Warnat and A. Brawanski, Registration accuracy and practicability of laser-directed surface matching, Computer Aided Surgery **7** (2002), 284-290.
[10] M.I. Miga, T.K. Sinha, D.M. Cash, et al., Cortical surface registration for image-guided neurosurgery using laser-range scanning, IEEE Transactions on Medical Imaging **22** (2003), 973-985.
[11] Y.F. Fan, D.S. Jiang, M.N. Wang and Z.J. Song, A new markerless patient-to-image registration method using a portable 3D scanner, Medical Physics **41** (2014), 101910.
[12] X.R. Chen, Z.J. Song and M.N. Wang, Automated global optimization surface-matching registration method for image-to-patient spatial registration in an image-guided neurosurgery system, Journal of Medical Imaging and Health Informatics **4** (2014), 942-947.
[13] M.N. Wang and Z.J. Song, Properties of the target registration error for surface matching in neuronavigation, Computer Aided Surgery **16** (2011), 161-169.
[14] L. Jiann-Der and H. Chung-Hsien, et al., Medical augment reality using a markerless registration framework, Expert Systems with Applications **39** (2012), 5286-5294.
[15] H. Bay, T. Tuytelarrs, et al., Speeded up robust features, European Conference on Computer Vision **1** (2006), 404-417.