A Survey on Image-Guided Surgical Robot

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Abstract- *The aim of this paper is to study various procedures and algorithms which help in Image-Guided surgery. There are many procedures that are being used to perform image-guided surgeries these days out of which the procedure of using a robust registration algorithm to reduce the impact of marker-recognition error on image-to-physical registration in the robot-assisted cranio and maxillofacial (CMF) surgery is the most promising one. Since the image-guided technology has been widely used in the CMF surgery, the surgical robot based on remote or cloud plan data has come into focus. One of the critical procedure of the image-guided surgical robot is the image-to-physical registration which has become a decisive factor of the operation result. The recognition error of the reference points is a main challenge for the registration. Hence, a new and improved method to cope with the noise in the image space was proposed. The image-to-physical registration is accomplished with the help of a group of implanted reference markers. The experimental results indicate that the proposed method is less sensitive to the number of the reference points and also the influence of recognition noise can be decreased effectively. This paper offers a collective foundational understanding of many cloud-based surgical robots.*

Keywords- Image-guided surgery, image-guided surgical robot, improved registration algorithm, medical image registration, point-based registration, surface-based registration.

I. INTRODUCTION

In the past few years, various procedures of robotic aided surgery have become popular in both the engineering and clinical fields. This has laid a solid foundation for the remote- and cloud-based surgical robot, or as image-guided surgical robot (IGSR) [1] – [3]. Generally, IGSR uses preoperative plan data as an objective guidance to control the intra-operative actions. The pre-operative plans are usually carried out by many surgical experts remotely and are stored in a cloud server. When IGSR is being applied, one of the crucial step is aligning the images from different sensors or different times [4] – [6]. The image-guide process can't be completed without fusing the pre- and intra-operative images in image- and physical-space. The result of this registration can decide the operation's effect directly, especially for the surgical operations which have a high requirement for accuracy, such as CMF surgery.

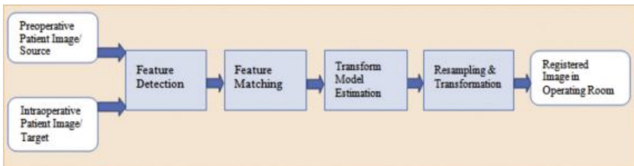


Image Registration Procedure

As it can be seen above, the goal of image registration is to find the best geometric transformation which can lead to the best overlap of two images (input and output images) from different spaces. This process usually contains two parts: The first one is finding the correspondences between the two images and then calculating the best transformation from one image to another. The main approach of connecting the two images is establishing a pair of corresponding features in the input and output images. The most widely used corresponding features for image registration in image-guided surgery usually include reference points which are preinstalled in the patient's body, and reference surfaces which are collected from corresponding regions as shown in the image.

The point-based methods were developed from the least-squares fitting algorithm [7]. With the help of the least-squares fitting algorithm, the registration of medical image and physical world via a group of implanted landmarks was completed. There has been much researches following and improving the implanted landmark-based registration. The surface-based methods were based on the ICP algorithm [8], followed by many studies in medical image and clinical areas. Certainly, there are also some studies focusing on the comparison and combination of the two kinds of methods. Like the one in which some experts compared the accuracy of the point- and surface-based registrations in image-guided neurosurgery. Also some other experts from other places proposed improvement methods respectively, combining the information of both points and surfaces. According to our surveys, the implanted-landmark-based registration [9] is more stable in clinical practice, since the surface information that can be collected during the operation is limited and easily deformed.

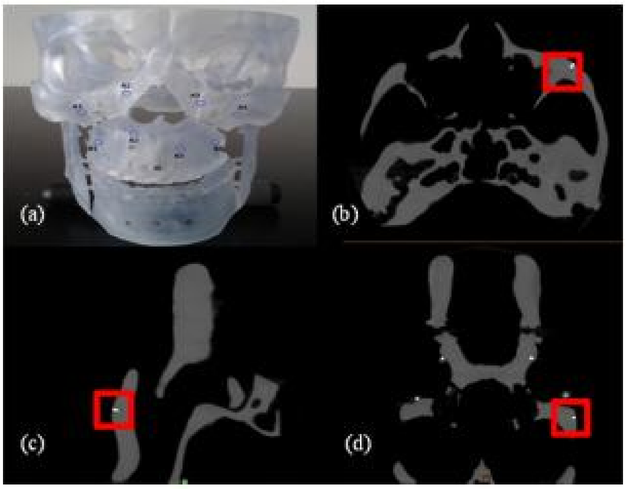
II. PROCEDURE OF THE IMPROVED ALGORITHM

A. REFERENCE POINTS IN IMAGE-SPACE

For the point-based registration, the number of the reference points is limited, so we need not do the similarity measure or iterative searching. The least-square fitting algorithm is the most used method for the point-based registrations. The registration for image-guided CFM surgery is a kind of rigid transformation in three dimensions, which can be expressed as, [xq,yq,zq,1] = [R T][0 1] [xp,yp,zp,1] where q(xq, yq,zq) and p(xp, yp,zp) are the coordinate values of the reference points in two spaces, where R = [R11, R21, R31][R12, R22, R32][R13, R23, R33] and T = [tx, ty, tz] T are the rotation matrix and translation vector.

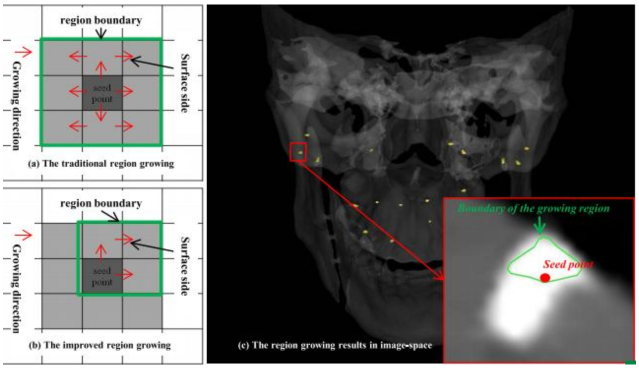
B. FEATURES/IMAGE-SPACE REGISTRATION

The point-based registration needs to implant some titanium nails or other markers into the patient's body before taking the CT scan. Generally, the markers have a quite different X-ray transmittance with the surrounding tissue, so that they can be distinguished easily from the CT images. Displays of the landmarks in CT images are as shown in the figure below.



Landmarks in Image-space and Physical-space.

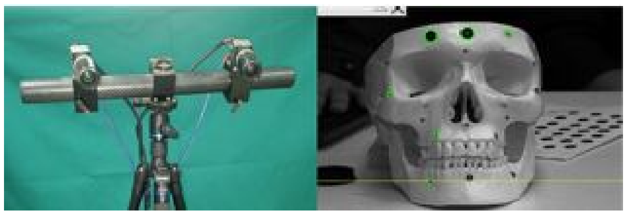
Firstly, we need to generate the fuzzy point set by choosing a group of seed points manually from the fiducial markers. Next, a group of potential points will be found via a seeded region growing algorithm [10]. The seeded region growing algorithm is a classical method of image segmentation, and the main idea is to control the growth of the target region by judging the similarity of the pixels outside and inside the region contour. The fuzzy model of reference points in the image-space is a set of S which is grown using the measure $\delta(z)$. The segmentation results of the landmarks are shown in the figure given below.



Recognition of Reference points in image-space.

C. PHYSICAL SPACE REGISTRATION

Surgical navigation is a technology that locates and tracks the instruments or anatomical structures via binocular stereo cameras. Most of the present commercially available image-guided navigation systems are based on infrared. They must rely on a probe which is equipped with infrared reflective markers to complete the localization of the target. To improve this situation, we established a surgical navigation system based on gray images and 3D digital image correlation algorithm, (3D-DIC) [11] [12]. According to the experimental results, there is no significant difference between the gray-based and infrared-based cameras on the recognition accuracy (both of them can reach the level of sub-millimeter). However, the gray-based navigation method can decrease the indirect errors produced by the probes. Landmarks acquired by the 3D-DIC system is shown in the figure below.



Landmarks of Physical-space captured by the 3D-DIC navigation System.

D. PRICNIPLE OF THE IMPROVED ALGORITHM

By Defining the reference point set in the physical-space as {qi}, and the reference point set in the image-space as {pi}, then, the procedure of the improved algorithm is as follows:

(i) Fuzzify{pi} and get a fuzzy model {Si}, where Si is a point set growing from pi;
(ii) Calculate the center points of each Si in {Si}, which were defined as cSi, and get the set of center points {cSi};
(iii) Replace the {pi} in the traditional method with {cSi}, take {cSi} and {pi} as the inputs of the least-squares fitting algorithm, and calculate the initial transfer matrix which is defined as RT0 = [R0, T0];
(iv) Transfer {Si} to M0 = {S 0 i |S 0 i = R0Si + T0} using [R0, T0], and take it as the initial input of the iterative calculation;
(v) At last, find out the most corresponding point set to {qi} from M0 via iterative calculation, then calculate the transformation matrix from {q 00 i } to {qi} via the least-squares fitting, define it as RTiter = [Riter, Titer];

Finally, the transformation matrix from the image-space to the physical-space can be calculated by RT = RT0 · RTiter.

The improvement of this method is that in addition to the distance factor, a geometry feature is introduced as a determining factor of the correlation judgment.

III. EXPERIMENTAL DISCUSSIONS

The most referred factor which can influence the registration accuracy of the point-based methods is the number of the reference points. So an experiment was designed to study the sensitivity of the improved method to the number of reference points. According to the experimental results, the improved algorithm is insensitive to the number of the reference points, and can suppress the influence of the noise effectively. The core of the improved method is fuzzifying the reference points in the image-space. This is because the reference points in the image-space are more susceptible to the recognition errors, and there is no good condition for region growing in the image of physical-space. The reference point set in the physical-space were intended to be the standard, and was used to search the corresponding points from the fuzzy reference points in the image-space. At present, the point-based registration is the most reliable and practical approach for clinical application. It usually causes some trouble because of its invasiveness. The optimal way for image-to-physical registration in MFC surgery is using the anatomical markers which are easy to be identified, such as the nasal spine, the glabella point, the dental cusps, and so on. For the anatomical-landmark-based method, it is difficult to recognize the landmarks automatically, both for the CT images and the navigation images. A viable approach is identifying the anatomical markers manually for the pro-operative images, and via probe for the intra-operative images. However, the traditional registration algorithms are usually unreliable to deal with the anatomical markers because of the noise.

IV. CONCLUSION

In this paper, we cover many methods used to perform image-guided surgeries, particularly the Image-guided CMF surgery. Aligning the pre-operative image and the intra-operative image is a critical procedure for the robot-assisted CMF operation, which has a high requirement for accuracy. A method of fuzzifying reference points in the image-space is proposed to reduce the accuracy loss caused by noise. An improved algorithm combined by the least-squares fitting and iterative algorithm is established to complete the registration of the fuzzy and asymmetric data. The results of the experiments demonstrate that the improved algorithm can suppress the influence of the noise effectively, and it is insensitive to the number of the reference points. The accuracy and robustness of the image registration algorithm is enhanced. Further, we can send all these data for Big-Data analysis.

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