論文の内容の要旨

Abstract of Dissertation

Image-guided catheter intervention using an electromagnetic tracking system and a freehand three-dimensional ultrasound

（電磁気式トラッキングシステムとフリーハンド３次元超音波を用いる画像誘導カテーテル治療支援システム）

欒　寛

Catheter intervention for carotid and cerebrovascular diseases is rapidly developing treatment modality. A catheterization procedure involves the insertion of a flexible thin plastic catheter, into a blood vessel to provide an effective method of drawing blood or delivering medications and nutrients into a patient's blood stream. The intervention is directed to a method and apparatus for catheter navigation in 3D vascular tree exposures. The position of the catheter is detected and mixed into the 3D image of the pre-operatively exposed vascular tree reconstructed in a navigation computer.

In the catheter intervention, fluoroscopy may be used to confirm the position of the catheter and to manoeuvre it to the desired artery. Injection of contrast agent is used to visualize arteries. But fluoroscopy has potentially harmful ionization radiation. It also cannot provide depth information. Although the image shows the geometry of artery, it still cannot interpret position and pose in space. In addition, the injected contrast agent will disappear instantly, which causes repetition of injection. In whole procedure, patient and surgeon suffer from large dose radiation. The large dose contrast agent also tends to cause the patient allergy.

To solve the above problems, we considered using other safe methods to guide the catheter intervention. The intra-operative interventional imaging modalities include CT, fluoroscopy, MRI and US. CT provide high quality 3D image, however, it causes ionizing radiation. Non-real-time imaging also limits its application. Fluoroscopy and contrast agent are applied in clinic, their problems come from ionizing radiations, no depth information and allergy, although they can provide high quality image in real time. MRI is another modality providing 3D imaging. The main drawbacks are high cost of maintains and MR-compatible tools are need in operative region. By contrast, US is particularly well suited for intra-operative 3D anatomic visualization because of its safety, low cost and short acquisition time. An ultrasound exam is a safe diagnostic procedure that uses very-high-frequency sound waves to produce an image of many of the internal structures of the body. The sound waves prevent patients and surgeons from ionizing radiations. The short acquisition time makes US intra-operative imaging possible. Although US have drawbacks like poor image quality and narrow imaging region, the poor image quality can be improved by image processing algorithm. The narrow imaging region can be treated by reconstructing 2D images into 3D volume.

In order to realize US image-guided catheter intervention, a new image-guided catheter navigation system based on a three-dimensional freehand ultrasound and an electromagnetic tracking system is proposed. The method employs the freehand ultrasound imaging system to reconstruct two-dimension Doppler ultrasound images of the vessel. The reconstructed three dimension volume is augmented by segmentation of vessel cross section and registration of the catheter path obtained from a tracked catheter passing the vasculature.

In order to reconstruct two-dimension ultrasound image of vessel, a simple, automatic and robust calibration was developed for the freehand ultrasound imaging system without a phantom. A needle equipped with an electromagnetic tracking sensor is employed. The needle is moved in the vicinity of an ultrasound imaging plane taken by a fixed ultrasound probe also equipped with an electromagnetic EM tracking sensor. The ultrasound images, tracker's and needle tip's physical coordinates are recorded simultaneously. For each ultrasound image, the needle tip is recognized and the image coordinates are identified automatically. A point registration between the needle tip image and physical coordinates is performed to estimate the calibration matrix. A RANSAC algorithm is applied to minimize the registration error. A serial of experiments were performed to evaluate the performance of the proposed method. In all cases of our calibration process, the needle tip can be accurately identified in US images. There is 85% of the located needle tip drop a 1mm field close to the imaging plane. An accurate transformation matrix can be obtained using a tip data set of 20 frames. A calibration process with 20 data frames takes less than 10 minutes. This time is shorter than most previous method and a bit longer than some method using wall phantom. The FREs in different imaging depths are measured. The average FRE is 1.2mm, which is similar to other method using EM tracking system. The results of each imaging depth show that there is no significant difference between different imaging depths. Using the same data, the performance of RANSAC is compared with the conventional SVD. SVD is sensitive to these significant noisy points, but RANSAC can identify significant noisy point and produce an accurate result. The TRE of the US imaging system is evaluated by the tracked needle tip. The results show that the proposed method achieves similar accuracy to the previous manual method. A phantom with balls is used to evaluate the navigation accuracy of the proposed method. These results prove that, in contrast to previous methods, this is a simple, automatic and robust method which can achieve similar accuracy and efficient. The accuracy of the proposed method satisfies the need of the catheter navigation system.

For the augmentation of the vessel volume obtained from the free-hand system, a novel segmentation and reconstruction method based on catheter path was proposed. Two-dimension segmentation is performed on the vessel cross sections using a modified region growing algorithm combining grayscale distribution, shape feature and area regularity criterions. The segmented cross sections are interpolated into the new center line registered by the paths of catheters, which are typically placed in vessels. Based on the interpolated cross sections, a new vessel volume is reconstructed and rendered for navigation. The proposed method was evaluated by the data from a vessel phantom and in vivo. The segmentation results of in vitro trail show that the proposed 2D segmentation method can extract an accurate contour of the bifurcation than conventional region growing only depending on intensity distribution and shape features. During the catheterization, the bifurcation presents the node of the vessel network, which determines the position and orientation of the catheter tip moving. It is important to produce an accurate contour on the cross sections of bifurcation, because the segmented contour affects the reconstruction directly. With an accurate reconstructed bifurcation, surgeons can identify whether the catheter tip enters the target vessel or not. In the cross section of bifurcation, the conventional region growing extracted the contour of two jointed cross sections. Based on the incorrect contour, a larger ellipse was estimated, which would produce incorrect contour information and corrupt the newly reconstructed vessel volume. By contrast, the proposed segmentation method used the area threshold to constrain the growing process and produce a correct contour in each cross section. The diameter evaluation of the entire vessel proved the proposed segmentation could produce an accurate estimate of dimension. The segmentation results of in vivo trail show that the proposed segmentation based on intensity distribution of Doppler images could extract an accurate contour of the vessel from the artifacts caused by heart and tissue motion. The clear contours of vessel are helpful to realize high quality reconstruction. The segmented vessel contours are reconstructed based on the center line registered by catheter path. From the in vitro and in vivo results, cooperated with the segmentation of cross section, a high contrast vessel volume is obtained, which provides a good visualization of the scanned vessel. The catheter path is acquired by EM tracking system, which usually is affected by the close metallic objects. However, the catheter path presents the dimension and geometry of the vessel during catheterization. Based on the catheter path, the reconstructed vessel is closer to the vessel that the catheter passes. The tracked catheter tip and the reconstructed vessel augmented by catheter path provide more true spatial position relation, which helps the surgeon understand the position of the catheter tip in the vessel during catheter navigation.

The accuracy of the proposed catheter navigation system was verified by the catheter path obtained from the entire vessel. The distances between the registered center line and path line of the entire vessel are computed. The registration accuracy yields an average value of 1.7mm and the errors of the trunk and bifurcation where the catheter tip moves drop below 2mm. These results suggest the technique satisfies the accuracy of 3mm required by the US image-guided catheter intervention. US-based navigation does not require patient registration. Both the US images and catheter path can be obtained intra-operatively. Thus, this system is less susceptible to user- and procedure-dependent error sources associated with patient registration. The overall clinical accuracy of an US-based system is therefore expected to lie closer in value to the overall accuracy (laboratory test) than is the case with conventional pre-operative image-based systems. Acquisition, reconstruction, segmentation and augmentation of the US volume finish in 20 minutes. The time also can be shortened by introducing some accelerative algorithms. The utilization of the catheter navigation will not prolong the surgery time. These results prove that the developed US image-guided catheter navigation system is applicable to catheter intervention.