A Navigation System for Minimally Invasive Abdominal Intervention Surgery Robot

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***Abstract*—This paper aims to present a navigation system design for image guided minimal abdominal surgery robot that could compensate for the patient respiratory movement. Currently computer-aided surgery navigation technology has been broadly applied to such fields as orthopedics and neurosurgery, but in the field of interventional surgery, it is still rarely reported. As described in this paper, we introduced a surgery navigation system which can be applied to the interstitial treatment. Multiply technique are used to immobilizing the patient body, making the route plan and tracking the surgery instrument, real-time ultrasound feedback and image registration is also used to enhance the precision of instrument positioning. The goal of this research is to develop a computer-aided surgery navigation system in minimally invasive surgery, and provides solutions to urgent requirements in optical precision positioning, planning and navigation in abdominal surgeries. So that it can fine supporting completion of the surgery operation, improve accuracy and efficiency of the traditional surgical methods, and reduce the suffering of patients from pain.**

***Keywords*—surgery robot, surgery navigation, minimally invasive surgery**

I. INTRODUCTION

In recent years, under the guidance of the medical image, minimally invasive surgery has become a hot interdisciplinary topic including interventional radiology, imaging guided interstitial treatment, and high-intensity focused internal radiation therapy. However, all these treatments need the assistance from imaging devices for tumor positioning, surgery planning and surgery navigation. A high-precision computer-aided navigation system is essential for minimal invasive surgery. With the development of medical image analysis and computer-aided diagnosis technology, 3D reconstructions and optical positioning based surgery navigation technology has become a hot research field in minimally invasive surgery.

A main challenge of surgery navigation is to registration and localization of the instrument's position so that they could be visualized in virtual space with CT/MRI reconstructed 3D tumors, organs and large vessels [1]. Currently, surgery navigation systems [2] use different methods for instrument tracking and most of them assume the rigidity of patient anatomic structures. As a consequence, surgery navigation system has been majorly developed for hard tissue surgery such as neurosurgery and orthopedics surgery. But in the field of abdominal interventional surgery, it is still rarely reported. Navigation in abdominal surgery is more complex because organs move and undergo deformation due to respiratory and cardiac function. So the major challenge of minimally invasive abdominal surgery is the uncertainty about the exact location of the tumor and associated organs, including large vessels. As described in this paper, we introduced a computer-aided surgical navigation system which can be applied to the abdominal surgery. Although it could not completely overcome the respiratory issues and the elastic deformation of abdomen, it could still play an important role in tumor positioning, surgery planning and real-time surgery navigation based on 3D reconstruction and visualization of abdominal organs.

The rest of the paper is organized as follows. Section II describes the architecture of the system and each part of the system. Section III describes the surgery from a clinical workflow aspect. And the last section is devoted to the conclusion and discuss.

II. SYSTEM DESIGN

The design goal of the navigation system is minimize the deformation of human body during the whole surgery procedure and make up for the necessary deformation due to respiration and heart function. The system consists of four subsystems: the patient immobilization system, the surgery planning system, the virtual navigation system and intraoperative image monitoring system.

A. The Patient Immobilization System

The design goal of the system is to minimize the deformation of human body especially the abdominal organs. As shown in figure 1, the tumor in patient abdomen is always moving due to the rhythmic breath and heart function, and the displacement amount of a tumor could be as much as 2 to 4 center meters (Figure 1). In such a bad condition, most navigation system could not be applied to abdominal intervention surgeries. Two methods are used to immobilize the patient body.

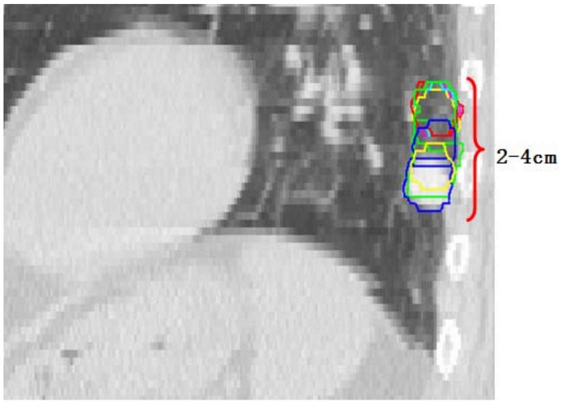

Figure 1 Patient Abdominal Movement

Firstly, a vacuum mattress is provided in which the patient body could be hold stable during the whole surgery procedure, including the preoperative CT/MRI image acquire, tumor identification, surgery route plan and the surgery operation. In such a circumstance, the major parts of the patient are relative static relative to the reference coordination system which will be used in the optical tracking system.

Secondly, a respiration monitoring system (Figure 2) is used in the surgery procedure, and the patient respiration is modeled and monitored by this system, and it could measure how much air had been inhaled or exhaled by the patient. The exact respiration condition when the patient CT/MRI image is acquired is recorded by the system, and this data is used to guide the puncture operation latterly. By this means, the respiratory movement is compensated by the system, which leads to a safe surgery operation that precision of navigation could be enhanced.

Figure 2 Respiration Monitoring System

B. The Surgery Visulization System

The surgery visualization system is the most important module in a surgery navigation system. GPU-accelerated algorithms are used for full patient body visualization and anatomical structure reconstruction.

Firstly, GPU Ray-Casting based direct volume rendering [4] is used to render the full patient body in surgery planning and navigation in real-time (Figure 3). This could provide a general view of the whole patient body, including critical organs and large vessels. During this algorithm, the DICOM 3.0 compatible 3D patient image (CT/MRI) is stored in the memory of the graphics card as 3D texture. A mapping table from the value in 3D-texture to the result color and opacity is stored into a 1-D texture in graphics card. Then for every frame during the rendering, a special texture which has the same size as the viewport is generated. That texture can be considered as a picture stuck on the viewport. Through every pixel of the texture, the ray from view point reaches the bounding box of the dataset and casts through the box. The position the ray reaches the box and the length the ray casting through also needed. And with the special texture, the pixel value are calculated by looking for the value in the 3-D texture for a sampling point, and mapping it to color and opacity value according to the 1-D texture. The colors and opacities will be blended together so as to be presented to the screen as the final color of that pixel.

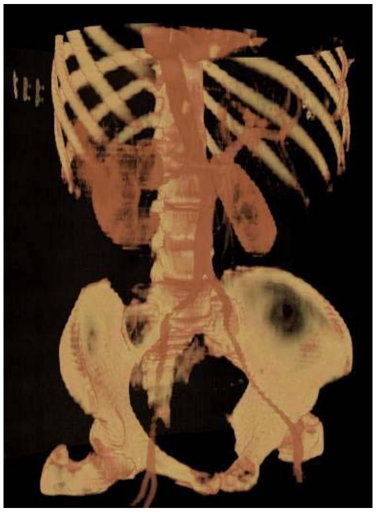

Figure 3 GPU Ray-Casting Volume Rendering

Secondly, GPU-accelerated Marching Tetrahedral (MT) algorithm [5] is used in the visualization system to generate isosurface based models, especially for the patient bone. The algorithm is implemented in DirectX10 GPU Shaders. To prepare the data for processing, a 3D-texture in graphic memory is generated to store the 3D CT/MRI data. And then, the entire region is divided into a lot of tiles and each tile is divided into six tetrahedrons. In the vertex shader stage of the GPU processing pipeline, the 3D-texture is sampled for each vertex, and the difference value between the sampling value and the specified value of the isosurface is calculated. In the geometry shader stage, a judgment will be done upon the difference value from upper stream for each vertex of the tetrahedron. If the difference value is positive, the vertex is inside the isosuface, otherwise the vertex is outside. The intersecting points between the tetrahedron and the isosurface are calculated and used to construct the 3D mesh models as shown in figure 4.

Figure 4 MT Algorithm Generated Mesh Model

C. The Surgery Planning System

In the surgery planning system, the surgeon plans a surgery route on the preoperative CT/MRI images and then superimposes the surgery route onto the patient's anatomy [3].

Firstly, important anatomical structure (Figure 5) is identified by the surgeon, including the tumor and the risk area of the body. Automatic segmentation and manual sketch could be used to reconstruct the 3D model of the tumor and risk area, the anatomical parameter of the tumor such as the size and volume is also calculated by the system.

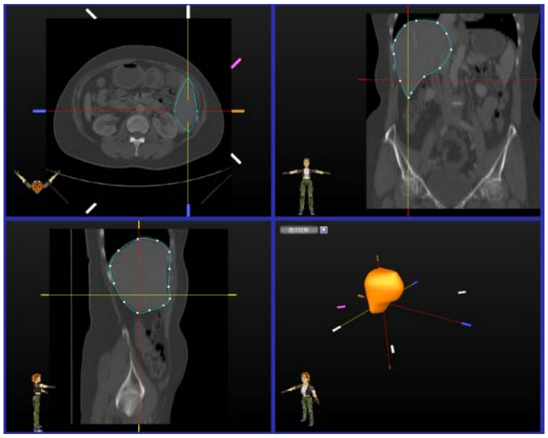

Figure 5 Anatomical Structure Identification

Then, based on the 2D CR/MRI image sections and the 3D tumor models, it's very convenient for the surgeon to make a surgery plan (Figure 6). During the surgery planning, the surgeon makes virtual surgery routes and simulates trauma field caused by these surgery instruments. The 3D trauma fields caused by these surgery routes are calculated using theoretical equations or empirical statistic methods and then be reconstructed based on marching tetrahedral isosurface extraction algorithms. Then the trauma field is rendered in three perpendicular section planes as well as in 3D virtual space along with 3D tumor model and full body model. The surgeon needs to make sure the surgery routes do not intersection with risk area and large vessels, and the trauma field could cover the whole tumor region. If one surgery route could not make this goal, more surgery route needs to be planned to cure the tumor.

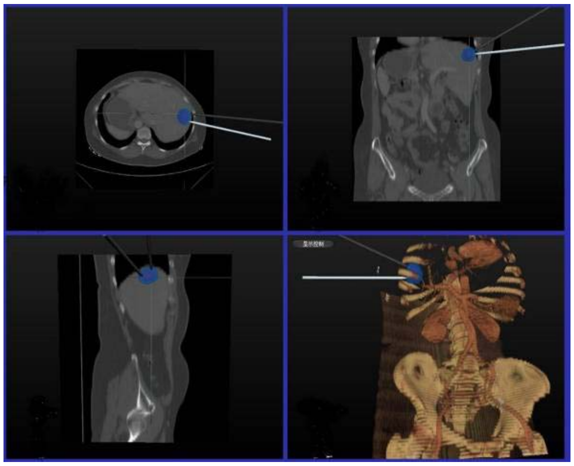

Figure 6 Surgery Planning

D. The Virtual Navigation System

The virtual navigation system is used to tracking and visualizes the surgery instrument using the NDI Polaris optical device (Figure 7) in the operation room. During the surgery, passive reflecting spheres are fixed with a known geometry on the surgery instrument, which is further captured by the optical device. Then, an image-to-patient registration is taken in order to visualize surgery instruments in the CT images of the patient,. In addition to the tracking markers, which are used as reference to define the coordinate system of the tracking system, we also placed CT/MRI markers in a known geometry on the vacuum mattress and patient body. During image acquisition, all CT/MRI markers must be inside the field of view. During the registration procedure, an integrated marker detection algorithm in the navigation software finds the CT/MRI markers in the image and determines the marker centers with sub-voxel accuracy. At least four pairs of CT/MRI markers are used to derive the transform matrix from patient coordinate system to image coordinate system. After the initial matrix is calculated, the transform error of each coordinates pair and the root mean square error are displayed to the surgeon, and the surgeon could adjust the marker parameter with largest error and refine the registration result.

Figure 7 NDI Polaris Vicra Optical Device

After the registration step, the relation between the images and the patient are fixed. And the surgery instrument (Figure 8) location could be tracked and rendered in the navigation software. However, the patient body may be slightly different from the visualized scene due to respiratory and hearth movement, so that the patient immobilization system is used here to monitor the patient breath condition. The surgeon will direct the patient to hold a breath similar to the condition when the CT/MRI image was taken, so that the deformation of the patient body could be minimized to an acceptable quantity.

Figure 8 Surgery Instrument

E. *Intraoperative Image Monitoring System*

Once the needle has been intervened to patient body, the relative position is rendered in the navigation software. However, the actual location of the instrument could be slightly different from the optical tracked position. Therefore, a real-time feedback of the instrument is necessary, which could also compensate for the patient abdomen movement. Intra-operative ultrasound image is also registered in the system [6] and rendered combining with preoperative CT/MRI images.

III. CLINICAL WORKFLOW

In this section, the full surgery process is introduced by describing the clinical workflow, from the surgery preparation to the actual insertion of the surgery instrument in a step by step way.

A. *Surgery Preparation*

Before the surgery, the patient is immobilized with the vacuum mattress which is attached to a rigid reference frame. The respiratory monitoring device is also wired by the patient to sense the breath condition of the patient, so that a real-time breath curve is gathered by the monitoring software, and the exact breath condition during the CT/MRI scan is logged by the software, this data will be used in the surgery navigation for minimize the deformation introduced by the breath. We also place the CT/MRI markers on the patient body and the rigid frame, which could be identified in the image and used in the registration of device to image space.

B. *Preoperative Image Acquire*

After the preparation, the patient is moved into the CT or MRI equipment, wiring the vacuum mattress and markers. The CT or MRI image is acquired and transferred to the PACS [7] (Picture Archive and Communication System) server using DICOM 3.0 communication protocols, which could be further retrieved by the navigation software. It is required that the breath condition of the patient should be recorded by software and the patient body should be immobilized during the scan process. And the surgeon need to make sure the CT/MRI markers is clearly visible in the acquired images, which is very important for the image registration process.

C. *Anatomical Structure Identification*

Once the CT/MRI image is acquired and sent to the PACS server. The surgeon could create a surgery in the navigation software based on the scanned image. And the surgeon could identify three type of important anatomical structure identification before the surgery, the first is the surgery targets, mostly the tumors; the second is the risk areas in the patient body, mostly is the critical organs that could result in massive hemorrhage; the last is the large vessels which should not be intersect with the surgery route and the damage field. Automatic segmentation and manual sketch is used to reconstruct the 3D model of the tumor and risk organ, the anatomical parameter of the tumor such as the size and volume is also calculated by the software.

D. *Surgery Route Plan*

Based on the 2D CT/MRI image sections and 3D anatomical structure models, the surgeon could plan the surgery route in 3D virtual space (Figure 4). The critical anatomical structures are also displayed in the scene; so that the route could be avoid intersecting with bone, large vessel or critical regions. The damage field that introduced by the surgery route could also be calculated so that the whole tumor region should be fully covered.

E. *Patient to Image Registration*

Before the surgery navigation procedure, it's necessary to establishment of a rigid relationship between two coordinate systems [8]: that by which the images were obtained and that superimposed on the surgical field. Once images have become registered to the patient, the surgeon can translate from any point on the surgical field to the same point on the images, and vice versa, using a transformation matrix dictated by the registration process.

In the context of optical tracking navigation, the registration is achieved by identifying corresponding points in the image and the optical devices. The navigation system uses the CT/MRI markers as correspondence points. The CT/MRI should be scanned fine enough to make the tiny markers easily visible in the CT/MRI images. The 3D models of human body as well as the markers are reconstructed in 3D scene, and the rough location in CT/MRI could be found by the surgeon, and then a refinement algorithm is carried out to find the exact location of each marker based on CT/MRI local attributes.

After that, the surgeon uses the registration tool to localize the marker in patient field. Four passive spheres is attached to the registration tool using a static geometry distribution, and the position of each sphere could be tracked by the optical device (Figure 5), so that the tip position of the registration tool could also be calculated.

When these point pairs are collected, a transformation matrix would be calculated so that it could transform real-world coordinates from the tracking system into the image coordinate system. This will be used in the subsequent navigation step to visualize the instrument position in relation to the CT/MRI data set.

F. *Surgery Navigation*

Once images have become registered to the patient, the surgeon can translate from any point on the surgical field to the same point on the images, and vice versa, using a transformation matrix dictated by the registration process. So the tracking system is constantly measuring the positions of the instrument and then transforms them into the coordinate system of the preoperative CT/MRI image. This allowed a 3D model of the instrument to be displayed at the position in the image that corresponded to the real-world position of the instrument in the operating room as shown in Figure 7. Meanwhile, the respiratory control system is used to monitor the patient breath so that the patient deformation is minimized when the surgery instrument puncturing into the patient body. When the surgery instrument has been inserted into the patient, the ultrasound image is also used to display for the actual relative position between the instrument and the tumor in real-time.

IV. CONCLUSION

In this paper, we have proposed an image guided surgery navigation system that could be used in the abdominal intervention surgery. The system could be used independently or be used combining with a surgery robot. The respiratory and hearth deformation is considered and compensated using the patient immobilization system, and the traditional optical tracking technology and real-time intra-operative image.

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