A Robot-Assisted System for Minimally Invasive Spine Surgery of Percutaneous Vertebroplasty Based on CT Images

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***Abstract*—This paper presents a robot-assisted system developed for spine surgery of percutaneous vertebroplasty. The system plays roles of assisting surgeon for puncture. Compared to navigation systems as well as conventional methods for percutaneous vertebroplasty, it is able to achieve better accuracy. With the help of the surgical planning system based on CT images, the surgeon could easily obtain the information of the target point, orientation, and depth of the surgical needle. Unlike other system based on vision, this robot system could achieve the target point with the desired angle without optical tracking system. A new method of coordinate transformation from the CT images to the robot is developed to cope with the orientation for the robot-assisted system.**

***Keywords*—robot-assisted surgery system, spine surgery, percutaneous vertebroplasty.**

I. INTRODUCTION

In recent years, the research and development of technology such as minimal or less invasive surgery has been carried out in various academic fields. Compared to conventional open surgery, the most important advantages of minimal or less invasive surgery are protection of sensitive parts close to the operating zone and shortening patients' recovery, especially in spine surgery. In order to achieve efficient minimally or less invasive surgery, orientation and precise surgical tool navigation is needed [1-3].

Percutaneous vertebroplasty is a new interventional technology developed recently for the treatment of vertebral metastasis, myeloma, hemangioma, and osteoporosis. Polymethyl-methacrylate (PMMA) is injected into the area needing treatment for pain relief, vertebral reinforcement and function maintenance. This kind of spine surgical operation, in general, requires long experiences and skills of surgeons since the surgical environment is very delicate and a slight mistake might cause serious results to patients. So the robot-assisted system for minimal or less invasive spine surgical system is actually needed by surgeons.

There are some reviews on the robot-assisted surgical systems [4-12]. According to these reviews, most of the medical robot-assisted surgery systems have been developed for laparoscopic operation, orthopedic operation and brain surgery. Most of the current surgical procedures at hospitals rely on surgeon's experience in open spine surgery. Some of them are based on the vision to confirm the orientation and the target point.

In this paper, we introduce a new robot-assisted spine surgery system, which is composed of a surgical planning system and a robotic system. Unlike other robot-assisted system, a new method of coordinate transformation from the CT images to the robot is developed. This system does not need an optical system; the combination of the robot and CT images is discussed in section III. In section II, the process and the problem of the percutaneous vertebroplasty are introduced. The architecture of the planning software is described in section IV. Some results are displayed in section V.

The main aims of this robot-assisted spine surgery system are:

- Image processing algorithm is integrated to help the surgeon pick out the puncture point in CT image.
- A robot system is designed to help surgeon fix the position and angle of the surgical tool under the planning system.
- A new method of coordinate transformation for orientation and combination of this system is developed.

II. REVIEW OF PERCUTANEOUS VERTEBROPLASTY IN SPINE SURGERY

A. Operation Process of Percutaneous Vertebroplasty

Fig.1 shows operation of conventional percutaneous vertebroplasty. Without any help of robotic system, the surgeon performs the operation of the spine surgery.

The process of the surgery can be described as follows. The patient was laid on his back on the X-ray bed. The shoulders of the patient, supported by a cushion, were moved downwards as far as possible, and the head was turned backward. With the help of CT machine, a series of X-ray images around the patient are scanned and analyzed, the affected vertebral body was picked out, and the puncture point was fixed. About 1%

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lidocaine was injected for local anesthesia to the cervical fascia. The surgeon maneuvered with his middle and fore fingers between the trachea and the carotid to press the anterior margin of the vertebrae, to push the carotid outward and the trachea to the other side. The angle between the puncture needle and the vertical plane of the vertebral body was between 15°-25°. The puncture needle was pushed into the vertebral body [13-14].

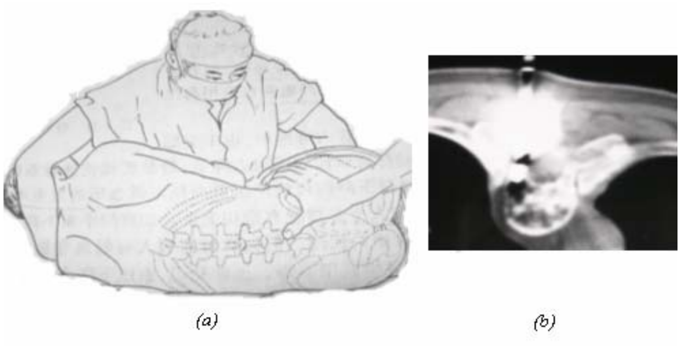

Figure 1. Conventional percutaneous vertebroplasty surgery

B. *Problem*

The most difficult thing of the percutaneous vertebroplasty surgery is the targeting the desired position to puncture on the patient's body. The main reason for incorrect placement of a puncture needle is probably because of the invisible body of the pedicle being penetrated in the intra operative operation. Generally the surgeon can not complete the puncture in one time, because he chooses the puncture point with his experiments. During the puncture, he can not see the surgical needle; the patient has to be examined in CT machine for several times, X-ray images are used to guide the puncture. Accuracy of the operation is improved to some extent by using the CT image information. However, there still exists high possibility that unintentional deviations due to tremor or slipping may occur during operations since the surgeon must conduct screwing manually. Once the surgeon finds an error operation from the CT images, he has to repeat the process described as above. These will increase pain of the patients, and exposure time from X-ray.

In this paper, we introduce a new surgical system employing the robotic system to assist the surgeon by targeting the desired position to puncture with high precision. The system can be instrumental in improving accuracy and reducing the X-ray exposure time and unintentional deviation time.

III. Phototype of the Robot-Assisted Surgical System for Spine Procedures

A. *System Architectures*

As shown in Fig.2, the robot-assisted surgery system consists of a surgical planning system, and a surgical robot system. In preoperative procedures, the patient will be tightly fixed on X-ray bed, and examined in the CT machine, X-ray images sequence will be transmitted to CT workstation. The planning system can obtain images through Ethernet with DICOM protocol. A metal mask mechanism is fixed on the edge of CT bed before, the surgical robot can be tied to it with high precision, we can recognize the mask in X-ray image, and the orientation between the surgical robot and the planning system is completed. With the help of planning computer, the surgeon determines a desired operational path of the surgical needle. Both information of the operational path and the movement of surgical area are transmitted to the controller through CAN, at last the robot conducts the targeting the desired position to puncture on the patient's body with high precision, the surgeon can easily complete the puncture.

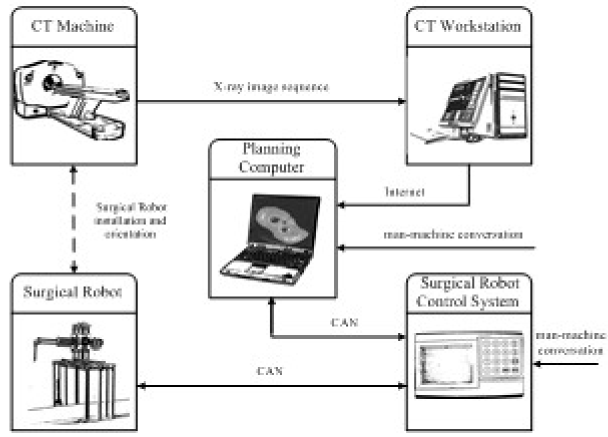

Figure 2. Architecture of a robot-assisted system.

B. *Surgical Robotic Prototype*

During the course of the percutaneous vertebroplasty surgery, a robot plays an important role of assisting surgery. We developed a surgical robot prototype. It can help the surgeon aim the puncture needle at the point with high precision. This robot is designed to operate in both passive and active mode. The prototype of the surgical robot is shown in Fig.3.

Figure 3. Surgical robot prototype.

Generally the robot prototype consists of a Cartesian type 3-DOF joints and 2-DOF rotation joints. The surgical needle can be fixed in a special mechanism, the five DOF can provide the position and the rotational angles of the surgical tool, help the surgeon to fix the puncture path with high precision. The surgeon can operate the surgical robot in active mode and passive mode. In active mode, the surgeon just picks out the puncture point on X-ray images; the robot will finish the rest work such as orientation and navigation. Contrast to active mode, passive mode can help the surgeon change the angles and position of the surgical tools as he needed. The man-machine conversation is a LCD and a series of functional buttons, which are controlled by a SOPC (System on programmable chip) [15]. The position and angle of the surgical tool is displayed on LCD in real time.

C. *Combination of the Surgical Robot and CT Image*

As to the surgery of percutaneous vertebroplasty, it doesn't need special track of the surgical tool before puncture; however the point and angle of the puncture tool require a high precision.

In this system we don't need a vision sensor to confirm orientation, a mental mask mechanism is fixed with the X-ray bed, and it can be recognized in the X-ray images with a graphics algorithm. As to CT machine, it has a coordinate of itself, the origin is in the middle of scanner, every CT image has a XYZ coordinate information in DCM file which supports DICOM protocol and is saved on CT workstation. The coordinate relation of all subsystem of the surgical system is shown in Fig.4.

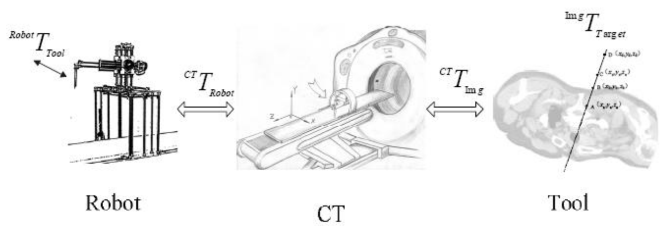

Figure 4. Coordinate relation of surgical robot prototype

How to convert a target position into the surgical robot coordinates using homogeneous transformation matrices is shown by the (1)-(4) below.

$$^{CT}T_{Tool} = {}^{CT}T_{Robot-origin} \cdot \underbrace{^{Robot-origin}T_{Robot-end}}_{Robot-Kinematics\text{-}Model} \cdot \overbrace{^{Rob-end}T_{Tool}}^{Tool-Geometry} \tag{1}$$

$$^{CT}T_{Robot-origin} = \overbrace{^{CT}T_{Img}}^{CT-DICOM-Protocol} \cdot \underbrace{^{Img}T_{mask}}_{Image-Matching-Algorithm} \cdot \overbrace{^{mask}T_{Robot-origin}}^{Robot-Mechanism\text{-}Geometry} \tag{2}$$

$$^{CT}T_{Target} = \overbrace{^{CT}T_{Img}}^{CT-DICOM-Protocol} \cdot \underbrace{^{Img}T_{Target}}_{Image-Recognising-Algorithm} \tag{3}$$

$$\Rightarrow {}^{Tool}T_{Target} = {}^{Tool}T_{CT} \cdot {}^{CT}T_{Target} \tag{4}$$

$^{CT}T_{Robot-origin}$ is the coordinate transformation from the robot origin to CT machine, this is the orientation of the robot in CT machine reference frame. $^{CT}T_{Tool}$ is the coordinate transformation from the surgical tool to CT machine. $^{Tool}T_{Target}$ is the relationship between the target point for puncture and the surgical tool.

DICOM (Digital Imaging and Communication in Medicine) is an independent, international standards development organization administered by ACR (American College of Radiology) and NEMA (National Electrical Manufacturers Association) Medical Imaging and Technology Alliance [16]. CT Workstation saves X-ray image sequence as DCM files, in the tag of the files, we can get Z coordinate of the image, and we can also get X and Y coordinate of the target from the image with image algorithm, finally the coordinates of the target on the image can be transformed to the CT. In same word, with the help of a metal mask mechanism, we can transform the coordinate relation between the surgical robot and CT.

D. *Control System*

The controller of the surgical robot is designed by us; the architecture of the controller is shown in Fig.5.

With the rapid development of the FPGA (Field Programmable Gate Array) and SOPC technology, it is possible to design a complex real time system in a single FPGA. According to the function and the special environment in hospital, a real time control system is designed. CAN-bus is adopted to transfer information between the planning computer and SOPC controller. The SOPC controller take the information into the speed and acceleration of each DOF, then it pass the information of DOF to each motor servo system. Step motor is installed on each robot DOF. We have designed step motor servo system with a core of DSP2407A [17]. A PID algorithm and is embedded in DSP to drive step motor. The motors make the surgical tool achieve the target position. At the same time the SOPC controller keeps a LCD and micro-keyboard in proper condition, the coordinates of the surgical tool can be seen on the screen, the surgeon can control the robot through the micro-keyboard.

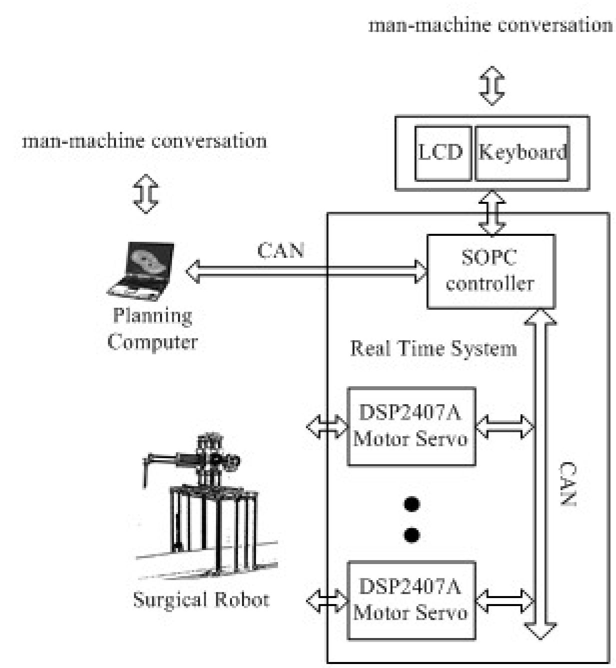

Figure 5. Architecture of robot controller.

Control loop is shown in Fig.6.

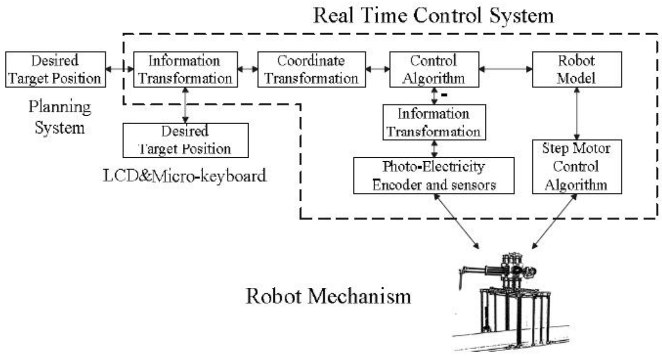

Figure 6. Control loop

IV. SOFTTWARE OF PHOTOTYPE

A. Software Architectures

The architecture of the software is shown in Fig.7. It can be divided into two main parts, the real time processing and unreal time processing. The main responsibility of unreal time processing part is to help the surgeon confirm the treatment scheme, the real time part could control the robot complete the treatment.

The DICOM protocol module can get the X-ray image on the CT workstation, and take image sequence from DCM files, simultaneity the special useful information is obtained from tag in DCM files. Some image processing algorithms are developed, for example image matching algorithm, image recognizing algorithm, and so on. With the help of image algorithm the orientation of the system is done [18-19].

As to the real time processing part, the robot module control five step motor with a PID algorithm, at the same time collect sensors' information, for example photo-electricity encoders, then the joint variables is calculated, it can get the position of the tool through the kinematics model. Safety processing and man-machine conversation should also be running.

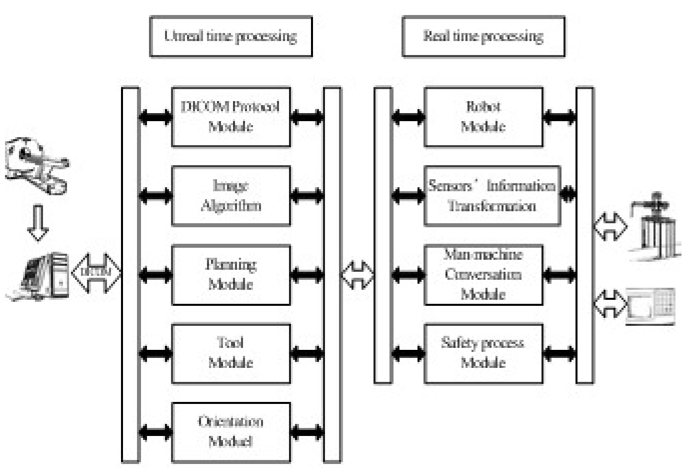

Figure 7. Software architecture

B. Planning System

As mentioned before, the surgeon can not see the surgical area precisely just by watching the X-ray images, the information of angle to insert of the needle can not be obtained during the operation. In our robot-assisted surgical system, the planning system can be guided by the surgeon. Once the depth and angle is confirm by the surgeon, the planning system will calculate the coordinate of a thimble fixed on the terminal of the robot, the needle will be inserted in the thimble. The thimble will make the needle just aim at the position of the puncture point, the angle is also promised. As the length of the thimble is fixed, so the depth of the puncture can be given to the surgeon.

In out robot-assisted system, the first role is to align various coordinates of all systems. As described in last chapter, once the orientation of the system is finished, we can obtain the coordinate of the point from the CT reference frame to robot reference frame. Accordingly the robot knows where a point indicated on the surgical system is in the real world.

During surgical procedures, the movement of the robot is measured simultaneously by built-in photo-electricity encoders, the state and coordinate is display on the LCD in real time; these will increase the safety level of the robot.

V. RESULTS

In this section, there are some results of experiments, which have been done in hospital.

Fig.8 shows the operation windows of the software on the planning computer. As shown in the figure, a DCM file is obtained on the computer; we can get the image sequence from the DCM file, special tags are shown at the right window, include the data of the patient which stipulated in DICOM protocol. Some function buttons are integrated in the window.

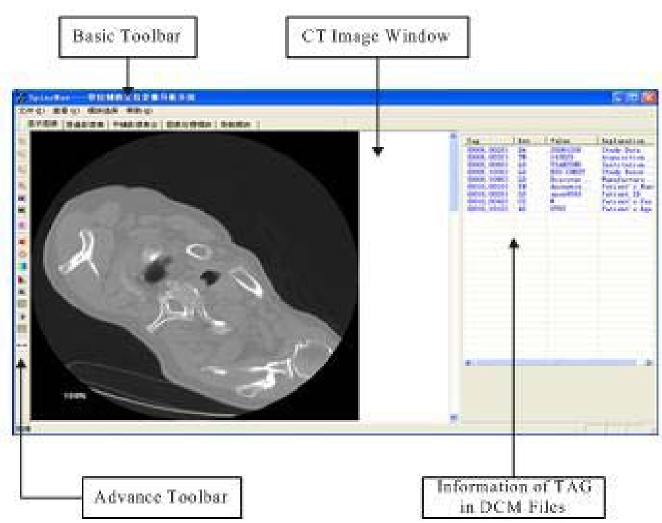

Figure 8. Windows of the software on planning computer

In the CT image data, air will appear with a mean intensity of approximately 1000 Hounsfield units (HU) [16], depending on the scanner hardware, CT can provide high spatial and high temporal resolution, excellent contrast resolution for the spine structure. A number of groups have developed techniques for computer assisted segmentation of CT images.

Fig.9 shows a group of results of operation to change the width and level of the CT images. Fig.10 shows a result of contrast enhancement with histogram equalization.

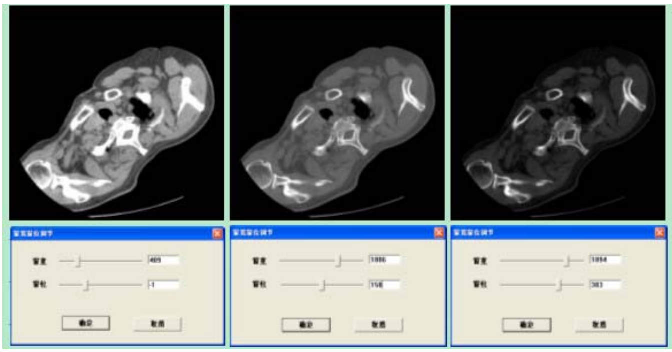

Figure 9. Results of operation.

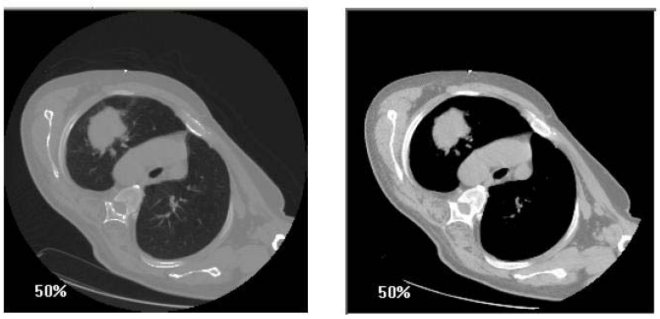

Figure 10. Results of contrast enhancement.

Fig.11 shows that how the robot is fixed on the CT bed. The surgical robot can be installed on the mechanism in the figure. As mentioned in last chapter, a mental mask mechanism can be used to get the coordinate transformation from this mechanism from CT image. Fig.12 shows the surgical robot system that installed on the CT bed.

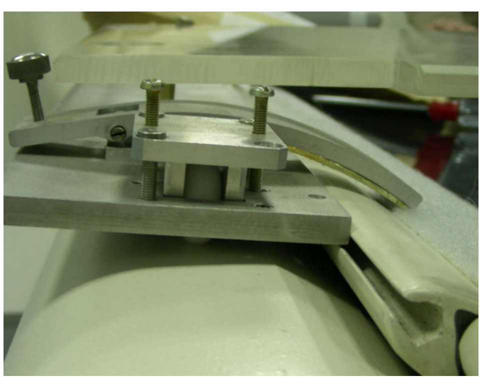

Figure 11. Mechanism of the robot used to be fixed on CT bed.

Figure 12. Surgical robot system.

This robot-assisted system is tightly combined with CT machine, testing must be done in hospital. As the special environment in hospital, abundance testing is needed. Till now the robot-assisted system can work together with CT machine, the designed objects have been realized, the error is less than 1mm; there are several reasons that affect the precision, the precision of the mental mask, the error of the image matching algorithm, and so on. Furthermore we will do more works to improve the system, for example, a 3D reconstruction from CT images could be more useful for the surgeon; a laser light sensor will be integrated to increase the precision of the system.

VI. CONCLUSION

In this paper, a robot-assisted surgery system for percutaneous vertebroplasty in spine surgery is developed. The system provided the surgeon with useful information successively. A new method of coordinate transformation for orientation and navigation of the system is presented. In our intending works, more tests such as animal tests are to be taken in hospital. We believe this system will give the surgeon a lot of help in the future.

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