NEEDLE TIP POSITIONING ON THE ABDOMEN WITH A NOVEL STEREOTAXIC ROBOTIC ASSISTANT

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In this article, a new stereotaxic robotic positioning assistant for percutaneous procedures is presented. Following the concept of mechanically safe systems, we describe the robotic system used to position the tip of a needle. Our system, called the CT-Bot, is compatible with medical requirements and offers an innovative approach to robotic needle insertion with computed tomography guidance. We explain the automatic registration algorithm and present the accuracy achieved with this system for entry-point positioning of the tip of a needle on CT-images.

INTRODUCTION

X-rays imaging devices are often used for diagnosis or therapy by radiologists who use them to accurately insert needles in internal organs of the abdomen. These percutaneous procedures are commonly used to reach small targets placed in the abdominal area (liver, pancreas, kidney). When high precision interventions are required (<5 mm), radiologists choose computed tomography devices that prove to be an excellent imaging modality given their resolution and their good tissues differentiation. But procedures such as radiofrequency tumor ablation are not totally safe for the radiologist who could potentially be exposed to high amounts of X-rays during CT-guided needle insertions. These are again potentially more harmful when a large number of procedures are performed by the same person.

Consequently, given the need for accuracy as well as the necessary X-ray protection, more and more image-guided robotic systems for percutaneous procedures have been proposed in the literature (see Taylor [10] for a good presentation). Even if clinical trials have already been achieved in some cases, current systems are not well-suited for abdominal interventions where the motions and the respiration of the patient create large disturbances that are difficult to compensate with a static needle holder.

We recently proposed some innovative ideas that we used in the design of a new robotic system with force feedback using a parallel mechanism [5,7]. The main innovation was that our robotic assistant involves two different kind of motion: first the positioning and orientation of a line supporting the needle using a parallel structure and second a needle driver unit that inserts the needle and spins it about its axis. This allows for security and safety of the patient while authorizing full movement of the needle.

Since this system is part of a complete project that start from the pre-operative images of a patient to the intervention in the medical operating room, an important point is the registration of the robot with respect to the patient. The main idea we detail in this paper is how to do the fully automatic registration and positioning of the tip of a needle. In so doing the radiologist can forego manually holding the needle before the insertion begins.

Starting from the workflow of the intervention, this paper describes the robotic setup. Then the image-based registration method is explained, together with the stereotaxic fiducials. Conclusions on the accuracy reached during a point-and-click paradigm for the selection of the entry point with automatic registration of the robot in the CT-image is given.

THE WORKFLOW OF A ROBOTIZED PERCUTANEOUS PROCEDURE

The medical workflow of a typical robotic insertion is decomposed in different steps. The pre-operative steps are:

1. Localization of the target using imaging devices such as CT-scan;
2. Planning of the trajectory of the needle in the images.

And during the procedure:

1. Image acquisition, automatic registration of the robotic assistant (using e.g. stereotaxic fiducials);
2. Selection of an entry point on the abdomen of the patient with an insertion angle (point and click paradigm);
3. Automatic positioning of the needle driver;
4. Image acquisition and trajectory validation;
5. Small incision at indicated point and beginning of the procedure;
6. While needle is not on target
   - 6.a Insertion of a few centimetres (with force feedback), synchronized with breathing motion;
   - 6.b Image acquisition for checking;
7. Target reached.
8. Release of the needle for free motion around the entry point;

This workflow is very similar to the one the radiologist does without robotic assistance. During these manual insertions, the time-consuming phases that expose the staff are the positioning of the needle tip on the proper entry point and also the alignment of the needle with respect to the planned trajectory. Once the entry-point is validated, he/she must still hold the needle while the insertion begins.

We think these phases are where a device like the CT-Bot can help by doing the positioning and the alignment of the needle. The radiologist can click on the control screen to choose an entry point on the CT-scan reference image and the robotic device does the automatic positioning. This greatly reduces the exposure time of the medical staff and allows for better accuracy.

The insertion phase (6), where the force feedback principle is used, is not developed here.

DESCRIPTION OF THE ROBOTIC SYSTEM: THE CT-BOT

1. Mechanical Description

Because the safety of the patient is undoubtedly the most important condition to be favoured in the design, the CT-Bot has been developed so that it is mechanically safe.

Like some recent works done on light robotic systems (see Berkelman *et Al*. [1] or Hong *et Al.* [3]) our prototype is also fixed on the abdomen of the patient, so that the motions of the patient and the external motions due to breathing are naturally compensated. Special straps are fastened to the body to avoid involuntary motion of the base support. We plan to adapt a deflating bag around the patient so that the system can be rigidly attached to the body. The base support makes it possible to fix the robotic positioning device with different orientation choices. This feature allows to select the best initial configuration according to the intervention objectives.

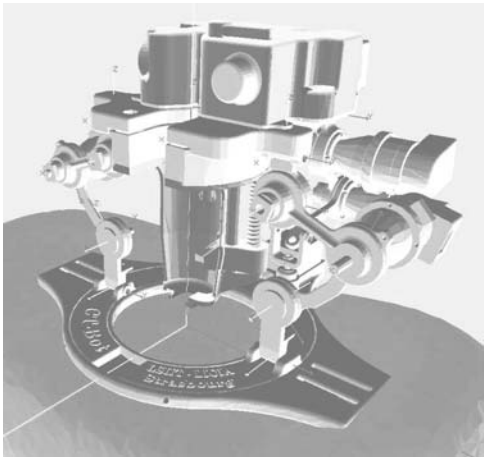

Fig. 1: Computer Aided Design (CAD) model of the CT-Bot.

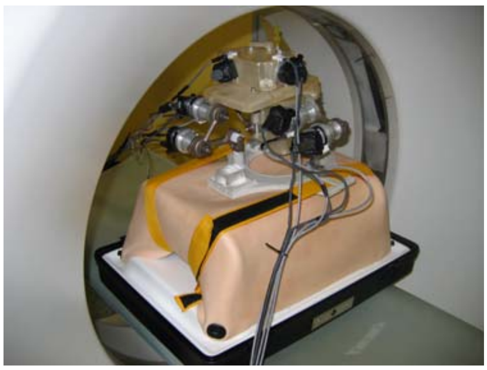

Fig. 2: The prototype in the CT-scan.

To fit in the CT-scan available space on the patient abdomen, the size of the positioning device has been limited to a 20 cm^3 cube. The weight is about 3 kg which is a typical acceptable value. Sterilization will be solved using a plastic film to protect all electronic devices that can be directly in contact to a human. The CT-scan compatibility is ensured by choosing a parallel structure that has no metallic parts crossing the X-rays plane. The mobility of the chosen mechanism, supporting the needle-holder, is five degrees of freedom which gives the required workspace for the motion of the needle.

The designed structure has three legs, i.e., three serial chains joining the base to the platform. Two opposite legs of the robot are symmetrical chains and form a planar 6-bar linkage with three degrees of freedom constrained. A 4-bar linkage is obtained using the third leg, restricting the last two degrees of freedom (see Fig.1 and Fig.2). According to the classification of Tsai and Merlet [8,11], this system is a parallel structure.

The solution of the robot kinematics is done in closed form using a Local Product Of Exponentials Formalism [5,9,12]. An approximated numerical Jacobian is used to study the workspace and the rigidity of the mechanism since the closed-form solution is not straight-forward.

2. Position Control

Using the previous solutions, we can control the robot actuators that are piezo-electrical motors with harmonic-drive gear reductors. A position-based loop is used to accurately set the position of the platform of the system that holds the needle.

To avoid any self-collision between the mechanical parts of the system, a realtime collision avoidance controller with a pre-computed operational grid has been used.

The calibration of the overall system is done by placing the platform in a known position/orientation reference. This part has to be more studied because of uncertainty on the positioning.

REGISTRATION PROCESS

1. The stereotaxic fiducials

To reference the system, we propose to use stereotaxic fiducials made of straight metal rods placed in the CT-scan volume (see Fig.3 and Fig.4).

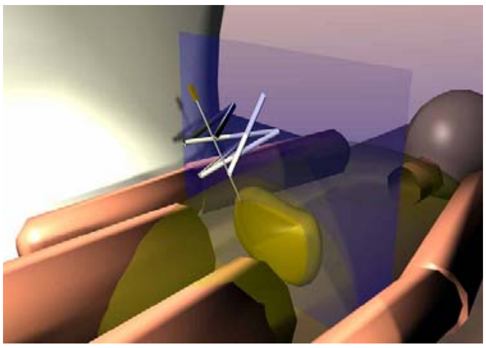

Fig 3. The stereotaxic principle

This kind of fiducial is well known by radiologists that often use them as coordinate frames for neurosurgery, for example.

Hence, stereotatic fiducials made of 30x30x40 mm plastic cubes with six fiducial lines [6] are used to accurately estimate the position and orientation of the location of the base of the robot.

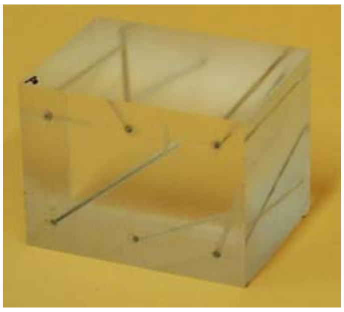

Fig 4. The Cube containing the fiducials

We propose to extend the use of stereotaxy, as proposed Brown [2] and Lavallée *et Al.* [4], so that the robotic device automatically registers itself with respect to the CT-image plane. Furthermore, patient to robot registration is necessary for further visual guidance. For that, we compute the relative transformation between the image planes and the end-effector holding the needle.

2. Registration Method

The registration method is based on a linear least-squares solution of a geometric problem. This pose reconstruction algorithm works with a single image (a slice) of the fiducial cube that has at least 5 points visible. We adopt a random sample-consensus method to achieve automatic registration with 6 visible points or more.

Today, an accuracy reconstruction of 1 mm in positioning of the cube is obtained using 512x512 image with 0.5 mm scaling factors. The needle tip position should be known by less than 5 mm using the forward kinematics.

VISUAL POSITIONING OF THE NEEDLE TIP

Once an insertion point is chosen in the CT-image, the CT-Bot must do the automatic positioning with respect to the selected entry point. The rigid body transformation to be executed is computed by using the registration of the cube in the image, knowing the position of the cube with respect to the robot, the relative motion is easily computed.

By installing the robot with a needle on the translating table of the scanner, our goal is to point a given position in the image with the tip of the needle.

RESULTS

1. Registration

The fiducials and the robot give the CT image shown on Fig 5. On this picture, the tip of the needle is also detectable.

We processed the image by thresholding the image with a value of 2000 to get the metal parts, and then we segmented it to obtain only the ellipsoidal shapes. After many trials with our software, we always get the following transformation:

$$R=\begin{bmatrix} 0.986 & -0.153 & -0.059 \\ 0.084 & 0.158 & 0.984 \\ -0.142 & -0.976 & 0.168 \end{bmatrix}$$

$$T=[-155.7\ -36.5\ 210.]$$

Fig 5. CT-image of the fiducials together with the needle, before the positioning.

This means that we can now map a pixel point to a spatial position.

2. Visual positioning

We indicate on the screen the current tip position in pixel and the pixel position of a target (metal needle) to reach with the tip of the needle. This translation is mapped to a relative Cartesian displacement to execute. The result can be seen on the Fig. 6 and Fig. 7 where one can easily check the tip position.

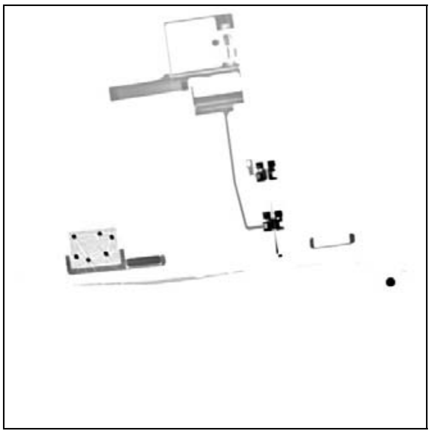

Fig 6. CT-image after the displacement

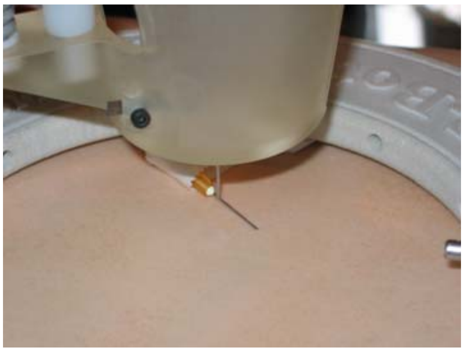

Fig 7. Picture taken after the displacement

Two trials of visual positioning have been successfully done with a final error that is less than 1 mm. The measure is difficult to quantify since we cannot mechanically measure the tip's position.

DISCUSSION

Firstly, the robot calibration error is inherent to the mechanism. This error should be considered as a constant error that does not influence the relative Cartesian displacement. This is important when absolute positioning is required. Then, the error in the single slice pose reconstruction directly affects the visual positioning. It should be noted that the sensibility of the global needle registration method is mainly correlated with the pose reconstruction which is done with an average error of 1 mm.

The current entry point selection and tip detection is based on pixel information given by a mouse click. This information is to consider with caution since the accuracy in mainly the responsibility of the operator.

CONCLUSION

This paper presents registration tests made using a safe robotic assistant for percutaneous procedures on the abdomen with a CT imaging device. After a short presentation of the overall setup, we explain how the registration process is done. Using a stereotaxic principle and image processing, we aimed to follow a point-and-click paradigm to guide a tip of a needle to a required entry point. Even is calibration and registration errors are present, the current scheme offers a true alternative to manual positioning of the needle before the intervention begins. In the future, we expect to do a manual insertion using the described positioning device as a passive guide for the needle.

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