CTBot: A Stereotactic-Guided Robotic Assistant for Percutaneous Procedures of the Abdomen

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Abstract. *This article presents a stereotaxic robotic positioning assistant for percutaneous procedures. 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 a novel approach to robotic needle insertion with computed tomography guidance. We explain the automatic registration algorithm and present the accuracy achieved with this system.*

Keywords: CT-guided robotic assistant, robotized percutaneous procedures

Introduction

For diagnosis or therapy, radiologists often use Computed Tomography scanners (CT-scans) to accurately insert needles in internal organs of the abdomen. During highly precise interventions, about 1 *mm* of accuracy, computed tomography has proved to be an excellent imaging modality given its resolution and good tissue differentiation. These procedures are not totally safe for the physician who is exposed to high amount of X-rays during CT-guided needle insertions. Such interventions are potentially harmfull when performing a large number of them.

Consequently, given the accuracy needs as well as the necessary X-rays protection, more and more visualy-guided robotic systems for percutaneous procedures have been proposed in the litterature (see Taylor [1] 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

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the respiration of the patient create large disturbances that are difficult to compensate with a static needle holder.

We recently proposed some novels ideas that we used in the design of a new robotic system with force feedback using a parallel mechanism[2, 3]. The main novelty was that our robotic assistant involves two different kind of motions: 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 real intervention in the medical operating room, an important point is the registration of the robot with respect to the patient.

Starting from the workflow of the intervention, this paper describes the robotic setup. Then the registration method is explained and conclusions on accuracy results of the automatic registration of the robot in the CT-image space is given.

1 The Workflow of a Robotized Percutaneous Procedure

The medical workflow of a typical 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.

The per-operative are:

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 not on target;
   (a) Insertion of a few centimeters, with force feedback and synchronized with breathing motion;
   (b) New image acquisition for checking;
7. Target reached.
8. Release of the needle for free motion around the entry point;

This workflow is very close to the one the radiologist really does in manual interventions. The insertion phase (6a) is where a force feedback principle is used to help the radiologist in detecting the transitions between the anatomical tissues. This important source of information helps him to guide the needle through the different layers of tissues between the image checks.

2 Description of the Robotic System: the CT-Bot.

Because the safety of the patient is undoubtly the most important condition to be favored in the design, the CT-Bot has been developped so that it is mechanically safe. Like some recent works done on light robotic systems (see Berkelman *et Al.* or Hong *et Al.* [4, 5]) 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 is 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.

To fit in the CT-scan available space, and 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 choosen mechanism, supporting the needle-holder, is five degrees of freedom which is the required workspace.

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. According to the classification of Tsai [6], this system is a parallel structure.

The solution of the robot kinematics is done in closed form using a Local Product Of Exponentials Formalism [7, 8]. An approximated numerical Jacobian is used to study the workspace and the rigidity of the mechanism since the closed-form solution is not straightforward.

A realtime collision avoidance controller with a precomputed operational grid is used to control the CT-Bot.

3 Registration Process

Once an insertion point and a target is chosen in the CT-image, the CT-Bot will have to do the automatic positioning with respect to the selected trajectory. Furthermore, patien-to-robot registration is necessary for further automatic visual guidance. For that, we must register the device in the CT-images in order to compute the relative transformation between the image planes and the end-effector holding the needle. Hence, stereotatic fiducials made of $30 \times 30 \times 40$ mm plastic cubes with six metal rods (see [9]) are used to accurately estimate the position and orientation of the location of the base of the robot.

The registration method is based on a linear least-squares method for initialization, then a Newton-Raphson method for better numerical results. This pose reconstruction algorithm works with a single image (a slice) of the fiducial cube.

Today, an accuracy reconstruction of 1 mm in position of the cube is obtained using 512×512 image with 0.5 mm scaling factors. Using the forward kinematics, we should obtain less than 5 mm of accuracy in registering the needle tip position.

4 Results

By installing the robot with a needle on the translating table of the scanner, we propose to compute the errors made in point and click motions made by the robot after it is registered in the CT-image. So, knowing the real position of the tip of the needle given by the CT-images and the theorical position computed using pose reconstruction and forward kinematics of the robot, we are able to characterize the accuracy of the registering method.

Firstly, there is a robot calibration error that is inherent to the mechanism. Then, the error in the single slice pose reconstruction directly affects the position of the tip of the needle. 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 2 mm.

5 Conclusion

This paper presents registration measurements made using a safe robotic assistant for percutaneous procedures on the abdomen with CT-guidance. After a short presentation of the overall setup, we explain how the registration process is done. Using stereotaxic principle and forward kinematics, we can compute the theorical position of the tip of a needle. Using CT-image, we show that per-operative visual feedback is crucial during trajectory following since reconstruction and calibration errors are present.

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