A New Robotic System For CT-Guided Percutaneous Procedures With Haptic Feedback

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Abstract. In this paper, we present a new design for a teleoperated robotic percutaneous intervention with computed tomography guidance. Percutaneous needle insertions are widely used in interventional radiology for radiofrequency ablations or biopsy procedures. Needle insertion robots guided by CT-images should improve accuracy and reduce X-ray exposure of the radiologist. We propose a new design with force feedback and CT guidance. A prototype is presented, together with a complete workflow of the system.

Keywords: percutaneous procedure; needle insertion robot; CT-guided intervention; teleoperated robot with force feedback.

1. Introduction

1.1 Motivation

New minimally invasive techniques were recently developed thanks to the related progress of medical imaging and medical devices. Among these methods, percutaneous interventions offer new possibilities for therapy as well as for diagnosis. These procedures consist in introducing a needle through the skin in order to perform local treatments on internal organs. Among these procedures, we are mainly interested in the radiofrequency ablations of tumors and in biopsies, that require high precision targeting. Radiofrequency consists in heating a tumor with a special radiofrequency needle directly inserted inside the tumor. This intervention is less painful for the patient than a classical surgical act and allows for faster recovery. The success of the procedure is highly correlated with the accuracy of the needle positioning. Biopsies also require high accuracy in targeting the living tissue that need to be analyzed given the small size of some tumors.

Currently, for these two techniques, the needle is held by the radiologist. A visual guidance is needed since freehand guidance with direct tactile feedback is not sufficient.

Ultrasound and X-rays imaging devices (CT-scan, fluoroscope) are often used for this

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purpose. To avoid critical organ areas, like e.g. the portal vein in the liver, or the spinal chord, the precision of the visual guidance is crucial. Today, manual interventions are routinely made on tumors of 3 to 6 cm, while recent CT-scans allow for the detection of tumors of 1 cm and below. Computed tomography has proved to be an excellent imaging modality given its accuracy for very precise localization (about 1 millimeter) and its good tissue differentiation. However, the destruction of these tumors with freehand insertion is very difficult due to accuracy problems. Furthermore, during a CT-guided needle insertion, the interventionist can be exposed to high radiation of X-rays. For these reasons, CT-guided robotic systems are very promising solutions.

1.2 Existing robotic systems

To our knowledge, the PAKY robotic system developped at the John Hopkins University is the most advanced existing solution for CT-guided intervention. The PAKY [1] is a one degree of freedom needle driver using a friction transmission applied to the body of the needle. It is a remote handling tool that puts the radiologist away from the X-rays source. This tool can be attached to other handling robots or passive arms, e.g., the RCM robot of John Hopkins, with two degrees of freedom or a positioning arm with multiple passive joints. For this robotic system, some methods have been developed for the automatic registration of the needle and for the visual servoing of the robot [2,3,4]. The main limitations of the existing system are the lack of force feedback during insertion, a limited exerted force on the needle due to the friction transmission, and the lack of real-time compensation of the movements and the respiratory motions of the patient. This lack of compensation of the physiological motions could be a critical problem for the safety of the patient.

Another image guided system for percutaneous intervention is the Ultrasound-guided UMI [5]. This robot has two degrees of freedom and is manually handled and positioned on the abdomen of the patient. It has a real-time visual servoing control loop that uses an on-board ultrasound probe for data acquisition. This is useful for the automatic guidance of the needle. However, the poor quality of the imaging device does not make accurate targeting easy to achieve. It seems difficult to reach tumors smaller than 1 cm or near bones. Furthermore, this robot has no force feedback capabilities, mainly because it is already held by the physician who cannot have an haptic feedback from the needle at the same time.

1.3 A new robotic design

A novel robotic system that solves the problems of force feedback, needle position accuracy and CT-scan compatibility required in radiofrequency and biopsy interventions is presented in this paper. The proposed robotic system aims to help the radiologist during percutaneous interventions made in the abdominal zone through a master and slave teleoperation workflow. The system is composed of an haptic interface driving a light robot attached to the patient body. The robot offers a workspace that is sufficient to position the needle in realistic intervention conditions. The system is composed of a five degrees of freedom parallel structure that holds a special needle driving tool as its end-effector. Force sensors are positioned between the robot and the needle insertion tool for the force feedback needs. The two degrees of freedom insertion tool uses a novel approach that removes the friction problem, keeping the translation and rotation movement actuated. The force feedback master arm is a commercial haptic interface.

2. The medical constraints

As introduced previously, the robotic device aims to replace the arm and the hand of the radiologist in some critical steps of an intervention, in particular during X-rays visual guidance of the needle. However, the goal is not necessarily to replace the physician, but to provide an assistance for the needle insertion. Thus the robot will work in a teleoperated mode with automatic guidance rather than in full automatic mode. A description of percutaneous procedures [6] indicates important constraints for the design: small operating space, sterility, compatibility to X-rays, safety, mobility, accuracy and above all tactile feedback.

The operating space constraint is due to the imaging device gantry space. There is no major restriction when dealing with C-arm fluoroscopy but in the case of the CT-scan the space constraint is really strong, especially when the patient is obese. So the full system must be contained inside a critical hemisphere of 200 *mm* around the entry point on the patient.

The sterility constraint implies that all parts of the system that can be potentially touched by the radiologist must be sterilized or packed in a sterile plastic bag.

As much as possible, metal alloys must be avoided inside the CT imaging device for imaging compatibility with the X-rays (diffusion). In contrast, synthetic materials are well suited.

For the safety of the patient, the robot must be quickly removable from the body or put in a movement-free mode to let the medical staff operate. The robot must not hamper with the radiologist, the patient, or the imaging device.

The required mobility of the needle is highly depending on the type of percutaneous intervention, but we can roughly conclude that three degrees of freedom for the initial positioning of the needle at the entry point and two more degrees of freedom for its orientation are sufficient. The rotation of the needle around its axis is not made by the positioning tool but by the needle driving tool.

The system must have a better accuracy than what a human can achieve by hand. It is designed in order to allow an accuracy of 2 *mm* or less inside the patient, with a possible exertable force of 20 *N* along the insertion axis. In-vivo animal tests showed that around 4 *N* is required for insertion in the body (see [7]). The haptic feedback must have a fine resolution so that the radiologist is able to feel thin transitions through tissue layers, membranes and changes in tissue density. This constraint is the major novel contribution of the project in regard to other well-known projects.

3. The robotic positioning device

Contrary to the PAKY which is connected to handling arms, we designed a robot that is positioned on the body of the patient in order to avoid some safety issues due to the motions of the patient with respect to the operating table and the motions of the chest due to breathing. The robot is made of two parts: a five degrees of freedom positioning device and a two degrees of freedom needle driving tool. The positioning device weights about 2 kg and has five degrees of freedom. It is attached using straps as the Light Endoscopic Robot [8].

Once this choice of a small and light structure was done, a mechanical structure that corresponds to the constraints of needle insertions was designed. Existing structures were studied weighting the pros and the cons, searching for a structure that minimizes flexibility and vibrations in order to keep a good accuracy during the needle insertion. The best compromise was a parallel structure. Parallel structures are used in many industrial and research applications that require rigidity and compactness in spite of heavy loads. In addition, they offer a very good absolute positioning of their end-effector. Their main drawback is the complexity of their modeling and control. So the design was achieved in order to obtain a structure that could be geometrically and mathematically modeled without too much difficulties. This structure is made of two 6-bar pantograph mechanism whose mathematical study was partially made in [9] (see Fig. 1).

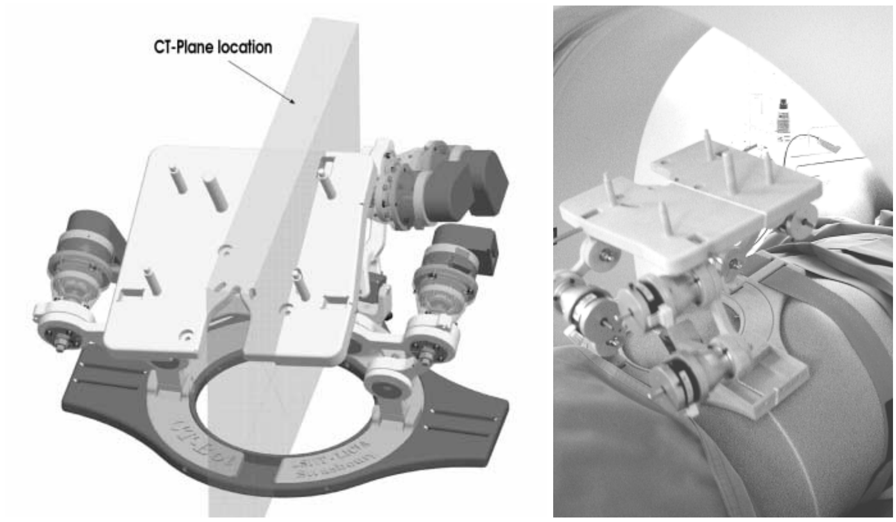

Fig. 1. The CAD model and the prototype under tests.

A numerical simulation with MATLAB and ODE dynamic simulation have shown that the modeling was correct and that the workspace was acceptable. Since important forces and torques are exerted on the end-effector and given the dimensions of the robot links, the active joints must support about 0.3 *Nm* when stopped. The actuated axes include an ultrasonic USR-30 motor from Shinsei Corp. together with encoders and gears. As these motors cannot be used to estimate the applied torques, the force along the needle axis is measured by force sensors positioned between the needle driving tool and the positioning robot. These sensors are three load cells from Sensotec that are symmetrically positioned around the insertion axis. The acquired forces are transformed into a force along the insertion axis.

The two degrees of freedom needle driving tool introduces a new concept for holding the needle. This device uses a special blocking part that avoid any movement of the needle and that transmits all the exerted forces to the sensors.

4. Architecture and workflow

The overall system is based on a master and slave architecture. Currently, the master is a six degrees of freedom commercial haptic device from Sensable Corp. and we are currently designing a dedicated haptic interface. The slave is the robotic device (five+two degrees of freedom) based on the principles detailed before. The workflow of a procedure is conceptually the same as proposed in [3]. The vision feedback is given by the CT-scan allowing the radiologist to verify each step in the procedure. The first four steps correspond to the positioning of the needle at the entry point, the last step is the insertion itself:

- Firstly, an image slice is acquired with the CT-scan and the robot position is reconstructed thanks to a stereotaxy algorithm together with a 3D fiducial attached to the robot (see the work of Susil [4] and a modified version in [10] with computation of maximal error bounds).
- Secondly, the entry point is either automatically selected by a planning algorithm, or manually by the radiologist.
- Thirdly, the robot is positioned at the entry point with the right orientation either automatically or manually with the haptic interface.
- Fourthly, another image slice is acquired to validate the needle trajectory. If a planning was made, the robot position is checked by using the stereotactic fiducial.
- Finally, an insertion mode is selected so that only the descent motions of the needle are possible. At the same time, the haptic interface is controlled to keep a line direction (two degrees of freedom) and a force control loop is used to provide the force feedback.

The radiologist may repeat this workflow as many times as required. There is a big advantage in switching between the positioning and insertion modes. This gives extra safety on the overall system. The only critical part is the needle descent, which has only one or two degrees of freedom (descent and self-rotation). The control of this last motion is made using force feedback, in order to use the radiologist abilities to detect the type of tissues by tactile sensing. Furthermore, the internal respiratory motions of the organ are taken into account by synchronisation of the robot and needle driver with the breathing machine.

5. Conclusion

This paper presented a novel concept for robotic percutaneous interventions. It introduces a novel positioning device built from a parallel structure together with a force feedback concept. The teleoperated system and its workflow is described. A prototype that is under test is shown. We think that our robotic system, together with the haptic interface, will become a valuable tool that will increase the performance of percutaneous procedures.

Acknowledgements

The authors wish to the Alsace Region Council for its financial support of this research work.

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