Achieving high precision in prostate biopsy thanks to robot closed loop control based on 3D ultrasound imaging

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Context

Prostate biopsy is the only examination that enables urologists to diagnose prostate cancer. It consists in taking off samples of the gland using a biopsy needle that slides in a needle-guide rigidly attached to a transrectal ultrasound probe. In clinical routine twelve systematic biopsies are distributed in the prostate volume and additional targeted samples can be taken in a given zone of interest (that has been detected earlier on an MRI image or during a previous biopsies session).

To perform prostate biopsies, the urologist uses the two-dimensional image as the only source of information while the patient is under local anaesthesia and the prostate experiences significant motions and deformations. Thus this gesture is difficult to perform but is also of the utmost importance as it constitutes the ground for therapeutic decisions making.

One key aspect of the procedure is the precision with which the needle aims at the desired biopsy location: the more accurate the needle placement is, the more accurate the diagnosis will be. An increase in the needle positioning process could also lead the way to focal treatments, that are known to present less side-effects

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than global ones.

Because of its crucial importance in terms of public health, robotic assistance to needle placement in the prostate has been the object of interest for the robotics community in the past years. A recent exhaustive overview of these systems can be found in [1].

Proposed system

A robot named Apollo which is aimed at assisting prostate biopsies through comanipulation has been developed. Its installation in a routine-like setting is shown on figure 1. Apollo, is an anthropomorphic arm that exhibits six degrees of freedom and a great transparency [2]. The first three axes (which constitute the shoulder and elbow) are equipped with motors, brakes are mounted on the three others that form the wrist.

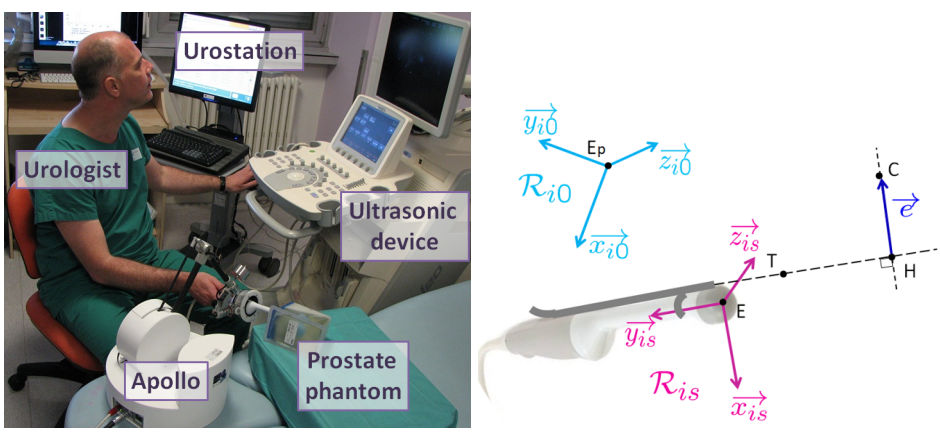

Figure 1: Proposed system in clinical-like setting and task modeling.

Two control modes have been developed: a free mode and a locked mode. In the first the surgeon controls the probe motion without interferences from the robot; in the second Apollo maintains the probe at its position precisely while exhibiting a low stiffness, which is important to ensure the patient safety. Apollo and its two control modes have been detailed in [2].

Although this system has been designed to be able to comanipulate the ultrasound probe together with the surgeon, it can be used to perform an automatic positioning of the probe, thanks to the 3 actuated joints. This is the object of the present paper.

The basic idea is to iteratively modify the position of the robot from an estimation of the error between the current target location and the desired target location in the prostate. In this closed-loop paradigm, a key issue is to measure the current target with respect to the prostate. This is achieved thanks to the Urostation, a device commercialized by KOELIS that performs registration between 3D ultrasonic images [3]. More precisely, the urologist first records an initial 3D image of the prostate (while the robot holds the probe in a locked mode), thus building a reference 3D volume. Through an interface, the urologist defines in this volume a target where the biopsy must be done. Then, using the robot in free mode, he/she moves the probe towards this target. When roughly positioned, the urologist switches to the locked mode. A new 3D image is then acquired and the positioning error can be computed thanks to the Urostation technology which registers the current 3D volume with respect to the reference 3D volume [4].

Robot control

In order to be able of controlling the robot, an interaction matrix between the robot displacements and the target error displacements shall be established. Our robot Apollo is able of actively controlling the position of point C, which corresponds to the wrist robot center, while the objective of the controller is to correct the position of the target point T. Point T belongs to the needle axis and is placed a few centimeters in front of the probe extremity; it corresponds to the center of the biopsy sample core and its location is the reference volume can be measured thanks to the Urostation. The wrist brakes being unlocked, when point C moves, a displacement of point T is described thanks to a lever model which fulcrum corresponds to the patient's anus.

Since the depth of the biopsy is controlled by the urologist in the ultrasound image, only the direction of the needle is seroved to the desired orientation. This means that only the two degrees of freedom of points C and T perpendicular to the needle axis are considered. As a result, the 2×2 interaction matrix between a small displacement δ_C of point C and the error variation δ_{ε_T} of point T, both

considered perpendicularly to the needle axis, writes:

$$\delta_{\varepsilon_T} \approx \begin{pmatrix} \alpha & 0 \\ 0 & \alpha \end{pmatrix} \delta_C \tag{1}$$

The control law uses an inverse of this estimated interaction matrix to compute a finite displacement d_C of point C to be sent to the robot from a measure of the error ε_T at point T:

$$d_c = \lambda \begin{pmatrix} \hat{\alpha}^{-1} & 0 \\ 0 & \hat{\alpha}^{-1} \end{pmatrix} \varepsilon_T \tag{2}$$

where λ is a correction gain and $\hat{\alpha}$ is an estimate of α.

Results

A first experimental result validating the approach is proposed in this paper. The experimental set-up is describe on figure 1. The probe extremity is inserted in a phantom that reproduces both the mechanical and echogenecity of a prostate and neighbouring tissues, including the anus and rectum.

A urologist first records the reference image and then engages the locked mode and releases the probe. A first set of movements is made in open loop, for which the point C displacement is imposed while point T displacement is measured. This allows to obtain an estimate for α (in this case: $\hat{\alpha} = 0.7$). Meanwhile λ is experimentally set to 0.5.

The desired target is then defined $5\,mm$ away from the needle axis along the x image direction. Figure 2 shows the successive positions of point T and the needle axis in the reference image frame during an automatic adjustment experiment. Within six iterations, the pointing error reached $0.7\,mm$, which is a satisfactory precision.

It can be observed that the convergence is not smooth. It is hypothesized that deformations and movements of the prostate phantom lead to unexpected variations of the error. However, thanks to the closed loop approach and an appropriate selection of gain λ, a final convergence if obtained.

Conclusion

We have been able to generate automatic small motions of the ultrasound probe that allows a satisfactory alignment of the needle axis with a biopsy target defined

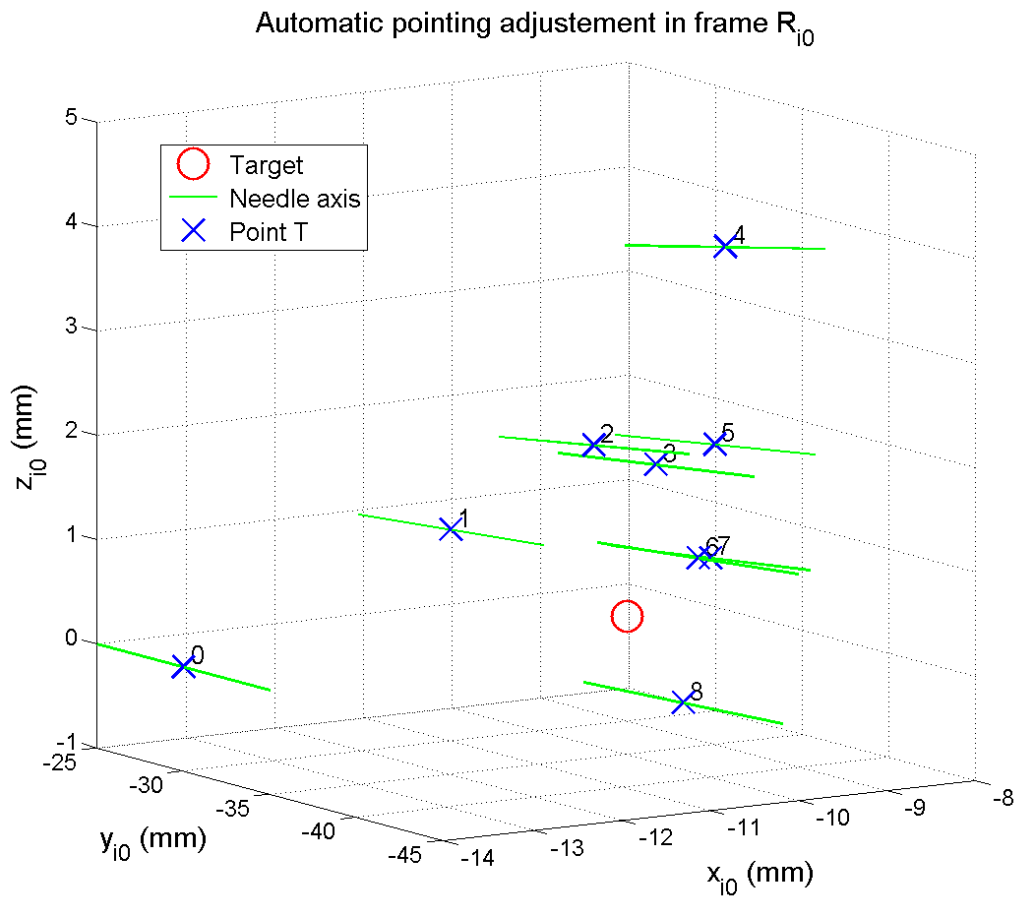

Figure 2: Successive positions of point T and the needle axis in the reference image frame during an automatic adjustment experiment.

with respect to the prostate, which is a moving and deformable organ.

This first proof of concept must now be further developed. Future work will include verification of the forces applied to the patient anus by the probe during automatic small adjustment motions and design of a more robust control.

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