Estimation of interaction matrix including anus elasticity in real time to control the probe tip in prostate biopsy.

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In transrectal prostate biopsy, anus imposes kinematic constraints so when robots manipulate the US probe, it might be needed to know the insertion point in the base frame in real time. In this paper, we developped a detection model of instrument insertion point displacement. We focused on the localization of the fulcrum center in real time including the environment insertion elasticity (anus). The proposed solution was tested and verified using a 6 DOF robot.

1 Context

Prostate biopsy is the only exam that allows urologists to diagnose prostate cancer. Although there are different clinical routines to perform this gesture, our work focuses on transrectal sampling. This method consists in sampling the gland with a needle attached by a guide to the ultrasound probe. Classically, twelve systematic biopsies are distributed in prostate volume [1]. However, in some cases, additional targeted samples may be taken in a given area of interest (which was detected per-operatively on an MRI image or in a previous biopsy session). This surgical gesture, predominant in the management of therapeutic treatment, has been proved difficult to achieve because the patient is only locally anesthetized and his prostate can move or deform significantly during an examination [2]. Robotic community has developed numerous devices in order to assist surgeons in their gesture by robotic to obtain a more precise needle placement [3].

2 Robotic system considered

It is in this context that the comanipulator robot APOLLO was designed to hold the ultrasound probe. APOLLO, is an anthropomorphic arm with six degrees of freedom and a high level of transparency [4]. Only the first three axes are equipped with motors(shoulder + elbow), the other three are mounted with brakes (wrist).

To improve surgeon clinical routine, two control modes have been developed. The first, the FREE MODE, let the surgeon moving the probe. The second, the LOCKED MODE, maintains the probe in a desired position while exhibiting low stiffness to ensure patient comfort and safety. These two control modes have been detailed in [4].

In this paper, we focus on a new control law able to reach a target with automatic adjustement of the probe tip. This control also takes anus elasticity into account.

3 Control based on the fulcrum probe estimation

APOLLO controller is based on a desired end effector velocity with respect to its base frame denoted V_P with P the wrist center [4]. To adjust the probe tip position, T, one need to compute velocity V_T from V_P. If it is considered that the insertion point, A, is fixed throughout the entire exam, then it coincides with the fulcrum probe, U, and it is possible to link V_P and V_T by the ratio between the probe length penetrated and not penetrated (see FIG.4) noted β :

$$\beta = d/(l-d) \tag{1}$$

Implemented in the expression :

$$\overrightarrow{V_T} = J_2 * \overrightarrow{V_P} \tag{2}$$

With :

$$J_2 = \begin{bmatrix} -\beta & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -\beta \end{bmatrix} \tag{3}$$

the interaction matrix linking cartesian P and T velocity.

But, during an exam, the insertion point (A) is not fixed because of the anus elasticity. Consequently, the fulcrum probe position, U, is not corresponding with the point A (see FIG.1) and changes position any time according to the anus elasticity. Morever, the penetration

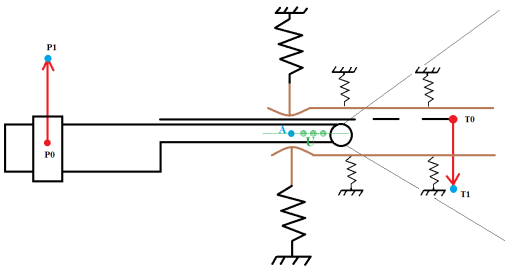

Figure 1: *Spotlight the difference between the insertion point (A) and the fulcrum probe (U).*

length changes during an exam so it is obvious that β changes.

In this way, we created an estimator of β along the axis of displacement able to update the Jacobian J_2 in real time :

$$\widehat{\beta} = k.\widehat{\beta} + (1-k).\beta_{inst} \tag{4}$$

With :

$$\beta_{inst} = (\overrightarrow{V_T}.\overrightarrow{x_P}/\overrightarrow{V_P}.\overrightarrow{x_P},\ 1,\ \overrightarrow{V_T}.\overrightarrow{z_P}/\overrightarrow{V_P}.\overrightarrow{z_P}) \tag{5}$$

Finally, the control law can be summed up by this simplified scheme with K a proportional gain linking position and velocity probe tip (T):

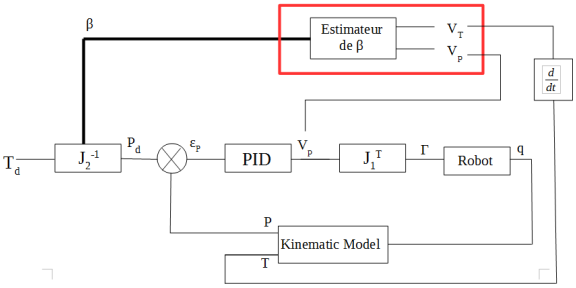

Figure 2: *APOLLO control law scheme.*

Note that similar problems have already been studied in laparoscopic surgery in [5], [6], [7], [8] with the insertion of an instrument in trocar but in a in a much more rigid environment than the anus.

4 Experiments and results

To highlight necessity and operation of such control law, displacements tests have been carried out. Initialization of β is made at 0.75 (β mean value) and the coefficient k in the estimator was manually tuned at k = 0.9. In FREE MODE, refreshement of estimator is always done every 250 ms with a fast convergence of $\widehat{\beta}$ (7s max). In LOCKED MODE, the refreshment of $\widehat{\beta}$ is done every second. However, it is not sent in control law to prevent jolt caused by changement in J_2 values, but is stored. When the surgeon switchs to FREE mode or sends another reference, the J_2 matrix is updated with the last stored $\widehat{\beta}$ values.

We sent series of guideline after moving probe in free mode during 7 seconds in order to make a 10 mm cross side on T. The cross was made in 8 deposits (4 return 10 mm). In order to validate data and results obtained from robot, this experiment was carried out with the supervision of the OPTITRACK camera system (see FIG.4).

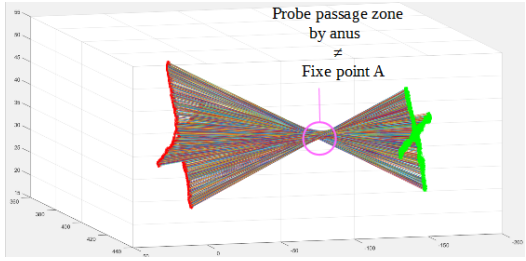

Figure 3: *Clear evidence of a passage area due to anus flexibilities.*

In addition, we measured β values after switching to locked mode which show us the insight of this estimator to take into account the anus elasticity :

- $\beta_{mesmain}$ hand mesured : 1.03
- β_{opti} Optitrack mesured: 1.05
- β_{est} given by estimator : 0.83

Then, we send a 10 mm guideline to point T :

- point T displacement with the implementation of $\beta_{mesmain}$ or β_{opti} in control law : 7.8 mm (22% of error).
- point T displacement with implementation of β_{est} in control law : 10.2 mm (2% of error).
- for the all cross, with implementation of β_{est}, the 8 displacements mean error is 0.42 mm (4.2% of error)

These results highlight the significant errors that may occur during a manual measurement which is very imprecise and the aboslute necessity to implement our control law which updates in real time and take into account anus elasticity which is promoted by the existence of a probe passage zone highlighted in FIG.3.

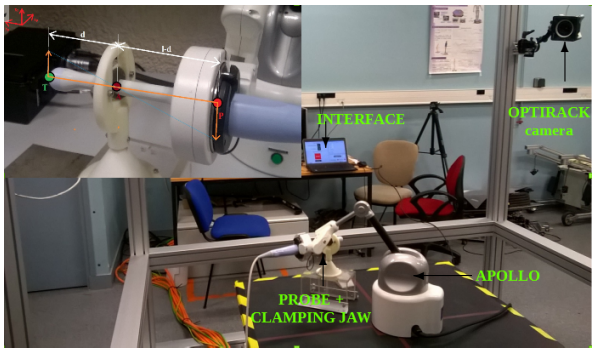

Figure 4: *Experiment set-up and explanation coefficient linking between point P, T and the anus.*

5 Conclusions

We are now able to reach a target defined in the framework of the prostate biopsies and to take into account anus deformations during the control of the robot.

References

[1] A. Ouzzane, P. Coloby, J.-P. Mignard, J.-P. Allegre, M. Soulié, X. Rebillard, L. Salomon et A. Villers. Recommandations pour la bonne pratique des biopsies prostatiques.*Progrès en Urologie*, vol. 21, no. 1, pages 18-28, 2011.

[2] M. Marchal. Modélisation des tissus mous dans leur environnement pour l'aide aux gestes médico-chirurgicaux. *Thèse*, Université Joseph Fourier, 2006.

[3] N. Hungr, M. Baumann, J. Long, and J. Troccaz. A 3-d ultrasound robotic prostate brachytherapy system with prostate motion tracking, *IEEE Transactions on Robotics*, vol. 28, no. 6, pp. 13821397, Dec. 2012.

[4] C. Poquet, P. Mozer, M.-A. Vitrani, and G. Morel. An endorectal ultrasound probe comanipulator with hybrid actuation combining brakes and motors, *IEEE Transactions on Mechatronics (TMECH)*, 2013.

[5] A. Krupa, C. Doignon, J. Gangloff, M. de Mathelin, L. Solert, and G. Morel. Towards semi-autonomy in laparoscopic surgery through vision and force feedback control. in *Experimental Robotics VII*. Springer, 2001, pp. 189-198.

[6] T. Ortmaier and G. Hirzinger. Cartesian control issues for minimally invasive robot surgery. in *Intelligent Robots and Systems*, 2000.(IROS 2000). *Proceedings*. 2000 *IEEE/RSJ International Conference* on, vol. 1. IEEE, 2000, pp. 565-571.

[7] B. Rosa, C. Gruijthuijsen, B. Van Cleynenbreugel, J. Vander Sloten, D. Reynaerts, and E. Vander PoortenBerkelman. Estimation of optimal pivot point for remote center of motion in surgery. *International journal of computer assisted radiology and surgery*, vol. 10, no. 2, pp. 205-215, 2015.

[8] Lin Dong and G. Morel, Robust trocar detection and localization during robot-assisted endoscopic surgery. *2016 IEEE International Conference on Robotics and Automation (ICRA)*, Stockholm, 2016, pp. 4109-4114.