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Ultrasound Guided Robotic Biopsy using Augmented Reality and Human-Robot Cooperative Control

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***Abstract*——Ultrasound-guided biopsy is a proficient mininvasive approach for tumors staging but requires very long training and particular manual and 3D space perception abilities of the physician, for the planning of the needle trajectory and the execution of the procedure. In order to simplify this difficult task, we have developed an integrated system that provides the clinician two types of assistance: an augmented reality visualization allows accurate and easy planning of needle trajectory and target reaching verification; a robot arm with a six-degree-of-freedom force sensor allows the precise positioning of the needle holder and allows the clinician to adjust the planned trajectory (cooperative control) to overcome needle deflection and target motion. Preliminary tests have been executed on an ultrasound phantom showing high precision of the system in static conditions and the utility and usability of the cooperative control in simulated no-rigid conditions.**

I. INTRODUCTION

MINIMALLY invasive percutaneous procedures under image guidance have a wide variety of applications in the fields of medical diagnostics and therapeutics. These procedures employ long, fine needles to access remote targets in the patient's body percutaneously. Biopsy and drug delivery are typical applications where these techniques are frequently used. Compared to equivalent clinical interventions performed under open surgery or laparoscopy, percutaneous needle punctures are fast, inexpensive, and minimize patient trauma. On the other hand it requires the localization of the target and of the needle trajectory using some forms of medical imaging technology. Among these technologies, the use of 2D ultrasound is common because of its minimal equipment requirement and real-time visualization. In practice, the target, such as a lesion suspected of being cancerous, may reside deeply within the body and may be adjacent to organs and tissues sensitive to injury. This makes precise needle placement of critical importance, but such precision is generally difficult to achieve in free hand procedure execution. The combination of poor image quality of the ultrasound images, their two-dimensional limitations and the flexibility of the needles used in these procedures, determine frequently many trajectory adjustments for the target reaching and sometimes the physician cannot conclude the procedure with the consequence big waste of time and stress for the patient. For these reasons the success of ultrasound guided interventions deeply depends on the clinician's abilities and requires very long training and particular manual and mental 3D reconstruction capability for the planning of the needle trajectory and the execution of the procedure. In the last years some technological aids have been developed to enhance the accuracy and to minimize the ability dependence using navigation system and/or robotic systems. In[1] Cleary *et al*. present a review of four interventional robotics systems: the AcuBot for active needle insertion under CT or fluoroscopy, the B-Rob systems for needle placement using CT or ultrasound, the INNOMOTION for MRI and CT interventions, and the MRBot for MRI procedures. A lot of works have been developed on robotic system for transrectal [2] and transperineal biopsy of the prostate with ultrasound guidance[3]. A robotic tool with an automatic image-guided control based on "visual servoing" is presented in [4] and [5]. On the other hand several navigation system for percutaneous interventions have been the subject of studies [6]-[9]. Fitchinger *et al*.[7] introduced an image overlay system to assist needle placement with CT scanning and Khamene *et al*. [9] showed an approach to biopsies performed using a 3D augmented reality guidance system with the using of Head Mounted Display (HMD). Commercially there are some navigation systems for percutaneous intervention, such as the Traxtal PercuNav [10] available in United States and Esaote Virtual Navigator [11].

The first integrated systems that offer both navigation functionalities and robotics [12]-[15] have emerged in recent years. In[15] Boctor *et al*. propose the use of a dual robotic arm system that manages both ultrasound manipulation and needle guidance and a navigation system based on 3D Slicer (http://www.slicer.org/).

Our system is also based on the combination of the advantages of virtual reality and robotics in one integrated system. The idea is to provide the clinician an augmented reality system, that allows to plan accurately and easily the trajectory and intra-operative helps him to execute the procedure, and a robot that allows to obtain the necessary precision. The system is designed to provide great accuracy, while keeping the biopsy procedure simple and intuitive:

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the clinician has only to select the biopsy target directly on the US image, using the mouse, and a skin entry point on the patient's body, using a digitizer. Subsequently, the robot positions the biopsy needle handler along the trajectory defined between these two points. In order to guarantee maximum safety, the insertion of the needle and the bioptic sampling is left to the manual execution of the clinician. An interactive graphical interface is provided to the surgeon with a 3D virtual scene where the optically tracked needle and probe and the relative scan plane are shown in real time beyond the traditional 2D View of ultrasound scan. A 3D model of anatomy reconstructed from precedent CT dataset can be integrated and visualized in the virtual scene. In order to compensate inaccuracy due to patient's motions or needle deflection we implemented a surgeon-robot cooperative control by means of a force/torque sensor. In this manner the robot, after the planned position achievement, follows the surgeon's movements allowing a fine adjustment of the needle trajectory in a natural manner during the needle insertion.

II. MATERIAL AND METHODS

A. *Hardware Design*

The setup of the system, represented in Fig.1, consists of an ultrasound image system (Au3 partner, Esaote Biomedica) equipped with a probe (Esaote 3.5 MHz CA11), an industrial 6 Degree Of Freedom (DOF) Robot Samsung ATI 2 with servo-controller, an optical localization system (Optotrak Certus, Northern Digital Inc.) and 2 Personal Computers (PCs). The navigation system and the graphical user interface are implemented on the first PC (PC1), while the cooperative control of the robot runs on the second one (PC2). The robot is equipped with a mini-45 Ati force/torque sensor (www.ati-ia.com), which is used as input data for the surgeon-robot interaction controller. The force values are acquired using a National Instrument PCI_6026E (www.ni.com) data acquisition card with a sampling time of 1ms.

The needle is handled by a holder fixed on the force sensor, which is attached to the robot wrist. This holder has been realized following two stages of design in order to find the most useful solution. The first prototype has been designed and manufactured as a 1 DOF mechanical slide. It is composed by two parts: one is fixed to the force sensor and then to the robot, while the other one is the effective slide which has been designed with the right tolerances to improve sliding without falling. Thanks to its geometry and to the boundary conditions created, this guide allows a stable insertion into soft tissues minimizing deflections of the needle. A second version of the holder prototype has a small cylindrical hollow handle to improve ergonomics when the robot is in shared-control modality. Both versions are equipped with infrared leds for the 3D localization of the end-effector in the space of the intervention.

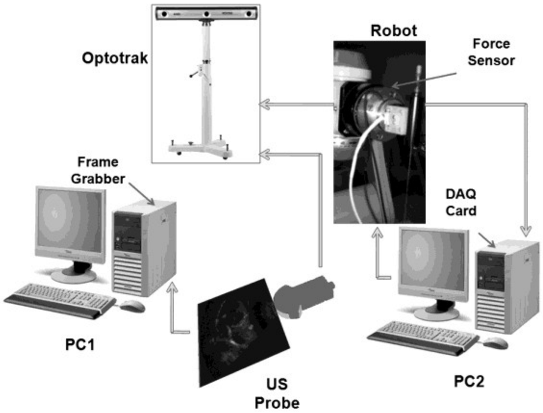


Fig. 1. Setup of the system.

B. *Calibration of the System Components*

The optical localizer is used to acquire and refer all geometrical relations, involved in the system, in the same reference frame by means of optical sensors placed on the instruments. The optical sensor attached to the ultrasound probe allows to acquire the 3D location of the sensor, rather than the one of the scan plane, required to determine the 3D position of the target. It is therefore necessary to find the position and orientation of the scan plane with respect to the reference system of the optical sensor. In the same manner the optical sensor on the robot end-effector provides the sensor position rather than position and orientation of the needle. These rigid-body transformations are determined through a calibration process.

Ultrasound calibration. Performing calibration by scanning an object with known geometric properties (phantom) has been a research topic for many years, starting from the simplest formed by a pair of cross-wires [16] or by a 3D pointer [17] to arrive to complicate phantom as the Z-fiducial phantom [18]-[21]. After several experimental trials implementing some type of phantom, we have decided to employ 2D alignment phantom [22] on the base of the good results we obtained in spite of simple phantom realization and calibration procedure. A 2D alignment phantom is based on the alignment of the scan plane with a thin board. The phantom realized is an epoxy resin shape absorbed in a water tank. Four corners of the shape are located in space using a digitizer then these corners are segmented manually in the ultrasound B-scan, thereby solving for the spatial calibration parameters.

Robot Calibration. To allow the robot the execution some trajectories in global reference system (optical localizer), it is necessary to determine the geometric relation between the robot end-effector (E reference system) with the optical sensor frame (F reference system) and between the global reference system and the robot reference system. The problem can be summarized in the simultaneous calculation of two unknown spatial relations (X, T Fig. 2). This problem is the same as the hand-eye calibration problem, well-known in robotics. The major part of existing solutions brings back to the resolution of a equations system of the type:

$$A \times X = X \times B \quad (1)$$

where A, B, X are homogeneous transformation matrix. A is the motion of the E reference system and B is the motion of the F reference system. In literature there are several solutions for this problem we have implemented a simple method based on Lie algebra [23]. This calibration must be performed at the beginning of the procedure and every time the robot or the localizer are moved.

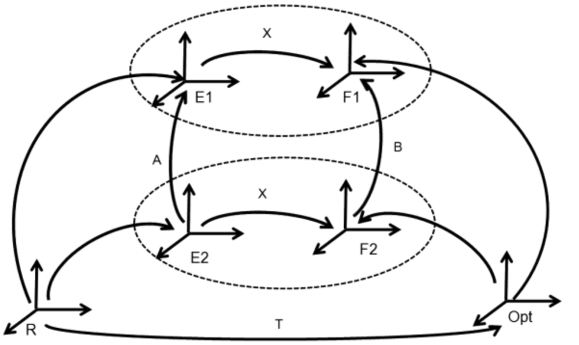


Fig. 2 The transformations between different reference systems at pose 1 and pose 2. (R: Robot; Opt: Optotrak; E: End-Effector; F: optical sensors).

C. *Software design*

We have developed two software applications: the first one that implements the navigation system running on the PC1 and the second one that implements the clinician-robot shared control running on the PC2.

Control Software. In the first phase of the procedure the robot is under position control in the robot reference system (implemented by robot controller). Based on the target and skin entry point location, the position of robot end-effector in the robot frame is determined (knowing the robot and needle calibration). Then the robot moves to the desired position with the appropriate orientation. A second position control loop in the global reference system has been implemented by means of the localizer to minimize the position error due to the industrial robot. This controller is embedded in the navigation system running on the PC1. After the desired position and orientation is reached, the clinician switches to "shared control" modality, the robot follows the surgeon movement by means of an admittance control law: the robot movement is proportional to the exercised forces:

$$x = Kf \quad (2)$$

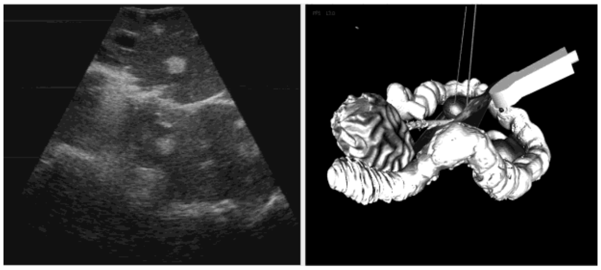
where x: 6x1 position and orientation vector; K: 6x6 diagonal matrix; F: 6x1 force and torque vector.

The application control software is implemented in C++ language and runs on PC2. This application can be divided in two main modules: the a*cquisition module* that manages the force sensor reading and filtering, and the *control module* that implements the control law and manages the communication with the robot low level controller.

Navigation System. Registering the pre-operative information relative to a patient (obtained by means of radiological devices) to the intra-operative information in the surgical room, consisting in the real patient and traditionally and supplementary (localized) devices, our system can offer the potentialities of surgical navigation, where the surgeon's perception is drastically improved by means of a virtual scene, with virtual surgical instruments and virtual patient aligned with the real instruments and patient.

The system is based on the EndoCAS Navigator platform [24] a modular open architecture that allows rapid developing of new functionalities. It allows: rapid generation of virtual patient specific models, their registration (ICP- Iterative Closest Point algorithm) and 3D visualization in a window using OpenSG library (www.opensg.com), the localization and visualization of surgical instruments interfacing with several tracking systems and all visualization functionalities present in a 3D virtual environment like changing point of view and the transparencies of the various objects, lights, etc.

In our system we visualize a 3D virtual scene with patient-specific virtual anatomy, the real time position of the ultrasound probe (with its 2D image), the target position, the selected entry point, the calculated trajectory and the instantaneous pose of the real needle (Fig. 3). In addition there is a conventional 2D window for the visualization of the ultrasound image where the surgeon selects, using the mouse, the target point of the procedure. Whereas the entry point on the skin is acquired using a digitizer.



(a) (b)

Fig. 3 Screenshot of the navigation system: a) conventional 2D View; b) 3D virtual view with patient specific virtual anatomy, and tracked instruments

III. PRELIMINARY EXPERIMENTS AND RESULTS

At first the system has been evaluated by non expert physicians in free hand biopsy procedures. To assess the performance and the accuracy of the system two types of experiments have been conducted. A first set of experiments have been made to test the global accuracy of the needle placement that depends on the several calibrations (robot, ultrasound probe, and needle) performed. The error was characterized in ideal rigid conditions using a home-built phantom composed of three peas of different diameter (10, 8 and 6 mm) of agarose (3% solution) positioned in a water tank. The goal of each trial was the insertion of the needle inside the selected pea after the selection of its centre as target, without manual correction on the orientation of the needle holder proposed by the robot and without patient-specific virtual anatomy models. Ten trials have been made for each pea. The results are shown in table 1. The reaching of the pea indicates that the positioning error of the needle is lower than the radius of the pea. A second series of experiments have been performed to evaluate the usability of the cooperative control for the compensation of needle deflection, deformation of tissue and target movement. For this type of experiments we used a tissue like liver by Kyoto Kagaku (www.kyotokagaku.com*)*, which intrinsically determines the above mentioned errors. Further an additional random error was introduced moving the surgical bed of few centimeters after the selection of the target (simulated tumors present in the phantom) and the trajectory planning. In this way the user cannot reach the tumor with the only insertion of the needle. Then the cooperative control is activated, in this modality the robot follows the user movements, the user can adjust the trajectory of the needle in a natural way (as in a freehand biopsy). The user can select again the target on the ultrasound image, then the new trajectory is visualized in the 3D virtual scene, allowing the user to place the needle for target reaching more easily. Thirty trials were performed by 3 non expert users. In all cases the user was able to place the needle for target reaching (verified on the ultrasound image).

TABLE I

GLOBAL ACCURACY OF THE NEEDLE PLACEMENT

Pea diameter	N°. trials	% Success	Error
10 mm	10	100	< 5 mm
8 mm	10	100	< 4 mm
6 mm	10	60	< 3 mm

IV. CONCLUSIONS

In this paper we presented an ultrasound-based biopsy system that provides clinician two types of aids: surgical navigation and robotic assistance. Surgical navigation enhances physician's perception allowing accurate and easy planning of the needle trajectory and target reaching verification. In particular the simultaneous 3D visualization of anatomy and of the scan plan drastically simplifies target localization. The automatic positioning of the needle holder coupled with the cooperative control functionalities allows to execute correctly abdominal bioptic procedures. Nowadays clinicians don't feel comfortable with leaving the whole percutaneous procedure to a robotic system. Therefore our system can offer a valid trade-off between full automatic and manual needle insertion. The ability and the body of knowledge of the doctor are perfectly integrated and mutually cooperate with our robotic platform .

REFERENCES

[1] K. Cleary, A. Melzer, V. Watson,G. Kronreif, D.Stoianovici: Interventional robotic systems: Applications and technology state of the art. Min. Inv. Therapy; 15:2; 101-113 (2006).

[2] L. Phee, D. Xiao, J. Yuen, C.F. Chan, H. Ho, C.H. Thng, C. Cheng, W. S. Ng: Ultrasound Guided Robotic System for Transperineal Biopsy of the Prostate. Proceedings of the 2005 IEEE International Conference on Robotics and Automation.

[3] G.S Fischer, I. Iordachita, C. Csoma, J.Tokuda, S.P DiMaio, C.M Tempany, N. Hata, G. Fitchinger: MRI-Compatible Pneumatic Robot for Transperineal Prostate Needle Placement. Transaction on mechatronics,13-3,295--305(2008)

[4] M.H. Loser, N. Navab: A New Robotic System for Visually Controlled Percutaneous Interventions under CT Fluoroscopy. In: Miccai, pp. 887-896(2000)

[5] J.Hong, T. Dohi, M. Hashizume, K. Konishi, N. Hata: An ultrasound-driven needle insertion robot for percutaneous cholecystostomy. Phys. Med. Biol., 49, 441--455(2004)

[6] S. Nicolau, X. Pennec, L. Soler, N. Ayache: A Complete Augmented Reality Guidance System for Liver Punctures: First Clinical Evaluation. In: Miccai,pp.539--547(2005)

[7] G. Fichtinger, A. Deguet, K. Masamune, E. Balogh, G. Fisher, H. Mathieu, R.H. Taylor, L.M. Fayad, S.J. Zinreich: Needle Insertion in CT Scanner with Image Overlay- Cadaver Studies. In: Miccai, LNCS vol.3217 ,pp. 795–803 (2004)

[8] A. Patriciu, D. Mazilu, D. Petrisor, L. Kavoussi, D. Stoianovici: Automatic Targeting Method and Accuracy Study in Robot Assisted Needle Procedures. In: Miccai, LNCS vol.2878, pp. 124–131(2003)

[9] A. Khamene, S. Vogt, F. Azar, T. Sielhorst, F. Sauer, H. Niemann: Local 3D Reconstruction and Augmented Reality Visualization of Free-Hand Ultrasound for Needle Biopsy Procedures. In: Miccai, LNCS vol.2879, pp. 344–355(2003)

[10] Traxtal Percutaneous surgical navigator, http://www.traxtal.com/percunav.html

[11] Esaote Virtual Navigator, www.esaote.it/

[12] G.Megali, O. Tonet, C. Stefanini, M. Boccadoro, V. Papaspyropoulos, L. Angelini, P. Dario: A Computer-Assisted Robotic Ultrasound-Guided Biopsy System for Video-Assisted Surgery. Miccai 2001:343-350

[13] P. Cheng,, A. Enquobahrie, R. Stenzel,, R. Lin, H. Zhang, Z. Yaniv, H. Kim, K. Cleary: Robot Assisted Needle Placement: Application developed using an open source image guided surgery toolkit (IGSTK).In: Miccai Ws. Proc., Copenhagen (2006)

[14] E.M. Boctor, M.A. Choti, E. C. Burdette, R.J Webster: Three-dimensional ultrasound-guided robotic needle placement: an experimental evaluation. Int. J. Med. Robot. And Comp. Ass. Surg.,4-2,180-191(2008)

[15] E. M. Boctor, G. Fisher, M.A. Choti, G. Fitchinger, R.H. Taylor: Dual-Armed Robotic System for Intraoperative Ultrasound Guided Hepatic Ablative Therapy: A Prospective Study. Proceedings of IEEE International Conference on Robotics & Automation, (2004)

[16] P.R. Detmer, G. Bashein, T. Hodges, E.P. Filer, D. H. Burns, D. E. Strandnessl:. 3D ultrasonic image feature localization based on magnetic scanhead tracking: In vitro calibration and validation. Ultrasound Med Biol;20:923–936, (1994).

[17] D.M. Muratore, R.L. Galloway: Beam calibration without a phantom for creating a 3-D freehand ultrasound system. Ultrasound Med Biol;27:1557–1566,(2001)

[18] R.M. Cameau, A. Fenster, T.M. Peters: Integrated MR and ultrasound imaging for improved image guidance in neurosurgery. SPIE Proc;3338:747–754, (1998)

[19] N. Pagoulatos, D.R. Hayno , Y. Kim: A fast calibration method for 3-D tracking of ultrasound images using a spatial localizer. Ultrasound Med Biol;27:1219 –1229,(2001)

[20] L.G. Bouchet, S.L Meeks,G. Goodchild, F. Bova, J.M. Buatti, W.A. Friedman: Calibration of three dimensional ultrasound images for image-guided radiation therapy. Phys Med Biol;46:559 –577,(2001).

[21] F. Lindseth, G. A. Tangen, T. Lang, J. Bang: Probe calibration for freehand 3-D ultrasound. Ultrasound in Medicine & Biology, 29(11):1607-1623, (2003)

[22] Y. Sato, M. Nakamoto, Y. Tamaki, T Sasama, I Sakita, Y Nakajima, M Monden, S Tamura: Image guidance of breast cancer surgery using 3-D ultrasound images and augmented reality visualization. IEEE Trans Med Imaging;17:681– 693, (1998)

[23] F. Park and B. Martin: Robot Sensor Calibration: Solving AX = XB on the Euclidean Group, IEEE Transactions on Robotics and Automation, (10), p. 717–721, (1994)

[24] G. Megali,V. Ferrari, C. Freschi, B. Morabito, F. Cavallo, G. Turini, E. Troia, C. Cappelli, A. Pietrabissa, O.Tonet, A. Cuschieri, D. Paolo, F. Mosca: EndoCAS navigator platform: a common platform for computer and robotic assistance in minimally invasive surgery. The international journal of medical robotics computer assisted surgery: MRCAS 2008;4(3):242-51.