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Robotically assisted ablative treatment guided by freehand 3D ultrasound

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Abstract. Robots can improve the accuracy of image-guided needle placement over traditional freehand techniques. While many research groups have demonstrated this, widespread clinical adoption of needle placement robots has not immediately followed, because (1) robots are generally expensive and (2) they are difficult to calibrate and register to the patient in a manner fast and user-friendly enough to be practical in the operating room. Our solution to these considerations is a novel, clinically applicable, low-cost system consisting of a robot (manipulating the needle through a surgeon-specified trajectory), guided by tracked freehand three-dimensional ultrasound (3DUS). We address cost by algorithmically enabling the robot to be unencoded, uncalibrated, and mechanically simple. We address ease of use by eliminating pre-operative registration, and nearly eliminating calibration. The surgical tool is tracked and thereby registered imager intra-operatively. A structured 3DUS volume, created using a tracked conventional 2DUS probe, provides the basis for accurate and reliable volumetric visualization, simulation, and planning. The system components are integrated using a 3D Slicer-based software package. Experiments have been conducted on both mechanical and calf liver phantoms (with embedded olives simulating tumors) with an overall accuracy of 2.54 mm and a targeting success rate of 100%.

Keywords: 3D ultrasound; Medical robotics; Image guided therapy; Calibration; Visual servoing

1. Introduction

Hepatocellular carcinoma presents over 1 million cases per year worldwide [1]. Liver is the most frequent location of metastasis from colorectal cancer, representing 130,000 new cases and 60,000 deaths in the US alone. Current treatment for liver cancer includes resection of part of the liver and ablative treatment. Unfortunately, most patients with primary and secondary liver cancer are not candidates for resection, primarily due to tumor location or underlying liver disease.

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For these reasons, an increasing interest has been focused on interstitial ablative approaches for the treatment of unresectable liver tumors. In addition to increasing the number of patients eligible for curative therapy of liver cancer, local tissue ablation is performed with lower morbidity than resection. It is also suitable for percutaneous and other minimally invasive approaches. Because many tumors cannot be seen with Trans Cutaneous Ultrasound (TCUS), minimally invasive percutaneous therapy may be ineffective at removing all malignant growths. One research approach to compensate for poor visibility in TCUS is registration of preoperative MRI/CT to TCUS [2]. However, as Russo et al. note, "the diagnostic accuracy of alternative techniques, i.e. pre-operative imaging (angiography, scintigraphy, CT, ultrasonography), and surgical exploration, does not exceed 60–80%. Intraoperative ultrasonography (IOUS), however, allows for early diagnosis and precise localization of many diseases, and it is an excellent guidance tool for accurate and radical surgical treatment." Intraoperative and laparoscopic ultrasonography both can provide both excellent real-time anatomical imaging and have been found most beneficial in a multitude of interventions.

In current clinical practice, IOUS-guided liver ablation is typically performed in two steps. First, the target tumors are identified in preoperative imaging, typically in CT or MRI. Second, these tumors are intra-operatively localized by means of IOUS. However, the two-dimensional nature of IOUS imaging leads to significant variations in results among users. Simultaneous manual handling of the IOUS probe and the ablator device is a challenging task that is prone to significant errors in the hands of even the most experienced physicians. Respiratory motion and liver surface deformation are two of the most significant sources of error. Galloway et al. [3] used IOUS and a laser ranger for better registration and assessment of liver motion and deformation. Jane Mary et al. [4] built respiratory motion models that help in registering preoperative MRI/CT to IOUS. Other solutions include real-time deformation modeling coupled with conventional tracker-based surgical navigation [5].

Compounding the collected 2D images into a 3D volume provides an excellent tool for intra-operative planning. Structured three-dimensional ultrasound (3DUS) volume provides more accurate and reliable tumor ablation planning compared to the limited 2D US planning [6]. However, even with the improved visualization of 3DUS, even experienced surgeons can experience significant targeting error when they insert the ablator freehand. Therefore, there has been a recent interest in robotically assisted US-guided needle placement (e.g. Ref. [7]).

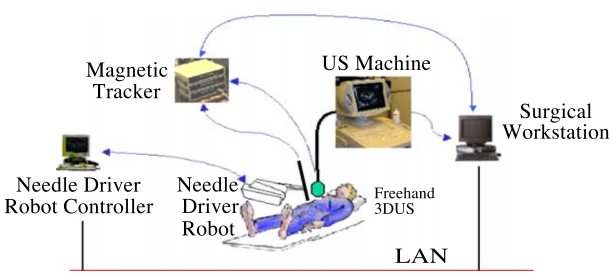

Fig. 1. Overall system architecture.

In response to the clinical issues outlined above, we have developed a novel, inexpensive system that reconstructs 3DUS from a handheld probe and uses a robot arm to accurately position the needle at the selected target, thereby greatly increasing the visualization, simulation, and planning power of the surgeon. This algorithm requires minimal calibration and removes the need for encoding, complex mechanical design, and pre-operative registration resulting in decreased system cost and set-up time.

2. Materials and methods

2.1. System overview

Figs. 1 and 2 demonstrate the schematic architecture of our experimental system and the physical set-up, respectively. Major system components include: (1) a PC-based surgical workstation providing overall application control, 2D and 3D ultrasound processing and surgeon interfaces; (2) a conventional 2D ultrasound system (SSD-1400 ultrasound machine, Aloka); (3) a five degree-of-freedom robot, composed of three prismatic and two rotational joints, for positioning a needle; and (4) an electromagnetic (EM) tracking system (Flock of Birds, model 6D FOB, Ascension Technology). We utilize the EM tracking system, rather than robot encoders to provide positional reference. The EM base unit is fixed to the operating table and individual sensors are attached to the ultrasound probe and needle holder.

2.2. Virtual RCM needle insertion robot control

The Virtual RCM [8] an algorithm that aligns the needle with the directional vector from the body entry point to the target within the liver, with the key performance criterion, besides accuracy and robustness, is fast convergence within very few cycles. To accomplish this without inverse kinematics, encoding of joints, or mechanical RCM enforcement, an incremental adaptive motion cycle algorithm is used.

This procedure requires only one piece of information in addition to the 6-DOF pose of the needle (readily available from tracker reading), namely the orientation of the robot base with respect to the Tracker base station. This is easily and quickly determined by moving

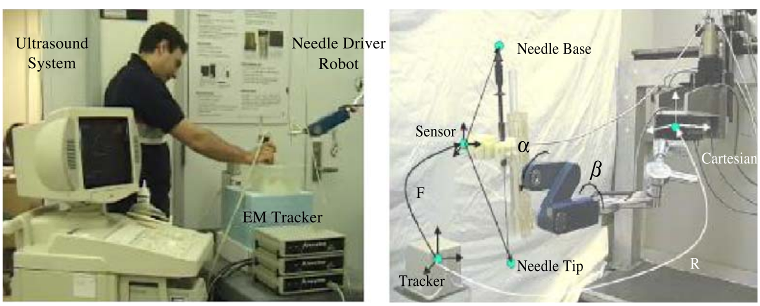

Fig. 2. Physical setup. (A) Illustrates the setup during freehand 3DUS capture. (B) The needle driver robot is comprised of a 3-DOF Cartesian stage, a passive unencoded adjustable arm, a 2-DOF motorized rotational stage, and a magnetic tracker attached to the tool holder.

the Cartesian stage arbitrarily (maintaining a safe distance from the patient) while recording sensor readings. Direction cosines yield the rotation matrix.

The 2-DOF motorized rotational "wrist" stage [9] can be used to provide a mechanically constrained fulcrum. However, the tool holder purposely removes the mechanical remote center of motion (RCM) property of the wrist by holding the needle off the RCM point. This demonstrates that the Virtual RCM algorithm outlined here can eliminate the need for an expensive, difficult to calibrate RCM wrist. Because the tool is not on a mechanically constrained RCM, the yaw and pitch DOF (α and β) of the wrist are not decoupled, and thus cannot be optimized individually, as is done in mechanically constrained RCM systems.

To optimize the needle alignment, a blind search of all possible α and β angles would eventually yield the correct alignment. However, it would be impractical (and perhaps impossible in the operating room) to repeatedly rotate the two joints a full 360° until the best alignment is determined from all possible discrete combinations of the two variables. To rapidly optimize α and β simultaneously, we draw upon heuristic search techniques developed in the field of artificial intelligence (AI). We discretize each rotational DOF and partition our search space into two subspaces, one for each angle. A heuristic function guides the search to optimal needle alignment. In practical terms, this means that the robot makes incremental motions, and after each it checks to see if the needle is becoming more aligned or less. This tells us which direction is likely to cause better alignment. By continually moving both angles, the robot is able to rapidly hone in on the proper alignment.

Selecting a heuristic function that quantifies improvement in needle alignment is not trivial. Good functions must not have local minima that may trap the algorithm before

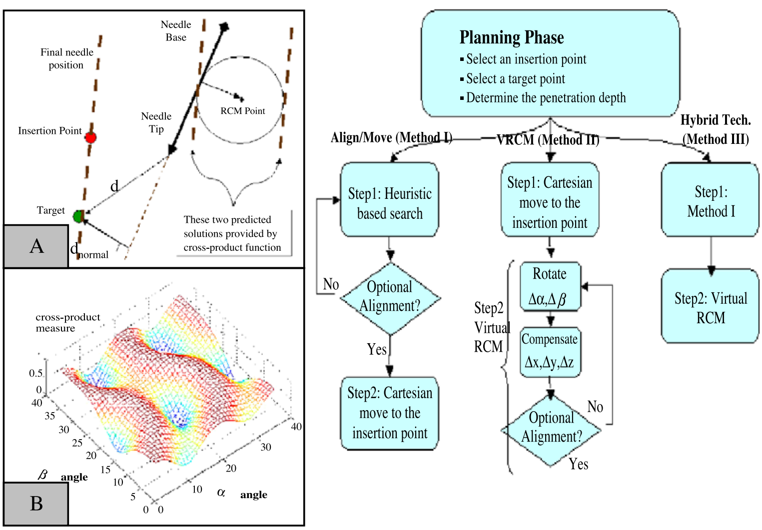

Fig. 3. "A" shows a potential heuristic function, the cross product function. "B" depicts the solution space for all possible cross product values as a function in angles. The chart is illustrating the robot control algorithms using this heuristic information as a feedback. There are three different implementations for this concept: (1) align the needle away from the subject and then move, (2) move to the insertion point and align using VRCM algorithm with small controlled increments, and (3) hybrid technique by combining "1" and "2", where we "first" align-move and "second" enhance the result by running VRCM.

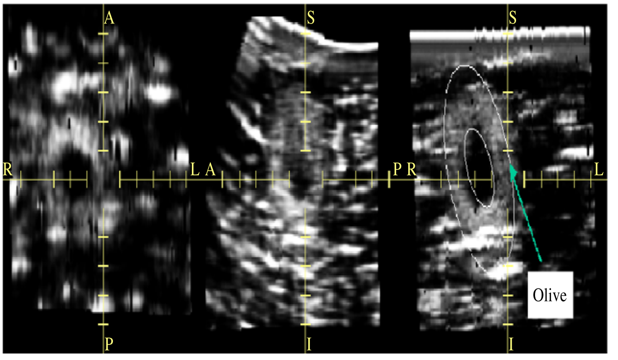

Fig. 4. Orthogonal slices of 3DUS reconstruction of an olive in calf liver phantom.

alignment is achieved, nor should they be sensitive to noise in tracker readings. Further, the function must not compound noise error. Based on these considerations, the cross product was determined to be a good choice for the heuristic function as in Fig. 3. To create the heuristic the cross product of vector from the needle base to the needle tip and the vector from the insertion point to the target is taken. Minimizing the magnitude of the result yields a needle aligned with the desired entry path.

2.3. Tracked freehand 3DUS

It is possible to reconstruct 3DUS volumes using a tracked 2DUS probe. The tracker records the path of the probe during the scan. The three stages of this process are acquisition, reconstruction and visualization. 3DUS allows more accurate planning because arbitrary slices through the 3D data set are possible.

3. Experimental procedure

The imaging protocol starts with an exploration phase, in which the user decides on the volume of interest (Fig. 4). We then plan the treatment, as in Fig. 5, and then execute it using the robot as follows: (1) before approaching the patient/phantom, the needle is

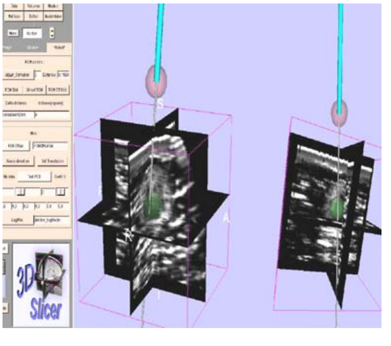

Fig. 5. Typical planning screen, with insertion and target spheres.

oriented to be parallel to the path between the entry and target points using the two rotational joints of the wrist, (2) the needle tip is advanced to the entry point using the prismatic joints, and (3) the alignment of the needle is fine-tuned by making precise small motions of all joints while maintaining the needle tip at a nearly fixed, software-controlled virtual remote center of motion (VRCM), as shown in Fig. 3. The last step is to insert the needle according to the pre-determined distance using real time 2D US as a monitoring tool.

4. Results and discussions

We first conducted experiments without an imager to test the accuracy of the VRCM control algorithms. The system achieved 0.78 mm translation and 1.2° rotational accuracy (this is within the tracker accuracy), in few iterative control steps (on average 15 steps) within 0.5–2 s. We then conducted needle placement experiments under 3DUS guidance using a calf liver with pitted olives embedded in the liver at depths ranging from 5 to 40 mm, to simulate cancerous lesions. Finally, in order to assess the geometric accuracy of the system, we employed a phantom consisting of several plastic pins (8 mm OD) immersed in a water tank. Targeting the center of each pin, the overall accuracy is 2.54 mm on average and a targeting success rate of 100% (7/7).

This demonstrates the utility of our novel, low-cost needle guidance system based on a generic robot and freehand 3D ultrasound. The main advantages of this approach are (1) it simplifies calibration of the robot to the imager, shortening the set-up phase, making the system more practical in a real-world operating room, and (2) it simplifies modular replacement of end effectors. With this approach, we only need to calibrate the tool tips (US and needle) to the EM tracker. The robot motion is not accomplished through inverse kinematics, so there is no need for pre-calibration; robot motion is based entirely on tool location.

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