Robot Assisted Needle Placement: Developed Using Image Guided Surgery Toolkit (IGSTK)

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Abstract

Using robot system position needles or needle shaped tools during clinical procedures such as biopsy, radio frequency ablation, and target drug delivery has a great potential in increasing accuracy and speed of the process, and minimizing trauma to patient. This paper describes a robot assisted needle placement system developed based on the Image Guided Surgery Toolkit (IGSTK). IGSTK is an open source software toolkit aimed at providing a robust and safe platform for researchers and clinicians for fast prototyping of image guided applications with minimum cost and effort.

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1. INTRODUCTION

1.1. Image guided needle placement

Needle and needle tools are widely used in the clinical environment, especially in minimum invasive procedures, for both diagnostic and treatment purposes. One of the most commonly practiced procedures is needle biopsy, in which clinicians deploy needles into patient body to sample a small amount of tissue for laboratory analysis. This procedure is mostly being used for lung, breast, liver, and prostate for tumor diagnosis and cancer staging. In other procedures such as radio frequency ablation, surgeon insert ablation needle into the center of tumor and use the radio frequency energy to 'cook' the tumor. Both procedures are minimum invasive, but they also require a great amount of experience to accurately targeting the tumor to achieve the best result. By overlaying real-time location of tracked surgical tool on top of pre or intra-operative images, image guided technology can provide insight into the patient anatomy, thus increase the accuracy of minimum invasive procedures.

1.2. Deck of card robot

The deck of cards robot is designed and manufactured by ARC Seibersdorf Research GmbH, Austria. (Figure 1 left). The robot has two joints (upper box and lower box, which can move parallel to each other) and 4 degree of freedoms ($\pm$19mm in translation and $\pm$ 30^o in rotation). Its unique shape gave it the name deck of card robot. Figure 1 right shows the system setup. The robot is mounted on the CT table after patient is in place. Robot arm is adjusted to position the needle holder close to the biopsy area. A CT scan is then acquired and loaded into robot assisted needle biopsy application. Surgeon can go through the image slices, identify tumors, and plan an optimal biopsy path by setting proper target and entry points to avoid important and vulnerable organs and tissues. The robot will then move the needle holder and align it with the planed path. Surgeon can advance the needle manually to hit the target. The deck of card robot can be operated remotely by multiple clients through TCP/IP communication. Client application should first connect to the server application as an active client before it can command the robot.

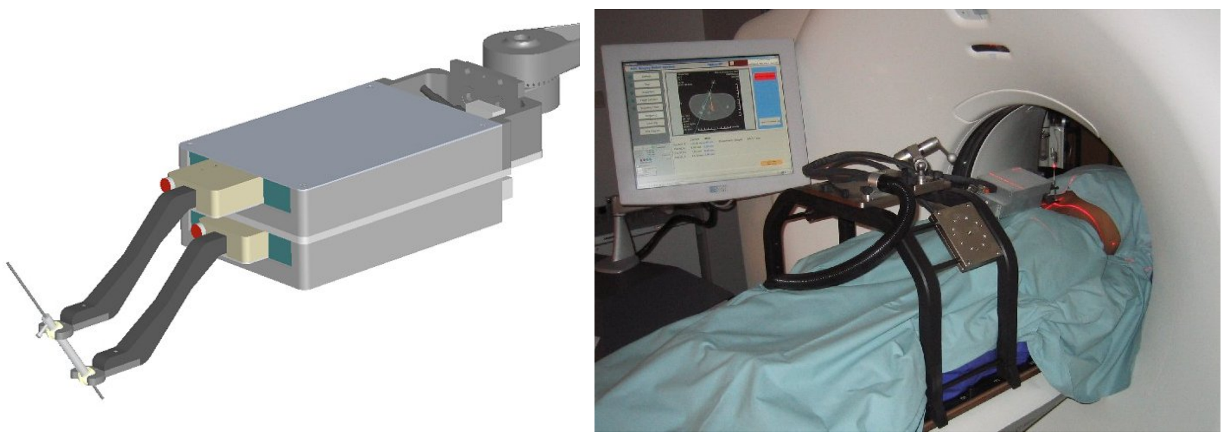

Figure 1. Deck of card robot (left) and robot assisted needle biopsy system setup (right)

1.3. Image-Guided Surgery Toolkit (IGSTK)

IGSTK is an open source toolkit designed for development of image guided surgical applications [1, 2]. IGSTK is developed on top of three other open source toolkits i.e. ITK (segmentation and registration), VTK (visualization) and FLTK for graphical user interface. IGSTK contains basic components needed in image guided surgery applications such as view classes for displaying and presenting results to the clinician, spatial object and spatial object representation classes for modeling and displaying physical object including images and anatomical structures, and tracker classes to handle and communicate with tracked surgical tools.

2. METHOD

The critical step in robot guided needle placement application is to determine the transformation parameters between the robot and patient/image coordinate system. This registration procedure is commonly performed using fiducial based (point-based) registration technique. In this procedure, surgeons examine the image slice by slice and identify fiducial markers and establish the pairing to the physical fiducial markers. This manual tagging and matching procedure is time consuming and is prone to human errors. Hence, we developed automatic fiducial marker detecting and matching algorithm.

We embedded 1mm diameter metal fiducial markers (19 in total) onto the surface of the cylindrical needle holder (Figure 2 left). Figure 2 right shows 3D reconstructed image of the fiducial markers from a CT scan. The markers follow a spiral pattern. The positions of each fiducial marker with respect to the robot space origin are known and are referred as the model points later in this paper.

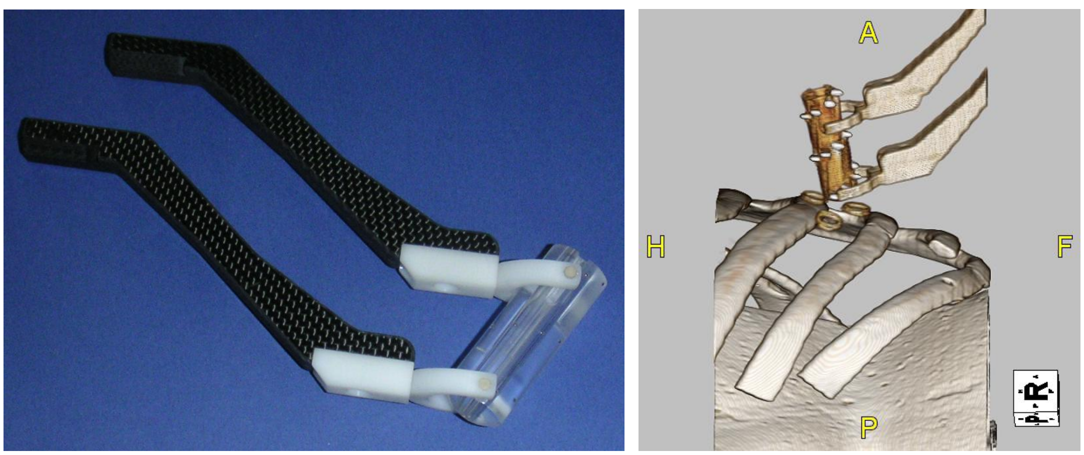

Figure 2. Needle holder with embedded fiducial markers (left), and reconstructed image showing the fiducial markers (right).

2.1. Fiducial point detection

Metal fiducial markers have very high absorption rate in CT images. Thus we can threshold the image, extract high intensity objects, and then calculate the centroid of each object as fiducial point position. In the case of the existence of other metal objects in the image, we used maximum and minimum size criteria to filter out non fiducial points such as needle, metal part of the robot, and metal implantation in patient.

Even if we use the size restriction, there are still some small objects in the segmentation results can not be separate from the true fiducial points. The goal for fiducial clustering is to filter out those false positive segmentation results. Given the high density distribution of fiducial markers in the end effecter (19 fiducials in total), and no other metal object except fiducial points are detected within or around plastic needle holder (needle can be filter out by size criteria), we can conclude that the remaining false positives are all outliers. We can then calculate the distance map of the segmented point set, and iteratively delete point with the largest average distance to the rest of the points, until the maximum distance between point pair is less or equal than the maximum scale of the model. This is similar to the max-cut clustering algorithm. More sophisticated algorithm can be used to cluster the similarity map between segmented points and model points.

Using the former two steps won't guarantee to segment out exact 19 fiducial points which is required by the next step landmark based registration. If a high threshold value is used, then we might miss detect some of the fiducial markers, if a low threshold value is used, then we might end up detecting too much false positive points, which does not the meet the assumption of the clustering algorithm that no points other than fiducial markers are detected within or around the needle holder area. Here we used two stage segmentation algorithms (Figure 3). First we use a high threshold value (3000) to segment the whole volume and followed by the clustering algorithm to extract the high confidence fiducial markers, this stage guarantee all the result points are true positive. We then use these points to extract the volume of interest which only contains the needle holder, and perform the segmentation again with a lower threshold (2000) followed by the clustering. This will guarantee to segment all the fiducial points. Because it's applied to a sub volume contains only the needle holder, it's much faster, and won't generate false positive segmentation results.

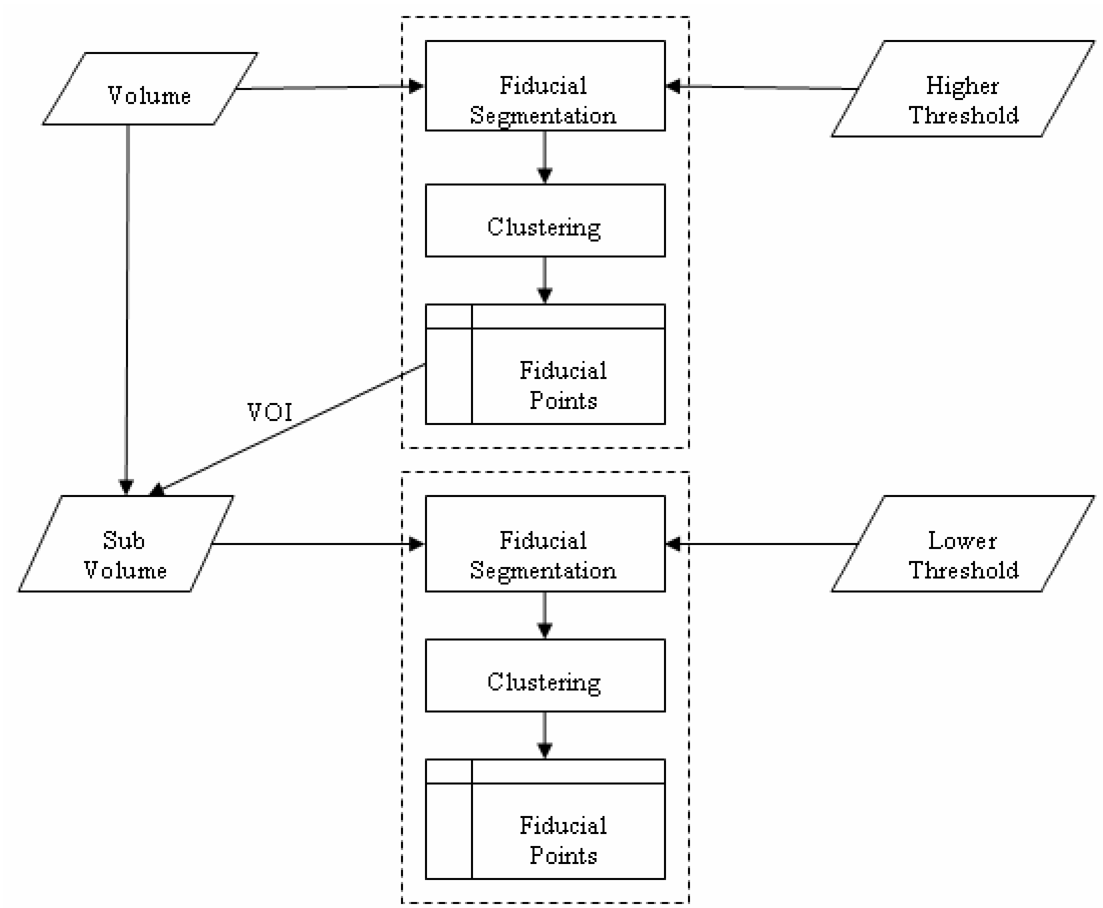

Figure 3. Flow chart for the two stage segmentation algorithm

2.2. Fiducial point matching and registration

After segmenting all the fiducial points in the image, we can then sort the points by projecting them on to its center axis, the axis of cylinder shaped needle holder. This axis can be approximated by extracting the principle component axis of the 3D points set. One design flaw of this particular end effecter is that it is symmetric with respect to the center plane perpendicular to end effecter's axis, which makes it hard for computer program to identify what's the right order of the point sequence. In this program we use the assumption that the point with largest Y coordinate (the lowest elevation, because the robot can not flip upside down, so the end effecter is always pointing downwards) corresponding to the smallest Z axis point in the model. A better solution to this problem is to manually take out one of the fiducial point on either upper or lower side of end effecter and make it asymmetric, and try the landmark based registration with two different orders of the points, and take the registration result with the smaller RMS error.

3. IMPLEMENTATION

The fiducial segmentation and matching algorithm was implemented using ITK classes. The algorithm takes an ITK image, a threshold, and maximum and minimum sizes as input and generates a segmented points list. The major classes used are [3]:

itk::BinaryThresholdImageFilter

itk::ConnectedComponentImageFilter

itk::RelabelComponentImageFilter

Fiducial clustering filter takes a list of sample points and list of the model points as input and returns the clustered points list. The communication between the application and robot server is through TCP/IP protocol. For this purpose, socket communication component of IGSTK was used. Other modules of this application, user interface, visualization, registration and path planning are implemented using view, registration components of IGSTK.

4. RESULTS

4.1. Application GUI

Figure 4 left shows the user interface of the application with control panel on the left, 3 standard 2D slice views and a 3D volume rendering on the right. The yellow cylinder is the needle holder, the purple square indicates robot's working region, a path is being planed to target the tumor while avoiding the ribs, and it is showing the robot being aligned with the planned path.

Figure 4 right shows the phantom study setup. After registering the robot, the application can command the robot to align with the planned path, and the robot is able to hit the pre-attached skin fiducial markers on the planned path.

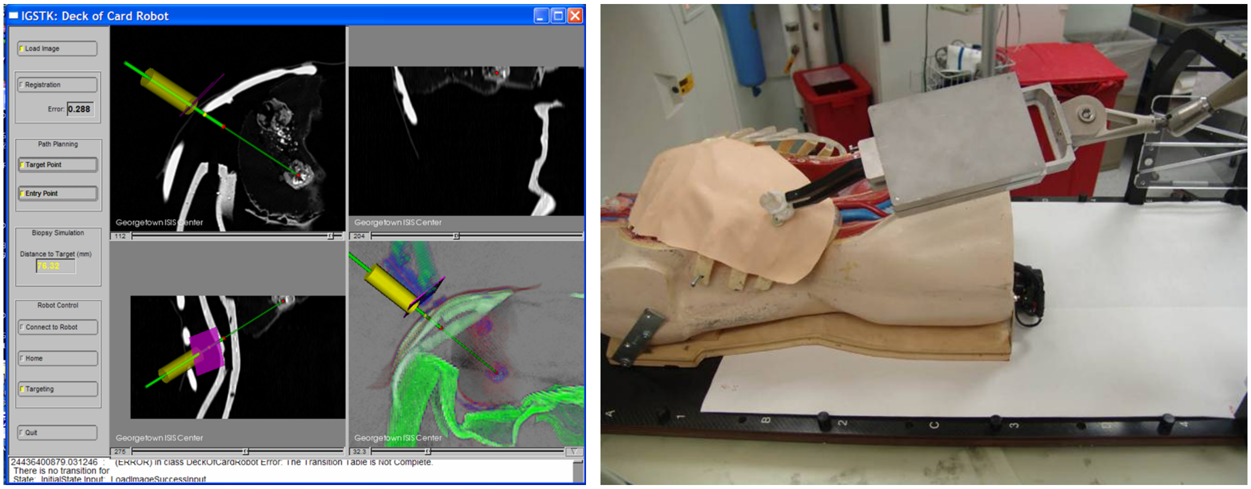

Figure 4. Application user interface showing the registered robot (left) and phantom study (right)

4.2. Validation study

To validate the whole system especially the robot registration and communication part, we acquired three groups of data, each group contains one home position and three other know robot positions. That's 12 scans in total. The image is reconstructed with 0.637x0.637x1.00mm resolution. It takes about 30 seconds to run the algorithm on a moderate PC with an image size of 512x512x105. The automated algorithm can successfully register all 12 data sets with an accuracy of 0.298$\pm$0.018mm RMS errors.

5. DISCUSSION & CONCLUSION

The results showed that the registration method developed here is robust. We are currently investigating to use more relaxed registration methods such as iterative closest points and model-to-image registration which do not require the exact same number of segmented fiducial points as in the model and the points pairing, and compare their success rate and accuracy to the this landmark based method. Furthermore, the algorithm doesn't take respiratory motion effect into consideration. In lung and liver biopsy, respiratory motion can introduce as much as 5 cm errors into the system. Motion compensation techniques must be used to reduce the motion error when using the robot assisted needle biopsy system.

6. DISCLAIMER & ACKNOWLEDGEMENT

This application is being developed as an example application with the release of IGSTK open source software toolkit, and it's not suitable for clinical use.

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