A Training Suite for Image Overlay and Other Needle Insertion Techniques

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Abstract. In order to develop accurate and effective augmented reality (AR) systems used in MR and CT guided needle placement procedures, a comparative validation environment is necessary. Clinical equipment is prohibitively expensive and often inadequate for precise measurement. Therefore, we have developed a laboratory validation and training system for measuring operator performance using different assistance techniques. Electromagnetically tracked needles are registered with the preoperative plan to measure placement accuracy and the insertion path. The validation system provides an independent measure of accuracy that can be applied to various methods of assistance ranging from augmented reality guidance methods to tracked navigation systems and autonomous robots. In preliminary studies, this validation system is used to evaluate the performance of the image overlay, bi-plane laser guide, and traditional freehand techniques. Perk Station, an inexpensive, simple and easily reproducible surgical navigation workstation for laboratory practice incorporating all the above mentioned functions in a "self-contained" unit is introduced.

Keywords: validation system, augmented reality, image overlay, mri, needle placement, percutaneous procedures, image guided surgery,

1 Introduction

In recent years, numerous surgical methods have been developed for needle-based surgery. Image-guided percutaneous needle-based surgery has become part of routine clinical practice in performing procedures such as biopsies, injections and therapeutic implants. Contrary to casual observation, needle-based surgery can be an exceedingly complex intervention. Translation and rotation motions, as well as bending and insertion forces can be combined for delicate needle control in needle-based surgery. The workspace and the means for guiding the surgical device, however are extremely limited. Last but not least, detecting and recovering from errors increases the risk of these otherwise appealing outpatient procedures.

Trainees usually perform needle interventions under the supervision of a senior physician. This is a slow and inherently subjective training process that lacks objective, quantitative assessment of the surgical skill and performance. A comparative validation environment is necessary for an efficacious analysis of CT/MRI guided assistance techniques to be used in needle placement procedures. Clinical equipment is prohibitively expensive and often inadequate for precise validation. Precise measurement of placement accuracy by MRI is greatly limited by paramagnetic needle artifact and lack of distinct small targets. Scanner time cost can exceed $500/hour making statistically significant trials impractical. To address these issues, we have developed a laboratory validation system for measuring operator performance of different assistance techniques and furthermore we are developing the *Perk Station*, an inexpensive, simple and easily reproducible surgical navigation workstation for laboratory practice with non-biohazardous specimens.

The validation system can be applied to various methods of assistance ranging from augmented reality guidance methods to tracked navigation systems. Preliminary accuracy assessment of our MR image overlay system has been performed, but the excessive cost of scanner time has thwarted a large-scale study of the accuracy of this system. Therefore, an off-line validation system has been created in order to study needle placement accuracy; in particular we look at the accuracy of the image overlay and compare it to that of other insertion guidance methods. This system will also provide a means to study the trajectory and gestures [1] throughout the insertion procedure in addition to the endpoint accuracy. The study of hand gestures for each of these methods will provide useful information that can be used to help minimize the number of re-insertion attempts needed, as each re-insertion causes significant discomfort to the patient. This system provides a less resource exhaustive and more accurate means by which to validate needle insertion procedures.

In this paper, we describe the needle insertion validation system shown in Fig. 1, its use for comparative analysis of the virtual image overlay, the bi-plane laser guide and unassisted freehand techniques. We also introduce the *Perk Station*, a "self-contained" system designed as a clinical training and evaluation system.

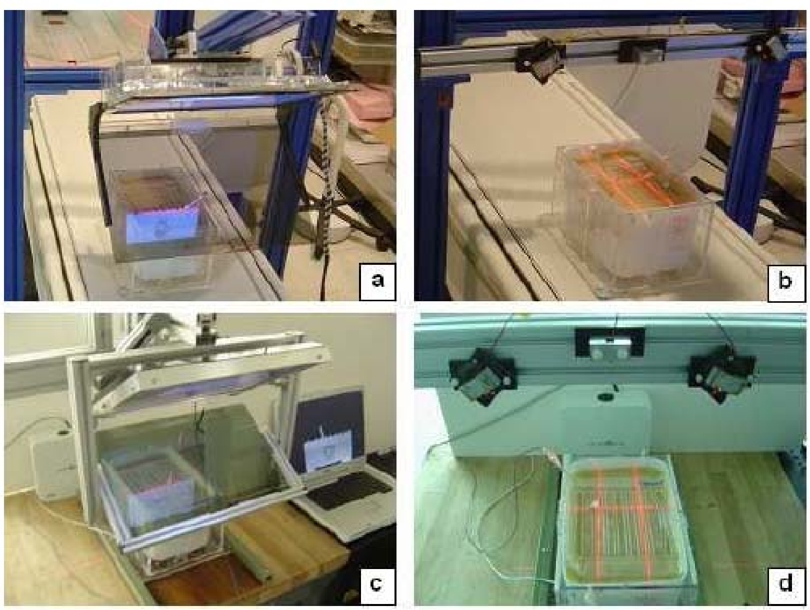

Figure 1. Image overlay (a, c) and bi-plane laser guide (b, d) AR needle placement systems with spine phantom. Feasibility trials in the MRI scanner (a, b) and the validation system with EM tracked needles in the laboratory (c, d).

2 System Description

The image overlay consists of a flat display and a half-silvered mirror mounted on a gantry as seen in Figure 1 (a,c). After calibration, when the physician looks at the patient through the mirror, the CT/MR image appears to be floating inside the body with the correct size and position as if the physician had 2D ‘X-ray vision’ regardless of view angle without any external tracking. Prior to needle insertion the image is transferred directly in DICOM format to the planning and control software running on a stand-alone laptop where we mark the target and entry points, draw a visual guide along the trajectory of insertion, mark the depth of insertion and push this image onto the overlay display [2]. The physician inserts the needle using the traditional workflow, while the overlay provides in-situ anatomical and guidance information in the image plane. The laser guide uses two laser planes; one transverse plane and one oblique sagittal plane as seen in Fig. 1 (b,d). The intersection of these two laser planes marks the needle insertion path. For convenience, a second oblique sagittal laser can be added to support bilateral interventions [3]. In tracked navigation [4], the planned needle path can be superimposed in orthogonal planes, in oblique plane including the needle, or in transparent volumes

2.1 Validation System

Electromagnetic (EM) tracking (Aurora, Northern Digital, Waterloo, Ontario) is utilized to provide the position of the tip and orientation of the shaft of an instrumented needle as described in [5]. All necessary components must be registered with one another in order to track the needle with respect to the preoperative plan generated on the MR/CT images. The components of the system include: the Aurora EM Tracker, a tracked needle, the tracked phantom, the MR/CT images used for pre-operative planning and the AR guidance system (e.g. image overlay or laser guide). The system is shown in Fig. 1.

2.2 Phantom Design

A human cadaver lumbar spine phantom was designed to mimic the anatomy of a patient and aid in the process of registration. Lumbar vertebrae and simulated intravertebral discs are placed in proper alignment and are embedded into a layered tissue mimicking gel (SimTest, Corbin, White City, OR) of two different densities emulating fat and muscle tissue. The gel phantom with lumbar spine is placed into an acrylic enclosure which was accurately laser-cut with 28 different pivot points spread over four sides for rigid-body registration. Stereotactic fiducial markers (MR-Spots, Beekley, Bristoll, CT) were placed on the phantom in precisely positioned laser-cut slots. The markers were placed in a ’Z’ shape pattern on three sides allowing for automatic registration between anatomical images and the phantom. Modularity allows other anatomical phantom to be placed in the enclosure.

2.3 MR Image Registration

In order to register preoperatively obtained MR or CT images (and their respective preoperative plans) to their corresponding physical space, techniques similar to those described in [6] are used (Fig. 2).

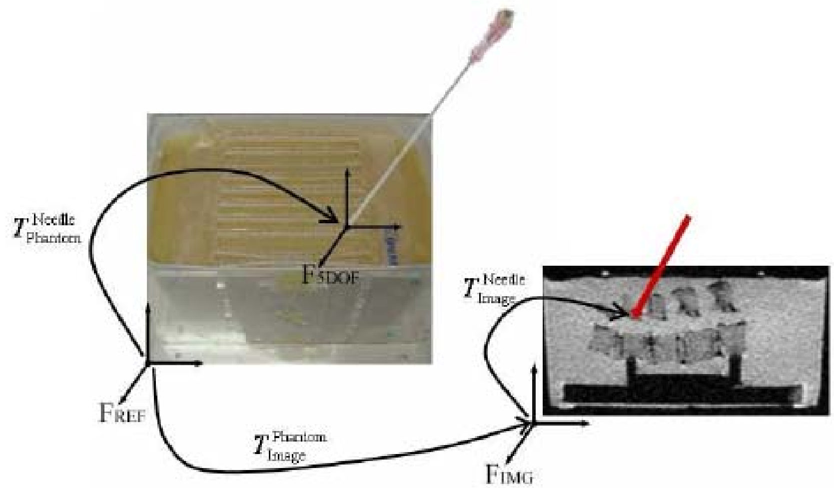

Figure 2. Frame transformations for the registration process shown on the spine phantom and its corresponding MR images. The tracked needle is represented in the original image space where the preoperative plan was made.

Axial images are taken near the center of the phantom; the locations of other images of the phantom are known with respect to this reference. The central image is used for registration, here the nine fiducial markers arranged in three Z-shaped patters are segmented by applying an adaptive threshold and morphological operations to the image. The centroid of each marker was then found and the position of each marker with respect to the DICOM image was recorded into a set of nine points. After the nine distinct points were identified, the transformation from the scanner's image space to the phantom's coordinate system was computed. The RMS error incurred in the image to phantom space registration for a typical MR image was 1.26mm.

2.4 Electromagnetic Tracker Registration

The NDI Aurora EM tracking system is used to localize an instrumented needle with respect to the phantom. A six degree-of-freedom (DOF) reference tool is fixed to the phantom and a calibrated pointer tool is used for rigid-body registration of the phantom to the tracker. Data was obtained by pivoting about 24 pre-defined divot points with the pointer. These points were used for registration between phantom coordinate system and that of the EM tracker by finding the transformation which aligns the known point locations obtained from the mechanical design specifications with the collected data points. The RMS error incurred in the rigid-body registration was 0.93mm. Once both steps in registration are complete, an instrumented needle may be tracked as it maneuvers along a planned path within the phantom. To maximize the system's accuracy, future efforts will include distortion mapping and error compensation similar to that described in [7].

2.5 Perk Station

The *Perk Station* comprises image overlay (Fig. 1 a,c), laser guide (Fig. 1 b), and standard tracked freehand navigation (Fig. 1 d), in a single suite. The general system concept is shown in Fig. 3. A detailed view of the *Perk Station* is shown in Fig. 4.

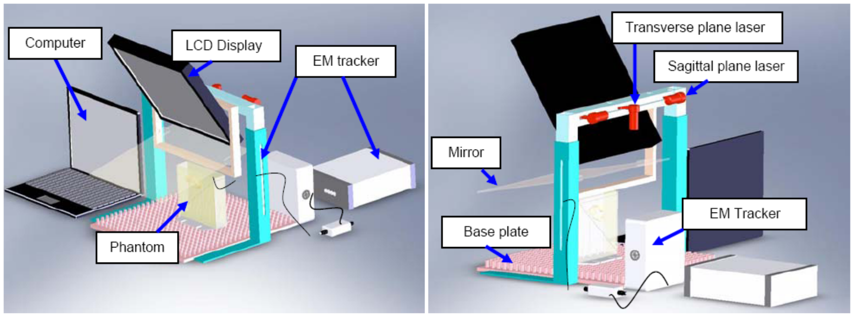

Figure 3: CAD design of the Perk Station: image overlay (left) and laser guide (right) shown with EM tracked navigation system.

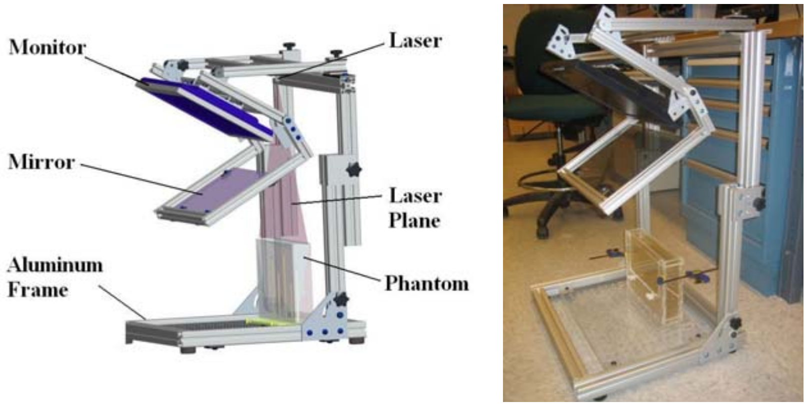

Figure 4: Perk Station with Image Overlay unit. CAD model (left) and physical realization (right) of the current design.

In all cases, the needle is tracked in real-time during the course of the insertion, not only the final tip position. The Aurora electromagnetic tracking system provides the tip position and axis orientation of the needle. The image overlay is mounted on one side and the laser guide and tracked navigation system on the opposite side. The user can swap between guidance techniques by turning the system around. Traditional freehand interventions can be evaluated by only using the transverse laser plane, functionally similar to the ones on the face of the MR scanner. The extruded aluminum frame is sufficiently strong to hold the weight of all components, yet the system is still sufficiently lightweight to be portable in a suitcase.

Another important part of the system is the “real-time” nature of the phantom shown in Fig. 5. Geometrical or anatomical phantoms are housed in an interchangeable rigid box (inside box). A reusable external housing (outside box) is equipped with external markers (stereotactic fiducials and EM tracking coils), and can be easily realigned under the overlay. The phantom and needle are tracked with respect to each other and registered to the MR/CT images. Using such phantoms, we can acquire MRI images for targeting, but then perform the needle placement in the laboratory. This arrangement makes it possible to perform hundreds of needle placements without holding up the MRI scanner, while the accuracy of electro-magnetic needle tracking significantly surpasses the usual accuracy of MRI-based evaluation.

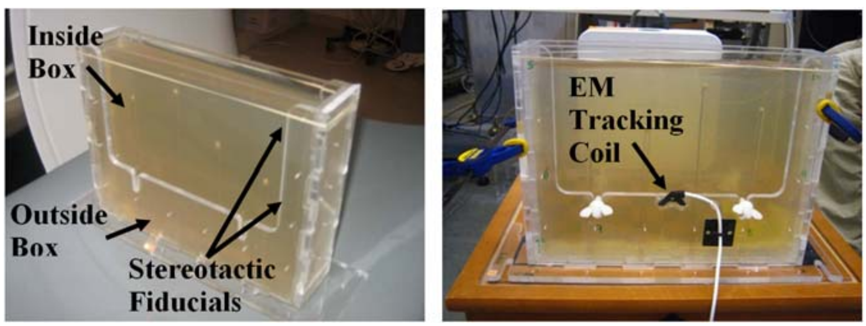

Figure 5: The “real-time” phantom.

3 Experimental Methods

Prior to beginning trials, numerous needle paths were created in the EasySlice planning software that the authors have developed and is described in [2]. The software stores the insertion and target points for each planned path as well as the angle of insertion needed to accurately reach the desired target. For each of the three needle insertion methods (image overlay, bi-plane laser guide and freehand interventions) presented, subjects were randomly assigned three different paths in three different axial MR slices. The entire insertion attempt was recorded with the tracking software. The software then provides insertion and target point error, both in and out of the image plane. Needle axis orientation error is also computed. Simple forms of gesture tracking are now provided, including distances from the trajectory during insertion and the number of re-insertion attempts.

4 Results

To demonstrate workflow, four needle insertions were performed with each technique in a clinical MRI environment. As expected, accuracy could not be assessed due to large artifacts as shown in Fig. 6(a). In the validation testbed, the measured needle trajectories were graphically overlaid on the plan and targeting MR image as shown in Fig. 6(b). Twenty insertions were performed with each technique. Position and orientation errors were measured. Initial analysis showed that the results correlate with direct validation performed using fluoroscopy described in [3]. The image overlay's mean error in the image plane was 1.4mm and 2.5^o with standard deviations of 0.5mm and 1.9^o respectively. The laser guide's average error was 1.8mm and 2.0^o (1.2mm and 1.8^o standard deviation), and freehand produced average errors of 2.0mm and 5.2^o (1.4mm and 2.3^o standard deviation).

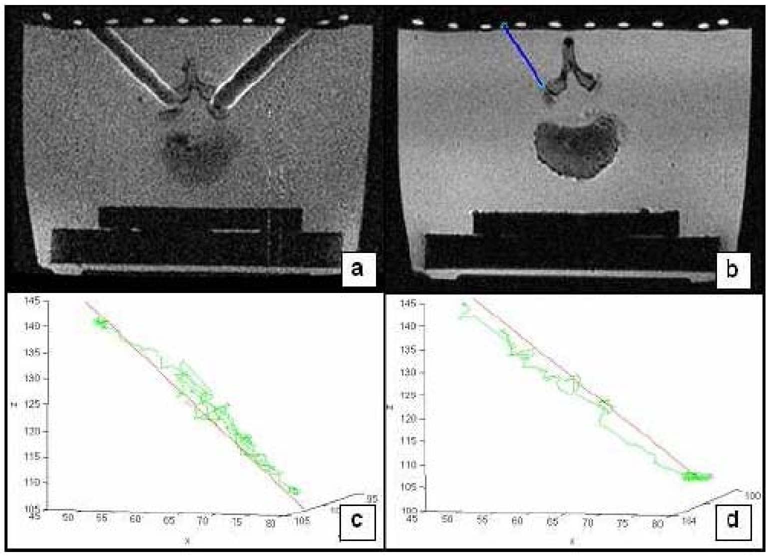

Figure 5. Typical results from an MR image (a) and a tracked path (b). Logged trajectory showing multiple corrections (c) and direct path (d).

5 Discussion and Conclusion

Initial assessments of the image overlay, laser guide, and freehand needle insertions were performed with the validation system. Experiments with experienced radiologists are currently underway. Future experiments will provide independent, large scale accuracy assessment of needle insertion procedures using commercial surgical navigation systems, image overlay, laser guidance, and traditional techniques. The goal is to quantitatively compare placement accuracy, consistency, and other important characteristics such as the needle trajectories throughout the entire placement procedure.

In typical needle placement procedures, the interventionalist will often probe the patient's anatomy until the desired target is reached. This probing action can result in a great deal of discomfort to the patient as well as significant bruising to the area. Analysis of the needle trajectory can provide information about the number of insertion and repositioning attempts that were made during an intervention. Fig. 5(c) illustrates a trajectory that resulted from repeated reinsertions and Fig. 5(d) shows an insertion with minimal repositioning attempts. This information enables researchers to study the systems' ability to minimize discomfort to the patient during the procedure.

The *Perk Station* is designed to be a replicable and adaptable tool for teaching computer-assisted surgery at all levels. To promote transferability, the complete design of the Perk Station, including hardware blueprints, phantoms blueprints, and software source code will be made publicly available as open source. Simple design and low costs allows interested parties to replicate the hardware and install the software. CT/MRI data and pre-made surgical plans will also be provided, so that users can operate the Perk Station without having access to medical imaging facilities. It is a small, portable, and light weight, and fits in a suitcase when disassembled. The apparent simplicity of the *Perk Station* should not underestimate its potential in teaching and training medical professionals, particularly medical students and residents. There is a general misperception and under-appreciation among the public of the skills required for needle based surgeries. In reality, trainees gravitate to learning centers where procedural skills are taught. There is popular trend toward minimization the steep learning curve associated with surgical interventions through the use of simulators. Static or declining reimbursements have driven the need for economical solutions: training systems of with accuracy, efficiency, simplicity, and low cost. The *Perk Station* promises to fit in these trends eminently.

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