

Perk Station—Percutaneous surgery training and performance measurement platform

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ARTICLE INFO

Article history:

Received 24 February 2009

Received in revised form 27 April 2009

Accepted 5 May 2009

Keywords:

Image guidance
Needle placement
Augmented reality
Surgical training

ABSTRACT

Motivation: Image-guided percutaneous (through the skin) needle-based surgery has become part of routine clinical practice in performing procedures such as biopsies, injections and therapeutic implants. A novice physician typically performs needle interventions under the supervision of a senior physician; a slow and inherently subjective training process that lacks objective, quantitative assessment of the surgical skill and performance. Shortening the learning curve and increasing procedural consistency are important factors in assuring high-quality medical care.

Methods: This paper describes a laboratory validation system, called Perk Station, for standardized training and performance measurement under different assistance techniques for needle-based surgical guidance systems. The initial goal of the Perk Station is to assess and compare different techniques: 2D image overlay, biplane laser guide, laser protractor and conventional freehand. The main focus of this manuscript is the planning and guidance software system developed on the 3D Slicer platform, a free, open source software package designed for visualization and analysis of medical image data.

Results: The prototype Perk Station has been successfully developed, the associated needle insertion phantoms were built, and the graphical user interface was fully implemented. The system was inaugurated in undergraduate teaching and a wide array of outreach activities. Initial results, experiences, ongoing activities and future plans are reported.

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1. Introduction

1.1. Image-guided needle interventions

Significant efforts have been devoted to image-guided percutaneous (through the skin) needle-based interventions during the past decade. Through the past two decades, there has been particularly strong interest in computed tomography (CT) guidance for a wide variety of needle-based procedures, including tumor biopsy [1], aspiration [2,3], neurological pain management [4,5], and a variety of tissue ablations [6–9]. Currently, over one million CT-guided interventions are performed in the U.S. every year. Magnetic Resonance Imaging (MRI) guidance has been somewhat lagging behind CT image guidance, but has been steadily gaining popularity and acceptance. For a long time, MRI has been known for its unmatched potential for guiding, monitoring and controlling therapy [10,11]. Even during the early years of MRI when high field

scanners were less common and image quality was poorer than today, MRI was found to be a superior image guidance modality in percutaneous procedures: it provided high sensitivity in detecting lesions allowed for good visualization of the pathology, and was superior soft tissue contrast helps to avoid critical structures in the puncture route [12,13]. Minimally invasive diagnostic and therapeutic image-based interventions have been performed under near real-time MRI guidance [14]. The trend that started nearly a decade ago continues today, with even better and faster scanners [15] and advanced assistive devices such as in-scanner robots [16].

In most image-guided needle placement applications, the success of the procedure is directly linked to the spatial accuracy of needle placement. This effect is particularly definitive, for example, in biopsy and other diagnostic procedures, where missing the target anatomy will likely result in faulty diagnosis. In localized treatments like radio-frequency ablation, needle placement accuracy is also of crucial importance, because faulty needle placement has been known as the most significant cause of failure [8]. Faulty needle placement may also violate sensitive structures, which exposes the patient to great risk and pain. Potential limitations of conventional unassisted free-hand needle placement include the

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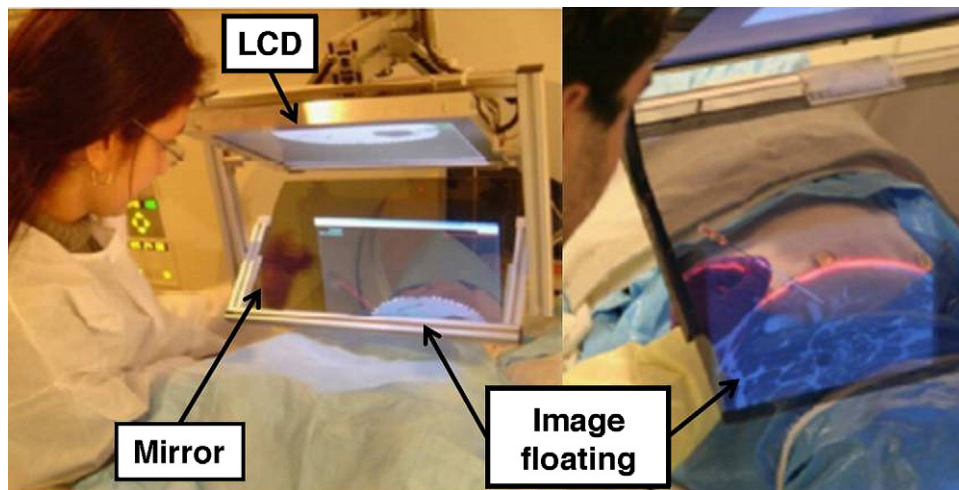


Fig. 1. The 2D image overlay concept, with CT (left) and MRI (right) guidance, cadaver experiments at the Johns Hopkins University Hospital.

physician's ability to align and maintain the correct trajectory and angle toward a lesion, especially in case of deep lesions. In contemporary practice, images are displayed on the operator's 2D console only outside the treatment room, where the physician plans the intervention. Then the physician enters the room, mentally registers the images with the anatomy of the actual patient, and uses hand-eye coordination to execute the planned intervention.

1.2. Surgical assistance techniques

To aid the physician in image-guided freehand needle placement procedures, an array of assistive techniques, such as medical robots, handheld needle guides and mechanical arms have been tried out.

A comprehensive review of surgical robotics can be found in literature [17–22]. Generally, it has been felt that robotics, especially in CT-guided procedures, brought significant cost and engineering complexity into the otherwise relatively straightforward needle placement procedures and therefore have not made a breakthrough to routine practice.

Bidwell patented a passive needle guided on a table-mounted arch system [23], but there is no published evidence of clinical use of it. Conceptually similar restraining systems combined with stereotactic instrumentation [24,25] also did not become popular, most likely because positioning the patient in the fixation system was prohibitively complex.

Handheld needle guides have been proposed by Palestrant [26] and a similar device was developed at the Johns Hopkins University, where the needle guide is preset to the desired insertion angle and the bubble level is held horizontally in-line with the transverse laser plane.

Several studies have found biplane laser guidance to be helpful in CT-guided insertions [27–29] and more recently in Refs. [30,31]. Here the trajectory of the needle is marked by the intersection of the transverse and a parasagittal laser planes. In order to support bilateral interventions, two parasagittal laser planes were used.

Several research groups have investigated true three-dimensional (3D) augmented reality systems ([32–37,38–40,66]), and chiefly among those, head-mounted display (HMD) devices ([35,36,38,39,41,42–44,66]). Contemporary 3D augmented reality devices require painstaking calibration and real-time spatial tracking of multiple (often four or more) components. These systems involve extensive engineering entourage and thus have not gained acceptance beyond pilot trials. To overcome some of the aforementioned limitations of 3D in-situ visualization and needle guidance, a simple yet powerful two-dimensional (2D) image

overlay concept was developed by authors at the Johns Hopkins University, offering CT-guidance [45] and MRI-guidance [46]. Both iterations of the overlay system consist of a flat display and a semitransparent mirror mounted on a gantry. The scanner, display, and mirror are co-aligned so that the reflection of a transverse image appearing in the mirror coincides with the patient's body behind the mirror. When the physician looks at the patient through the mirror, the CT/MR image appears to be floating inside the body with correct size and position as if the physician had 2D 'Tomographic Vision' by virtually slicing the body as shown in Fig. 1. A virtual needle guide along the specified trajectory is superimposed on the overlaid anatomical image. The most attractive feature of the 2D image overlay concept is that the physician has optical guidance in executing the intervention without turning attention away from operative field, while performing the same actions as in conventional freehand procedures.

1.3. Need for training system

Freehand needle placement, even when used with assistive techniques such as image overlay was found to be limited by requiring hand stability [45,46]. A need is seen to develop a training system on which physicians can hone their skills in variety of clinical situations. Surgical training and simulator systems have reported in the recent past for simulating abdominal surgery, gynaecologic or arthroscopic procedures [47,48]. Various simulators for different endoscopic procedures like laparoscopy [49], hysteroscopy [50,51], liver surgery [52,53] and most recently for eye surgery [54] have been proposed. There is little literature pertaining to training systems for performing needle placement interventions. Contrary to casual observation, needle-based surgery can be a complex intervention. Translational and rotational motions, as well as bending and insertion forces can be combined for delicate needle control in needle-based surgery. Space and the means for desired maneuvering of the surgical device, however are extremely limited. Last but not least, detecting and recovering from errors such as internal bleeding increase 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. Current evaluations of needle-based surgery are also rather simplistic: usually only needle tip accuracy and procedure time are recorded, the latter being used as an indicator of economical feasibility. Many important nuances that pertain to collateral morbidity, side-effects,

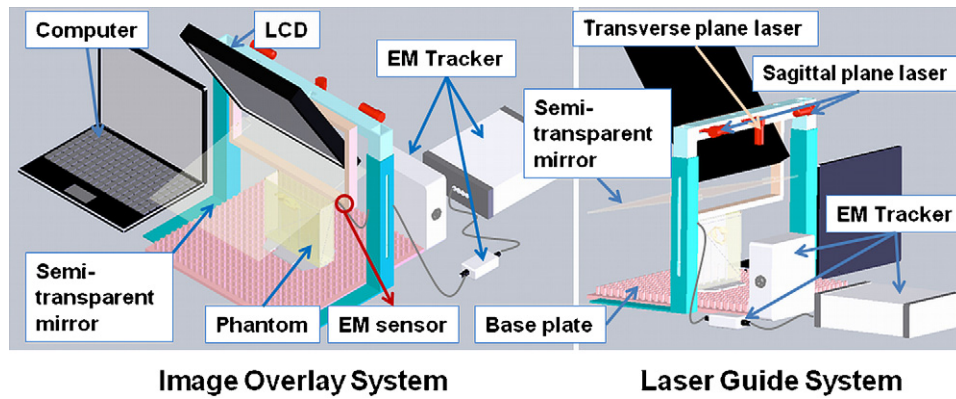


Fig. 2. Perk Station – conceptual design; image overlay (left) and biplane laser overlay (right).

pain and patient discomfort are not captured in current performance evaluation methods.

Inherent to the argument of objective assessment, is the question: what constitutes a fair and standard basis or test, on which trainees can be assessed upon? In a clinical setup, trainees and physicians usually practice on patients or, at best, on animal models. Comparative studies and evaluations across trainees cannot draw statistically significant and meaningful conclusions in such a situation as each trainee is working with a different subject. Also, it becomes impossible to measure the relative performance of the same person with different guidance modalities. Even hypothetically, if in a clinical setup, relative performance on different guidance was to be measured for the same surgeon, it would lead to unsustainably large and winding clinical trials with unsupport-

able costs. The use of a standard phantom with ground truth data, the invariable subject, is a key element to carry out unbiased comparative studies. The convenience and throughput of teaching and practicing the basics using a phantom in lab cannot be overlooked either.

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-bio-hazardous specimens [55,56]. In the long run, this system will also provide a means to study the trajectory and gestures throughout the insertion procedure in addition to the endpoint accuracy. The study of hand, arm, and body gestures for each of these methods

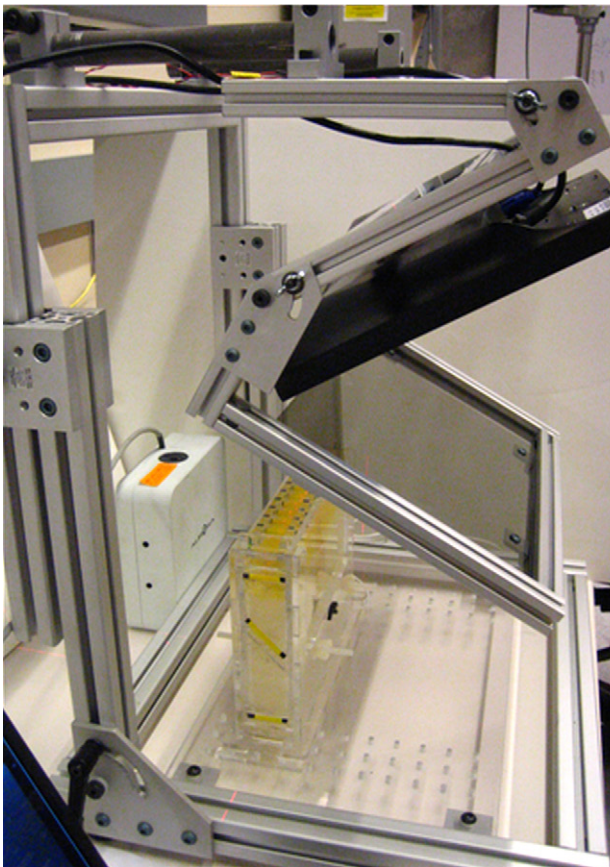


Fig. 3. The Perk Station – actual prototype; image overlay (left) and biplane laser overlay (right).

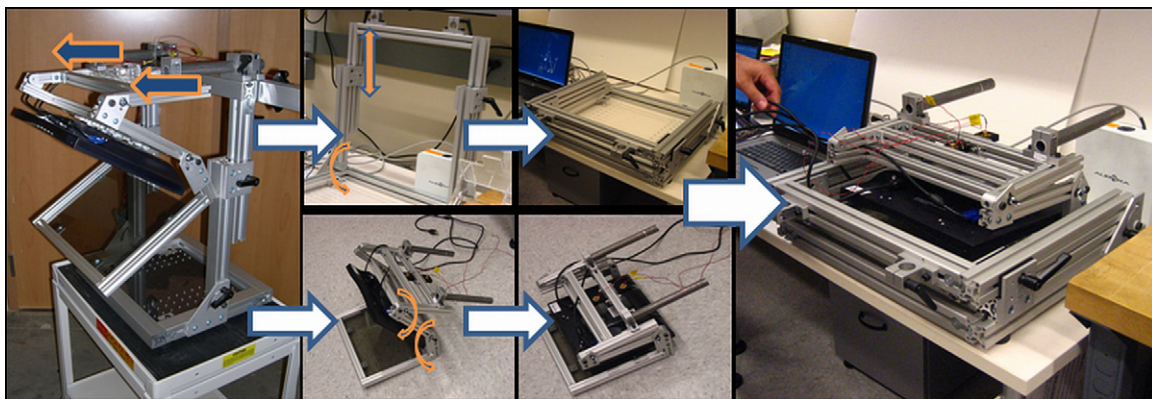


Fig. 4. Perk Station folding for storage and transportation.

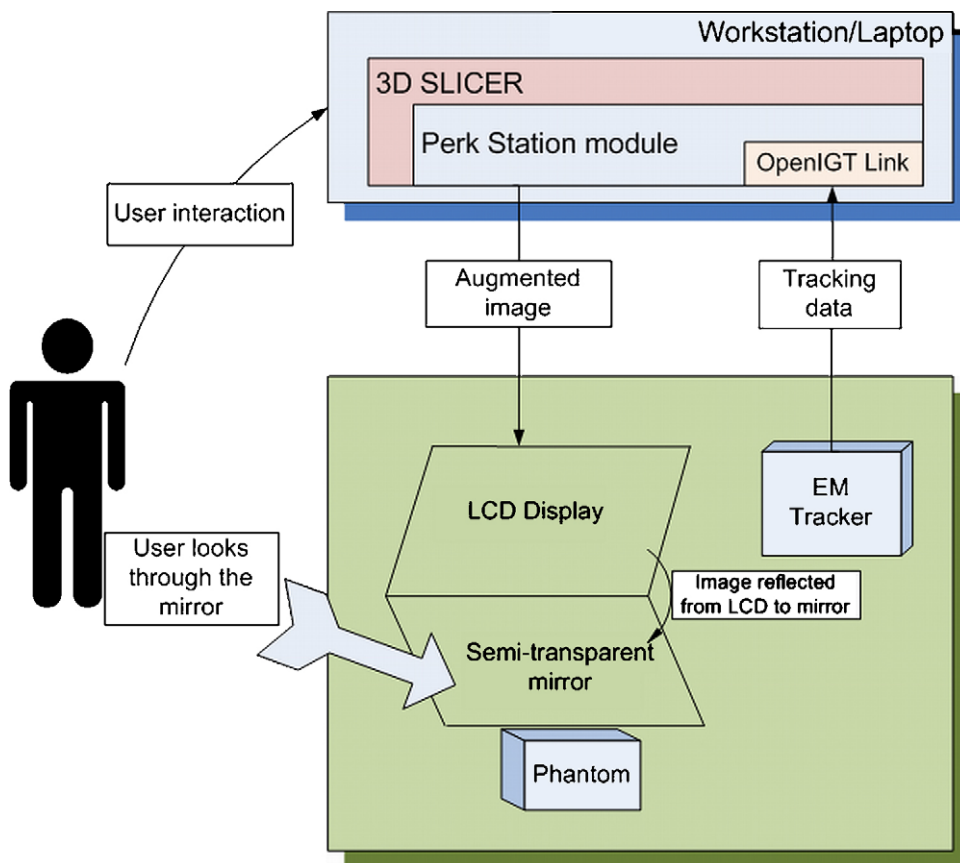
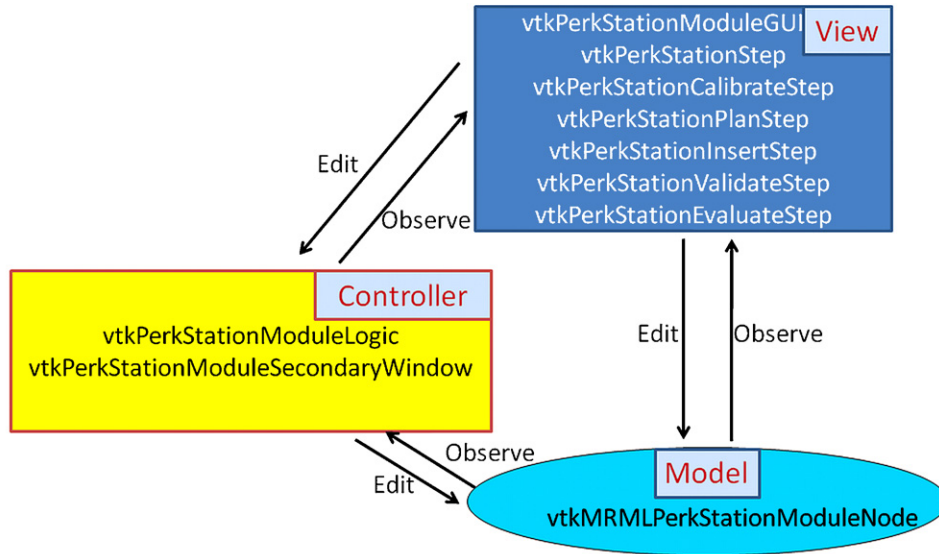


Fig. 5. Software systems perspective.

3D SLICER			
Slicer base	Module 1	Module 2	Module N
VTK	ITK	Tcl	KWWidgets
OpenGL		Window system	
Computer hardware			

Fig. 6. 3D Slicer abstraction diagram.

Perk Station module architecture: Observer “MVC” pattern



“Observe” means generic event mechanisms are used to pass information.
 “Edit” means code can directly call methods

Fig. 7. Perk Station modular software architecture.

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 and risk to the patient. This system promises a less resource exhaustive and more accurate means by which to validate needle insertion procedures. We intend to point out that primary objective of this work is to unite most of our prior contributions under one training and evaluation platform, and making it extensible to integrate other assistance techniques.

2. Perk Station: System design and implementation

2.1. Hardware design

The Perk Station supports the following guidance modalities: 2D image overlay [45,46], biplane laser guidance [30], handheld laser protractor and, single transverse laser for conventional free-hand needle insertion. The Perk Station is trivially extensible to

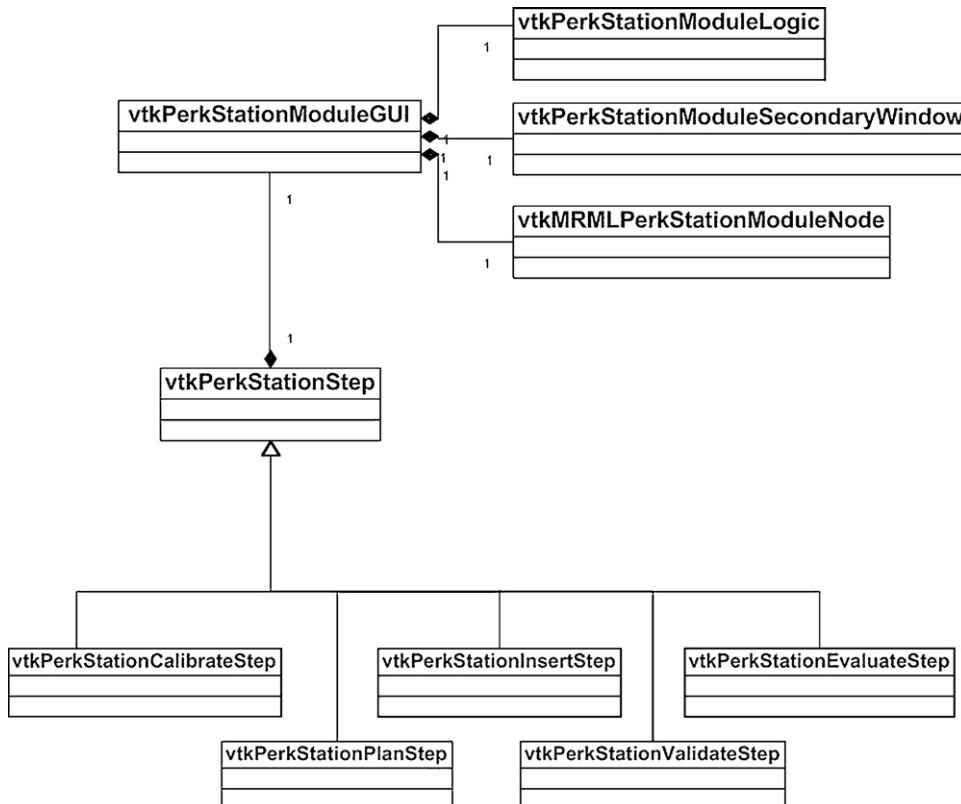


Fig. 8. Perk Station module class diagram.

support tracked freehand navigation, such as provided in the well-known Stealth Station® (Medtronic SNT, Louisville, CO). As an offline training system, the Perk Station uses non-bio-hazardous phantom subjects and is driven by a single laptop computer. For trajectory and gesture study, an electromagnetic (EM) tracking system (Aurora System-Northern Digital, Waterloo, Ontario) is incorporated. The conceptual design of the complete system is shown in Fig. 2.

The overall system consists of a flat panel LCD display, a transverse plane laser, two parasagittal plane lasers, and an electromagnetic tracker. The image overlay system shown in Fig. 3(left) comprises of a flat panel LCD display and a semi-transparent mirror aligned in such a manner that the reflection of the image appearing in the mirror coincides with the phantom behind the mirror. The transverse plane laser provides additional guidance in image overlay technique, as the image projection plane coincides with transverse laser plane. The Perk Station uses image data and is not modality specific; thus it can support both CT and MRI without the need of altering its design configuration. The biplane laser system shown in Fig. 3(right) consists of two parasagittal plane lasers and a transverse plane laser. Two parasagittal lasers are incorporated in the system to accommodate bilateral needle insertions. The transverse plane laser defines the z-plane of insertion, while the adjustable parasagittal laser defines the in-plane needle angle. The line of intersection of the parasagittal lasers and the transverse plane laser defines the needle trajectory. In conventional freehand technique, the transverse plane laser alone is used for guidance. The EM tracker can be used alone or in conjunction of image overlay for gestures and/or trajectory studies. By tracking the needle tip and the phantom simultaneously, we can also measure the accuracy and trajectory of needle placement in complex non-transparent phantoms. The image overlay is mounted on one side of the system and the laser guidance on the opposite side. The user can swap between the techniques simply by turning the system around. The handheld laser protractor and conventional transverse laser guidance is available on the biplane laser side, by simply turning off the parasagittal lasers.

The main structure of the Perk Station is an extruded aluminum frame, which is light weight but sufficiently strong to hold the weight of all devices. The base plate is designed to allow the phantom to be translated from one side to the other side during the training. The structure is designed to be portable, and is therefore sufficiently lightweight and able to be folded to be placed in a suitcase as seen in Fig. 4. The overall dimensions of the folded system are $57 \times 55 \times 29$ cm. The weight of the whole system including with main structure and image overlay system is 16.5 kg. We chose a balance between high structural stability and light weight. In the laboratory, we favor increased accuracy over easy portability. A lighter, more portable but somewhat less accurate version suffices for demonstrations and outreach purposes.

2.2. Software design

2.2.1. Software systems architecture

From the software systems perspective, the major components are: Perk Station LCD display, corresponding mounted mirror, EM tracker, and a workstation or laptop running a graphical user interface. Fig. 5 depicts how the components interact. The workstation/laptop running the software 3D Slicer, is connected to Perk Station LCD display over a DVI port. The EM tracker is connected through a serial port to the workstation. The user interacts with navigation software that communicates a graphically augmented image over the DVI port to Perk Station LCD display; by virtue of mechanical arrangement, the augmented image is projected over to the semi-transparent mirror and appears to float within the phantom; software receives needle and phantom tracking data sent by

EM tracker through OpenIGTLink [57] protocol, and updates the needle position/orientation on the augmented image.

2.2.2. 3D Slicer as development environment

We chose 3D Slicer¹ as the platform of the Perk Station graphical user interface (GUI). 3D Slicer is a free, open source software package designed for visualization and analysis of medical image data. 3D Slicer utilizes underlying open source software libraries: Insight ToolKit (ITK) [58] for image analysis, segmentation and registration; Visualization ToolKit (VTK) [59] for visualization and interactive rendering and manipulation; OpenGL for graphics acceleration; Tcl/Tk and KWWidgets for GUI deployment. Fig. 6 depicts the layers of abstraction for 3D Slicer. 3D Slicer acts as an *end-user application* environment that provides a cross-platform GUI framework. There are many compelling features of 3D Slicer that makes it an ideal choice for us to deploy our software through its framework. Among many, we list the quintessential features of 3D Slicer that enables our application:

2.2.2.1. Open source, and modular architecture. The modular architecture of 3D Slicer allows for seamless integration of a custom 'software module'. 3D Slicer has undergone a very rigorous software design process. It follows Observer Module/View/Controller (MVC) design pattern [60] that maximizes component reusability. This is achieved by isolating logic (controller) from user interface (view) considerations resulting in an application where it is easier to modify either the visual appearance of the application or the underlying logic without affecting the other.

2.2.2.2. Multiple segmentation, registration, and algorithms. Registration of planning image and validation image is a requirement for our application to compute targeting errors. 3D Slicer has many registration algorithms built-in that were contributed by researchers around the world. Specifically, segmentation and image enhancement filters are also potentially useful for us.

2.2.2.3. GUI framework and ability to customize the GUI layout. The existing well-defined GUI framework and ability to customize it lets us plug-play the functional code of our application. The default layout of three orthogonal 2D-slice viewers and a 3D viewer can be rearranged to one's requirement. There is a separate dedicated panel for module-specific GUI controls.

2.2.2.4. Visualization. Slicer provides the capability to render and visualize multiple volumes/images in 2D orthogonal views, oblique views and 3D view.

2.2.2.5. Medical reality modeling language (MRML) support. Visualizing medical data involves combining various types of data sets (images, transforms, label maps, etc.) into a single scene. MRML [61] is format defined in 3D Slicer as a standard for describing such scenario.

2.2.2.6. Transformation mapping. The coordinate transformations from image space to scanner/device space, and to and from display space is accomplished by means of separate transformation matrices. This kind of representation facilitates effective management of secondary display attached to Perk Station.

2.2.3. Software components and architecture

Fig. 7 shows the software architecture of the Perk Station module that conforms to MVC pattern as is followed in the 3D Slicer's software design process. In MVC, the *model* represents the information

¹ 3D Slicer is available as an open source download at <http://www.slicer.org>.

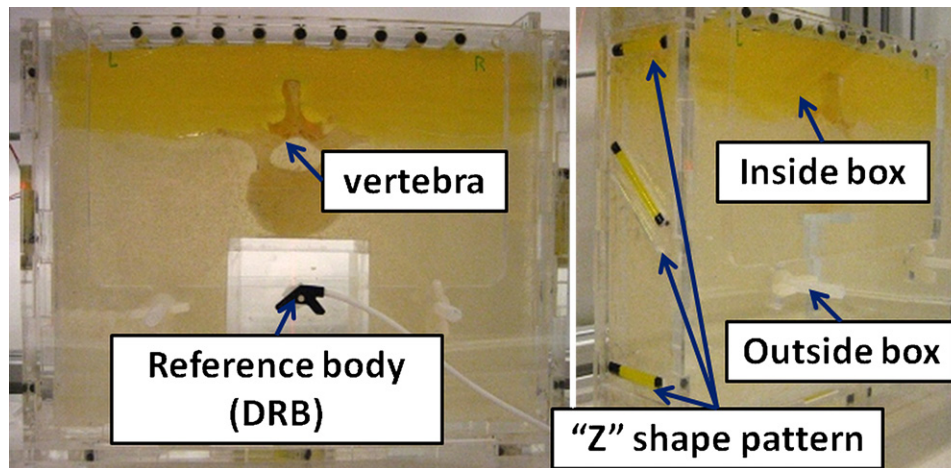


Fig. 9. Lumbar vertebra phantom.

(the data) of the application; the *view* corresponds to elements of the user interface; and the *controller* manages the communication of data and the rules used to manipulate the data to and from the model.

Correspondingly, for Perk Station: MRML node houses all the data (images, transforms, calibration parameters, etc.) representing *model*; GUI, WizardGUIStep(s) that house all the user interface elements, widgets represent *view*; and the Logic, *SecondaryMonitor* that manage the image manipulation (Perk Station's LCD display in our case) by means of transformations represent *controller*. The model, view, and logic interact by observe (event)/edit (call methods). GUI can call methods in MRML and logic classes. Logic can observe GUI and edit MRML node. MRML can only observe logic and GUI classes.

Fig. 8 illustrates the classes of our module, and their relationships. We now describe each class component in a somewhat greater detail. The main responsibility of *vtkPerkStationModuleGUI* is to create the user interface controls (widgets). A workflow based user interface is chosen, in order to be more intuitive. This kind of interface runs like a 'wizard' set-up which guides the user through each step, by loading relevant interface controls, and providing user with intuitive instructions to carry out the task. Besides GUI management, this class is also responsible for handling user interaction via keyboard and/or mouse. It further percolates these user events to be handled in individual steps of the workflow. *vtkPerkStationModuleGUI* notifies and also calls methods in *vtkMRMLPerkStationModuleNode*, *vtkPerkStationModuleLogic*, *vtkPerkStationSecondaryMonitor* with whom it has aggregation relationship.

vtkMRMLPerkStationModuleNode class holds all the data and parameters that define the system state. These include the planning and validation images, information about images, calibration parameters, planned entry and target locations, validation location, and evaluation parameters.

vtkPerkStationModuleLogic class is responsible for providing the functionality of saving the experiment on a xml file, which could be later loaded back in the software for further analysis. Upon request, this class establishes connection with the EM tracker to receive real-time tracking data.

vtkPerkStationSecondaryWindow is a key class that is responsible for managing the display on the Perk Station's LCD display, referred from here on as secondary window, directly, and indirectly what the physician/trainee looks through the mirror. We make a distinction between the secondary display, and the laptop/workstation's display on which 3D Slicer is running. The display on laptop is already managed, specifically the matrix transformations, by 3D Slicer, and

our module within, tailors it to our requirements, however, the image display and corresponding matrices for transformations on secondary monitor are exclusively managed our module. This class has public methods that allow for image to be flipped, scaled, translated, and rotated for calibration step. It also enables for 3D objects, for example needle trajectory in form of a cylinder, to be overlaid on the image for plan and insertion step.

vtkPerkStationSecondaryWindow maintains transformation matrices that define the mapping from display's space to scanner's space; and the matrix that keeps track of all the scale/translation/rotations applied to the image.

vtkPerkStationStep serves as an abstract base class for the individual steps of the workflow. A derived concrete class is defined for each step. This base class has an *aggregation* relationship with *vtkPerkStationModuleGUI* class. The classes derived from *vtkPerkStationStep* are *vtkPerkStationCalibrateStep*, *vtkPerkStationPlanStep*, *vtkPerkStationInsertStep*, *vtkPerkStationValidateStep*, and *vtkPerkStationEvaluateStep*. These classes exploit base class's aggregation relationship to access methods in *vtkPerkStationModuleLogic*, *vtkPerkStationModuleSecondaryWindow*, and *vtkMRMLPerkStationModuleNode* to access system's state parameters.

vtkPerkStationCalibrateStep implements the GUI and functionality of the calibration step the workflow. This class is responsible for providing methods for users to align the fiducials as seen on the image with fiducials as seen on phantom through the mirror, using keyboard and mouse. This is achieved internally by calling appropriate methods in *vtkPerkStationModuleSecondaryWindow*. There is also a functionality to save the calibration settings done in a xml file, which would enable quick re-load if necessary.

vtkPerkStationPlanStep implements the GUI and functionality to plan the intervention. A 'plan' in Perk Station terminology means an entry-target pair. It enables point and click mechanism to mark the entry and target points on planning image. It then automatically calculates, displays the needle angle, needle depth and requests *vtkPerkStationModuleSecondaryWindow* to overlay a trajectory guide to assist the intervention. There is also a capability to save the plan or reset the plan

vtkPerkStationInsertStep implements the GUI and functionality of actual insertion phase. In case, the needle is tracked using EM markers, the class provides the capability to connect to EM tracker and receive tracking data. It uses pre-computed transformations (described in Section 2.5) to bring needle tracking data into image coordinate space. This data is used to overlay the actual tracked needle position and orientation, alongside the planned trajectory.

vtkPerkStationValidateStep performs error computation comparing planned entry-target locations with actual entry-target data

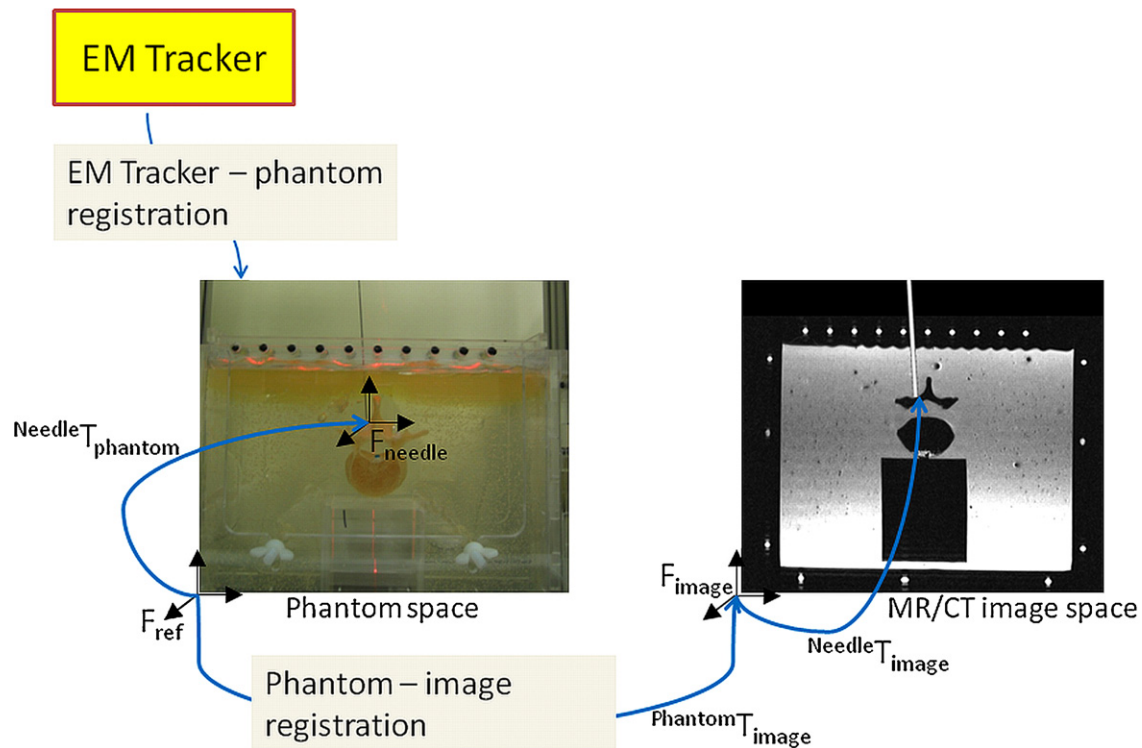


Fig. 10. Coordinate transformation map.

obtained if the needle was electromagnetically tracked. If the needle was not tracked, then a validation image/volume is acquired, which is then registered to planning image to perform the error computation. The user can also specify actual needle path by two clicks on the validation image. There is a capability to reset the validation, in case the user clicked at a wrong location by mistake.

vtkPerkStationEvaluateStep implements GUI and functionality of the final step, which is to present student/trainee with evaluation metrics on how he/she fared with the intervention. This could be variety of metrics, ranging from calibration errors, planning errors to validation and trajectory errors. There is also a possibility to integrate gesture related metrics into this class

2.2.4. Integration of Perk Station module within 3D Slicer

A module can be integrated within 3D Slicer in four possible ways, namely: (1) Built-in modules; (2) Loadable interactive modules; (3) Scripted modules; (4) Command line modules. The 'built-in' modules have complete access to 3D Slicer's internals and are tightly coupled. These types of modules are generally reserved for the core functionality of 3D Slicer. The 'scripted' modules are integrated inside 3D Slicer by means of a Tcl or Python script that describes the module. These modules have limited access to 3D Slicer's internals. The 'command-line' module lets integration of an '.exe' file (Windows platform) or '.so' (Unix platform) along with a module description in form of an xml file. The command-line modules have restricted access to 3D Slicer's internals. Lastly, the 'loadable interactive' modules, are optimally coupled and have complete access to 3D Slicer's internals. We chose our Perk Station module to be integrated as a loadable interactive module inside Slicer, as we found this type of integration as most powerful in terms of its access to internals and seamless in terms of its ease of deployment. The loadable modules don't need to be compiled and built inside 3D Slicer tree. This minimizes the risk of potential code side-effects on core 3D Slicer. For easy deployment, the loadable module can be distributed as a plug-play '.dll' file. This permits

potential user to download/install 3D Slicer from web or keep an existing installation of 3D Slicer, and just copy our module's '.dll' file in the installation directory.

2.3. Visualization/augmented display

The software uses the powerful Visualization ToolKit (VTK) for rendering the image and 3D objects on the secondary monitor. The needle trajectory is rendered as a 3D object overlaid on the monitor by means of OpenGL graphical primitives. The system creates the impression as if the CT/MR image was floating inside the body in the correct pose and magnification, giving the physician tomographic vision. The details of this technique can be found in Refs. [45,62]. This technique can also be characterized as an in-situ visualization tool, where the medical image is rendered in the context of the procedure, spatially registered with the patient's body. This visualization technique does not alter the traditional unassisted procedure to which physicians are accustomed; it rather augments the amount of visual information in the field of action.

2.4. OpenIGTLink interface for EM tracker

The OpenIGTLink protocol [57] is a straightforward programming interface for transferring images, pose measurements, and controls information between components of an Image Guided Therapy (IGT) system. The data is transferred at a user specified rate to a socket. A socket is a programming unit interface provided by operating system, between an application process (in our case, 3D Slicer) and a TCP/IP protocol stack (in our case, OpenIGTLink protocol).

The data received from tracker at serial port is re-packed to follow the OpenIGTLink protocol, and the packed data is relayed over a socket. The OpenIGTLink within Perk Station module listens on that socket to receive the packed data inside Slicer. The data is unpacked to retrieve header information about the device sending the data, and the actual tracking data. The tracking data received is used for

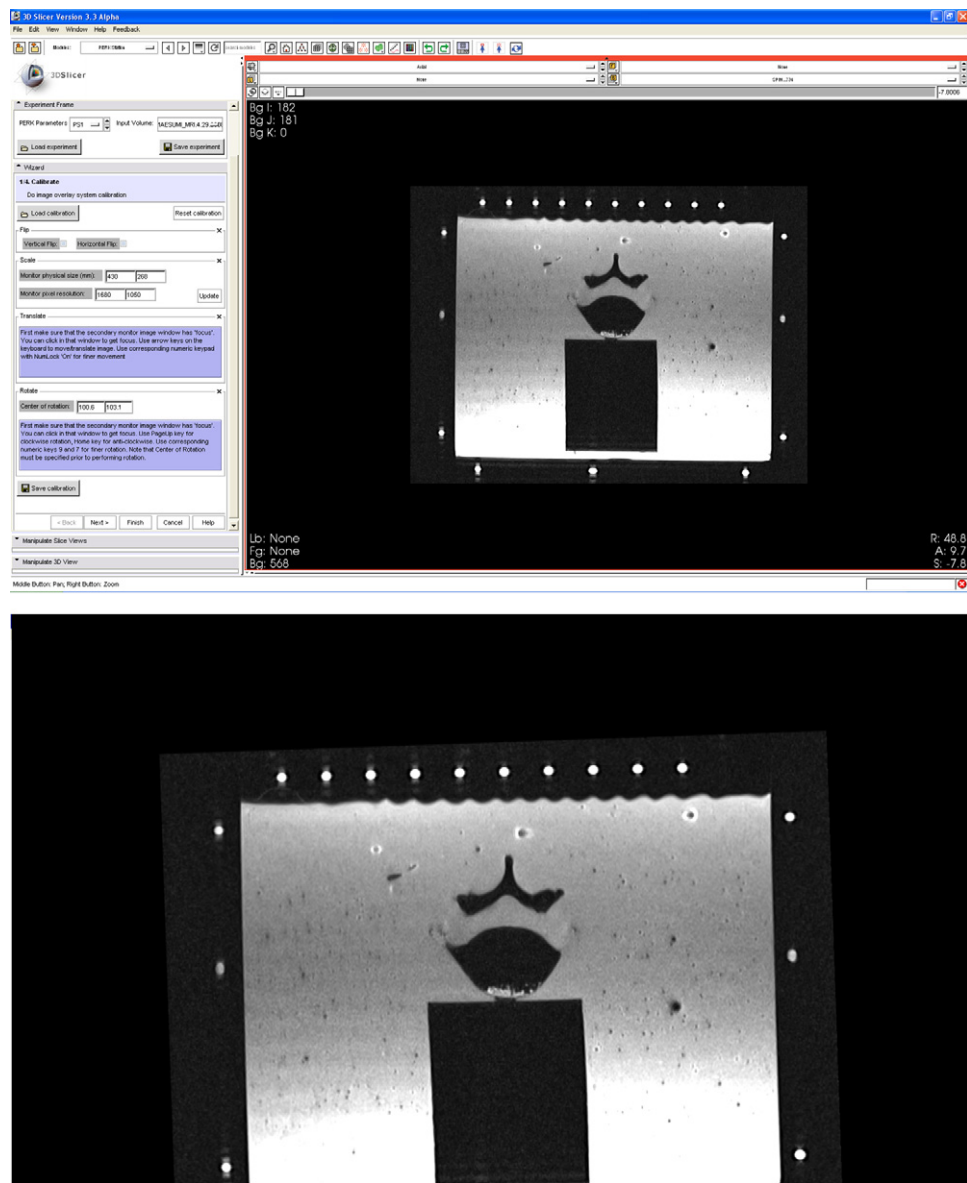


Fig. 11. Calibration step GUI; the calibration take place only on Perk Station LCD display (bottom), the display on the workstation laptop is unaffected (top).

registration and/or visualization to overlay the needle position and orientation on the image.

2.5. Validation system

The components of the validation system are: Aurora EM tracker, a tracked needle, the tracked phantom, CT/MR images used for pre-operative planning and the augmented reality guidance system (e.g. image overlay or laser guide). EM tracking is utilized to provide the position of the tip and orientation of the shaft near the tip of an instrumented needle as described in [63]. All the necessary components must be registered to one another in order to track the needle with respect to preoperative plan generated on CT/MR images.

2.5.1. Phantom design

A human cadaver lumbar spine phantom (Fig. 9) was designed to simulate the physical and anatomical reality of human tissue. Lumbar vertebra was embedded in tissue mimicking gel of different stiffness to emulate muscle and fat layers. Plastisol (M-F, Manu-

facturing Company Inc), the material used in the phantom with the vertebra, were used to simulate the density of muscle tissue. The phantom's two tissue layers were made by mixing different ratios of the Plastic liquid PVC and the plasticizer adipate ("Liquid Plastic" and "Liquid Super Soft Plastic"). The ratios of liquid PVC to adipate for the layers were 4:1 and 5:1 respectively from the bottom to the top. The gel phantom (inside box) with the vertebra was placed in an acrylic enclosure, a reusable external housing (outside box) which was accurately laser-cut with 28 different pivot points spread over four sides for rigid-body registration. Stereotactic fiducials (MR-Spots, Beekley, Bristoll, CT) were placed in the phantom in precisely positioned laser-cut slots. The markers were placed in a z-shape pattern to facilitate registration between the CT/MR and navigation space. A modular design methodology allows for various kinds of geometrical or anatomical phantoms (inside box) to be 'plugged' in the external housing.

2.5.2. Transformation map

Fig. 10 depicts the transformation map between different coordinate systems. EM tracker is registered with phantom by means of

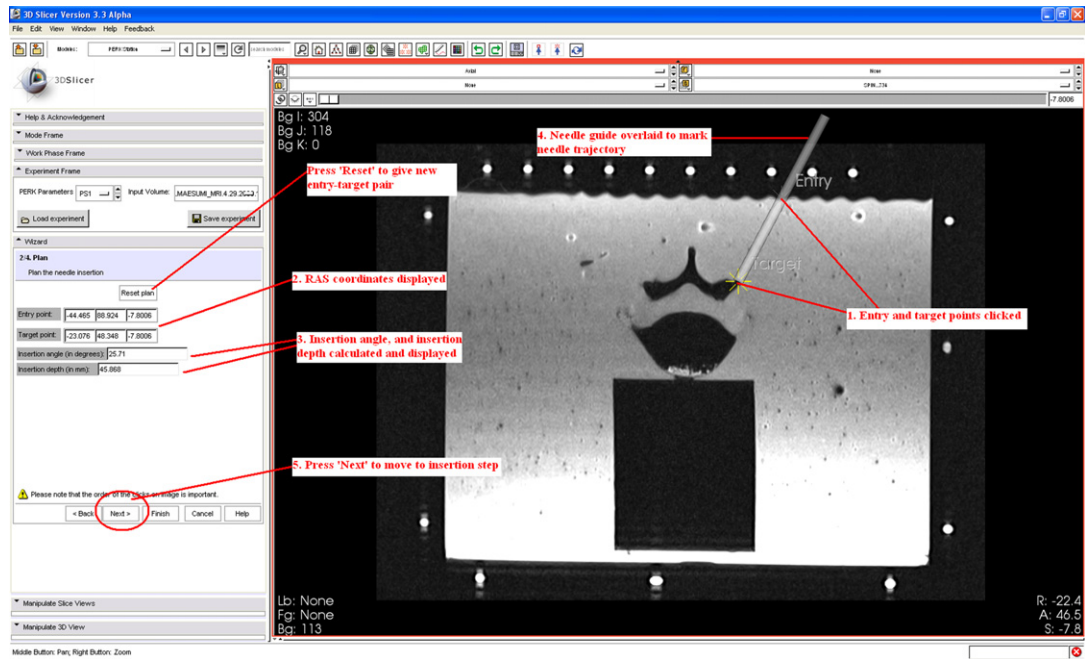


Fig. 12. Planning step GUI; skin entry and target points are given by mouse clicks and then the computer draws a virtual needle guide on the CT/MR image. Insertion depth is calculated and presented to the user.

reference rigid-body mounted on the phantom. The instrumented needle is also being tracked with respect to reference body on phantom; this gives us the transformation from needle to phantom ($NeedleT_{phantom}$). The phantom is registered to CT/MR image coordinate frame; this gives us transformation from phantom to image ($PhantomT_{image}$). Using the two transformations above, one arrives at transformation of needle to image space ($NeedleT_{image}$). Now the needle can be tracked in image space as it maneuvers along a planned path within the phantom.

2.5.3. EM tracker–phantom registration

A dynamic EM tracking reference body (DRB) is mounted on the phantom, and a calibrated EM pointer tool (provided by Northern Digital, Waterloo, Ontario) is used for rigid-body registration of the phantom to the DRB. Data are obtained by pivoting about 28 pre-defined divot points with the pointer. The computed transformation aligns known point locations obtained from the mechanical design

specifications with the collected data points to register phantom coordinate system with that of the EM tracker.

2.5.4. Phantom–image space registration

In order to register preoperatively obtained CT/MR images (and their respective preoperative plans) to their corresponding physical space, techniques similar to those previously described by Lee et al. [64] are used. Axial images are acquired 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. The nine fiducial markers arranged in three z-shaped patterns are segmented by applying adaptive thresholding and morphological filtering. The centroid of each marker is then found, and the position of each marker with respect to the image origin is recorded. After the nine distinct points are identified, the transformation from scanner’s image space to phantom’s coordinate system is computed by aligning the points with known locations. Once both steps of reg-

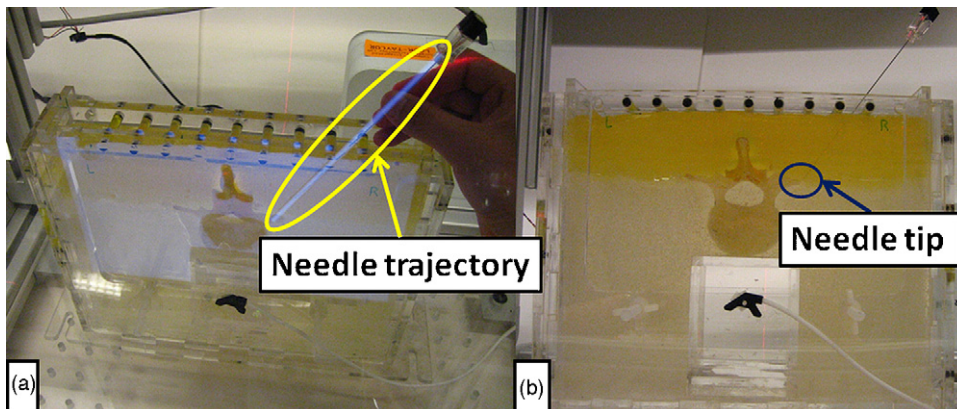


Fig. 13. Needle insertion step; needle trajectory overlaid on image, seen through mirror (left). Validation step; needle tip and trajectory observed in transparent phantom with overlay image turned off (right).

istration are complete, an instrumented needle may be tracked with respect CT/MR image space.

3. Perk Station: System workflow

3.1. Workflow operation in image overlay mode

Multiple axial CT/MR images are acquired of the phantom beforehand. The z-planes of acquisition covering all the targets embedded inside are marked on the phantom to aid the registration process later.

3.1.1. Calibration

The objective of this step is to register the Perk Station with the phantom. The phantom is screwed on the base plate of Perk Station. The position of the phantom is so adjusted that one of the marked z-plane of acquisition coincides with the transverse plane laser guide. The corresponding image is loaded up in the software. In this stage, the software sends the image to the Perk Station's LCD display (secondary monitor), in correct physical dimensions. The image displayed on monitor, gets projected on the mirror, and when seen through the mirror, the image appears to be floating on the phantom. Based on how the secondary monitor is mounted with respect to the mirror, a horizontal or vertical flip may be required. Once the correct flip arrangement is chosen, the image as seen on 3D Slicer display on laptop corresponds to what is being seen through the mirror. Now the software enables the user to translate/rotate the image as seen through the mirror, so that it aligns with the fiducials mounted on phantom to achieve registration. This fiducial alignment achieves in-plane registration. For registration in the z-direction, the image projection plane is aligned with the laser-guide plane, which is also the plane of acquisition. This is achieved by fine-adjustment of mirror-display mount. First we ascertain that the transverse laser plane, the mirror and the display surface are at 60° angle. Second, we ascertain that these three planes intersect in a single line. Third, we check the alignment of all laser planes. It is worthwhile to mention that registration of image only takes place on the secondary monitor. Even though, the image is scaled, moved, rotated, and flipped, the image as displayed on the laptop/workstation stays undisturbed (Fig. 11). This enables the user to zoom in and out the image in the slice viewer during the insertion planning stage, without affecting the calibration. There is an option to save current calibration in an 'xml' file, a function that turned out to be most useful in our practice.

3.1.2. Planning

Once the image overlay and associated lasers are calibrated and registered with the phantom, the software receives the skin entry and target points through mouse-clicks. The software calculates the insertion angle with respect to vertical axis and the insertion depth from the skin entry point. The software graphically overlays a virtual needle guide on the secondary monitor/mirror to assist the user to perform the intervention. There is an option to reset the plan, in case the user wishes to perform another needle intervention with the same image (Fig. 12).

3.1.3. Insertion

If the needle has EM trackers at its ends and is being tracked by the EM tracker, the software can start receiving tracking data, and the actual needle position and orientation can be overlaid on the image, along-side the planned trajectory. Fig. 13 shows the planned trajectory overlaid on the phantom as seen through the mirror.

3.1.4. Validation

Upon completing the insertion, the needle tracking data accumulated over the insertion step is overlaid along-side the planned

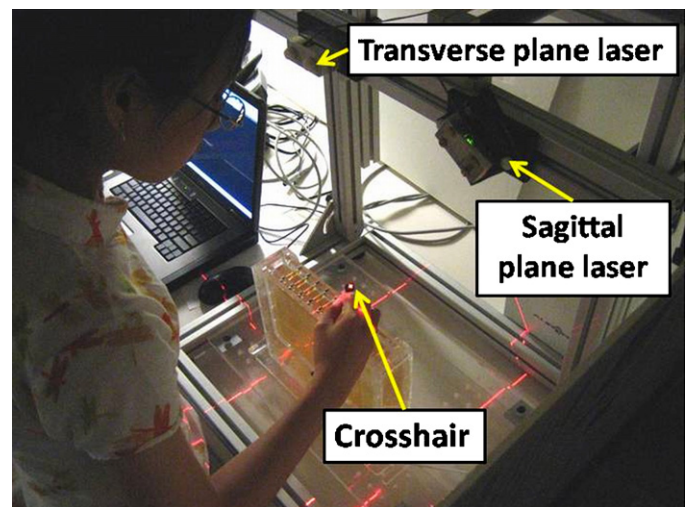


Fig. 14. Needle insertion with biplane laser guidance.

trajectory. Entry point error, target point error, and out of plane error are calculated. The entire needle tract can also be overlaid, qualitatively showing the extent of reinsertions and adjustments needed.

3.1.5. Evaluation

Finally, the user is presented with various error metrics, assessed over all the steps for objective evaluation of the intervention. These may include calibration errors, planning errors, and actual target point errors. Other statistical measures and gesture related measures can also be presented at this step.

At this point, the user can save the whole experiment onto a file. The data about calibration, planning, insertion, validation, and evaluation steps could be of potential use for further analysis or large scale studies.

3.2. Workflow operation in biplane laser guide mode

The software loads up the planning image as with the image overlay. The entry and target points are marked. The software then calculates the insertion angle and insertion depth and provides this to the user. The transverse plane of the laser guide defines the insertion plane. The adjustable angle guide for parasagittal laser is set to the insertion angle using an integrated protractor as directed from software and translated along the rail until the crosshair generated at the intersection of the two lasers (transverse and parasagittal) is coincident with the percutaneous entry point. The trainee places the needle tip at the entry point and aligns the shaft such that a crosshair generated by the intersection of the lasers is also present on the head of the needle. The needle is inserted to the specified depth while maintaining alignment under the laser crosshair as shown in Fig. 14.

3.3. Workflow operation in conventional freehand mode

When used for traditional freehand needle insertion, the software loads up the planning image and the entry and target points are marked as with the previous two modalities. The software then calculates the insertion angle and insertion depth and presents it to the user as would be done on a standard CT/MR console. The trainee inserts the needle with that angle and depth without any concurrent visualization by mentally registering the plan to the physical phantom without any additional guidance.

3.4. Quick practice and demonstration mode

One of the principal functions of the portable Perk Station is quick demonstration, when we usually skip the calibration stage and sometimes even the entire planning stage by reloading previously saved insertion plans, and we usually forego full quantitative evaluation.

4. Initial experience and ongoing work

The Perk Station has been successfully designed and constructed. The accuracy of the image overlay and biplane laser guidance systems was clinically adequate when deployed in actual intra-operative environment [45,46,62]. The major components contributing to inaccuracy of the system are imaging procedure, system calibration and the relative position of the operator's eye. The accuracy of the Perk Station in the laboratory is being evaluated. Another set of experiments are underway with an objective of conducting a gesture/trajectory study. The experimental protocol is as follows. Prior to beginning trials, numerous needle paths are created in the planning. 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, biplane laser guide and freehand interventions) presented, subjects are randomly assigned three different paths in three different axial MR slices. During the entire insertion attempt, needle tracking information is recorded. The software then provides insertion and target point error, both in and out of the image plane. Needle axis orientation error is also computed. As such, there are no performance metrics for a percutaneous surgery. One of the goals of the Perk Station is to support clinical training centers in defining appropriate metrics. The current system measures parameters such as time, accuracy, re-insertions, needle trajectory, and needle dynamics. What these measurements mean in terms of performance, is a subject of current research. Simple forms of gesture tracking are now provided, including distances from the trajectory during insertion and the number of re-insertion attempts. The trials are in data collection phase, post data collection, extensive analysis will follow to extract and pin-point a sequence of labeled surgical gestures that constitute a successful insertion. The ability to automatically detect surgical motions will be useful in evaluating physician dexterity, providing training feedback and enhancing motions during percutaneous surgery, an approach promisingly explored earlier by Lin et al. in laparoscopic robotic surgery [65].

The Perk Station debuted in undergraduate teaching at Queen's University in 2008. This teaching aid served as complimentary practical workbench to theoretical coursework. The hands-on surgical experience provides a new vista to experience interventions. It is especially inspiring and stimulating for young minds as they actually see and participate in, not just read about, an application of engineering in medicine. Currently, the training interface is being optimized and cleaned up before the coming teaching term.

The Perk Station has been presented in various demonstrations and outreach events with overwhelming success. All age groups can connect with the concepts presented in the Perk Station, from very young children, through university students, to adults. The Perk Station has been booked solidly to appear in outreach events and demonstrations throughout the year. In January 2009, we took the Perk Station to its high school debut in biology and computer science classes. Experimenting with the Perk Station appeared to be a profoundly novel and exciting experience for high school students. Many of them seemed to have been energized to learn more about the potentials of computing and engineering in medicine.

This initial experience made us confident that a similar impact would be achieved in a larger outreach program. We are in the process of replicating several copies of the Perk Station. Two systems will remain in our new Undergraduate Surgical Navigation Laboratory at Queen's University and two systems will be assigned to the Computing and High-Tech Academic Mentorship Program (CHAMP) of Queen's University, for nationwide high school outreach tours.

To promote transferability, the complete design of the Perk Station, including hardware blueprints, phantom designs, and software source code will be made publicly available as open source, managed by the National Alliance for Medical Image Computing (NAMIC).² Upon sufficient refinement and evaluation of the current iteration of the system, it will be posted for download, free of charge. The distribution website will also supply medical image data and pre-made surgical plans so that users can operate the Perk Station without having access to medical imaging facilities. Documentation and tutorials will also be provided on the website. Simple design and low cost allows interested parties to replicate the hardware and install the software. The Perk Station is modular, so users can further downscale its functions and thus save on hardware. We contemplate establishing a Perk Station Depot to offer fully assembled Perk Stations for sale at goods cost. The target price is well below \$1,000, including phantom and laptop computer. (The electromagnetic tracker and tracked needles will not be included in this stripped-down version.)

5. Conclusion

In conclusion, the Perk Station is a simple, inexpensive replicable and adaptable tool for teaching computer-assisted surgery at all levels, from high-school science classes to clinical residency. It is small, portable, and light weight, and it fits in a suitcase when disassembled. The apparent simplicity of the Perk Station should not belie its potentials 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 also popular trend to minimize the steep learning curve by using simulations. Patients and patient advocates are less tolerant of training on clinical cases. Increased clinical workloads have also demanded increased provider productivity. The changing financial climate and commercial initiatives have catapulted to the forefront the need of training and performance evaluation without involvement of human subjects. 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.

Acknowledgements

This work is part of the National Alliance for Medical Image Computing (NAMIC), funded by the National Institutes of Health through the NIH Roadmap for Medical Research, Grant U54 EB005149, under the National Centers for Biomedical Computing program.³ The authors also acknowledge financial support from the U.S. National Institutes of Health (1 R01 CA118371-01A2) and a Teaching and Learning Enhancement Grant Award of Queen's University.

² National Alliance for Medical Image Computing (NAMIC), <http://www.namic.org>.

³ National Centers for Biomedical Computing, <http://nihroadmap.nih.gov/bioinformatics>.

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