# Design and development of a mobile image overlay system for needle interventions

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*Abstract*—

**Previously, a static and adjustable image overlay systems were proposed for aiding needle interventions. The system was either fixed to a scanner or mounted over a large articulated counterbalanced arm. Certain drawbacks associated with these systems limited the clinical translation. In order to minimize these limitations, we present the mobile image overlay system with the objective of reduced system weight, smaller dimension, and increased tracking accuracy. The design study includes optimal workspace definition, selection of display device, mirror, and laser source. The laser plane alignment, phantom design, image overlay plane calibration, and system accuracy validation methods are discussed. The virtual image is generated by a tablet device and projected into the patient by using a beamsplitter mirror. The viewbox weight (1.0kg) was reduced by 8.2 times and image overlay plane tracking precision (0.21mm, STD=0.05) was improved by 5 times compared to previous system. The automatic self-calibration of the image overlay plane was achieved in two simple steps and can be done away from patient table. The fiducial registration error of the physical phantom to scanned image volume registration was 1.35mm (STD=0.11). The reduced system weight and increased accuracy of optical tracking should enable the system to be hand held by the physician and explore the image volume over the patient for needle interventions.**

## I. Introduction

Many medical procedures such as biopsies, spine injection, needle based aspirations, local ablation therapies are performed percutaneously (i.e., through the skin). Typically, the physician has to determine the needle insertion location, orientation, and depth from image slices displayed on a computer screen. The needle placement errors in percutaneous procedures have been long associated with human [1], target uncertainty [2], tissue deformation, needle deflection [3] and imaging limitations. The procedure being manual, the needle is inserted into desired target location by trial and error method through repeated confirmation imaging scan and needle reinsertions. The outcomes for these procedures are associated with longer procedure time, increased patient discomfort, and radiation exposure.

Previously, a static image overlay system [4] was proposed for aiding CT (computed-tomography) image-guided percutaneous needle placement. The system consisted of a monitor and a semi-transparent mirror configured together (called as viewbox), such that the 2D (two-dimensional) image in the monitor is reflected by a semi-transparent mirror. The virtual image appears floating inside the patient at the correct 3D position. The system provided accurate image guidance for musculoskeletal interventions of the shoulder, hip and spine [5,6]. However, since the system was either fixed to CT/MR (Magnetic resonance) imaging system [4] or on a floor-mounted frame over the patient table (Figure 1a) [7], it allowed for only limited access around the patient, required careful and tedious calibration, and was prone to misalignments due to structural deformation or unintended physical contact with the device. To overcome the mentioned problems, adjustable image overlay system (Figure 1b) was proposed [8]. The viewbox was attached to a floor mounted articulated counterbalanced arm and continuously tracked by optical tracker. The device displayed the correct image in the virtual image overlay plane depending upon the position w.r.t phantom. Due to large mechanical structure of the device, precise movement was limited and consumed useful space in the procedure room.

To overcome these limitations, we propose a mobile image overlay system (Figure 2) of much lighter weight and smaller dimensions, as well significantly better image quality and intrinsic accuracy. We present the design details and first prototype of this system.

## II. Methods and Materials

### A. System Description

"The main objective the proposed design is to overcome the practical difficulty of accurately positioning the viewbox by eliminating the need of a heavy and large counterbalanced arm". This is achieved primarily by reducing the weight of viewbox by replacing the 15" monitor with 10.1" tablet display device. The proposed system (Figure 2) consists of i.) viewbox, ii.) optical tracker and iii.) host computer. The viewbox (Figure 3a) consists of tablet device, mirror and laser source similar to [4]. A host computer was required due to insufficient computational capacity to run image re-slicing software and non-availability of IEEE-1394a interface for optical tracker with the tablet device. The tablet device is connected as secondary display device with the host computer through wireless network. A line type laser source

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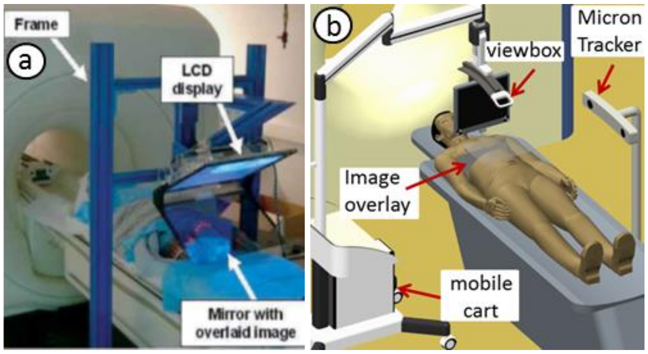

Figure 1: Static image overlay [7] (a) and adjustable image overlay [8] (b)

is used to indicate the physical location of virtual image overlay plane over the patient. The display device and the mirror are attached together and the virtual reflected image is seen through the mirror. A set of planar markers are displayed in the virtual image overlay plane which is directly seen by the optical tracker for automatic self-calibration. The viewbox is equipped with planar marker on the sides to determine the pose of image overlay plane during the entire procedure. Another set of markers are fixed upon the patient for co-registration of scanned images and the viewbox w.r.t patient position. The system can be hand-held by the physician and used for exploration of the image volume over the patient. The image re-slicing software displays the correct image in real time corresponding to the 3D position of the image overlay plane i.e. the system w.r.t patient. The intended clinical applications of the system are parathyroidectomy, musculoskeletal needle injection, percutaneous access to blood vessel, and percutaneous nephrolithotomy.

The system is designed (Figure 3a) using "Creo 2.0" (Parametric Technology Corporation Inc., MA USA) and MicronTracker (Claron Technology Inc., ON Canada) is chosen for optical tracking. The tracking data is acquired by the Plus toolkit (www.plustoolkit.org) and visualized by 3D Slicer (www.slicer.org). The first prototype developed is shown in Figure 3b. The appearance of this embodiment of the viewbox resembles the Sonic Flashlight [9] developed for direct visualization of ultrasound images using real-time tomographic reflection.

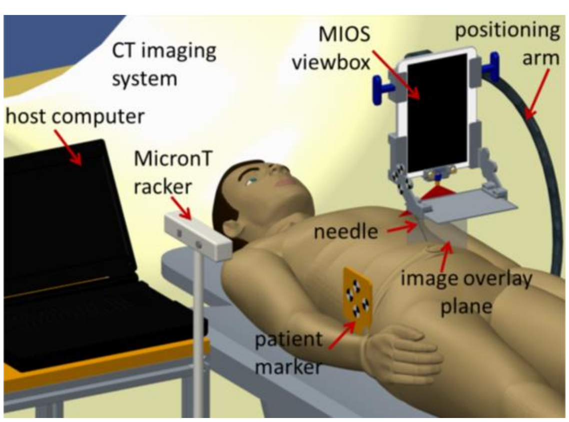

Figure 2: Mobile image overlay system concept

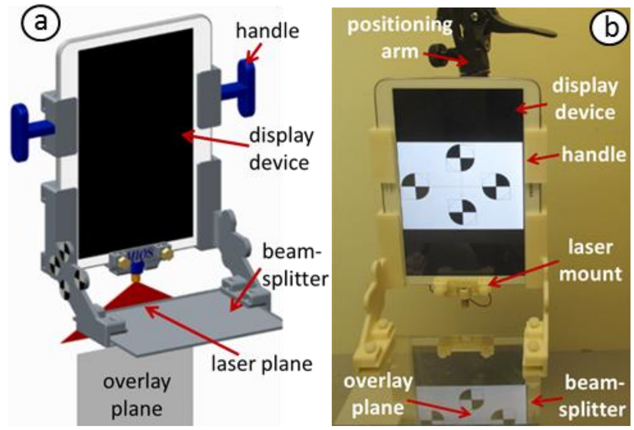

Figure 3: Viewbox mechanical design (a) and prorotype developed (b)

## B. *Workspace Analysis*

The purpose of the workspace analysis was to determine the optimum angle and distance between the display device and the mirror with following objectives i.) viewing the complete depth of the virtual image overlay plane when seen through the mirror; ii.) sufficient gap below the mirror and patient; iii.) oblique rotation of image overlay plane by ± 35° and iv.) sufficient vertical space for needle injection of length 70 mm. The musculoskeletal needle injection, and parathyroidectomy are the clinical procedures which defines the constraints for the workspace analysis. Based on the study done for previous system [8], a 90-degree mirror-display viewbox configuration was selected. The display device and the mirror are attached together with 3D-printed brackets as shown in Figure 3a. A 3D-printed handle attached to the display device is used for holding the system by hand for exploration over the patient. A positioning arm can be used for fixing the device during needle insertion.

## C. *Selection of display device*

The brightness of the reflected image in the virtual plane depends upon the luminance of the display surface. The previous adjustable system [8] was equipped with a monitor of luminance 250 cd/m$^2$. The Galaxy Tab 3 (Samsung Inc. South Korea) was chosen as display device due to its large display size (10.1") and high luminance value (492 cd/m$^2$). The tablet device was used as secondary display device for the host computer through wireless connection using a commercially available Android app "iDisplay" (Shape Inc. Germany).

## D. *Beamsplitter v/s Semi-transparent mirror*

The previous systems [4,8] used semi-transparent mirror made of polycarbonate sheet with a transparent thin coating of aluminum. The accuracy of virtual maker (image overlay plane) pose detection depends upon the reflection component of the mirror. Higher reflectivity was achieved by using beamsplitter glass (Edmund Optics Inc. USA) with Reflection/Transmission (R/T) ratio of 75/25. Beamsplitter consists of a thin, flat glass plate with substrate coating on one side and anti-reflection coating on the other side.

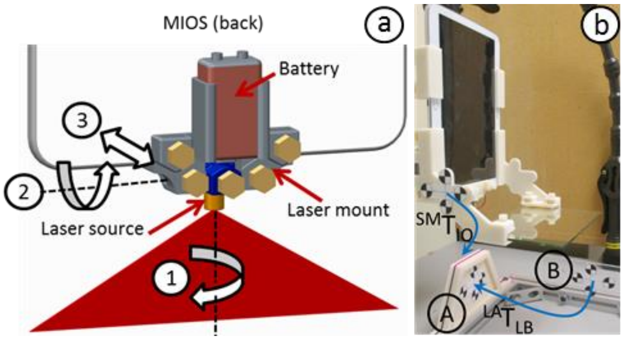

Figure 4: Laser mount design (a) and alignment setup (b)

### E. *Laser plane*

A line-type laser source similar to the one applied in [1] is used to indicate the physical location of virtual image overlay plane above the patient. The previous systems [1,8] were equipped with 650nm red line type laser source of power output 1mW. However the 1mW laser source had poor visibility in the normal (procedure room) lighting conditions. Hence a 5mW output source was chosen that satisfies FDA class IIIa requirements.

The laser source is attached to the display device using custom designed laser mount having three degrees of freedom as shown in Figure 4a. A laser alignment tool was developed to align the laser plane and image overlay plane with the aid of MicronTracker and 3D Slicer. The tool consist of two markers *A* and *B* attached perpendicular to each other as shown in Figure 4b and the transform ${}^{LA}T_{LB}$ between markers are predetermined. Marker *A* represents the laser plane rendered in the Slicer scene and it is continuously tracked by the MicronTracker through marker *B* and applying the transform ${}^{LA}T_{LB}$. The laser plane is aligned with the virtual image overlay plane in two steps i.) manually align the viewbox until the image overlay plane aligns with laser plane in the 3D Slicer screen and ii.) manually adjust only the laser mount until the laser line cuts through the center dark line upon the alignment tool indicating the position of marker *A*.

### F. *Phantom Design*

The accuracy of the system is validated by performing image-guided needle insertion with a validation phantom. The phantom (Figure 5) is made of an acrylic box consisting of four sets of 3D-printed blocks. Each block is set at different height and consists of four pillars. CT-Spot fiducials (Beekley Corporation, USA) are placed upon each pillar and seven PinPoint multi-modality fiducials (Beekley-

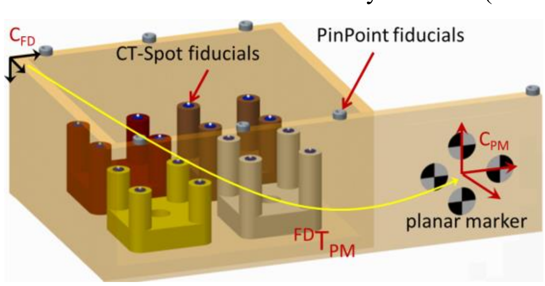

Figure 5: validation phantom concept

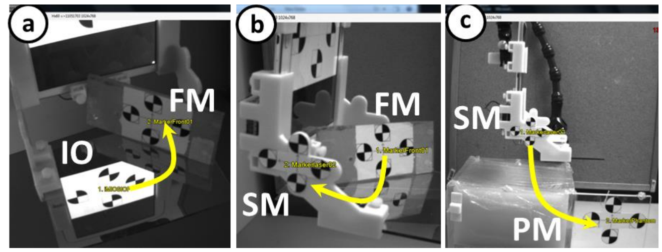

Figure 6: Image overlay plane calibration using MicronTracker

Corporation, USA) upon the top surface. The PinPoint fiducials are used to register the phantom to the planar marker attached on the front side. The planar marker is used to locate the phantom w.r.t image overlay plane. The CT-Spot fiducials are used as target points for needle insertion for system accuracy validation. The acrylic box is filled with tissue mimicking gel made of agar and gelatin. The phantom is CT scanned for ground truth and loaded into the 3D Slicer visualization software (Figure 8a).

### G. *Image overlay calibration method*

A calibration method developed for [8] was adopted for the current system. The marker displayed in the virtual image overlay plane is directly seen by the MicronTracker through the beamsplitter mirror. Due to limited field of view of the tracker camera, an additional marker (front marker, FM) was placed above the mirror during calibration. The transform ${}^{IO}T_{SM}$ between the side marker (SM) and virtual image overlay (IO) plane is calculated by applying the two transforms i.) ${}^{IO}T_{FM}$ – transform between image overlay plane and temporary front marker (Figure 6a) and ii.) ${}^{FM}T_{SM}$ – transform between temporary front marker and side marker upon the system (Figure 6b). The MicronTracker is placed such that the marker upon the system and the phantom (patient) are seen together (Figure 6c) for simultaneous tracking during the procedure. The position of the image overlay plane w.r.t phantom is determined by real-time calculation of transform ${}^{IO}T_{PM}$ (${}^{IO}T_{SM}$ X ${}^{SM}T_{PM}$) between phantom and the system.

### H. *Experiments and Results*

#### a. *Image overlay plane detection accuracy*

An experimental study (Figure 7) with 10 repeated trials was conducted to determine the accuracy of virtual marker pose detection by MicronTracker. For each trial, minimum of 300 poses were recorded w.r.t tracker coordinates. The recorded precision for current and previous system [8] were 0.11mm (STD=0.05) and 0.55mm (STD=0.05) respectively.

#### b. *Workspace design*

The viewing angle through the mirror is 20° as compared to 7.5° for design similar to earlier system described in [1]. Needle of length up-to 125 mm can be used.

#### c. *System weight reduction*

The viewbox weight of the current system is 1.0 kg as compared to the previous system [8] which was about 8.2 kg.

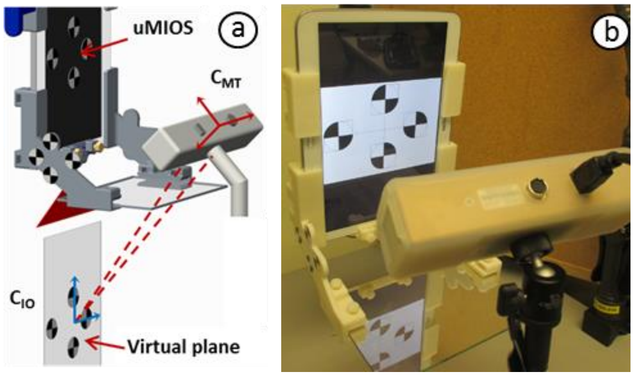


Figure 7. Virtual marker pose detection accuracy

*d. Phantom registration*

The physical location of the phantom is registered to the passive planar marker w.r.t tracker coordinates by applying the transform ${}^{FD}T_{PM}$ (Figure 5a), which is determined by probing the PinPoint fiducials using the MicronTracker tracked stylus (Figure 8b). The scanned image volume is registered to the physical phantom by overlapping the probed physical points with the same points in the scanned image volume. The phantom registration using MicronTracker was repeated 10 times and the root mean square error for fiducial registration was 1.35 mm (STD=0.14).

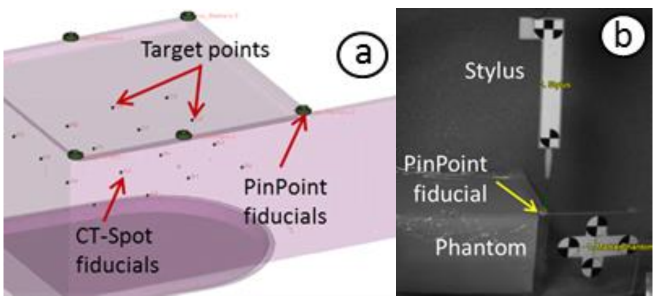


Figure 8: Image volume in 3D Slicer (a) and phantom registration (b)

## III. Discussion and Future Work

The objective of the proposed design was to completely mobilize the system and improve the accuracy compared to earlier systems. The viewbox weight of the current system was reduced by 8.2 times and image overlay plane detection accuracy was improved by 3.2 times compared to previous system [8], thus enabling the system to be hand held by the physician and explore the image volume over the patient. Slower image update rate between the host computer and tablet device was observed when the system was used to browse the image volume over the phantom.

The image overlay plane detection accuracy was comparable to the tracking accuracy of the MicronTracker device. Thus validating our initial hypothesis of achieving higher accuracy with high luminescence display and R/T ratio mirror. The image overlay plane calibration using MicronTracker is simpler with fewer steps, automatic and can be done away from the patient space as compared to the Z-frame registration method described in [10] for static system.

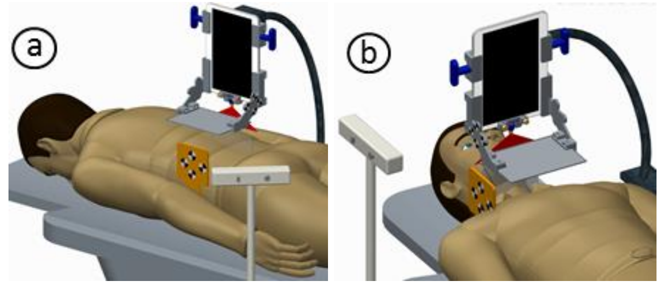


Figure 9: musculoskeletal injection (a) and parathyroidectomy (b)

Based on successful pre-clinical testing of the previous static image overlay system [5, 6], the mobile image overlay system with reduced weight, increased tracking accuracy and easier maneuverability can be used for wide range of procedures. The clinical procedures such as musculoskeletal injection (Fig. 9a), parathyroidectomy (Fig. 9b) and nephrolithotomy are validated by simulation using CAD tool.

The 3D Slicer module developed so far can display the sliced image upon the tablet device, further development is in-progress to specify the target and entry point and generate the needle insertion line. Improve the image update rate between the host computer and the tablet device. Phantom and cadaver studies need to be performed to evaluate the accuracy. Furthermore, the mechanical design needs to be refined considering the design for manufacturability and assembly.

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