

An Image Overlay System with Enhanced Reality for Percutaneous Therapy Performed Inside CT Scanner

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Abstract. We describe a simple, safe, and inexpensive image overlay system to assist surgical interventions inside a conventional CT scanner. The overlay system is mounted non-invasively on the gantry of the CT scanner and it consists of a seven degrees-of-freedom passive mounting arm, a flat LCD display, and a light brown acrylic plate as a half mirror. In a pre-operative calibration process, the display, half-mirror, and imaging plane of the scanner are spatially registered by imaging a triangular calibration object. Following the calibration, the patient is brought into the scanner, an image is acquired and sent to the overlay display via DICOM transfer. Looking at the patient through the half-mirror, the CT image appears to be floating inside the patient in correct size and position. This vision enables the physician to see both the surface and the inside of the patient at the same time, which can be utilized in guiding a surgical intervention. The complete system fits into a carry-on suitcase (except the mounting adapter), it is easy to calibrate, mounts non-invasively on the scanner, without utilizing vendor-specific features of the scanner.

1 Introduction

During the last decade, significant research has been devoted to three-dimensional (3D) medical images for surgical simulation and planning. Typically, these 3D medical images are shown on a flat 2D display on the wall of the operating room, the surgeon must mentally register the computer model with the anatomy seen in the surgical field, and use hand-eye coordination to execute the surgical plan. Therefore, the actions of the physician are not truly objective, primarily because images and patient are not registered accurately. In search of better comprehension of pre-acquired images, augmented reality displays are becoming more popular in the medical field. Roberts et al. [7] created a frameless image-overlay system with a stereoscopic microscope for neurosurgery. Fuchs et al. [8] and Sauer et al. [12] built augmented reality systems fusing ultrasound and MRI images with video input. In these systems, the visualization method of the images uses the principle of stereoscopic display, e.g. a polarized shutter system or two small monitors located on the user's head. The authors have previously discussed potential errors of binocular

system approach [3] and hypothesized that the ultimate intra-operative visualization technique may be simultaneous view of the surgical field as seen by the surgeon operation and the patient's internal anatomy. Navab et al. [11] also followed this thought of train and blended video input and C-arm fluoroscopy with the use of a video camera co-registered with the X-ray source. In reference [3], we presented an image overlay system that provided accurate depth perception and overlay of image slices of a pre-acquired 3D volume on the patient's body. In a subsequent publication, Stetten reported the use of this overlay method for displaying real-time transcutaneous ultrasound images [9, 10]. The presented work evolved from our earlier research [3], by applying the principle of 2D image overlay for in-scanner CT-guided interventional procedures. We attached the overlay system to the gantry of the CT scanner and made the CT image "float" inside the patient, in correct size and position. This solution gives the surgeon 2D "X-ray vision" that promises to be especially useful in in-plane needle placement procedures, when the needle is inserted inside plane of the current CT slice. Our system differs from most virtual reality displays by its inherent simplicity, safety, and low cost.

2 Materials and Method

2.1 Principles

The task of the system was to make a CT image slice "appear" in the exact same location where it was acquired, while the patient is still in the scanner. By superimposing the image on the patient, the physician can see the surface and the inside of the body at the same time. This is expected to help the physician finding the optimal access to the target, while minimizing the collateral damage to normal healthy structures. The basic principle of the CT overlay system is shown in Fig. 1., and we will describe each component further below.

Perhaps the most important element of principle is that we do not project the CT image into the surgical field, we merely make it appear there, hence the name "virtual reality" display. The central piece of the system is a half-mirror, which has two useful properties: one can see through the half-mirror and see the scene behind it, while at the same time one can also see reflections in the half-mirror. The reflections are fainter than they would be in a full mirror and the transparent scene is also fainter than it would be through clear glass, but with proper lighting, a reasonable compromise can be achieved between the two. The overall concept is as simple as this: acquire a CT slice, render the image on a distortion-free flat panel display and position the display above the half mirror, so that the reflection of the CT slice coincide with the patient's body that we see behind the mirror. As we demonstrated in [3], this system results in an optically stable alignment of the real view and the image in the mirror, provided that the mirror, the display and the scanner were properly aligned earlier. The key questions are how to build a system like this, which is also lightweight, inexpensive, easy to setup, easy to calibrate, independent from the actual CT scanner, and ergonomic to both patient and physician.

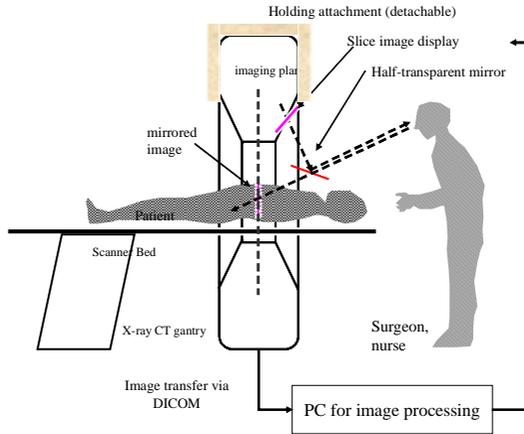


Fig. 1. The configuration of the X-ray CT Image Overlay System

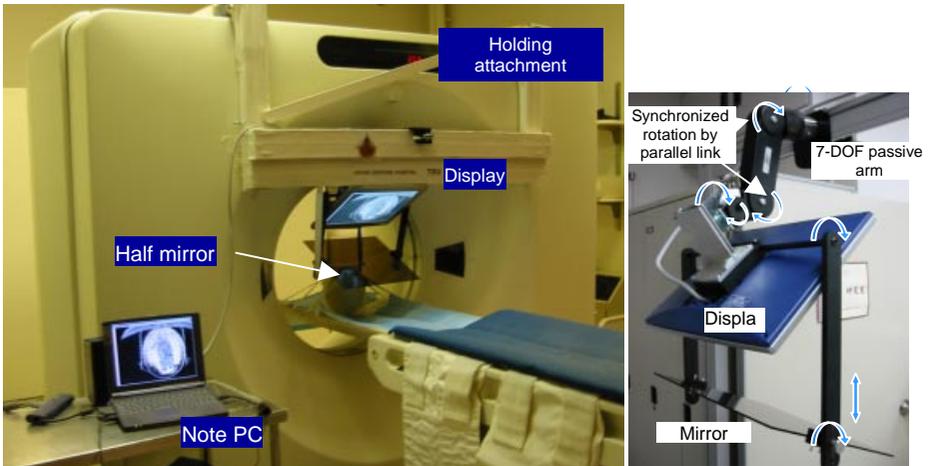


Fig. 2. (Left) An overview of the CT Image Overlay System. (Right) The 7-DOF passive arm

2.2 System Description

The overview of the system is shown in Fig. 2 (left). It comprises a holding arm and the unit including an LCD flat panel monitor (LT-1500MA, SHARP Co. Ltd. Japan) and a half-mirror. A personal computer acquires the X-ray CT image via a DICOM and calculates the image’s size and rotation for displaying the slice on the LCD.

The Holding Attachment

In current CT imaging systems, an image slice is taken at the center of the gantry, and so we have to position the mirror of the overlay system accurately on the center of the gantry. The simplest way to achieve this would be to attach the devices directly onto the CT gantry, but safety regulations prohibit us from making alterations to the

scanner. In order to achieve non-invasive mounting, we constructed a wooden holding attachment that hung down from the gantry and secured the 7-DOF passive arm (Fig. 2, left). This made the system easily detachable, which can be easily installed on a variety of CT gantries.

Degrees of Freedom of the Overlay Device

To fit any position and direction of the image slice, a seven degree-of-freedom (7-DOF) passive arm was designed (see Fig. 2, right). We could adjust the angle and distance from the mirror to the display, and the angle and distance from the display to the CT gantry.

Sterilization Considerations

The system was conceived for in-scanner percutaneous procedures, for which sterilization is not a difficult issue, as the needle is not in direct contact with the image overlay device. When the device is used in open surgical procedures, sterilization will become a more significant issue. Draping the entire device with transparent sheet would result in foggy images. In order to overcome this problem, we designed the display and the mirror to be easily detachable and easy to be sterilized, making necessary to cover only the display. We used a light brown acrylic plate for the mirror and the arms were made of aluminum with a black alumite satin finish; all parts suitable for EOG sterilization.

3 Registration Method

Registration of the CT image and patient is perhaps the most critical element of the system. Although many registration methods have been studied in the field of augmented reality [4, 5], they do not lend themselves well to a lightweight design, for depending heavily on dedicated instrumentation and intensive calculation. A complicated calibration procedure would certainly be prohibitive to widespread use of the device. We applied a simple triangle fiducial marker with single image acquisition. Three acrylic plates form a triangular prism shown in Fig. 3(1). A flowchart of the registration is shown in Fig. 3.

Step 1. Place the triangle marker on the CT scanner bed and turn on the laser marker of the scanner to indicate plane of acquisition

Step 2. Take a transverse CT slice, transfer the image to the personal computer via a DICOM link, and flip the left-right image direction. (We need to flip the image, so that in the mirror we can see it in the correct orientation.)

Step 2.5. Pre-calibrate the display resolution to obtain a full-sized image.

Step 3. Adjust the image to its full size.

Step 4. Render the image on the flat panel display, adjusting the virtual image in the mirror with the edges of the real object behind the mirror.

Upon completing registration, we can observe an image slice in an accurate position. We replace the calibration object with the patient in, while making sure that the mirror and display are not moved.

The above calibration procedure was executed by a software package developed by the authors using VC++6.0 with a Windows 2000 operating system.

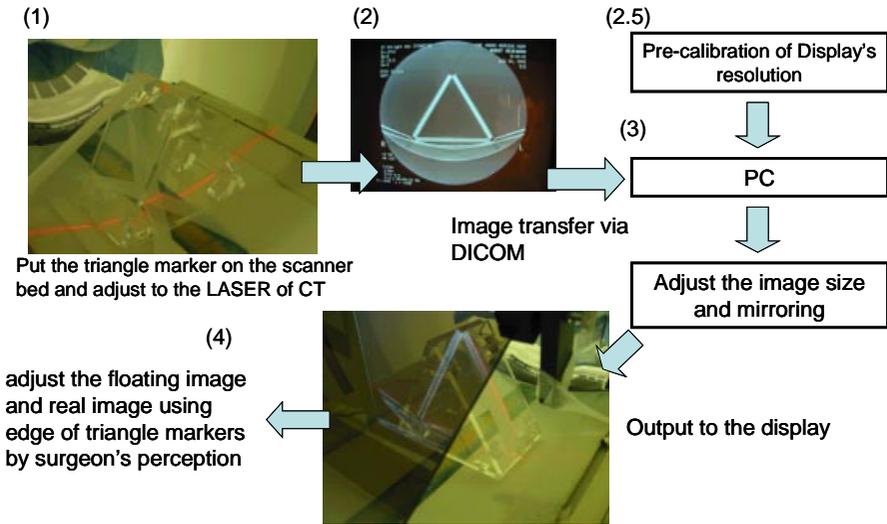


Fig. 3. Simple registration procedure

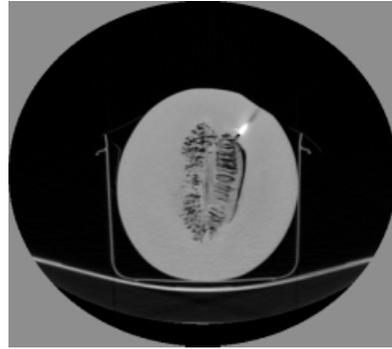
4 Experiment

We developed a proof-of-concept prototype to confirm the principle, simplicity and the potential clinical applicability of the system. In Reference [3], we have presented a method for performing evaluation of the accuracy of human perception with using the overlay device. Now we present the results of a phantom experiment, in which we performed in-plane needle insertions into a honeydew melon to a pre-determined target. First, the acrylic prism was placed on the scanner bed and the registration procedure was completed, then we removed the calibration object from the scanner. A small steel ball marker (diameter = 1 mm) was placed deep inside a honeydew melon for target. We secured the melon on the scanner bed and took a scout view image. The steel ball in the scout view indicated the plane of imaging and needle insertion. We moved the scanner bed accordingly, acquired the image and sent it to the computer via DICOM link. The full-sized mirrored image was created by the image processing software and rendered on the flat panel display. Because the system has retained calibration, the mirrored CT image of the melon coincided with the silhouettes of the real melon behind the mirror. Figure 4 shows a picture from the experimental results. Then, using only this image guidance system, a surgeon successfully inserted a needle into the melon. The surgeon selected the entry point and oriented the needle, so that the line of the needle passed through the target and the transverse laser plane of the scanner cast on the needle. Once correct orientation was confirmed, the surgeon entered the needle to the pre-calculated depth. As Figure 4 shows, the surgeon made contact with the pre-implanted steel ball inside the melon.

5 Discussion

The experiment was an overall success: we mounted the overlay device in a non-invasive manner on the gantry, calibrated it, and hit the pre-implanted target with a

standard 18 G aspiration needle. We also identified many future extensions to the system, which could increase the clinical usefulness of the system, and at the same time, we learned about shortcomings of the current prototype.



The tip of the needle hits the steel ball inside the honevdeaw

Fig. 4. Phantom experiment

Mounting proved to be quite cumbersome. In the next prototype, we plan to change the size of LCD monitor, and to build more rigid adapter. Likewise, setting up the 7-DOF passive arm, then adjusting the mirror with respect to the display need to be more intuitive before clinical use on human subjects is considered. As also in Figure 2, the location of the crossbar of the mount forced us to lower the display and mirror, thus not leaving enough room for a potential human subject. Therefore, the mount also needs to be re-designed to make the system ergonomically feasible. The current display and mirror are relatively small and rigidly fixed on the mount at the time of calibration. This confines the field of view and target to fairly small area. The primary application we keep in focus is percutaneous needle placement to the spine, so the current hardware is expected to be sufficient for that application, but in the long run some “panning function” with in the plane of imaging will be useful. In this proof-of-concept prototype system, we did not provide any assistance to the surgeon, other than the overlaid raw CT image. In a more advanced system image processing tools and path planning tools will guide the surgeon. The physician could either mark the entry point on the skin pre-operatively or select it intra-operatively in the acquired CT image. In either case, the trajectory of the needle can be drawn in the image, so the surgeon can easily align the needle on the line, while keeping the needle in the plane of the scan using the CT laser. We must also note that as the surgeon enters the needle into the body, the needle disappears from the view. If we reacquire the image, the needle will re-appear, this time inside the body, supposedly coinciding with the trajectory pre-determined for the needle. Doing so could mimic the functionality of CT-fluoroscopy, without the harmful side effects of large amount of X-ray dose to both surgeon and patient. Even with the current hardware and software, we could mimic 3D functionality on slice-by-slice basis, by acquiring a volumetric CT and moving the table back and forth and injecting the matching CT slice into the overlay display. With more sophisticated image processing tools one can add multimodal images into the overlay. For example, we can co-register pre-operative MRI images

to intra-operative CT, then re-slice the MRI in the current plane of imaging and inject that cut into the overlay display. With more sophisticated hardware one could change the orientation of the mirror and display, enabling to inject re-formatted images in an oblique plane onto the field. With the current system, we have used simple, raw cross-sectional CT images that are familiar to a surgeon.

The concept of a 3D image using a half-mirror is not a new one, related research has been presented by several investigators, also including our group [1, 2, 3, 4, 6, 9, 10]. As mentioned earlier, Stetten's ultrasound display mechanism uses the same overlay concept, yet it targets an entirely different set of applications and clinical problems. Stetten's system is a versatile hand-held device that is rather difficult to keep in alignment with the surgical site in a long or delicate application. The quality and the accuracy of CT images often allow for more accurate targeting than ultrasound. CT guidance promises to be particularly useful in spine punctures (nerve blocks, facet joint injections), as well as biopsies of the head, neck, and perhaps lung, and possibly in many other procedures. The system is also appears to be most promising if applied on helical CT or cone-beam CT, by which we can acquire near-real-time images and update the view rapidly, in order to keep up with the effects of organ shift and tissue deformation. Development of a clinically feasible version is in progress, which we will present at the conference, together with more thorough experimental evaluation.

6 Conclusions

We demonstrated a simple, inexpensive, and accurate 2D image overlay system with real depth perception inside a CT scanner. Results from a phantom experiment indicate that an ergonomically advanced version of the system may be useful in a wide range of needle-placement applications. Research and development continues toward that goal.

Acknowledgements

This research project is partly supported by the National Science Foundation under the Engineering Research Center grant #EEC9731478, Nakatani Electronic Measuring Technology Association of Japan and the Grant-in-Aid for Scientific Research #14702071. We are grateful to Drs. James S. Zinreich and Bruce Wasserman for housing the experiments in the Division of Neuroradiology of the Johns Hopkins Hospital. Last, but not least, we are indebt to Vincent L. Lerie, R.T for spending long hours with us in the scanner room, without whom our research would not have been as much fun.

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