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Magnified Real-Time Tomographic Reflection

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Abstract. Real Time Tomographic Reflection (RTTR) permits *in situ* visualization of ultrasound images so that direct hand-eye coordination can be employed during invasive procedures. The method merges the visual outer surface of a patient with a simultaneous ultrasound scan of the patient's interior. It combines a flat-panel monitor with a half-silvered mirror such that the image on the monitor is reflected precisely into the proper location within the patient. The ultrasound image is superimposed in real time on the patient merging with the operator's hands and any invasive tools in the field of view. We aim to extend this method to remote procedures at different scales, in particular to real-time *in vivo* tomographic microscopic imaging modalities such as optical coherence tomography (OCT) and ultrasound backscatter microscopy (USB). This paper reports our first working prototype using a mechanically linked system to magnify ultrasound-guided manipulation by a factor of four.

1 Introduction

The innovation described in this paper derives from an extensive body of prior work whose goal has been to look directly into the human body in a natural way. From the discovery of X-rays over a century ago, clinicians have been presented with an amazing assortment of imaging modalities capable of yielding maps of localized structure and function within the human body. Continual advances are being made in magnetic resonance (MR), computerized tomography (CT), positron emission tomography (PET), single photon emission computerized tomography (SPECT), ultrasound, confocal microscopy, optical coherence tomography (OCT), and ultrasound backscatter microscopy (UBM). Each of these is a *tomographic* imaging modality, meaning that the data is localized into voxels, rather than projected along lines of sight, as are conventional X-ray images. Tomographic images, with their unambiguous voxels, are essential for our present work.

New techniques to display tomographic images in such a way that they extend human vision into the body have lagged behind the development of the imaging modalities themselves. In the practice of medicine, the standard method of viewing an image is still to examine a film or screen rather than to look directly into the patient. Previous experimental approaches to fuse images with direct vision have not met with widespread acceptance, in part, because of their complexity. Our approach is simpler, and thus, we hope, more likely to find its way into clinical practice. If so, the proposed research could have a broad impact on the use of imaging in the interventional diagnosis and treatment of disease.

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2 Real Time Tomographic Reflection: A Review

Although our research may eventually be adapted to a wide variety of imaging modalities, our roots are in ultrasound. Ultrasound is appealing because it is non-ionizing, real-time, and relatively inexpensive. The transducer is small and easily manipulated, permitting rapid control of the location and orientation within the patient of the illuminated slice. Ultrasound is thus well suited for guiding invasive procedures, but difficulty arises in determining the spatial relationships between anatomical structures, the invasive tool, and the ultrasound slice itself.

Percutaneous ultrasound-guided intervention encompasses a wide range of clinical procedures [1-3]. In such procedures, the needle may be manipulated freehand with the ultrasound transducer held in the other hand or by an assistant. Alternatively, a needle may be constrained by a guide attached to the transducer so that the entire length of the needle remains visible within the plane of the ultrasound scan. In either case, the operator must look away from the patient at the ultrasound display and employ a displaced sense of hand-eye coordination. The difficulty in mastering these skills has motivated research into developing a more natural way to visually merge ultrasound with the perceptual real world.

Fuchs, et al., have developed a head mounted display (HMD) for ultrasound, following two distinct approaches to what they call *augmented reality*. In the first approach, they optically combine a direct view of the patient with ultrasound images using small half-silvered mirrors mounted in the HMD [4]. More recently, they have replaced direct vision with miniature video cameras in the HMD, displaying video and ultrasound images merged on miniature monitors in the HMD. The second approach permits greater control of the display, although it introduces significant reduction in visual resolution [5-7]. In both cases, the HMD and the ultrasound transducer must be tracked so that an appropriate perspective can be computed for the ultrasound images. Head-mounted displays, in general, restrict the operator's peripheral vision and freedom of motion.

In related work by the Medical Robotics and Computer Aided Surgery (MRCAS) laboratory at the CMU Robotics Institute, DiGioia, et al., have merged real-world images with CT data while achieving a reduction in the total apparatus that the operator must wear [8,9]. In their system, called *image overlay*, a large half-silvered mirror is mounted just above the patient with a flat panel monitor fixed above the mirror. Images of CT data on the monitor are reflected by the mirror and superimposed on the view of the patient through the mirror. The operator needs only to wear a small head-tracking optical transmitter, so that the three-dimensional CT data can be rendered from his/her particular perspective. Special glasses are needed only if stereoscopic visualization is desired. A second tracking device must be attached to the patient to achieve proper registration between the rendered CT data and the patient.

We have modified DiGioia's approach, applying it to ultrasound with significant simplification. By restricting ourselves to a single tomographic slice in real time (i.e. ultrasound), and strategically positioning the transducer, the mirror, and the display, we have eliminated the need for tracking either the observer or the patient. This is possible because we are actually merging the *virtual image* in 3D with the interior of the patient. The word "virtual" is used here in its classical sense: the reflected image is optically indistinguishable from an actual slice hanging in space. Ultrasound produces a *tomographic* slice within the patient representing a set of 3D locations that lie in a plane. The image of that tomographic slice, displayed at its correct size on a flat panel display, may be reflected to occupy the same physical space as the actual slice within the patient. If a half-silvered mirror is used, the patient may be viewed through the mirror with the reflected image of the slice superimposed, independent of viewer location. The reflected image is truly occupying its correct location within the patient and does not require any particular perspective to be rendered correctly. We have adopted the term *tomographic reflection* to convey this concept [10-13].

Masamune, et al, have previously demonstrated the concept of tomographic reflection, which he calls *slice display*, on CT data, although not in real time [14]. A slice from a stored CT data set is displayed on a flat panel monitor and reflected by a half-silvered mirror to its proper location within the patient. Since the CT scanner is not physically a part of this apparatus, independent registration of the patient's location is still required. Furthermore, the static data does not change during a procedure. Using a real time imaging modality such as ultrasound eliminates these restrictions, resulting in what we call *real time tomographic reflection* (RTTR).

To accomplish tomographic reflection, certain geometric relationships must exist between the slice being scanned, the monitor displaying the slice, and the mirror. As shown in Fig. 1, the mirror must bisect the angle between the slice and the monitor. On the monitor, the image must be correctly translated and rotated so that each point in the image is paired with a corresponding point in the slice to define a line segment perpendicular to, and bisected by, the mirror. By fundamental laws of optics, the ultrasound image will thus appear at its physical location, independent of viewer position. The actual apparatus we have constructed is sketched in Fig. 2.

Superimposing ultrasound images on human vision using RTTR may improve an operator's ability to find targets while avoiding damage to neighboring structures, while generally facilitating interpretation of ultrasound images by relating them spatially to external anatomy. As such, it holds promise for increasing accuracy, ease, and safety during percutaneous biopsy of suspected tumors, amniocentesis, fetal surgery, brain surgery, insertion of catheters, and many other interventional procedures.

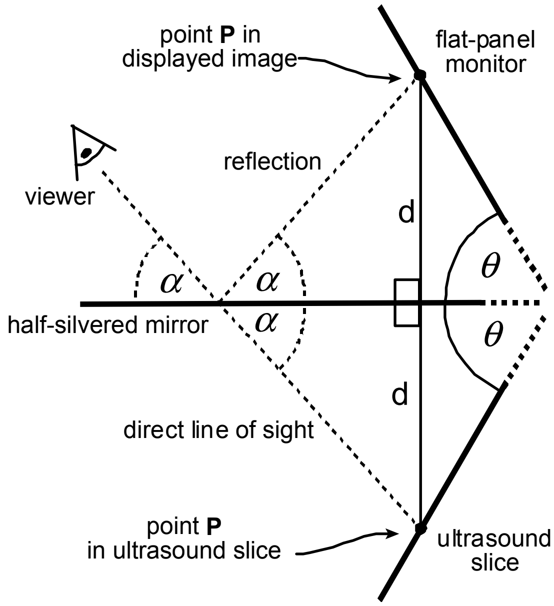

Fig. 1 The half-silvered mirror bisects the angle between the ultrasound slice (within the target) and the flat-panel monitor. Point P in the ultrasound slice and its corresponding location on the monitor are equidistant from the mirror along a line perpendicular to the mirror (distance = d). Because the angle of incidence equals the angle of reflectance (angle = α) the viewer (shown as an eye) sees each point in the reflection precisely at its corresponding physical 3D location.

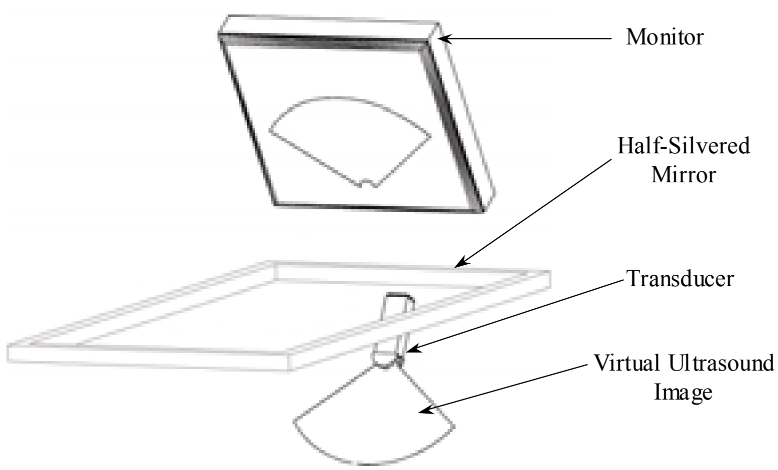

Fig. 2 Schematic representation of the apparatus. A flat-panel monitor and an ultrasound transducer are placed on opposite sides of a half-silvered mirror such that the mirror bisects the angle between them.

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Fig. 3 Photograph, from the viewpoint of the operator, showing a scan of a hand using the apparatus in Fig. 2. The reflected ultrasound image is merged with the direct visual image.

In Fig 3, a human hand is seen with the transducer pressed against the soft tissue between the thumb and index finger. While not a common target for clinical ultrasound, the hand was chosen because it clearly demonstrates successful alignment. The external surfaces of the hand are located consistent with structures within the ultrasound image. The photograph cannot convey the strong sense, derived from stereoscopic vision, that the reflected image is located within the hand. This sense is intensified with head motion because the image remains properly aligned from different viewpoints. To one experiencing the technique in person, ultrasound targets within the hand would clearly be accessible to direct percutaneous injection, biopsy or excision.

3 Ultrasound Magnification Experiment

In the present work we intend to develop systems that provide hand-eye coordination for interventional procedures on patients and research animals *in vivo* at mesoscopic and microscopic scales. A number of other researchers are presently involved in this pursuit [15-17], but none has applied tomographic reflection. We have demonstrated an adaptation of RTTR, described below, in which the target is remote from the display and may be at a different scale. Interventional procedures could be carried out using a robotic linkage between the actual remote effector (such as a micropipette) and a hand-held “mock effector” constructed at a magnified scale.

We envision that real-time *in vivo* tomographic microscopy will be an important application of RTTR. This can be achieved by removing the actual target from the operator’s field of view, enabling procedures at different scales and/or remote locations. Interventional procedures could be carried out remotely and at different scales by controlling a remote effector with a scaled-up model or “mock effector” held in the operator's hand. The mock effector would interact spatially in the operator's field of view with the virtual image of a magnified tomographic image from the remote operation.

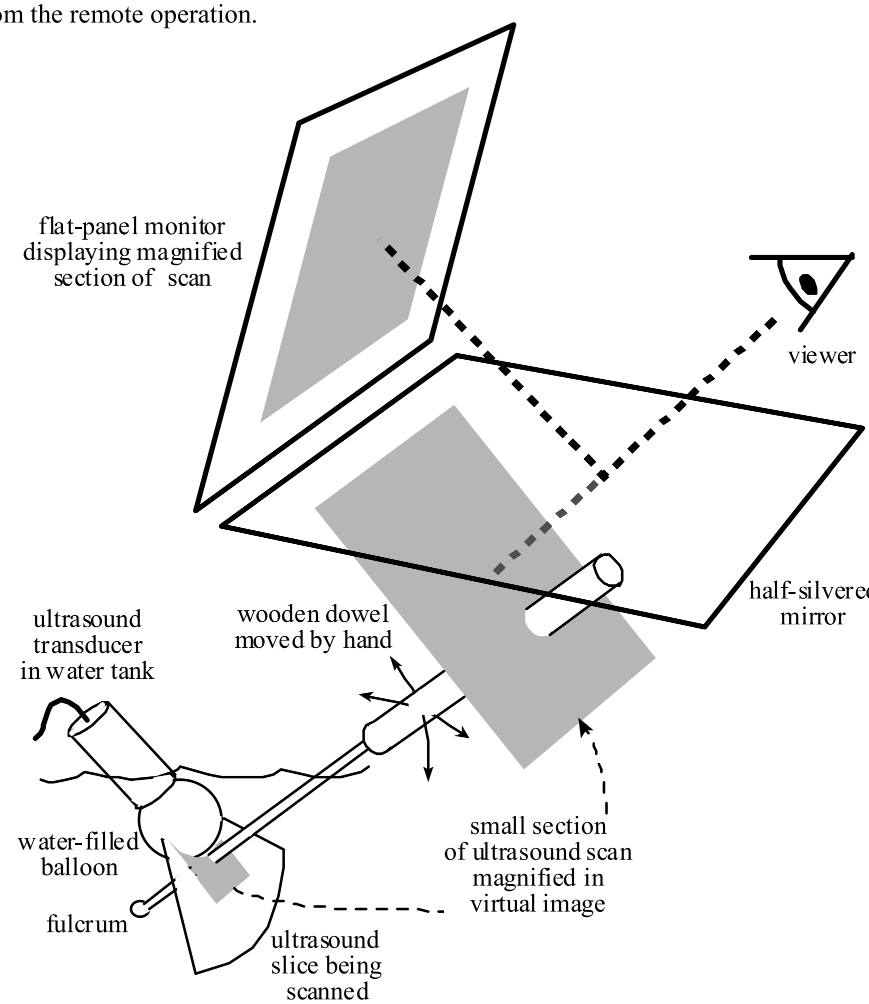


Fig. 4 Apparatus demonstrating magnified RTTR using a lever to control a remote effector at a magnified scale.

This concept has been put into practice using the apparatus shown in Fig. 4, as a proof of concept. Starting with the previous floor-standing apparatus, the ultrasound transducer was removed from the operator's field of view, and a small water-filled balloon placed before the transducer in a water tank. A lever consisting of two sections of wooden dowel, 3/4" and 3/16" in diameter, was attached by the small end to one side of the water tank. The fulcrum was 4 times as far from the virtual image as it was from the actual ultrasound slice. This resulted in a mechanical magnification of four, which matched the magnification between the actual 3/16" effector and the 3/4" "mock effector". The operator held the mock effector, as shown in Fig. 5 and 6, moving it to control the actual effector remotely with two translational degrees of freedom. The small dowel produced an indentation in the balloon visible by ultrasound. A small section of the ultrasound slice was magnified by a factor of 4 and displayed on the flat-panel monitor so that virtual image was reflected to merge visually with the mock effector.

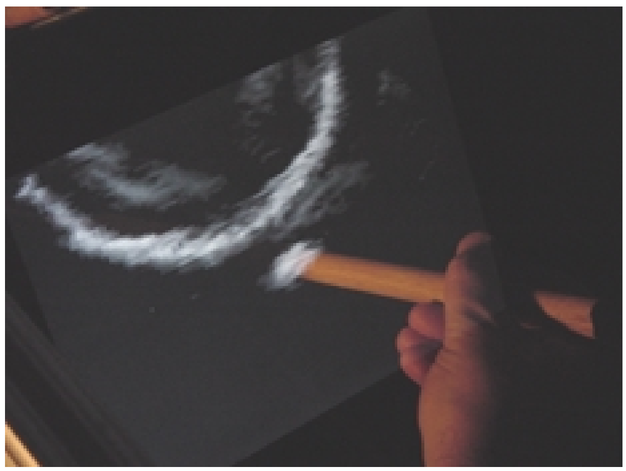
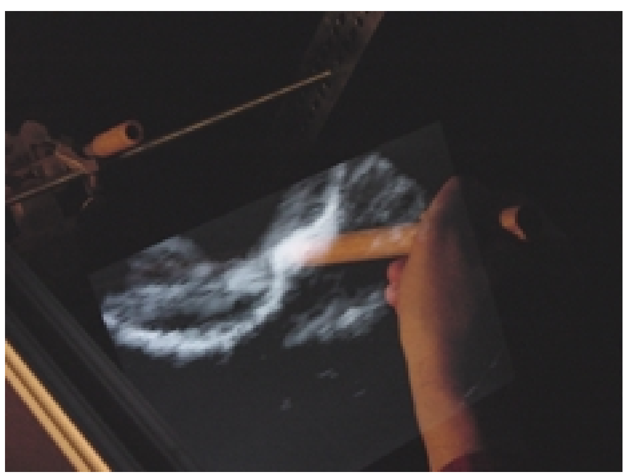


Fig 5 *Mock effector* (3/4" wooden dowel) interacting with the virtual image of a magnified ultrasound scan of the balloon, seen through the half-silvered mirror.



. **Fig 6** Result of *actual effector* (3/16" dowel) pressing into balloon visualized by merging *mock effector* (3/4" dowel) with virtual image.

Figs. 5 and 6 show images captured with a camera from the point of view of an operator looking through the half-silvered mirror. The operator's hand is shown holding the mock effector (i.e., the 3/4" end of the dowel). The actual effector (the 3/16" cross-section of the dowel being scanned in the water tank) is magnified to 3/4" in the virtual image and accurately tracks the mock effector as it appears to cause the indentation in the magnified image of the balloon. The extension of the dowel into the water bath is hidden from view by selective lighting.

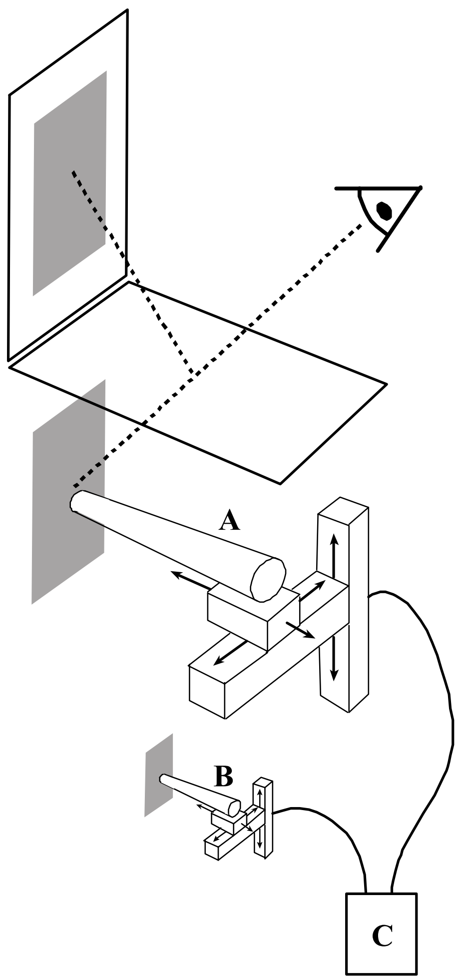


Fig. 7 Apparatus demonstrating magnified RTTR using an electro mechanical linkage to control remote effector at a magnified scale (see text).

The preliminary work already described has demonstrated remote RTTR using a wooden dowel to mechanically link the actual effector and the mock effector. Clearly, mechanical linkages have severe limitations for real microscopic manipulation. We plan to develop electro-mechanical linkages that work on the same principle, as shown in Fig. 7. System **C** is shown electronically linking mock effector **A** to actual micro-effector **B** (e.g. a micropipette). **A** and **C** are both capable of 3 degrees of translational freedom in this illustration, although rotations could also be incorporated. A semitransparent mirror visually merges the magnified image from an *in vivo* tomographic microscope at the site of the micro-effector with the mock effector using RTTR. System **C** acts as a servo controller, so that the operator manually controls the mock effector using hand-eye coordination, and the actual micro-effector moves accordingly. At present, we are planning to implement this system using several imaging modalities as described in the following section.

4 Magnified Remote RTTR for *in vivo* Micrsocpy

A number of appropriate mesoscopic/microscopic (10-20 μ resolution) imaging modalities have recently become available that scan from an *in vivo* surface to produce tomographic slices at depths of 1-2 mm. We intend to use two of these as test-beds to develop remote RTTR.

The first of these modalities is *ultrasound backscatter microscopy* (UBM), which operates similarly to conventional ultrasound, except at higher frequencies (50-100 MHz) and has been shown capable of differentiating normal lymph nodes *in vivo* from those containing metastatic melanoma cells [18]. The other *in vivo* microscopic imaging modality that we propose to use for remote RTTR is *optical coherence tomography* (OCT). This relatively new modality uses reflected coherent infrared light in a manner similar to ultrasound. OCT has proven capable of producing real time tomographic images *in vivo* of the epidermis [19].

The mesoscopic/microscopic scale of resolution of UBM and OCT may prove very important for diagnosis, biopsy, and therapy, being able to delimit the extent of multi-cellular structures of differing types. Operating *in vivo* at these scales is an exciting frontier where remote RTTR may play an important role. We have demonstrated the first step towards these applications.

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