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Laser Needle Guide for the Sonic Flashlight

David Wang[a,c,d], Bing Wu[b,c], George Stetten[a,b,c,d,e]

[a]Department of Biomedical Engineering, Carnegie Mellon University, Pittsburgh PA 15213, USA;
[b]Department of Psychology, Carnegie Mellon University, Pittsburgh PA 15213, USA;
[c]Robotics Institute, Carnegie Mellon University, Pittsburgh, PA 15213, USA;
[d]University of Pittsburgh Medical Center, Pittsburgh PA 15261, USA;
[e]Department of Biomedical Engineering, University of Pittsburgh, Pittsburgh, PA 15261, USA

Abstract. We have extended the real-time tomographic reflection display of the Sonic Flashlight to a laser guidance system that aims to improve safety and accuracy of needle insertion, especially for deep procedures. This guidance system is fundamentally different from others currently available. Two low-intensity lasers are mounted on opposite sides of a needle aimed parallel to the needle. The needle is placed against a notch in the Sonic Flashlight mirror such that the laser beams reflect off the mirror to create bright red spots on the flat panel display. Due to diffuse reflection from these spots, the virtual image created by the flat panel display contains the spots, identifying the projected destination of the needle at its actual location in the tissue. We have implemented our design and validated its performance, identifying several areas for potential improvement.

1 Introduction

In interventional radiology, it is often necessary to insert a needle outside the plane of an ultrasound scan. Because, in such cases, the tip of the needle is not visible until it reaches the ultrasound scan, a potential exists for the needle to miss the target, requiring multiple needle insertions and unnecessary trauma to the patient. Hence a method to accurately guide the needle to the target in just one attempt would be valuable.

Typically, needle guides are attached to the ultrasound probe and restrict the needle to travel along a specific path within the ultrasound plane. They have been routinely used to perform needle biopsies of various organs, including the liver, kidney, prostate, and breast [1], [2], [3], [4]. The needle pathway is indicated on the monitor by means of guide lines superimposed on the ultrasound image. While steerable in-plane needle guides are currently being developed [5], the needle is still restricted to travel in the scanning plane.

Needle guides have also been developed to operate out of the plane of the ultrasound scan. Two commercial systems are currently available. The PunctSURE™ vascular access imaging system (Inceptio Medical Technologies, L.C., Kaysville, Utah) is a variation on traditional ultrasound systems, presenting real-time cross-sectional and longitudinal B-mode scans simultaneously on the display side by side. With the vein centered in the cross-sectional scan, the longitudinal ultrasound array is properly oriented parallel to the vein. The needle, when inserted in the plane of the longitudinal scan, can be visualized in its entirety, and no needle guide device is needed with the system.

The second system is the Site-Rite™, (CR Bard, Murray Hill, New Jersey) in which an out-of-plane needle guide attaches to the ultrasound probe, restricting the needle to a pathway that intersects the ultrasound scanning plane at specific depths, ranging from 0.5 cm to 3.5 cm, in 1 cm steps. The choice of depth depends on which of 4 disposable needle guides is attached to the probe. After guiding the needle into the vein, the guide can be separated from the needle, facilitating insertion of a catheter.

Both guidance systems suffer from a lack of perceptual coupling between the act of needle insertion and visual feedback from the ultrasound image, with the display located separately from the transducer. With the PunctSURE, the user can follow the needle trajectory, but must look away from the site of operation in order to do so. Such displaced hand-eye coordination causes attentional shifts and may introduce errors and variability in the operator's performance. The mental imagery involved in locating the target is a demanding cognitive process, subject to error. The Site-Rite permits prediction of the needle trajectory, but restricts the insertion to a fixed number of pre-determined angles, depriving the operator of the ability to perform insertions along an arbitrary path.

We propose to solve these problems by using a new ultrasound guidance system called the Sonic Flashlight (SF), and adapting the needle with two small lasers. As described below, the operator will use the lasers to illuminate targets in a virtual ultrasound image projected directly within the patient by the SF, and thereby "home in" on the target following a straight line. The procedure will occur without looking away from the patient or physically restricting the angle of insertion.

We start by reviewing the concept of Real-Time Tomographic Reflection behind the Sonic Flashlight in Section 2. We then explain our proposed method in Section 3 and present experimental results in Section 4. We conclude with a proposal for future work.

2 Real-Time Tomographic Reflection

Real-Time Tomographic Reflection (RTTR) was separately proposed by Stetten et al. [6], [7], [8], [9] and Masamune et al. [10]. Stetten's RTTR system was developed for real-time visualization of ultrasound. It functions by fixing the relative geometry of the ultrasound transducer, the display, and a half-silvered mirror to produce a virtual image of a tomographic slice (a sector-scan B-mode ultrasound image) at the actual scanned plane within the body (see Fig. 2.1). Through the half-silvered mirror, the ultrasound image is projected as if it "shines out" from the probe and illuminates the inner tissue, which is no longer occluded by the proximal surface of the skin. For that reason, this implementation of RTTR was named the Sonic Flashlight. Using the

Sonic Flashlight, there is no need to track the observer, the patient, or the transducer, due to the direct registration between the virtual image and the ultrasound beam. Moreover, the patient, the ultrasound image, the surgical instrument, and the operator's hands are merged into one perceptual environment for all observers looking through the half-silvered mirror, facilitating cooperation or training.

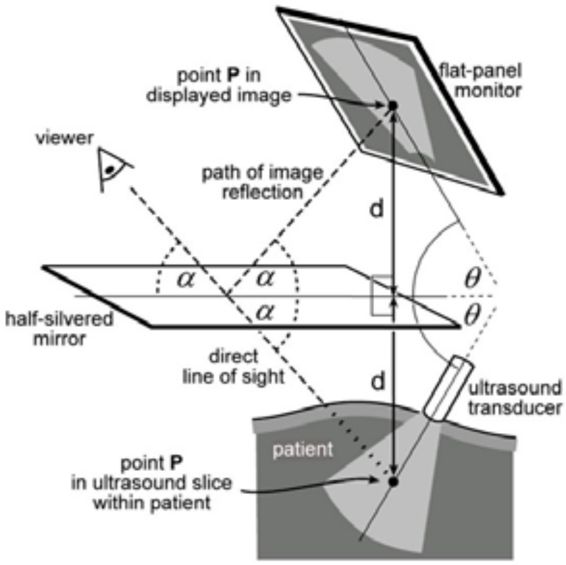

Fig. 2.1. Optics of Real-Time Tomographic Reflection (RTTR) in the Sonic Flashlight

3 Method

We have applied the concept of RTTR to produce a new method of needle guidance, capitalizing on the fact that the optical geometry of RTTR works as well for light hitting the display as coming from it. If a low-intensity laser is aimed at a target in the virtual image, it can be used to define a straight path for needle insertion,. As shown in Figure 3.1, if the laser beam hits the mirror, it will both reflect and pass through. The part that passes through the mirror will create a light spot on the skin, which shows the point the needle should enter the body. The part of the laser beam that reflects off the mirror will create another light spot on the flat panel monitor at exactly that point in the image displaying the target. As the image on the flat panel monitor reflects off the half-silvered mirror to create a virtual image, a diffuse reflection of the laser spot also shows up in that virtual image, at the actual location within the patient where the needle will intersect the ultrasound scan.

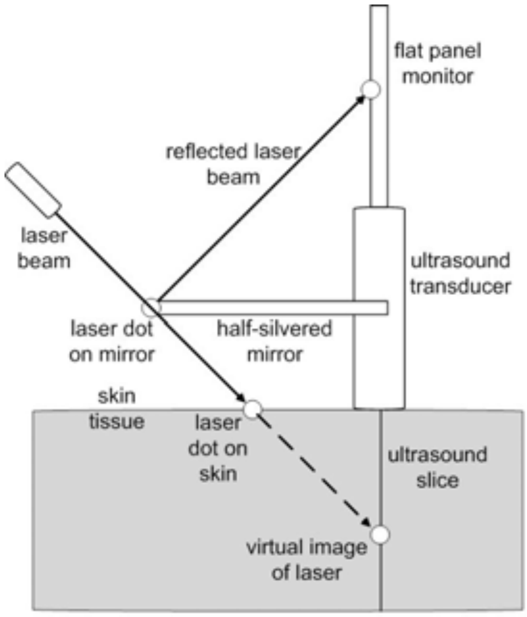

Fig. 3.1. Laser Needle Guide optics overview (see text).

In order to have the laser beams strike as closely as possible to the needle destination, we place the laser generators parallel to, and as close as possible to, the needle. As shown in Figure 3.2 two lasers are used so that the mid-point of the two spots in the virtual image flank the destination of the needle. Since the lasers must reflect off the half-silvered mirror, the needle is positioned in a small notch cut into the edge of mirror.

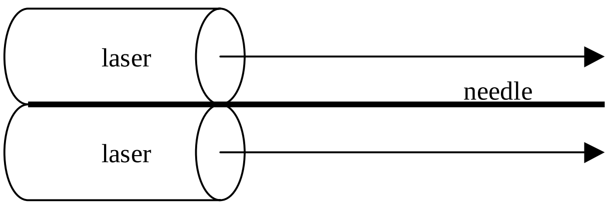

Fig. 3.2. Positional relationships between the two lasers and the needle

4 Experimental Results

We have tested two implementations of the laser needle guide described in Section 3. In the first implementation, we used an older Sonic Flashlight prototype (Model 4), and used it to guide the insertion of a needle into a water tank to hit a small spherical target mounted in the tank. The water surface in the tank was covered with loose screening, which permitted penetration by the ultrasound beam and the needle. As shown in Figure 4.1, each of the lasers generates four pairs of bright spots, labeled 1-4 (the spots are red if you are reading a color version of this paper). The needle is difficult to see in the darkness, but was inserted into the tank to hit the target, while maintaining contact with a notch in the edge of the mirror. Following the paths of the laser beams, the four pairs of spots are as follows: The laser beams traverse the lower half of Figure 4.1 from left to right, striking the mirror (4) and splitting into two beams. The upper (reflected) beams reach the flat panel monitor (1) while the lower beams penetrate the mirror to product bright spots on the surface of the water covered by white screening (3). The virtual image (2) of the spots on the flat panel monitor (1) accurately flank the target at its actual location in the water tank. The photograph does not convey the strong perceptual depth of these spots felt by the observer. By keeping the lasers aimed on either side of the target, we successfully and easily reached the target with the needle.

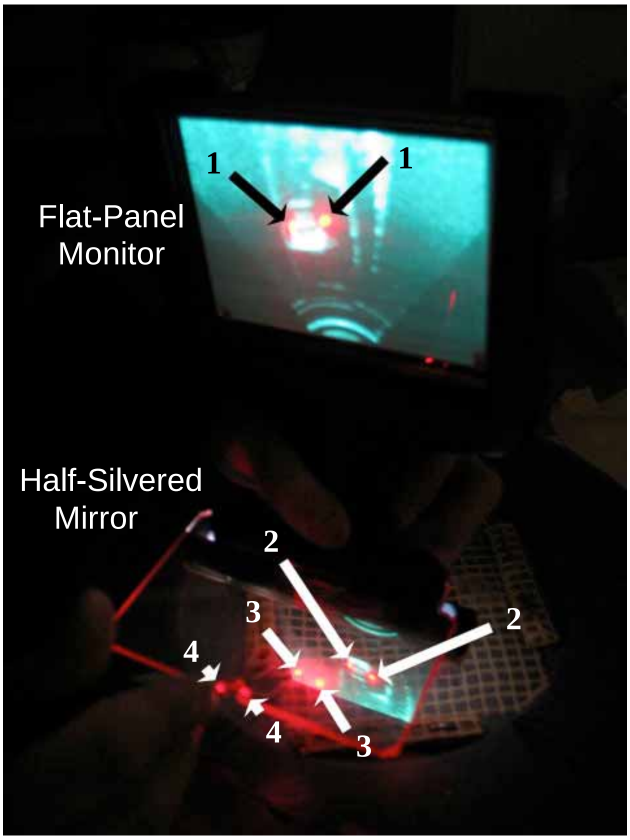

Fig. 4.1. Using a two-laser needle guide with the Model 4 Sonic Flashlight (see text).

In the second implementation of the laser needle guide, we used a more recent prototype of the Sonic Flashlight (Model 6), which is more compact and produces higher quality ultrasound images than the Model 4. In this case, a gel phantom containing a simulated vein was used as a target. Although a clear photograph of this apparatus in operation proved difficult to obtain, it was nonetheless easy to use. When we penetrated the phantom and pushed the needle toward the target, the needle bent slightly, changing its course. Due to the pliable nature of the gel, the deviation was easily corrected by realigning the laser with the target, and we hit the target successfully without having to withdraw the needle.

4 Conclusions and Future Work

We have demonstrated the feasibility of the two-laser needle guide with the Sonic Flashlight. Whereas the Sonic Flashlight with unaltered needles has shown good accuracy for relatively shallow targets such as veins in the arm, the addition of laser guidance may be appropriate for deeper procedures such as biopsies of the liver or kidney. The longer needles required for deeper procedures would lend themselves nicely to the apparatus, given the requirement that they maintain contact with the edge of the mirror. We are planning more extensive testing by examining human performance, in a special facility equipped with optical tracking.

Several areas for potential improvement could be addressed. First, we would like to eliminate the laser spot visible on the half-silvered mirror itself, due to scattering within it and on the mirror's surface. This spot is of no particular use and may be a potential distraction. The solution is to keep the mirror surface clean so as not to scatter light, and perhaps to find a different type of mirror that minimizes internal scattering. Another area for improvement is the specular surface of the flat panel monitor. Ideally we want the monitor to scatter the laser beam to create a red spot instead of reflecting (or absorbing) it. This could be accomplished by adding an antiglare diffusive surface. Finally, we are considering various schemes for reducing the number of lasers from two to one.

Since lasers are involved in this system, a safety analysis of potential damage to the retina is warranted. A number of paths for the laser light are created by reflections. Although the light attenuates at each of these, potential danger still exists. Our present apparatus uses two Class 3B lasers, which should not be viewed directly or in a specular reflection, but normally will not produce a hazardous diffuse reflection. Therefore the safe operation of the apparatus will depend on eliminating direct paths or specular reflections to the eye of the operator or patient.

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