Towards an Ultrasound Probe with Vision: Structured Light to Determine Surface Orientation

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Abstract. Over the past decade, we have developed an augmented reality system called the Sonic Flashlight (SF), which merges ultrasound with the operator's vision using a half-silvered mirror and a miniature display attached to the ultrasound probe. We now add a small video camera and a structured laser light source so that computer vision algorithms can determine the location of the surface of the patient being scanned, to aid in analysis of the ultrasound data. In particular, we intend to determine the angle of the ultrasound probe relative to the surface to disambiguate Doppler information from arteries and veins running parallel to, and beneath, that surface. The initial demonstration presented here finds the orientation of a flat-surfaced ultrasound phantom. This is a first step towards integrating more sophisticated computer vision methods into automated ultrasound analysis, with the ultimate goal of creating a symbiotic human/machine system that shares both ultrasound and visual data.

Keywords: ultrasound, laser, structured light, computer vision**,** Sonic Flashlight.

1 Introduction

The term "augmented reality" has generally meant augmenting the "reality" of the human operator by the introduction of information beyond the normal powers of human perception. The added information often comes from imaging modalities such as ultrasound (US), magnetic resonance (MR), or computed tomography (CT). These imaging data may simply be displayed, or they may be further analyzed, for example, to provide graphical overlays of segmented structures. If the augmented reality system includes a video camera, analysis of that video data can further help augment the experience of the human operator. Finally, the analysis of the video stream and the other imaging data can be combined within the computer analysis, as it is in the mind of the operator. Thus the "reality" being augmented can include not only human's but also that of the ultrasound machine and associated computer algorithms.

Our laboratory has developed a particular augmented reality device, which we call the Sonic Flashlight (SF). The SF merges an ultrasound image into the visual viewpoint of the operator using a half-silvered mirror and miniature display mounted directly on the ultrasound probe [1]. We call the general approach of optically reflecting such a virtual image into its actual location *in-situ* display.

Fig. 1 (left) shows the Sonic Flashlight and (right) the operator's point of view using it to guide insertion of a needle into a vein in the upper arm of a cadaver. The in-situ virtual image is shown magnified in the white box. The needle tip is visible as a bright spot within the dark cross section of the vein (adapted with permission from *Radiology* [2]). The SF is capable of displaying not just the raw ultrasound data but also the results of further analysis, such as automated segmentation of structures in the ultrasound data or color Doppler flow data (see below).

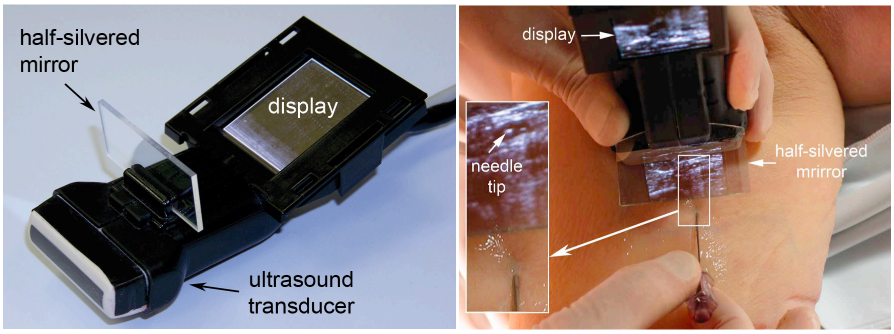

Fig. 1 Sonic Flashlight device for viewing ultrasound in-situ (see text).

A number of other researchers have developed systems to overlay ultrasound data on the human visual system using head-mounted displays to overlay the ultrasound image on what the operator would see, as captured by video cameras [3][4]. The video information these systems capture can also be automatically analyzed using computer vision methods. At present, the SF lacks this ability, since the visual information is merged optically without ever being captured. To provide the computer with the same merger of ultrasound and visual information that the SF provides the human operator, we now add video capabilities to the ultrasound probe.

Others have done this before us. Flaccavento, et al. described a system to track the location of an ultrasound probe in 3D space, using three stationary cameras that monitor patches adhered to the ultrasound probe. Since the cameras are stationary, this system restricts motion of the probe during the procedure and requires separate tracking of patient location [5]. Attaching the video camera directly to the ultrasound probe provides a simpler solution, as was proposed by Sauer and Khamene, who used it to permit graphical overlays on the video image to show a line of possible entry points for needle biopsy in the plane of the ultrasound scan [6]. Chan, et al., used stereo cameras mounted on the US probe with computer vision methods to determine needle location relative to probe [7]. More recently, Rafii-Tari, et al., attached passive optical markers to the skin along the patient's spine and used a camera mounted on an ultrasound probe to register the probe to the patient's anatomy, permitting accumulation of 3D ultrasound data and navigation within that data [8].

We wish to accomplish something along the lines of Rafii-Tari, but without requiring optical markers. Our goal is to use the surface of the patient directly as the visual coordinate frame for the computer, just as the human operator already does when scanning the patient with an ultrasound probe. To accomplish a proof-of concept, we turn to the use of structured light, as described next.

2 Using structured light to determine surface orientation

One of the most straightforward tasks in computer vision is to locate a surface using structured light, such as that generated from a projector or one or more lasers. A video camera with known geometric relationship to these light sources yields images in which the location of the light hitting a surface can be triangulated to locate the surface in 3D space relative to the camera. A simple version of this is shown in Fig. 2. An apparatus consisting of a laser projector with four beams and a video camera is shown in two different orientations with respect to a surface. The pattern of laser spots on the surface as detected by the video camera is sufficient to solve for their location on the surface relative to the camera.

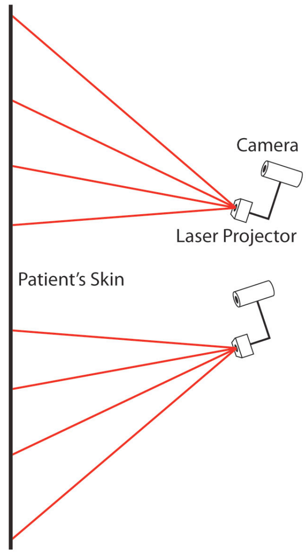

Fig. 2 Structured light used to determine tilt of probe against skin.

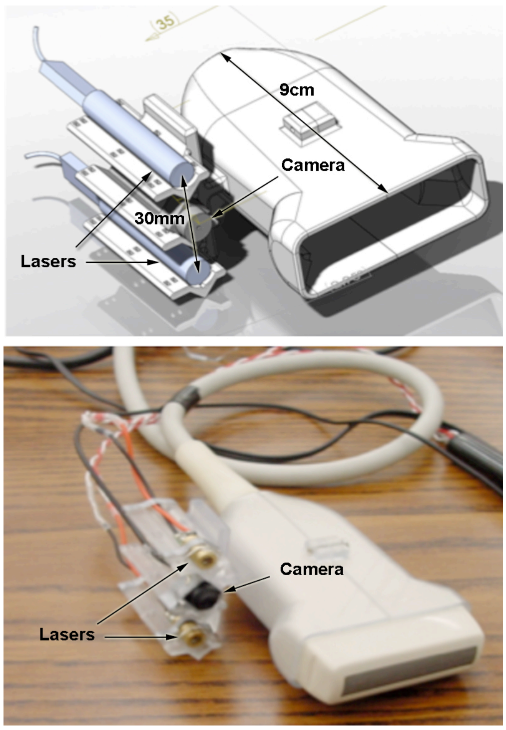

Fig. 3 Design (top) and actual device (bottom) with camera and lasers mounted on probe.

Our implementation of this concept uses a plastic shell (see Fig. 3) constructed around an ultrasound probe (Terason Model 2000.) that accommodates the rigid parallel mounting of two 5-milliwatt red laser modules 30mm apart and a miniature color video camera (Supercircuits PC208) half way between them. The lasers each produced a red spot on the surface of a gel phantom (Blue Phantom, Inc.), within the field of view of the video camera. The location in the video image of each of the red spots was determined in real time as the centroid of clusters of thresholded pixels, and these locations were used to determine the orientation of the phantom surface with respect to the ultrasound probe.

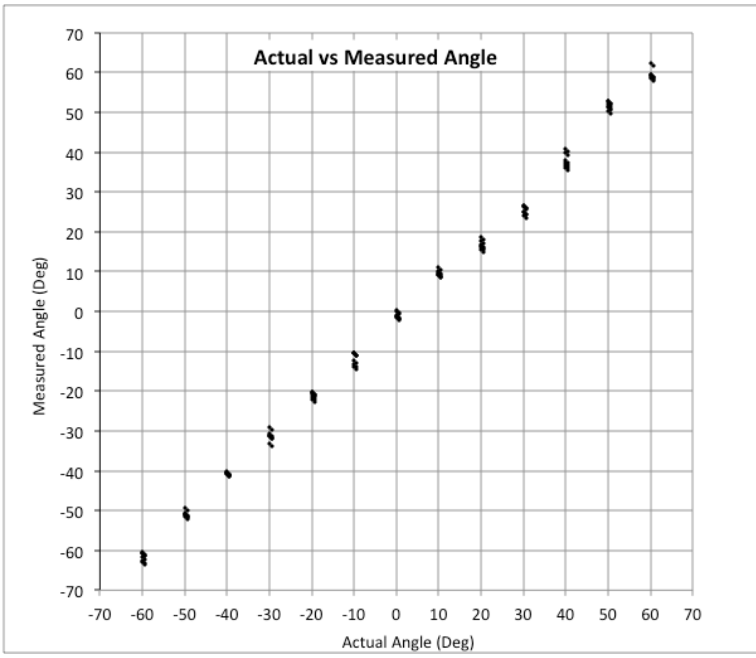

Fig. 4 Measurements of probe angle relative to the surface of a phantom computed from location of laser spots in video image.

We tested the system by holding the ultrasound probe at known angles relative to the flat surface of the gel phantom between +60 and -60 degrees relative to perpendicular (0 degrees). The results are shown in Fig. 4 as a scatter plot for six separate trials. RMS error is ± 2.1 degrees. A video showing the device in operation is available online at

http://www.vialab.org/main/Images/Movies/ProbeSightDemo1.m4v

Clearly, the system has determined orientation with sufficient accuracy to be able to disambiguate Doppler, as will be discussed next.

3 Using surface orientation to disambiguate Doppler

Doppler in ultrasound provides information about the velocity of a target with respect to the ultrasound probe. Frequencies in the ultrasound signal are shifted upwards when the target moves towards the transducer, and downwards when moving away from it. In most commercial ultrasound scanners, motion is mapped to color superimposed on the grayscale ultrasound image, ranging from red (towards the transducer) to blue (away from it). A problem in clinical medicine arises when

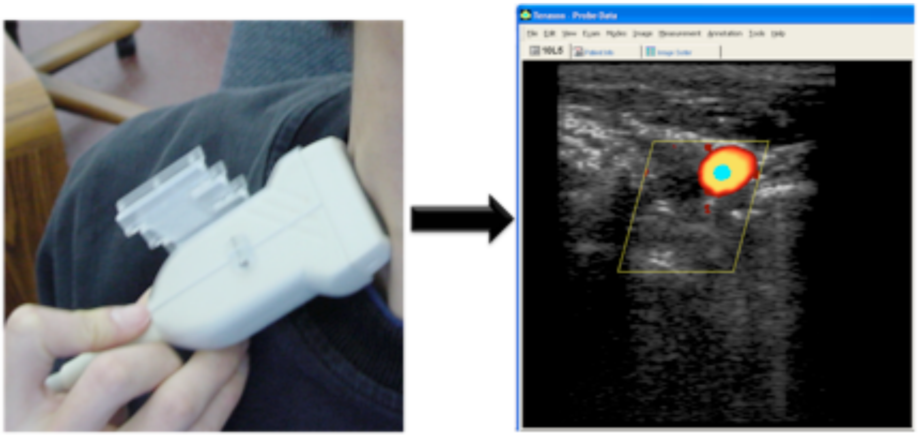

Fig. 5 The Ultrasound probe (left) being held at an angle to the surface of the skin and the corresponding Doppler (right) information from blood-flow in a vessel.

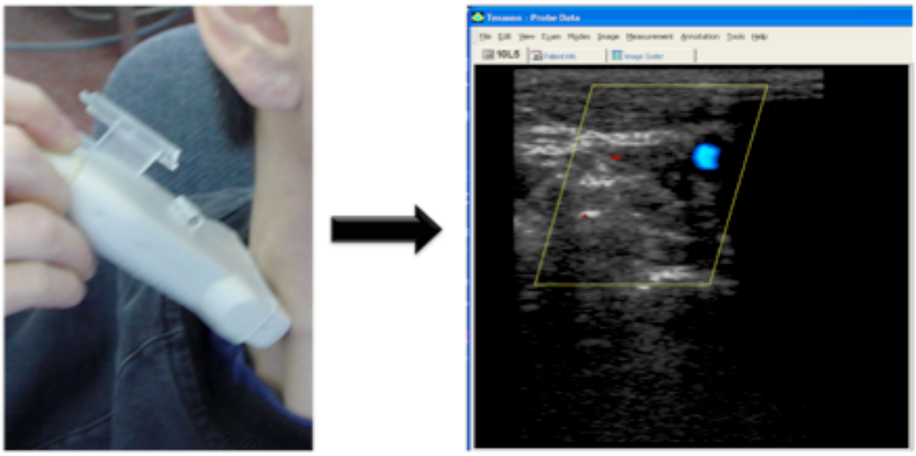

Fig. 6 Once the Ultrasound probe is tilted past orthogonal (left), the Doppler color changes to blue (right) even though we are still looking at the same anatomical structure.

interpreting color Doppler, in that arteries and veins often run in opposite directions, both roughly parallel to the skin surface. Thus, tipping the transducer one way or the other along the path of a given vessel can change its appearance in the image between red and blue. This concept is shown using the same ultrasound machine from the experiment above (see Figs. 5 and 6), but without the camera and lasers attached. The area of the neck being scanned contains two major vessels roughly parallel to the surface, the jugular vein and the carotid artery. Without knowledge of transducer angle, the corresponding blood flow direction in anatomical terms (towards or away from the heart) is ambiguous. This is especially troublesome when looking at recorded images, in which information about transducer angle is no longer available, but it also makes color Doppler less reliable in real time when using it to guide insertion of a catheter into the jugular vein. It is crucial not to accidently insert such a catheter into the carotid artery, where it can cause brain damage by generating clots.

We have explored differentiating these vessels in terms of the ultrasound data itself without knowledge of transducer angle with some success [9], but we would prefer to have transducer angle as an additional feature. Saad, et al., have attempted to characterize transducer angle using image-processing techniques applied directly to the ultrasound data, but their method yields only the absolute value of the angle, not its direction [10]. The independent determination of surface angle presented above is one solution.

4 Discussion

Clearly a flat phantom is not a legitimate test for a clinically useful device. Human external anatomy consists of surfaces that are not only curved but also deform and move relative to each other based on elastic tissue covering an internal articulated skeleton. We are currently developing systems that replace our simple fixed laser modules with a laser scanner projector capable of producing a more complex structured light pattern, both spatially and temporally. Note that, for example, while the two lasers used in our experiment are sufficient for a single camera to determine the location and orientation of a flat surface, the four laser beams shown in Fig. 2 could also determine some measure of curvature in the surface. We are further exploring the use of algorithms for determining surfaces from stereo disparity without structured light, using more than one camera. Although this permits the determination of 3D location for a potentially large number of surfaces points, it also requires correspondences for those points to be established in the multiple video images. Our intermediate goals include incorporating both structured light and stereo disparity to find 3D surface location of actual anatomical structures, such as the arm and neck, and to use that information to facilitate 2D/3D registration of real-time ultrasound data with pre-acquired CT or MR images. Towards this end, we are funded by the National Library of Medicine (NLM) to combine two major open-source software libraries, OpenCV and ITK. OpenCV (Open source Computer Vision library, opencv.willowgarage.com) was originally developed by Intel Corporation. ITK, (Insight segmentation and registration ToolKit, www.itk.org), is a project of the NLM.

In addition to analyzing these images, we plan to transmit and record stereo video from the cameras, to be displayed on stereo-capable screens with LCD shutter glasses, overlaying the ultrasound data at its known location. We anticipate having to address the difference between the intra-camera distance and the intra-pupillary distance of the viewer in the graphical placement of the ultrasound image.

Ultimately, we want to merge these systems into a special model of the Sonic Flashlight (see Fig 7) to provide a system that can combine the ultrasound and visual

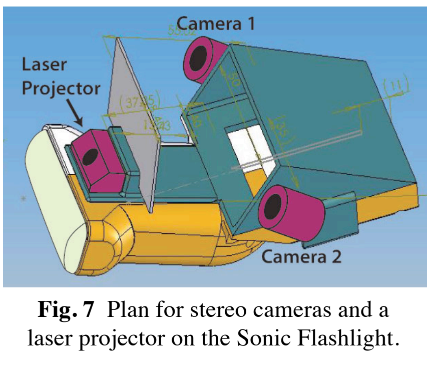

Fig. 7 Plan for stereo cameras and a laser projector on the Sonic Flashlight.

data in both the mind of the operator and in the software of the computer. We then intend to explore how the human and the machine can help each other to understand what each is seeing, for the benefit of the patient.

5 Conclusion

We believe the major contribution of our work, thus far, is to combine visual and ultrasound information gathered from a single device in such a way that data fusion can occur in the computer receiving both data streams, without requiring any special markers on the surface. These preliminary results lay the groundwork for more sophisticated systems combining computer vision and ultrasound.

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