Optimizing a Head-Tracked Stereo Display System to Guide Hepatic Tumor Ablation

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Abstract. Radio frequency ablation is a minimally invasive intervention that introduces—under 2D ultrasound guidance and via a needle-like probe— high-frequency electrical current into non-resectable hepatic tumors. These recur mostly on the periphery, indicating errors in probe placement. Hypothesizing that a contextually correct 3D display will aid targeting and decrease recurrence, we have developed a prototype guidance system based on a head-tracked 3D display and motion-tracked instruments. We describe our reasoning and our experience in selecting components for, designing and constructing the 3D display. Initial candidates were an augmented reality see-through head-mounted display and a virtual reality "fish tank" system. We describe the system requirements and explain how we arrived at the final decision. We show the operational guidance system in use on phantoms and animals.

Keywords. Radio-frequency ablation, hepatic tumor, stereoscopic 3D display, head-mounted display, augmented reality, virtual reality, interventional radiology.

Background and Introduction

Radio frequency ablation (RFA) is a first-line treatment for non-resectable hepatic tumors. This minimally invasive intervention (MII) uses high-frequency electrical current, introduced—under 2D ultrasound guidance—via a percutaneous needle-like probe, to heat the targeted tissues to physiologically destructive levels. RFA probes are characterized by manufacturer-specified ablation zones that are typically spheres or ellipsoids. The interventional radiologist who performs the procedure must place the probe such that the entire tumor as well as a safety boundary of several millimeters thickness are contained within the ablation area. Frequent tumor recurrence on the periphery of the original tumor [2] indicates that probe placement accuracy may be a major cause for the low 5-year survival rates of hepatic carcinoma patients.

We hypothesize that physicians will more accurately target RFA to hepatic tumors using a contextually-correct 3D visualization system than with standard 2D ultrasound alone. If proven beneficial, 3D guidance could decrease the high post-RFA tumor recurrence rate [4]. Our experience in developing and evaluating a guidance system for breast biopsy [6] yielded results that support this hypothesis.

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1. Choosing a Display System

Our research team has developed 3D guidance for MIIs since the mid-1990s; all our systems were based on see-through head-mounted displays (ST-HMDs) [State05]. We demonstrated superior targeting accuracy in breast lesions when comparing ST-HMD guidance with the standard 2D method [6]. In addition to stereoscopy and head-motion parallax, the system based on motion-tracked ST-HMDs provided a view of the patient that included a synthetic opening into the patient, showing live echography data and 3D tool guidance graphics in registration with the “real world,” and therefore also with the patient (Figure 1) as well as the motion-tracked instruments (Figure 2, which shows the ultrasound transducer in the breast biopsy guidance system, and an early RFA guidance system prototype based on a video see-through HMD).

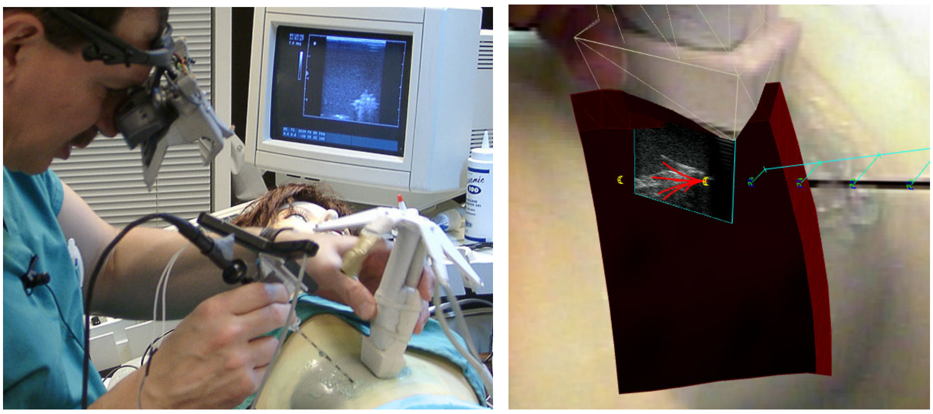

Figure 1. Left: RFA guidance system with see-through head-mounted display. Right: view inside HMD with 3D guidance graphics indicating relationship between needle-like RFA probe and ultrasound image plane.

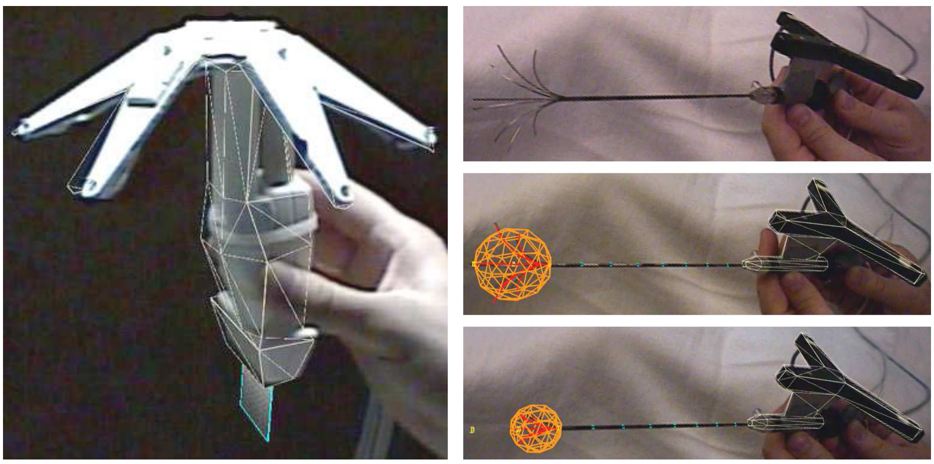

Figure 2. Left: ST-HMD view of ultrasound transducer with infrared LEDs for motion tracking. Note ultrasound image below transducer. Right, top to bottom: motion-tracked RFA probe with deployable tines and real-time registered guidance graphics. The ablation region (sphere) is scaled based on current tine length.

Stereoscopic visualization with head-motion parallax can also be implemented with fixed displays, i.e. without mounting the display on the user's head. Such "fish tank" displays use CRT monitors and frame-sequential shutter glasses [3], or (at a larger scale) projection displays and passive polarized glasses. Recently, novel devices based on LCD panels and a semi-transparent mirror have become available from Planar Systems, Inc. [5]; these use passive linearly polarized glasses.

While we obtained encouraging results in the past with ST-HMD systems, we are disappointed with the bulky and uncomfortable, low-resolution devices resulting from today's state of the art in HMDs. Moreover, since there are no satisfactory video see-through devices on the market, we always constructed our own, with rather modest resources [7]. For these reasons, when designing the RFA 3D guidance system, we considered both an ST-HMD approach and a commercial fish tank system (Figure 3). With respect to the "augmented reality" (AR) view provided by the ST-HMD, we noted that in MIIs—our driving problem—the "interface" between the relevant components of the real world (in our case, the patient, the RFA probe and the ultrasound transducer) and the virtual display (in our case, the echography image, the RFA probe representation inside the patient, and the 3D guidance graphics) is essentially limited to the location where the RFA probe penetrates the skin (Figure 1, right). Furthermore, once the probe pierces the skin, it is moved only lengthwise through this entry point, which is no longer under constant observation by the radiologist. The radiologist then focuses on internal anatomy as he guides the probe into the tumor. From this we conclude that MII (our driving problem) may in fact not derive much benefit from exact registration between real and virtual imagery as provided by an ST-HMD, at least not during the most critical final phase of the probe targeting approach, as the probe tip is introduced into the tumor.

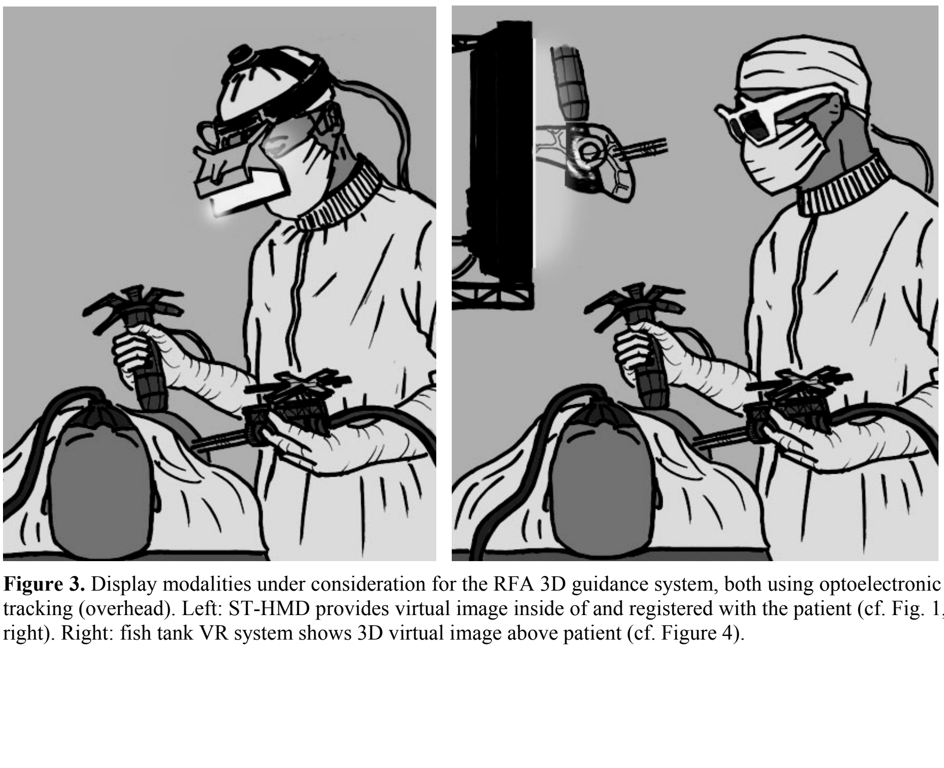

Figure 3. Display modalities under consideration for the RFA 3D guidance system, both using optoelectronic tracking (overhead). Left: ST-HMD provides virtual image inside of and registered with the patient (cf. Fig. 1, right). Right: fish tank VR system shows 3D virtual image above patient (cf. Figure 4).

The above considerations led us to favor a fish tank type display even though it does not offer registration between virtual display and internal patient anatomy. Since our display metaphor proposes life-size representations of the ultrasound image and of the RFA probe, projection displays are unsuitable; and CRT-based stereo has disadvantages such as the requirement for active stereo glasses, which can exhibit flicker. The Planar SD1710 display [5] was almost ideally suited: its small 17-inch 1280x1024 display can fully contain our 3D display elements at life size. Furthermore, it does not exhibit flicker and has manageable bulk.

2. Display System Implementation Details

We mounted a motion tracker on the Planar display as in handheld augmented reality applications. Thus both the tracker base and the display can be moved relative to each other at any time without recalibration; this improves visibility of the tracked system components. The control software ensures that the 3D display preserves orientation; e.g., the virtual representation of the RFA probe in the display is always shown parallel to the handheld RFA probe. In other words, as opposed to the registration in both position and orientation provided by the ST-HMD, this technique maintains only orientation alignment; it introduces a translational offset between the location of the instruments in the real world on the one hand, and their virtual counterparts in the 3D display on the other hand. Our interface has three presentation modes that differ in how these user-induced translational movements of the instruments are echoed in the 3D display (orientation changes are always fully shown, as mentioned):

- **A. Centered mode:** The ultrasound image is always shown in the center of the 3D display. It is not possible to move the ultrasound transducer such that it leaves the display area.
- **B. Free mode:** The user can interactively define the position offset between an area within the patient and the 3D space seen inside the display. Translational motion of the instruments is shown fully within the display, and it is possible to move the ultrasound transducer such that it leaves the display area.
- **C. Delayed mode:** This is a combination of the above two modes. The ultrasound image is initially centered as in (A), but the user may move the ultrasound transducer, even outside the display. However after a short lag, the system "catches up" and re-centers the ultrasound image. This allows the user to perceive high-speed translational motion of the ultrasound transducer and image; at low speeds or statically, this is equivalent to (A), at high speeds, to (B).

For all three modes above, the system continually calculates the appropriate transformations for the RFA probe, in order to always show the correct pose relationship between it and the ultrasound image.

Given the small size of the display, it is important for the system to accurately track the user's eyes, in order to minimize geometric distortions. We have developed a fast and accurate method to calibrate the user's eyes to the head tracker [8].

Table 1 summarizes the principal characteristics of the two display techniques we have considered using for the RFA guidance system (ST-HMD and fish tank VR system).

Table 1. Characteristics of the two display technologies under consideration

	See-through HMD	**"Fish tank" VR system**
Availability	Custom-designed and built	Commercially available
Display configuration	Fixed to user's head, motion-tracked with head	Fixed to room, but motion-tracked (can be moved)
Head gear	ST-HMD, tracker	Lightweight glasses, tracker
Resolution	800x600 in our recent build; higher resolution yields bulkier device	1280x1024 in current device, available at higher resolutions
Registration between patient and ultrasound image (and between RFA probe and its virtual representation)	Yes ("true" augmented reality)	Partial only: orientation alignment but offset in position

3. Using the Head-Tracked Fish Tank Stereoscopic Display

At present there is no controlled study comparing the performance of the head-tracked fish tank display to an ST-HMD device. The interventional radiologist (Burke) who has used the fish tank display extensively, reports that depth perception is good and that the display correctly portrays three-dimensional relationships during RFA probe targeting. A depth perception study conducted with this display revealed that most subjects (a randomly selected group of 23) were able to determine which of two objects located only a few millimeters apart in depth was closer, based solely on stereoscopic and motion parallax cues provided by the fish tank display.

Our 3D guidance system has been tested on specially constructed liver phantoms [1]; the completed system is currently used in a controlled animal study to ablate liver carcinomas in woodchucks (Figure 4, left). The study randomizes each woodchuck to either the ultrasound-only conventional guidance method or to our ultrasound-with-3D-guidance technique. We will report at the study's completion.

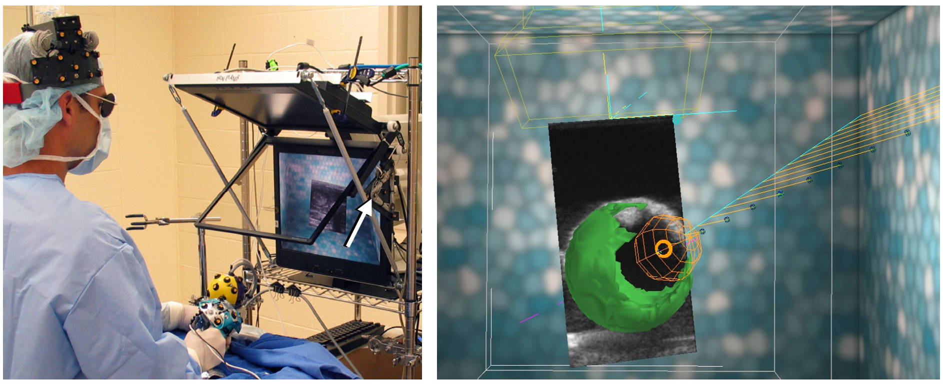

Figure 4. Left: RFA guidance system in use on woodchuck with liver tumors. The interventional radiologist wears polarized glasses and a large but lightweight head tracker with infrared LEDs. He holds a tracked ultrasound transducer (left hand) and a tracked RFA probe (right hand). Note the triangular LED tracking panel on the right side of the display (white arrow). Right: View inside Planar display shows the transducer, the echography image, and the RFA probe (cf. Figure 1, right). The ablation region (cf. Figure 2, right) is also shown (wireframe sphere). The tumor is visible as a partially hollowed out spherical object.

4. Conclusions

We have described an orientation-aligned stereoscopic head-tracked display used within a 3D guidance system for minimally invasive hepatic tumor ablation procedures. Despite our extensive past experience with augmented reality technology and video see-through head-mounted displays, we have given preference to this type of virtual reality visualization. The characteristics of the driving application on the one hand, and the state of the art in head-mounted display technology on the other hand, have led us to this choice. The availability of a high-quality desktop-size stereoscopic display has also significantly aided our decision.

5. Future Work

We are currently enhancing our prototype RFA guidance system to support multiple ablation passes over a single tumor, a technique used to treat large lesions and which poses a difficult three-dimensional problem for the interventional radiologist. Figure 4 (right) shows a "volume carving" visualization that informs the radiologist which parts of a large tumor have already been ablated. We expect our high-quality display to play a significant part in an effective experimental system for these complex interventions.

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