Augmented Reality Guided Respiratory Liver Tumors Punctures: A Preliminary Feasibility Study

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ABSTRACT
CT-guided radiofrequency ablation (RFA) has evolved rapidly over the past decade and become a widely accepted treatment option for patients with liver tumors. However, it is hard for doctors to locate tumors precisely while avoiding the surrounding risk structures with 2D CT images, which only provides limited static information, especially in case of respiratory motion. This paper presents a novel augmented reality guidance modality for improving the precision of liver tumors punctures by providing visual cues of 3D personalized anatomy with respiratory motion. Optical see-through display devices Epson MoveRio BT300 and Microsoft HoloLens are used to mix pre-operative 3D personalized data and intra-operative physical scene. Here an augmented reality based surgical navigation pipeline is proposed to achieve the transformation from raw medical data to virtual guidance information and precisely superimpose this information onto real experimental animal. In addition, to alleviate the difficulty during needle placement induced by respiratory motion, we proposed a correlation model to real-timely predict the tumor position via regression based respiration state estimation and the statistical tumor motion model. We experimentally validated the proposed system on in vivo beagle dogs with artificial lesion, which can effectively improve the puncture efficiency and precision. The proposed augmented reality modality is a general strategy to guide the doctors perform precise percutaneous puncture under respiration conditions and has the potential to be used for other surgical navigation tasks.

CCS CONCEPTS
• Human-centered computing → Mixed / augmented reality;
• Computing methodologies → Computer graphics;
• Mathematics of computing → Regression analysis.

KEYWORDS
Augmented Reality, Surgical Navigation; Virtual-real Alignment, Correlation Model, Statistical Motion Model

ACM Reference Format:

1 INTRODUCTION
Radiofrequency ablation (RFA) therapy for liver tumor is a widely used local mini-invasive percutaneous puncture treatment technology. Traditionally, surgeons in RFA surgery are guided by the ultrasound and computed tomography (CT) imaging to place the needle into the target tumor. However, the ultrasound is too fuzzy for the surgeons to distinguish the tumor with the surrounding tissues during percutaneous puncture, while CT images can provide more clear guidance images, but it cannot provide real-time intra-operative guidance [Kim et al. 2012; Lee et al. 2010]. Besides, the “Heads up” display of 2D intra-operative guided images further increases the operation difficulty and reduces the operation precision, since it lacks direct coordinating of surgeons’ hands with the vision [Cazzato et al. 2016; Crocetti et al. 2016].

Beyond the traditional 2D image-guided modality, augmented reality (AR) is a promising technology for surgical navigation and attracts widespread attentions from academy and industry communities since it can integrate virtual objects into the users perception of reality by graphics technologies. Philips developed an augmented-reality surgical navigation system to assist traditional image-guided minimally-invasive surgical guidance by combination of 3D X-ray imaging and optical imaging to provide surgeons with a unique augmented-reality view of the inside and outside of a patient during surgical procedures. However, it is still not convenient enough for doctors since hand-eye coordination is also a prerequisite conditions for doctors. Optical see-through head-mounted display (OST-HMD) can well tackle this issue, it can provide the on-patient see-through guidance modality and enhance the surgeon’s perception of the depth and spatial relationships of surrounding structures through the augmented reality-based fusion of 3D virtual objects with real objects [Bernhardt et al. 2017; Guha et al. 2017]. Nowadays a lot of researchers have developed augmented reality navigation system
for different medical application [Qian et al. 2018; Xie et al. 2017], but their guidance information is in static mode, which is not suitable for applications in dynamic conditions, especially for the free breathing.

This paper presents a comprehensive workflow for augmented reality based surgical navigation of needles in respiratory tumor targeting for RFA or other therapies where 2D images is not precisely enough to locate the lesion. In our prototype, we develop a collocation mechanism for all utilities to precisely align the coordinate system of optical measurement system, the augmented reality visualization system with the real objects, including puncture needle, tumor and liver on the animal. Besides, for respiratory motion, we propose a internal-external correlation model to associate the motion of surface makers on animal abdomen with that of internal tumors, here regression model is proposed to estimate the respiratory state and then predict the respiratory tumor position according to the statistical tumor motion model. With our augmented reality guidance modality, surgeons can more intuitively locate the target tumors in a more efficient and accurate manner. The overview of our system is shown in Fig. 1.

![Figure 1: The pipeline of our augmented reality based surgical navigation system.](image)

### 2 METHODOLOGY

#### 2.1 Raw medical data acquisition and processing

We employ a Beagle dog to perform the animal experiment. To accurately construct the spatial information between liver, tumor and ribs, we place 6 NDI surface marker as landmarks on the skin that near the ribs of it, shown in Figure 2. The ground truth of the respiratory motion is obtained via 4D-CT imaging, which records the deformation and displacement of the internal organ together with the surface marker under the free-breathing respiratory motion. At the same time, we continuous tracking the surface marker with the optical tracking system.

The Materialise Mimics software is used for manually segment the CT images of the abdomen into different tissues and accurately reconstruct the 3D geometric of the patient-specific model, including the liver, tumor and the surface marker on the dog’s skin. The 3D models denotes with $M = (V, E)$, where $V$ is the set of vertices (in CT-image coordinate) on the model surface and $E$ is the set of edges (forming the triangles).

Marker locations $S_M(t) = \{s_1(t), \ldots, s_n(t)\} s_i(t) \in \mathbb{R}^3, t \in \mathbb{R}_+$($n = 6$) and the tumor location $S_T(t) \in \mathbb{R}^3, t \in \mathbb{R}_+$ under the CT coordinate are calculate from the center of the patient specific 3D model. The surface marker position $O_M(t) = \{o_1(t), \ldots, o_n(t)\} o_i(t) \in \mathbb{R}^3, t \in \mathbb{R}_+$($n = 6$) under world coordinate is directly get from the optical tracker. With this procedural, we acquired the marker movement in both CT-device and world coordinate. The marker locations obtained by CT can map into the world coordinate by apply the transformation $T_{CT}^{TRA}$.

We analyze the continuously captured periodical marker movement with tracker tracked location data $O_M(t)$ to get the average marker movement period $\bar{O}_M(t)$. Then we sort the CT-extracted marker position $S_M(t)$ and its corresponding tumor position $S_T(t)$ by placing its mapping $S_M'(t)$ in the proper order which follows the movement in $\bar{O}_M(t)$. Then we perform the data augmentation via spline interpolation, which allows generating complete respiration sequences for surface marker and tumor.

![Figure 2: Raw medical data acquisition.](image)

#### 2.2 Respiratory motion reconstruction

In order to provide precisely navigation information to the surgeon, we reconstruct the respiration surface marker motion and tumor motion via statistical motion model. In present stage, we only consider the correlation between liver tumor and surface markers during respiration.

We assume that the respiration cycle is a regular repeat consists the state an exhalation-inhalation stage and the inhalation-exhalation stage. Calculate the mean state $\bar{s}_{M, T}(t_{ref})$ as reference state, we can calculate the deformation field of the tumor and markers position set. The deformation field therefore can represent as vectors between a reference state $\bar{s}_{M, T}(t_{ref})$ and the rest position in the displacement sequence.

$$\Delta s = s_{M, T}(t) - \bar{s}_{M, T}(t_{ref})$$  \hspace{1cm} (1)

We assume the position of the tumor and surface markers at specific respiration state follow the Gaussian distribution. Thus their displacement can be represented as a mixture of Gaussian distributions of different respiration states. Which can represented as following:

$$p(x) = \bar{s}_{M, T}(t_{ref}) + \sum_{n=1}^8 p(\Delta s_{M, T}(t_n))p(x|\Delta s_{M, T}(t_n))$$  \hspace{1cm} (2)
where $\Delta S_{M,T}$ is the set of marker and tumor displacement in the respiration states. In our work, we regress the respiration cycle to eight state $\{\Delta S_{M,T}(t_1), \ldots, \Delta S_{M,T}(t_8)\}$ (shown in Figure 1).

### 2.3 Tumor Position Prediction

Based on the previous statistically motion modeling, we can represent the periodic motion of liver tumor and surface markers as a linear combination of the eight respiration states.

$$\Delta S_{M,T}(t) = S_{M,T}(t_0) + c \cdot \Delta S_{M,T}(t_n \in \mathbb{C})$$

where the $S_{M,T}(t_0)$ is a reference state of the intra-operative respiration, $c_i \in \{c_1, \ldots, c_n\}, n = 8$ is a component in the vector of coefficients represents the current breathing state.

We assume that the internal-external respiration motion has a correlation that at a specific time, the tumor and the surface marker displacement are at the same respiration state.

For a intra-operative tracking state of surface marker $O_M(t)$, the breathing state $c$ can compute equally by least square regression:

$$O_M(t) = S_{M,T}(t_0) + c \cdot \Delta S_{M,T}(t_n)$$

$$O'_M(t) = T_{Tra} \cdot c_{Tra} \cdot O_M(t)$$

where $T_{Tra}$ is the transformation from tracker to the CT device coordinate, which we used for motion modeling. $C_{Pre}$ is the transformation from patient intra-operative pose to the pre-operative pose in the medical data acquisition phase. Thus the tumor position at the corrsponding time is predict as:

$$s_T = s_T(t_0) + c \cdot \Delta s_T(t_n)$$

where the $s_T(t_0)$ is the tumor position at the intra-operative reference state, and $c_i$ is the component of the linear coefficient.

In the end, the predicted tumor position needs to map the world coordinate in order to provide the proper information for the navigation system via transformation $s_T(t) = T_{CT} \cdot s_T(t)$

### 2.4 Dynamic virtual-real alignment

Here Epson MoveRio BT300 is employed to display the virtual guidance information superposed on real objects, while HoloLens is equipped with the surgeon assistant to wear in a fixed position, monitoring the overall puncture process to provide surgeon with supplementary information in other perspective and recording the video.

**Figure 3: Coordinate transformation**

**System Calibration** Figure 3 illustrates the collocation process of our AR prototype. Here we define the coordinate of optical tracker as the world coordinate, while attach optical markers on every utility in surgical scenario and holographic display devices. For each utility, we adopt two steps to achieve the precise system calibration, which are global and local transformation.

We first perform global transformation from utility coordinate to the world coordinate by $T_{U_{Dis}} = \{ T_{New}, T_{Ani}, T_{Dis1}, T_{Dis2} \}$, denoting transformation from marker coordinate fixed on utilities to the world coordinate.

Then we apply a local transformation from the utility coordinate to the optical marker via:

$$T_{U_{Dis}} = T_{Opt} \cdot T_{dev}$$

Finally, we calculate the transformation $T_{Dis} \in \{ T_{Dis1}, T_{Dis2} \}$ from global coordinate to the device display coordinate, which is the inverse of $T_{Dis}$.

#### Dynamic alignment

Considering that doctors equipped with OST-HMD need to observe the respiratory liver tumor from different views, while manipulate the needle targeting the tumor, we present an accurate dynamic alignment method to perfectly superimpose 3D images of the needle, liver, tumor, surface markers onto the surgical region in situ. The specific implementation can be divided into pre-operative process and intra-operative process.

**Pre-operative process:**

- Scan a frame of CT image of animal and get the positions of body surface trackers in the CT coordination system $S_M(t)$.
- Record the location of six body surface trackers in the optical tracker coordination system $O_M(t)$ at the same time.
- Calculate $T_{CT}\cdot s_T$ according to the Eq. 8 and send it to correla-

**Intra-operative process:**

- NDI tracker captures transformation of optical markers on needle and surface markers in real time $T_{New}, T_{Ani}$.
- Take a frame of CT scan, calculating $T_{CT}\cdot s_T$ with Eq. 5 for the patient pre- and intra-operative alignment.
- Display the virtual guidance information on MoveRio and HoloLens according to:

$$Disply = T_{Dis} \cdot T_{V_{Dis}}$$

where $T_{V_{Dis}} \in \{ T_{New}, T_{Ani}, O_M, T(t) \}$.

### 3 EXPERIMENT

To validate the effectiveness of our navigation system, an experienced surgeon was invited to adopt both traditional CT-guided and augmented reality guided modalities to insert the ablation needle into the dog respiratory liver tumor. According to suggestions from the surgeon, we define only a puncture no further than $3.50mm$ from the tumor center as an "accurate" puncture, needle adjustment is allowed for achieving the accurate puncture.

#### 3.1 Material

Experiment animal: beagle dog, female, 36months, 12kg. Percutaneous liver puncture of experimental animal was performed after general anesthesia.

Animal tumor model was build by implanting the iodine oil in animal liver. We first scan the dog abdomen to determine the
appropriate position of tumor implantation, and then use the sticky tape to attach the locator on the animal abdomen skin around liver. Besides, we can choose the optimal needle insertion path (7th subcostal), insertion angle (perpendicular to the skin) and distance (8cm) from the puncture point on the skin. Last, the surgeon injected the prepared iodine oil (2ml) into the liver.

3.2 Result
In the augmented reality navigation modality, we use the NDI Polaris to track all the utilities in surgical scenario, so that the operation region is limited in the tracking region of NDI Polaris. Besides, the surgeon wears the Epson MoveRio to locate the moving tumor while the assistant wears the HoloLens to monitor the overall process and record the video. The operations can be seen in the Fig. 4.

Figure 4: The surgeon performed AR-guided needle insertion.

The percutaneous puncture results of traditional CT guided modality and our augmented reality modality can be seen in Fig. 5 and Table 1, which illustrates that compared with traditional navigation modality, our method allows surgeon intuitively targeting the lesion from different insert angles with high accuracy, while it can also reduce the number of needle adjustments.

Figure 5: The sagittal plane of the needle insertion result in CT. (a) traditional CT-guided puncture, (b), (c) and (d) AR-guided puncture from three different insertion angles.

Table 1: Accuracy comparison of AR-guided and traditional CT-guided modalities.

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3.3 Discussion
In our current prototype, the ablation needle is modeled as rigid body. However, the deformation of ablation needle cannot be ignored, we now require the surgeons hold the needle in a proper way to keep the puncture direction along the needle direction in order to reduce the errors induced by needle deformation.

4 CONCLUSION
This paper presented a preliminary feasible study of using the augmented reality guidance modality to achieve the respiratory liver tumor puncture. The performance of this novel navigation modality is validated on a beagle dog with artificial lesion. Experimental results demonstrate that surgeons with AR-guided information can target the lesion more easily, more efficiently and more accurately than using the traditional 2D CT images guided modality.

Considering that our current correlation model can only predict the tumor moves along with the surface markers, which can’t provide the information of other key structures in target region, such as vessels. Thus, our immediate plan is to achieve the non-rigid registration of such key structures in order to provide more comprehensive navigation information for the surgeons. Besides, we will be also interested in investigating the modeling method of flexible needle during puncture. Furthermore, we will extend this promising guidance modality to other challenging surgical scenarios, such as deep brain stimulation, where electrode needs to be placed in a high-precision target region.

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