

Video-based Guidance System for Brain Tumor Biopsy

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Abstract

We present the system design and the methods of video-based guidance to assist with brain tumor biopsy procedures. The system comprises of a three-dimensional (3-D) position sensor, a CCD camera, a liquid crystal display (LCD) and a graphics computer equipped with a video capture board. The markers for positional measurement are attached to the CCD camera, a surgical tool, and the patient head. In order to be integrated into the camera-viewing capacity, 3-D images of the head and guidance indicators are visualized to form a life like video image. For reliable guidance, we propose a description style of surgical plan and the visualization method. The style of the surgical plan, called the "safety map", is a sphere surface highlighting the covering area of anatomically significant tissues and obstacles around the target for the indication of the biopsy needle's insertion starting-point. The safety map can be visualized in exactly the same way as it would be in a real life situation during surgery. We also present guidance methods of needle insertion and graphics techniques for AR systems.

The preliminary experiments were performed at the National Cancer Center. Augmented reality technology provided interactive visualization of surgical plans. A high degree of flexibility in terms of views was created by using general devices which are a CCD camera and a LCD. The display of the safety map enabled a successful completion of both craniotomy and biopsy needle insertion procedures. The trajectory display of the needle and the pass detection led the needle pathway into the target point with reliability.

Key words: Augmented reality, Interactive system, Video-based guidance, Biopsy

1. Introduction

Biopsies are performed for cytological diagnostic purposes. In the brain tumor biopsy, a small hole of the skull is created and then a needle is passed through the brain into an abnormal organ in order to obtain a small

amount of tissue. The result of cytodiagnosis is used for surgery application decision; if the tumor is malignancy, the surgery is performed, else if tumor is benignant, the surgery is canceled. This invasive procedure reduces risk of damage to adjacent tissues for confident test of surgery application compared with incision procedures.

In neuro-surgical intervention, a number of images from medical scanners are presented to the surgeon. It is not so easy for the surgeon to accurately decide current position of the surgical tool in the slice images. Modern computer systems provides surgeons to recognize intravital 3-D structures by volumetric visualization of the images and note points of interest such as the center of the diseased tissue in digital images as pre-operative planning [1], [2], [3]. Furthermore surgical planning by using quantitative analyzing systems and surgical simulators [4] is coming. These plans are precisely quantified. For successfully using of these plans, the correspondence among spaces of the plans and real-life world is required. Due to the correspondence of them, computer-assisted surgery (CAS) systems are often employed. CAS systems display the surgical tool's position in the spaces of pre-operative plans during surgical interventions.

Most CAS systems create orthogonal-image-based indicator generated by basic computer graphics methods for positional purposes. These methods of visualization however require the surgeon to often look away from the area in question in order to confer with one of the system's monitors with regards to the exact position of the surgical tool. Moreover the orthogonal-image-based systems are not efficient enough in indications of the orientation and the 3-D structure of tumors and adjacent organs. Whereas augmented reality (AR) systems are effective for these purposes. They visualize surgical plans in the real-life scene, and enable plans to be more accurate in orientation in a patient's body. Furthermore AR systems provide surgeons to perceive to outbreak danger situations by video scene during conferring plans, although the situation was unexpected beforehand and has not be registered to the system.

There has been a considerable amount of work on AR systems for surgical guidance. Concerned with biopsy, AR systems by using ultrasound images have been proposed [5], [6]. An AR system for breast cancer biopsies by using a stereo video-see-through head-mounted display (VSTHMD) has proposed by Fuchs et al. [5]. On see-through display systems, eye movements, which change the eye-viewing capacity, make positional error between computer graphics (CG) image and the real-life scene. VSTHMD systems are exactly precise in the above problem, however cause blind situation when the system is down. Thus we use a simple video-see-through display composed of a CCD camera equipped with a positioning sensor and a LCD to enable to accurately recognize 3-D structure. By measurement of the camera-viewing volume including distortion factors, the millimeter-order accurate merging of CG image and the real-life scene is enabled. The system configuration provides flexible viewpoint change and flexible relocation of system devices. They are useful for the recognition of 3-D structures and the adaptation in the practical situations of surgeries respectively. Among previous works, the most closely related one is the system for breast cancer surgery proposed by Sato et al. [7], [8]. This system had a CCD camera with a positioning sensor too. However flexible viewpoint change was not presented for the recognition of 3-D structures of the space. Moreover any guidance methods of surgical tools have not been presented in these works. Therefore we propose the convenient system design and the unique guidance methods of AR system for the biopsy.

2. System Configuration

The system is composed of an optical 3-D position sensor (Polaris, Northern Digital Inc.), a CCD camera, a liquid crystal display (LCD), and a graphics computer with a video capture board (Onyx2, SGI) as shown in figure 1. A marker is attached to the camera, a surgical tool, and the patient head respectively for positional purposes in accordance to a real-life situation. An intra-vital 3-D structure is described by computer-generated replicas of a tumor, vessels, a ventricle, a skull and a skin which have been constructed from CT images of the patient and registered into the coordinates of the real-life patient by using a surface-based positioning method. Camera parameters were measured in the coordinates of the positioning marker attached to the camera. Current camera-viewing volume is computed by referring to the parameters and current position of the camera. The coordinates of the replicas and the biopsy needle are integrated into the camera-viewing volume in an accurate geometrical manner. In figure 2, coordinate systems are shown. Then the intra-vital 3-D structure is visualized within a live video image (720x486 pixels). The configuration provides accurate plan visualization, flexible viewpoint change, and relocation of system devices such as relocation of a 3-D position sensor.

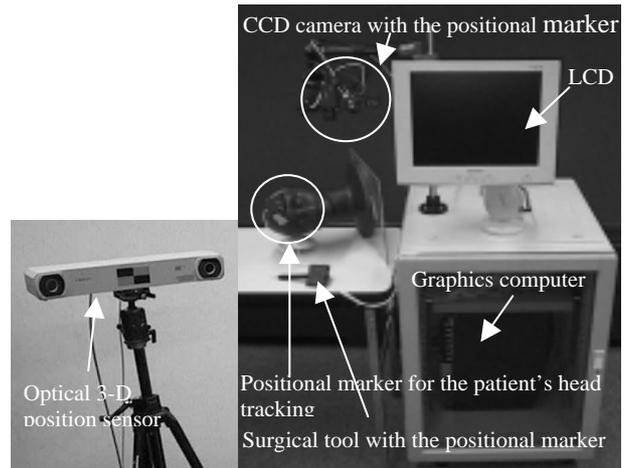


Figure 1 System components

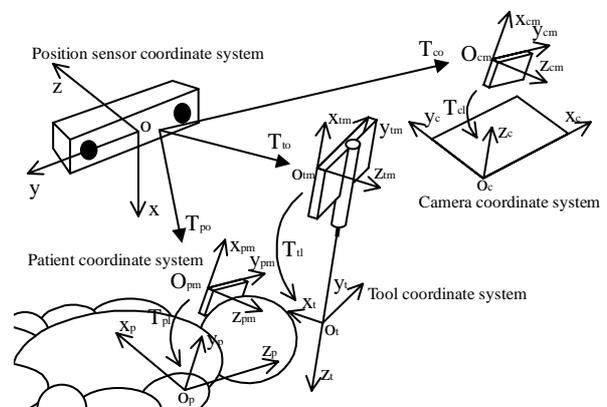


Figure 2 Coordinate systems

2.1. CG Models' Registration

We present the "model handler", that is a 3-D *mouse* to conveniently register CG models' initial locations into the real-life space, and registration procedures.

The registration is composed of two steps: (1) initial registration by using the model handler, (2) positional modification for accuracy. The model handler has a positional marker, three pads to abut against the body surface, and a grip as shown in figure 3. The pads' shape is hemispherical. For initial registration of the CG models, the model of the skin surface is generated from the patient's CT images, and registered into the coordinates of the model handler as all pads are landed on the surface of the skin model. All coordinates of intra-vital models (CG models) are corresponded with the coordinate of the skin model. The surgeon grasps CG models by using the model handler, and virtually moves all virtual tissues into the real-life patient. Actually virtual models don't exist and are invisible in the real world, but visible in the mixed world displayed on the LCD. The surgeon locates the model handler as the pads are neighboring the real patient's skin, and then slides it along the skin. Since both of the surfaces of the skin model in the virtual world and the patient's skin in the

real world are on the surface of the model handler's pads, CG models are quickly positioned into the patient's body. After the initial positioning, the object to which CG models are registered is changed from the model handler to the tracking positional marker attached to the patient's head. Then, a surface-based method [9] is employed for positional modification. By specifying points on the patient's skin by using 3-D positional probe, the modification is performed.



Figure 3 Model handler

3. Guidance Methods

For more reliable guidance, we propose unique visualization methods. Since the needle's trajectory way may be a line, the keys of biopsy procedures are decisions of the insertion starting-point and the insertion direction and depth from the starting-point. For guidance of them, we propose two methods: (1) the surgical plan called the "safety map" and the visualization method, and (2) the guidance methods of needle insertion.

3.1. Insertion Starting-point Guidance

In the decision of a needle's insertion starting-point, one point on the skin from which there is no significant tissue and no obstacle on the needle pathway to the target should be selected. For the visualization of the starting-point candidates on the skin, the safety map is introduced. The safety map is a sphere surface highlighting covering area of anatomically significant tissues and obstacles around the target. During the surgery, it is projected onto the replica's skin in just the same way as it would be projected onto the head of a real-life patient in the mixed scene as shown in figure 4. From the plan is described as the style of sphere surface and projected rapidly in the surgery, the surgeon is able to quickly change the plan and the map-projected objects at will.

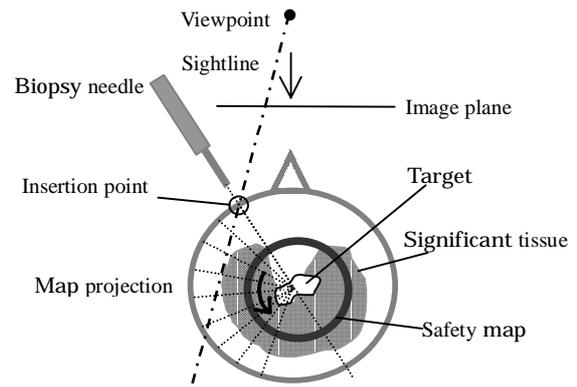


Figure 4 Schematic diagram of the safety map projection.

3.2. Direction and Depth Guidance for the Insertion

After the decision of starting-point, direction and depth of the needle insertion are decided. The guidance information is indicated as a guiding arrow and a relative coordinate between the needle tip and the target point. The guiding arrow and the relative coordinate shows the direction and the distance of required movement of the needle respectively. The guiding arrow is displayed in the mixed scene as 3-D indication and at the top-left corner of the monitor as 2-D indication. The arrow in the mixed scene has a frame ring and axes to recognize the arrow's orientation. The relative coordinate includes an angle between the needle trajectory and the line passing through the needle tip and the target. Additionally intra-vital models, such as a tumor model, and needle trajectory are displayed to show the condition in the patient. The collision detection of the needle trajectory and interesting objects, that are the target tumor and anatomically significant tissues, is also implemented. In the needle insertion, the surgeon changes the needle direction toward the target by looking the arrow's indication, the relative distance, and the trajectory's angle. After confirmation of that the system shows the status that the trajectory way passes through the target, he inserts the needle into the brain until Z-coordinate in the cylindrical coordinates is zero, i.e. the needle tip reaches the target.

4. Graphics Techniques

4.1. Retention of Anteroposterior Relation

On graphic techniques, we propose a retention method of the anteroposterior (front-to-back) relation among a tool and intra-vital organs' models. In AR systems, the retention of the anteroposterior relation among the real-life world's and computer-generated world's objects is one of the most significant terms. When anteroposterior

relation is not conserved, visual illusion often occurs and then causes irregular recognition.

Considering the depth retention in AR systems, Berger [10] has proposed the method using a contour based approach and labeling method of each contour point as being behind or in front of, depending on whether it is in front of or behind the virtual object. This labeling step required that the contours can be tracked from frame to frame, and a proximity graph is then built in order to group the contours that belong to the same occluding object. Then active contours were employed to accurately recover the mask of the occluding object. Although this method can be adapted many situations, the procedures are complex and currently difficult to perform in real-time. Kanbara et al. [11] has generated video-see-through images by defining the color of virtual objects' workspace, and performed the procedures in real-time. However provision of workspace's color is exactly difficult in the most medical cases.

Our graphics method, called the "ray-pervious polygon rendering", is simple and straightforward. First of all, models of surgical tools are generated. The models' colors are then changed to the ray-pervious color of the color blending, and models are rendered in regular rendering procedures. After all models are rendered, the anterior regions of surgical tools are disappeared in the CG image. By combining the CG image and the real-life video image, a mixed image preserving anteroposterior relation is created. Required conditions of this method are two points: Both of (1) shapes of surgical tools and (2) positions of surgical tools are known. Since many surgical tools are rigid and the tool's positions are already measured in the positional guidance, above two conditions are achieved in the many cases of medical interventions' guidance. Although this method is not suitable for the application to distortion-free objects such as fingers, enough useful for our purpose in detail in section 5. From using only general procedures in rendering, all of the procedures are completely performed in real-time.

4.2. Boundary-enhanced Visualization

We describe a rendering technique for AR systems of CAS in this subsection. Interesting parts of objects in the patient are boundaries in many cases. On the other view, transparent display of interior part of the objects is more convenient. Therefore we present the rendering technique for the boundary-enhanced visualization. For this, the four lights of graphics are located side-out of viewing volume and illuminate as parallel ray toward the center of viewing volume. Then a boundary-enhanced image is generated. The blending of CG image and real-life video image is performed with the rate computed by following equation:

$$(R, G, B, A) = (R_{cg} + (1 - c_r)R_v, G_{cg} + (1 - c_g)G_v, B_{cg} + (1 - c_b)B_v, A_{cg} + (1 - c_A)A_v).$$

Where (R, G, B, A) is a color component vector of the combined pixel, (R_{cg}, G_{cg}, B_{cg}, A_{cg}) and (R_v, G_v, B_v, A_v) are color component vectors of the CG and the video pixels respectively, and (c_r, c_g, c_b, c_A) is coefficients of the color blending:

$$(c_r, c_g, c_b, c_A) = \left(\frac{R_{cg}}{R_{max}}, \frac{G_{cg}}{G_{max}}, \frac{B_{cg}}{B_{max}}, \frac{A_{cg}}{A_{max}} \right),$$

where (R_{max}, G_{max}, B_{max}, A_{max}) is the vector of maximum values of color components.

The procedures have been implemented by using the OpenGL library, and are performed on a graphics hardware accelerator.

5. Experiments and Results

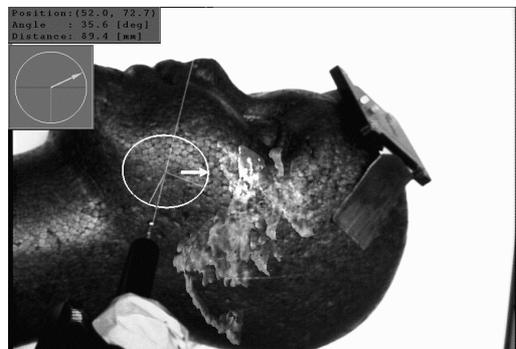
A preliminary examination of the guidance using a phantom was performed at the National Cancer Center. Figure 5 shows three examples of guidance images. In figure (a), virtual objects of a tumor (white) and a ventricle (gray) were visualized within a live video image. This visualization provided precise orientations to the plans in the patient. A high degree of viewpoint flexibility was achieved by using a general monocular planar monitor. The system also allowed us to change the location of the 3-D position sensor which was convenient in practical situations of surgeries. The biopsy needle's trajectory (gray line from the needle tip) was also displayed. The guiding arrow (white arrow with axes and a ring) indicated the direction to the tumor in relation to the cylindrical coordinates of the needle. Required needle movement (axial distances and an angle) was displayed at the top left corner of the window. The safety map in figure (b), which highlights the covering regions of the skull and ventricle and the craniotomy region of a surgical plan, was projected onto the surface of the phantom's skin in the mixed scene. The safety map visualization and the guiding indication were effectively performed in the interactive planning of the craniotomy and needle insertion procedures. In figure (c), the image considering current anteroposterior relation among the surgical tool and the anatomical replicas is shown. It was successfully enough to reduce irregular recognition in terms of depth.

6. Conclusion

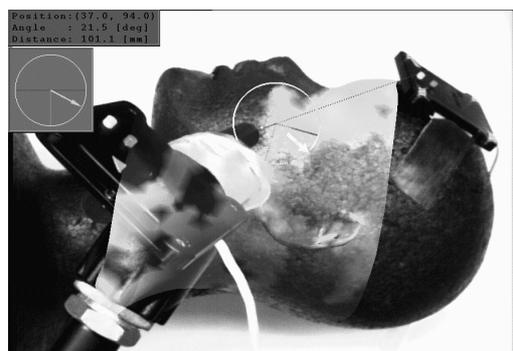
The video-based guidance system for brain tumor biopsy has been proposed. A phantom experiment confirmed the advantages of flexible viewpoint changes, the safety map as a form of visualization, and guidance indicating with cylindrical coordinates. Especially the safety map was significantly effective in visualization; it appeared more clearly in the mixed scene rather than direct map

projection in the real world. The ray-pervious polygon rendering was convinced for resolving depth relation between the real-life video image and computer-generated image.

Our system has also the capacity of the application to the laser coagulation and the hyperthermia of abnormal tissues.



(a)



(b)



(c)

Figure 5 Examples of guidance image. (a) Visualization of intra-vital models of a tumor (white) and a ventricle (gray), and guidance indication. (b) The safety map visualization. (c) The safety map visualization in the case considering anteroposterior (front-to-back) relation among the surgical tool and the anatomical replicas.

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