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A Low-cost Mobile System with Multi-AR Guidance for Brain Surgery Assistance*

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Abstract— **Surgical operation especially brain surgery requires comprehensive understanding on the surrounding area of the surgical path. Augmented Reality (AR) technology provided an effective way to increase the surgeon's perception on the plan. However, current applications were hindered by the expensive hardware and limited guidance information. In this paper, an AR system especially designed for brain surgery was proposed, which featured in low-cost system components and multi-AR guidance. A light-weight AR glasses was utilized together with normal mobile phone to provide mobile AR to the surgeon. A web-based application was implemented for compatibility of various mobile devices. Multi-AR information was designed for surgical guidance, including planned operation path, dangerous areas, and three quantitative guidance metrics. Patient's specific 3D model was reconstructed based on CT images, and the phantom was utilized to evaluate the effectiveness of the system. The experimental results indicated that the assistance of the multi-AR guidance outperformed the results of with no AR guidance at all and with virtual path guidance only. As a result, our system could help the operator to perform the operation tasks easier.**

Clinical Relevance— **This proposed method provided a potential way for brain surgery with multiple AR guidance information with the assistance of a low-cost AR system, which may improve the surgeon's cognition on the surgical site.**

I. INTRODUCTION

Brain surgery requires extremely comprehensive understanding on the brain structures for the surgeon. Augmented Reality (AR) technology provided an intuitive way for the surgeon to actually "see" the planned surgical path during the operation. Léger et. al. compared traditional navigation, mobile AR and desktop AR, and concluded that the user's performance was better when mobile AR was used[1]. Different display strategies were proposed by researchers including AR with Head Mounted Display (HMD), projective-AR, and etc[2]. However, one of the major problems hindering the applications of the AR HMDs was the extremely high costs (from US$ 800 to US$ 3000)[3]. Besides, the commercially available HMD were not directly suitable for surgical AR guidance[4]. Therefore, researchers proposed some self-developed hardware system for AR guidance. For example, Carbone et.al. combined both video and optical see-through technology and proposed a new AR device for guiding maxillofacial surgical tasks[4, 5], which is however not commercially available currently. Fotouhi et.al. designed a system with two reflective-AR displays for robotic surgeon[6]. While AR was provided with multi-view, such setup may not suitable for the scenario where surgical team presented. Research indicated that surgeons prefer a focused target area, while little context information around[7]. Therefore, many studies reported on the efforts of expanding the view with different guiding information. Eyüpoglu et. al. proposed a method to differentiate the tumor zones as three layers and rendered with different color[8]. Ha et. al. provided the distance between surgical instruments and target organs in their AR system[9].

The main contributions of this manuscript were listed as following:

- A low-cost surgical AR system comprising a cheap head mounted device and a regular cell phone was proposed.
- Apart from commonly provided spatial alignment with virtual objects and surgical scene in most of AR-guidance, multi-AR guidance was designed for the surgical operation.
- Experiments indicated that the multi-AR guidance achieved higher rating in the targeting tasks by provided more intuitive information to the operator.

This manuscript is arranged as follows: In session "System description", an overview of our system, including both hardware and software design is provided. In session "Experiments and Results", detailed setup for phantom construction and the evaluation results for the system is described. In the end, discussion and conclusion are given in session "Conclusion and future work".

II. SYSTEM DESCRIPTION

A. Hardware

The hardware component of our system including a mobile device for both video capturing and display, a modified surgical tool with a marker attached for tracking, a light-weighted head mounted device, and a phantom which was used in the experiments for system evaluation (see Fig. 1). The mobile device shown was a Mi 6 from Xiaomi Corporation with a screen of 5.15" display. It was mounted on an AR/VR

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glasses from ANTVR (http://antvr.com/) for AR display, with a price of $25 only. Actually, any mobile device with 4.5-6.0 inch screen can be used. Moreover, the mobile device can be basically any Android phone or iPhones above iOS 11. Wireless network is required to access the software/application.

Figure 1. Hardware of the system, showing the mobile phone, the AR glasses, and the tracked surgical tool.

B. Image guided AR system

A self-developed software ARNav was run in the mobile device. The software was implemented using AR.js, which was a pure Web-based solution for AR application. Therefore, no installation was required.

A two-step registration method proposed by the author earlier[10] was adapted for brain surgery in this paper. Different Coordinate Systems (CSs) were involved: virtual CS, operation CS, reference CS, and tracking CS. The relationship among different coordinate systems was illustrated in Fig. 2, where O_0, R_0, and T_0 denoted the origin of O-CS, R-CS, and T-CS, respectively.

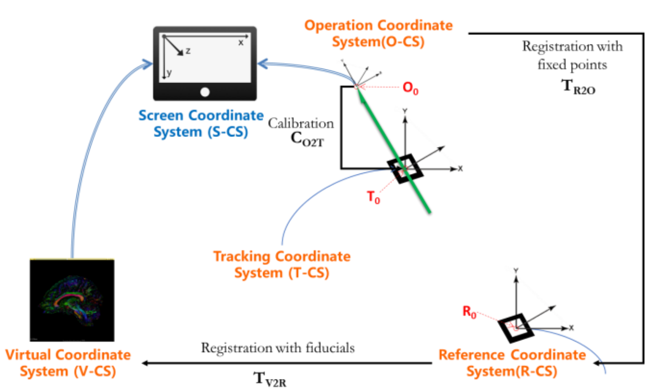


Figure 2. Relationship among different Coordinate Systems (CSs) and objects in the system

The virtual CS (V-CS) refers to the 3d coordinates in 3D Slicer, where the patient-specific brain model was reconstructed using preoperative medical images. A reference CS (R-CS) was required to complete the procedure, which was designed to be fixed on the operation table where the patient (the phantom skull in the experiment) was laid on. The registration between the V-CS and R-CS can be done with a set of fiducials attached on the patient. In contrast, the registration between T-CS and R-CS was performed with some fixed registration points, which enabled the registration before the operation. The standard pivot calibration was performed to determine the offset between O_0 and T_0.

$$t_O = t_V \cdot \mathbf{T}_{V2R} \cdot \mathbf{T}_{R2T} \cdot \mathbf{C}_{T2O} \quad (1)$$

C. Multi-AR guidance generation

In order to provide effective surgical guidance, several types of guidance information was generated as "Multi-AR guidance", which was virtually provided to the surgeon with our AR system, including the planed surgical path, brain tissue area where needed to be avoided, and quantitative guidance metrics. Basically, the guidance was presented according to the preoperative planed path by the surgeon, which was defined by a polyline with several vertexes in between the start and end point. The areas which were tended to be voided during the operation was also identified be the surgeon in the patient's specific model. Additionally, three different quantitative guidance metrics were defined and utilized to assist the surgeon's operation in real time.

1) DTO: the distance from the current tool tip location to the operation location, i.e. the end point of the surgical path;

2) DTP: the distance from the current tool tip to the planned path, which indicated the positioning deviation of the tool;

3) DTD: the nearest distance from the current tool tip to the forbidden areas, which were manually identified by the surgeon before the operation.

A 2D illustration of the corresponding measures is given in Fig. 3. Be notice that all the calculation was actually done in a 3D local coordinate system.

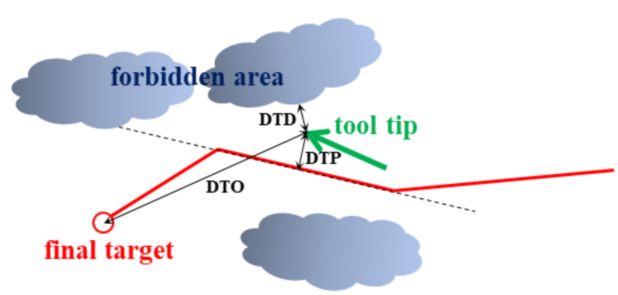


Figure 3. Definition of the quantitative guidance metrics

By tracking the position of both the marker B and the end tip of the surgical tool simultaneously, the location and the pose of the surgical tool can be estimated and all the three metrics can be calculated accordingly. The real time values of these three guiding metrics were calculated and displayed virtually on the screen in real time.

In addition to the numerical display of the metrics, dynamic rendering strategy was also designed to enhance the guidance in an earlier recognized way. Thresholds were set for each metric with a minimum value. Once the threshold was reached, the corresponding number was rendered in color red as a warning to the operator.

III. Experiments and Results

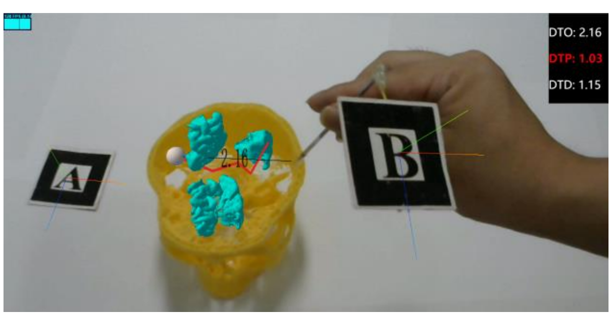
A. Phantom construction

The 3D model of the skull was reconstructed in 3D Slicer (https://www.slicer.org/), based on the original obtained CT data from the hospital. The model was converted to format of gcode, and the phantom was printed using a JennyPrinter 3 (HangZhou Jenny Technology Co.,Ltd). The CT images and the reconstructed 3D model was imported to our software ARNav and shown to the surgeon. In our phantom experiments, the surgical path was simplified as the combination of several straight lines, whose start and target point were defined in the corresponding position in the 3D model.

B. AR system demonstration

The screenshot of the software was shown in Fig. 4. Fig. 4(a) shows the operation site with our system, and Fig. 4(b) shows the view during the operation with AR effect.

(a)

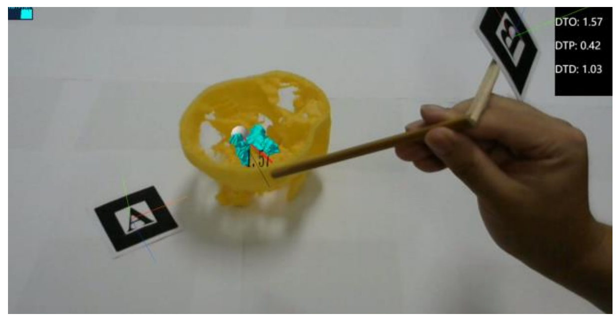


(b)

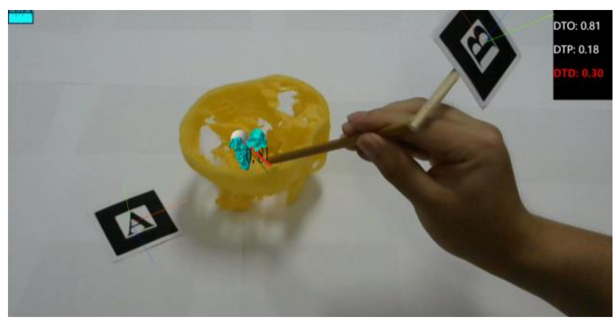
Figure 4. (a) View for system setup before the surgery. (b) view during the operation with AR guidance

As seen, the view of surgical site in real world was represented by a phantom skull and a surgical tool hold by the surgeon's hand. Two markers made with paper card were utilized for coordinate tracking. Some virtually generated objects were augmented onto the view of the actual surgical scene, which was discussed in detail in Session III C. The surgical operation was mimicked as the trajectory following task. In the augmented view, the surgical path was rendered as a red polyline, and the tumour area was modelled as a white sphere. During the operation, surrounded brain areas needed to be voided from touching by the surgical tool, were virtually highlighted in blue as a warning.

Beside, as designed, the colors for each metric differed according to its real time value. Fig. 5 shows the corresponding views when the operator tried to follow the pre-defined trajectory to the target position, where DTD changed from 1.03 in (a) to 0.30 in (b). The text of DTD was rendered in red to indicate that the current operation was close to the dangerous areas, which needed to be aware by the surgeon.



(a)



(b)

Figure 5. Color varied for different value of metrics (in the unit of centimeter) (a) View when DTD=1.03(≥1.00). (b) View when DTD=0.30(<1.00)

C. Evaluation for operation guidance

To assess the system performance, the guidance accuracy was evaluated by recording the actual and calculated value of DTO. The surgical path was planned as a straight line along a plastic ruler, whose zero point was aligned with the designed target. The results were listed in Table I, and the average error for DTO was 0.22±0.20cm.

TABLE I. EVALUATION FOR THE GUIDANCE ACCURACY

	Angle 1	Angle 2	Angle 3	Angle 4	Error (mean±SD)
0.00	0.10	0.00	0.00	0.10	0.05±0.10
1.00	1.00	1.00	0.90	0.90	0.05±0.10
2.00	1.90	1.90	2.00	2.30	0.13±0.10
3.00	3.60	3.00	3.10	3.40	0.28±0.30
4.00	4.60	3.90	4.20	4.30	0.30±0.20
5.00	5.50	5.00	5.30	4.30	0.38±0.30
6.00	5.90	6.50	6.30	6.30	0.30±0.20
7.00	7.40	7.40	7.40	7.40	0.40±0.00
8.00	8.60	8.40	8.20	8.20	0.35±0.20
9.00	9.00	9.00	9.20	9.20	0.10±0.10
10.00	10.00	9.90	10.20	10.00	0.08±0.10
Error (mean±SD)	0.27 ±0.30	0.15 ±0.20	0.18 ±0.10	0.27 ±0.20	0.22±0.20

In order to evaluate the effectiveness of multi-AR guidance, an experiment was designed and performed. The user was asked to perform a targeting task following the planed path by pointing to the star and end point of the polyline. Three different ways were tried by each user:

a) the user reviewed the path in the 3D view before the operation and later performed the task in free hand;

b) the user performed the task with our system, but only the virtual path was augmented;

c) the user performed the task with our system, with all types of multi-AR guidance provided.

Each user was asked to rate the performance of each way in a range of 0~10 according to their easiness to access the target. A total of 5 people were participated in the experiment, and the final scores for each way were listed in Table III.

TABLE II. EVALUATION FOR DIFFERENT AR GUIDANCE

	AR Guidance Information		
	With no AR guidance	***With only path guidance***	***With Multi-AR guidance***
Score (mean±SD)	5.4±1.2	6.8±0.9	7.2±1.3

IV. CONCLUSION AND FUTURE WORK

In this paper, a system provided assistance for the surgical operation was proposed. Multi-AR guidance was generated including the surgical path, surrounding tissue areas, and three quantitative guidance metrics. All the guidance information was provided to the operator in in the form of augmented reality, by utilizing a low-cost head mounted AR/VR glass. In such may, the guidance was direct and in real time during the operation. Preliminary results indicated that with our multi-AR guidance, the operator could complete the targeting task easier. The technology applied in the system could be utilized in different applications for AR guidance with affordable price.

Limitation remained in this study. Most of all, the evaluation of the system was performed in a no-clinical environment and the testers neither real surgeons nor medically trained. Besides, although our design with multi-AR guidance achieved the highest score in the experiment, some testers reported that although the multi-guidance ensured the operation along the pre-defined path, it also added extra time for him to process the information. In our future work, detailed evaluations for the system performance on both accuracy and time cost will be performed. Besides, a modified strategy to visualize multi-AR guidance will be evaluated as well.

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