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Development of a surgical navigation system based on augmented reality using an optical see-through head-mounted display

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ABSTRACT

The surgical navigation system has experienced tremendous development over the past decades for minimizing the risks and improving the precision of the surgery. Nowadays, Augmented Reality (AR)-based surgical navigation is a promising technology for clinical applications. In the AR system, virtual and actual reality are mixed, offering real-time, high-quality visualization of an extensive variety of information to the users (Moussa et al., 2012) [1]. For example, virtual anatomical structures such as soft tissues, blood vessels and nerves can be integrated with the real-world scenario in real time. In this study, an AR-based surgical navigation system (AR-SNS) is developed using an optical see-through HMD (head-mounted display), aiming at improving the safety and reliability of the surgery. With the use of this system, including the calibration of instruments, registration, and the calibration of HMD, the 3D virtual critical anatomical structures in the head-mounted display are aligned with the actual structures of patient in real-world scenario during the intra-operative motion tracking process. The accuracy verification experiment demonstrated that the mean distance and angular errors were respectively 0.809 ± 0.05 mm and $1.038° \pm 0.05°$, which was sufficient to meet the clinical requirements.

1. Introduction

During the past decades, computer-aided navigation system has experienced tremendous development for minimizing the risks and improving the precision of the surgery [2]. Nowadays, some commercially-available surgical navigation systems have already been tested and proved for clinical applications such as eNLight and NavSuite (Stryker Corporation, USA), Portable Nanostation (Praxim, France), and MATRIX POLAR (Scopis medical/XION, Germany). Meanwhile, many research groups also have presented their systems in the literature, for example, TUSS (Queen's University, Canada), VISIT (University of Vienna, Austria), IGOIS (Shanghai Jiao Tong University, China), etc. [3–7]. However, all of these systems use computer screen to render the navigation information such as the real-time position and orientation of the surgical instrument, and virtual path of preoperative surgical planning, so that the surgeons have to switch between the actual operation site and computer screen which is inconvenient and impact the continuity of surgery.

In recent years, due to the great development of Augmented Reality (AR) technology, more and more wearable AR devices have appeared like Google Glass, Skully AR-1 (An AR motorcycle helmet) [8], and etc. AR is an integrated technique of image processing, and in AR system, real objects and virtual (computer-generated) objects are combined in a real environment. Furthermore, real and virtual objects are aligned with each other, and run interactively in real time [1,9,10]. Due to the advantages of AR visualization, developing a surgical navigation system based on AR is a significant challenge for the next generation. For example, after the registration of the preoperative CT in relation to the intra-operative realistic scene, surgeons can superimpose the virtual CT data onto the patient's anatomy [11]. In 2010, Liao et al. [12,13] developed a 3-D augmented reality navigation system for MRI-guided surgery by using auto-stereoscopic images, and the system creates a 3D image, fixed in space, which is independent of viewer pose. In addition, Navab et al. [14] from Technical University of Munich have demonstrated a very practical

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application of AR. They developed an X-ray C-arm system equipped with a video camera, so that a fused image that combines a direct video view of a patient's elbow with the registered X-ray image of the humerus, radius, and ulna bones was produced.

This study presents an AR-based surgical navigation system (AR-SNS) using an optical see-through HMD (head-mounted display), which encompasses the preoperative surgical planning, registration, and intraoperative tracking. With the aid of AR-SNS, the surgeon wearing the HMD can obtain a fused image that virtual anatomical structures such as soft tissues, blood vessels and nerves integrated with the intra-operative real-world scenario, so that the safety and reliability of the surgery can be improved.

2. Materials and methods

2.1. The hardware architecture of AR-SNS

The AR-SNS is constructed based on a high-performance graphical workstation (HP), a 2D LCD monitor (G2200W, BenQ), an optical tracking device (Polaris Vicra, NDI Inc., Canada) and an optical see-through HMD (nVisor ST60, NVIS, United States) (Shown in Fig. 1). The workstation is equipped with a 4 GB memory card, a core i7 CPU and an nVIDIA Quadro FX4800 graphic card, running on the windows 7 operating system. As for HMD, it uses high-resolution microdisplays featuring 1280×1024 24-bit color pixels per eye, for vivid visual rendering and integration with reality.

2.2. The software framework of AR-SNS

The AR-SNS is developed under the platform of the Integrated Development Environment (IDE) of VS2008. All of the functions are programmed in Microsoft Visual C++ and some famous toolkits are also involved, such as the Visualization Toolkit (VTK, an open source, freely available software system for 3D computer graphics, image processing, and visualization etc., http://www.vtk.org/), CTK, ITK, IGSTK and QT, and then integrated into the AR-SNS.

Fig. 2 shows the framework of AR-SNS, and is described as follows: on the basis of the preoperative CT data of a patient, image segmentation is conducted, so that 3D models including hard and soft tissues, especially critical anatomical structures such as blood vessels and nerves can be reconstructed. After 3D reconstruction, preoperative planning is implemented so that an optimized osteotomy trajectory can be obtained. Then, with the support of the optical tracking device, the calibration of the surgical instruments is performed, and the point-to-point registration [15–17] and surface matching [18,19] methods are used to determine the spatial relationship between virtual coordinate system (VCS, refers to the computer screen coordinate system) and real coordinate system (RCS, refers to the patient coordinate system) [2]. In addition, an optical see-through head-mounted display is adopted so that an immersive augmented reality environment can be obtained and the virtual tissue can be integrated with the direct view. Finally, after calibration of the patient's position in relation to the HMD, the position and orientation of the virtual model will change with corresponds to the movement of HMD and patient, and match the real anatomical structures during intra-operative navigation process, so that the preoperative plan rendered in HMD can be transferred to the real operation site.

2.3. 3D-reconstruction and preoperative surgical planning

Based on the original CT data, the segmentation of the hard tissue is conducted by using a threshold and region growing combined method, and for the soft tissue in each image, semi-automatic region growing method is adopted, and if it is over-segmented or under-segmented, manual modification is also used. Then, 3D surface models can be reconstructed through the marching cubes algorithm [20]. Fig. 3 shows a 3D pelvis model and a bladder imported into AR-SNS after the 3D-reconstruction. All of the work including the image segmentation and 3D modeling is realized.

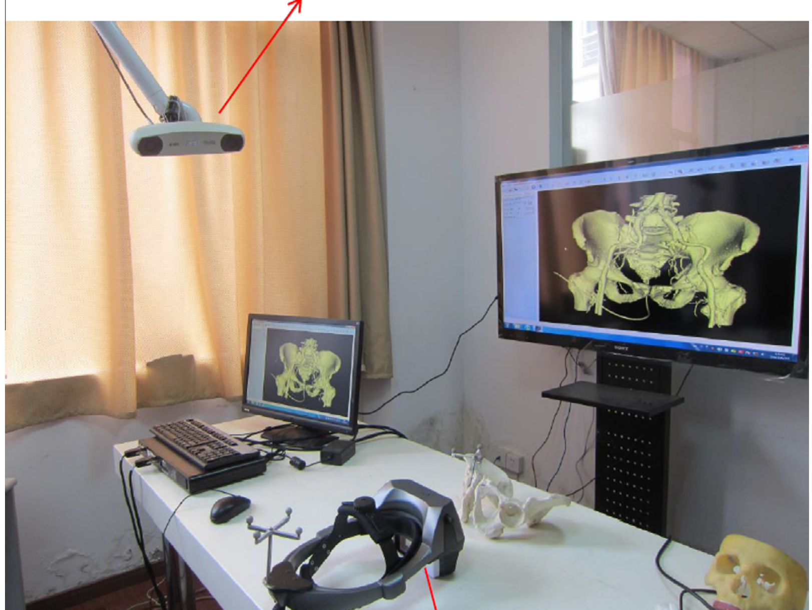

Fig. 1. The hardware of AR-SNS.