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Stereoscopic Three-Dimensional Visualization for Immersive and Intuitive Anatomy Learning

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***Abstract*—Conventional anatomy education makes use of two-dimensional (2D) images of three-dimensional (3D) anatomical objects to illustrate their spatial locations and interrelationships. Good visual-spatial ability is needed to mentally transform or fuse multiple images that are required to understand a concept. While animations and videos are developed for anatomy learning, the presentation of 3D anatomical objects on 2D planar computer screen does not render the depth perception necessary for intuitive understanding of the spatial details and subtlety. To enhance anatomy education, a stereoscopic 3D visualization system is proposed in this paper. Depth perception is naturally rendered using active stereo technology to create an immersive learning environment which allows students to directly interact with and explore the virtual anatomical objects. In addition to translation, rotation, zooming in and out, the body parts are modeled as multi-layer objects so that the outer layers can be set to semi-transparent to expose the inner layers, while the associations between the inner and outer layers can also be depicted. A pilot study is conducted to evaluate the system usability and user interface of the proposed stereoscopic 3D visualization system. The response of the 14 healthcare students who participate in the study is positive. They appreciate the intuitiveness and flexibility offered by the system, which can facilitate anatomy learning. Feedbacks are collected to further improve the system.**

Keywords—anatomy education, computer-assisted learning, visual-spatial ability, stereo vision, immersive virtual reality.

I. Introduction

Anatomy is an essential foundation of health and medical sciences. Healthcare professionals refer to the knowledge of anatomy to make clinical diagnosis and decisions. Anatomy education is conventionally conveyed though lectures, textbooks, autopsy and dissection. In the latter, cadavers are used to illustrate the anatomy of human body and elaborate the knowledge. While this approach has long been adopted since the Renaissance, it has several limitations [1]. Other than issues concerning cost, safety and practicality, problems like the difficulty in associating cadavers with living patients, or with various imaging modalities that healthcare professionals rely on for making clinical decisions, presents challenges to the educational principle [2].

On the other hand, while complex three-dimensional (3D) anatomical objects are involved, textbooks for learning and teaching anatomy usually provide two-dimensional (2D) images of the 3D anatomical objects, where many 2D images are needed to depict the 3D objects and their spatial relationship. Students need to mentally transform and fuse the 2D images from different views to appreciate the corresponding 3D objects. The learning process could be demanding to some students for it is not intuitive, which requires good visual-spatial ability [3]. The cognitive load is also high.

Advances in information technology have improved traditional anatomy education. Multimedia (e.g. text, audio, animation, video) are used to develop software running on personal computers to elaborate the anatomy in three dimensions [4]. Computer graphics and virtual reality technology are used to display the geometrical models of the 3D anatomical objects on standard computer screen [5]. Using a computer mouse, students can interactive with and explore the virtual anatomical environment. Although multimedia can improve learning experience and offer more flexibility than textbooks, the interactions with animated anatomical objects and videos remain limited. Furthermore, this kind of multimedia-based anatomy learning software is indeed “non-immersive”, which only displays 3D objects on 2D computer screen. It does not provide sufficient information to facilitate depth perception, which hinders the anticipation of the spatial relationships of complex anatomical components. Although computer graphics effects, e.g. lighting and shadows, may indirectly provide cues of relative depths of the anatomical objects, stereoscopic visualization is a straightforward approach that renders not only realistic depth information but also creates an immersive virtual environment for intuitive anatomy learning [6, 7].

To this end, a stereoscopic 3D visualization system for anatomy learning is proposed in the paper. With the idea conceptualized and specification defined in early 2014, the first prototype was developed later in November of the same year, by the Centre for Smart Health of the School of Nursing, The Hong Kong Polytechnic University, in collaboration with the Dracaena Life Technologies Co., Ltd. The architecture, hardware, software and user interface of the system will be discussed, followed by a pilot study on system evaluation. Currently, the target users of the system are undergraduate students of healthcare disciplines, which can be extended to secondary school students studying biology or sciences.

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II. Stereoscopic 3D Visualization System

The architecture, hardware, software and user interface of the proposed system are discussed in the section.

A. *System Architecture*

The overall system architecture is shown in Fig 1. The anatomical data, which are essentially 3D polygonal meshes, are first cleaned up and reduced in size for presentation at interactive rates. Depending on the classification requirements of the applications, e.g., for general nursing education or for Chinese medicine, the anatomical structures are organized in a hierarchy list to facilitate the subsequent presentation of the layered structures as required by the disciplines concerned. A set of hierarchically ordered anatomical meshes and their corresponding literal database are then created.

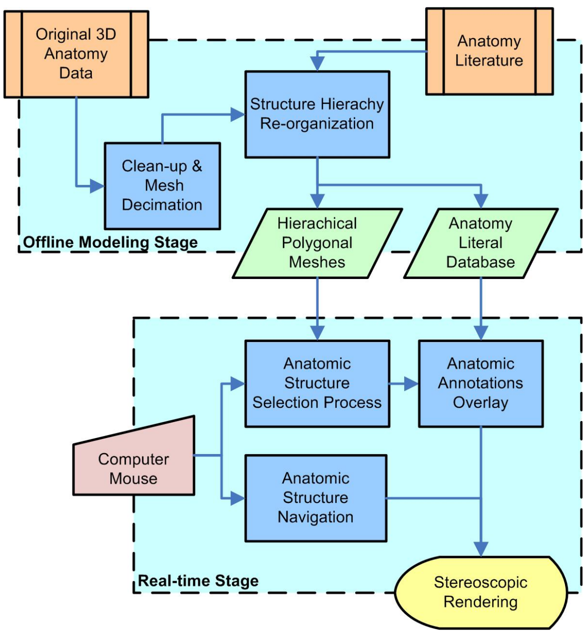

Fig. 1. System architecture.

1) *Geometric modeling of anatomical structures*

The process of representing structural topology through polygonal meshes, parametric representation or mathematical models is generally referred to as geometric modeling. In anatomy navigation applications, polygonal meshes (mostly triangular meshes) are one of the most common modeling methods due to its simplicity and the flexibility for extension to incorporate computational models, e.g. the integration of finite element method based deformable model by means of tetrahedral representation. Fig. 2 shows a view of the polygonal mesh of the heart where level of details (LOD) in different parts can be seen.

In the modeling framework, a polygonal model based on the commercially available Anatomium P1 dataset (21st Century Solutions Ltd) is constructed. The dataset is created from 3D scan data of multiple individuals following medical norms. In the proposed system, the anatomical structures are further polished according to the general standard in anatomy teaching, e.g. some moving parts like cardiac valves are adjusted so that the physiological details could be better presented. In order to boost the overall rendering performance, on top of the LOD of the mesh resolution provided, mesh simplification based on clustering decimation is conducted so that some of the vertices are collapsed without creating noticeable degradation to the overall visualization quality. The individual meshes are also re-organized in order to match the subsequent object selection process.

2) *Visual and selection rendering*

In the proposed system, selection of anatomical objects of interest is achieved by clicking on the corresponding objects. Since the traditional selection buffer mechanism under OpenGL can be very slow in most graphics workstations, color-tagging technique is exploited, with processes like lighting, texturing and fogging being switched off. Finally, colors from the framebuffer are read and the object selected at a specific pixel position is obtained in terms of identity numbers (ID). Fig. 2 shows an example of the rendered color-tags for selection purpose. However, since hierarchical organization is not available from the dataset, it is instead self-defined in this study so that the overall process can be managed more effectively. Here, a unique ID is assigned to every selectable object or structure which is rendered using the ID and the associated color.

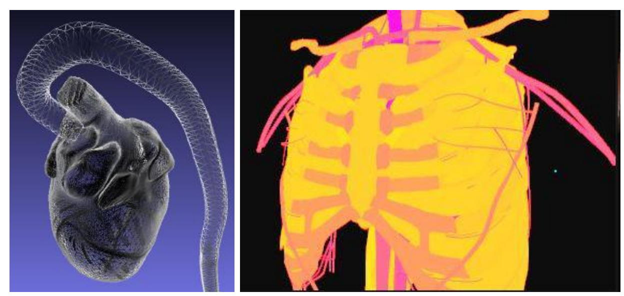

Fig. 2. Polygonal mesh of pericardium and descending aorta (left), selection framebuffer of color attachment (right).

B. *Hardware*

The proposed system is developed using active stereo technology. A full HD 3D projector (1080p, 1920×1080, 16:9) is used to display the anatomical images. Battery-operated shutter glasses, synchronizing with the projector via infrared signals, are used to block the left and right eyes alternatively. The stereoscopic images are projected onto a screen mounted on the wall. A high performance computer equipped with an Intel Core i7-4770K 3.5 GHz CPU, 16 GB RAM and an Nvidia Quadro K5000 display card is used to render high quality images interactively in real time. Common stereoscopic formats are provided, including HDMI 1.4 and quad-buffered stereo.

C. *Software*

The visualization of 3D anatomy begins by loading the vertex and primitive data of the anatomical models into the data structures. The graphics rendering pipeline, i.e. the processing of vertex, geometry and pixel, is then followed.

Depending on the resolution of the dataset, the process may take a few tens of seconds. Smooth stereoscopic rendering is achieved by quad buffering, with double buffering, i.e. front and back buffer, of the images for the left and right eye respectively.

D. User Interface

Users can navigate and explore in the virtual anatomical environments using a computer mouse. They can translate, rotate or zoom in/out the anatomical objects. The system also enables the visualization of anatomy in a layer-by-layer fashion, in a way like peeling onion skin, so that the external parts can be made semi-transparent to expose the inner parts. Textual descriptions of the anatomical parts are also displayed as pop-up texts when they are picked by the user. See the illustrations in Fig. 3 and Fig. 4.

III. EVALUATION

A. Pilot study

A pilot study is conducted to evaluate the usability and user-friendliness of the proposed system. The study attempts to gain insights into the research question of whether the proposed approach can facilitate anatomy learning from the perspective of learners. Fourteen students from various healthcare disciplines, including nursing and physiotherapy, participated in the study voluntarily. They have previously received anatomy education in conventional settings so that they are able to appreciate the differences between the two learning approaches. The subjects are asked to use a computer mouse to stereoscopically visualize and interact with a virtual cardio-respiratory system. After a demonstration of the usage of the system, they are requested to perform basic manipulation tasks, e.g. translation, rotation and identification of specific anatomical parts. They are then allowed to freely navigate in the virtual anatomical environment and explore the cardio-respiratory system. The whole evaluation process, including the collection of feedback using a questionnaire, takes about 30 minutes to complete for each subject.

B. Feedback Collection

After using the system, the subjects are asked to fill in a 16-item system evaluation questionnaire, with 9 items on system usability (SU) and 7 on user interface (UI). A 7-point Likert scale is adopted, with "1" indicating strongly disagree and "7" strongly agree. The questionnaire is designed with reference to the IBM Computer Usability Satisfaction Questionnaires [8], Technology Acceptance Model [9] and the Questionnaire for User Interface Satisfaction [10]. The subjects are also asked to provide their after-use comments.

C. Results

The feedback of the 14 subjects is positive in general. They find that the proposed system is helpful for anatomy learning, which can depict the spatial details and relationships of the anatomical objects more clearly when compared to the traditional approaches. Table I shows their feedback on SU, UI and overall satisfaction. Table II and Table III show their responses to the individual items of the SU and UI construct. The average score of the items in the SU construct ranges from 5.57 to 6.21 (SD = 0.62 to 1.03), and that of the UI construct is within 5.29 to 5.86 (SD = 0.84 to 1.38).

TABLE I. GENERAL USER FEEDBACK

Feedback	Average Score
System Usability (9 items)	5.84±0.83
User interface (7 items)	5.57±0.99
Overall (16 items)	5.72±0.92

Fig. 3. Stereoscopic 3D visualization of human anatomy: (a) cardiorespiratory system, (b) arcus costalias, (c) left inferior lope, and (d) tricuspid valves.

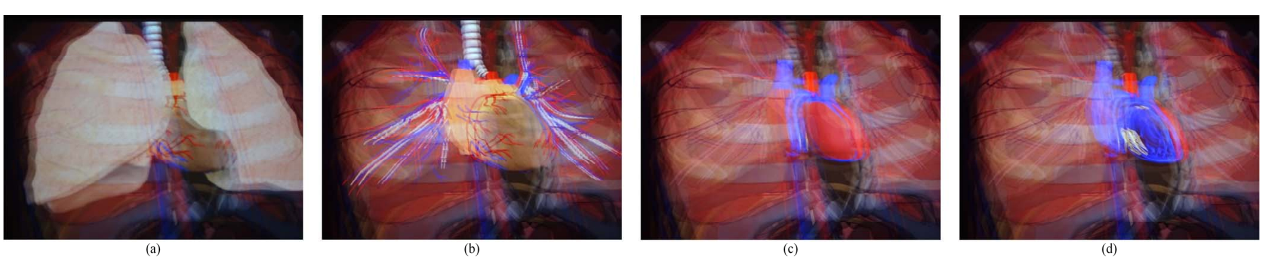

Fig. 4. By sequentially setting the outer layers to semi-transparent, the stereoscopic views of (a) lung, (b) pericardium, (c) heart, and (d) tricuspid valves are projected on the screen.

TABLE II. FEEDBACK ON SYSTEM USABILITY

No.	Item	Mean	SD	Min	Max
SU1	Easiness to use	5.79	0.89	4	7
SU2	Easiness to learn	6.21	0.80	5	7
SU3	Comfort of use	6.00	0.78	5	7
SU4	Effectiveness	5.93	0.62	5	7
SU5	Efficiency	5.79	0.80	4	7
SU6	Expected functions and capabilities	5.57	0.76	4	6
SU7	Facilitation of learning	5.86	1.03	4	7
SU8	Performance improvement	5.57	1.02	4	7
SU9	Overall satisfaction	5.86	0.77	5	7

TABLE III. FEEDBACK ON USER INTERFACE

No.	Item	Mean	S.D.	Min	Max
UI1	Comfort of use	5.79	0.97	4	7
UI2	Quality of visual display	5.86	0.86	4	7
UI3	Quality of stereoscopic effect	5.64	0.84	4	7
UI4	Adequacy of colors used	5.71	0.91	4	7
UI5	Naturalness of colors used	5.29	1.38	3	7
UI6	Responsiveness to operations	5.36	0.93	4	7
UI7	Completeness of textual description	5.36	1.01	3	6

IV. DISCUSSION

The results of the pilot study show that the proposed anatomy learning system is well accepted by the subjects. The average SU and UI scores, as well as the scores of the individual items, are all above 5. It is noted that, on user interface, some subjects rate 3 for “Naturalness of colors used” (item UI5) and “Completeness of textual description” (item UI7) respectively. Regarding item UI5, since the color of the anatomical objects in the prototype is painted with a style similar to that in computer animations, the subject consider that the current way of presentation is different from that seen in real anatomy. In this regard, computer graphics techniques like texture mapping and photorealistic rendering can be applied to show the appearance of real human anatomy. For item UI7, a subject points out that the current prototype does not provide some details of the cardio-respiratory system and therefore the associated textual description is not available. This is due to the limitation that the current prototype is developed using non-medical grade models which do not contain the details. A more advanced and complete system is being developed using medical-grade anatomical datasets, where better accuracy and higher level of details can be achieved to ensure high fidelity replication of human anatomy.

The idea of stereoscopic anatomy learning is being scaled up for teaching a large group of students. Instead of active stereo technology, the passive counterpart is adopted, where circularly polarized 3D eyeglasses are used. This is more practical since the cost of this type of eyeglasses is lower, so that they may be provided for free and the financial burden is minimal in case of loss or damage. Conversely, students can also afford to buy their own 3D eyeglasses to make simple the logistics and for better hygiene.

Furthermore, control using hand gesture has been implemented in an upgraded version of the prototype. By predefining a set of hand gestures, users can navigate the entire virtual anatomical environment in a “contactless” manner simply by “waving” their hands. It is achieved using Leap Motion (Leap Motion Inc.), a device capable of tracking hands and fingers, with the precision of distinguishing metacarpal, proximal phalanx, intermediate phalanx and distal phalanx at high frame rates so that hand motion can be recognized in real time.

V. CONCLUSION

Effective learning of the spatial relationship between anatomical object requires good visual-spatial skills. Conventional representation of 3D anatomy as 2D images in textbooks or as animations in computer software cannot provide the depth information that is crucial for unleashing the power of visual-spatial ability. As stereo vision is the most direct and intuitive way to render depth perception, it is employed here to develop an immersive and interactive visualization system for anatomy learning. The system facilitates experimental learning and nurtures engaging educational settings to promote active learning. The result of the pilot study shows that the system is a promising method to complement conventional anatomy education. Further effort will be made to enhance the anatomical precision and the user interface. The performance of using hand gestures as input will also be evaluated. More importantly, the learning effectiveness of the proposed approach will be investigated.

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