Educational Application of Virtual Reality in Graphical Simulation of the Construction Process of Chinese Dougong

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Abstract - The research described in this paper uses a state-of-the-art technique, known as virtual reality (VR), to recreate the complex structure and construction processes of dougong, a unique characteristic of ancient Chinese architecture, in an environment where users can interact with objects with a high degree of realism. Virtual reality has become a powerful tool in the field of education, as it enables students to examine digital assets in a virtual environment without relying on expensive props or compromising the safety of the students in an on-site demonstration. This gives students a more in-depth picture of dougong than in previous studies, multimedia system which connects 3-D models made in Autodesk 3DS Max with the Oculus Rift VR glass hardware system has been conducted as an example of the application of VR in engineering education to facilitate the learning of complex architecture and engineering. The authors believe that systems like this can be applied to both additional types of dougong and other, similarly sophisticated construction systems, which can help engineering students understand the structure and construction of these complex buildings and infrastructures.

Key Words: architecture, ancient construction, Chinese dougong, civil engineering education, dougong, intelligent system, graphical simulation, virtual reality

I. Introduction

The dougong is a well-known and unique characteristic of ancient Chinese architecture, the term referring to the components located at the intersections of pillars comprising the roof support system of ancient Chinese buildings. In Chinese, the word “dougong” consists of two parts, “dou” and “gong,” denoting the two basic elements of the dougong structure. Specifically, the word “dou” denotes the inverted cap for support, and the word “gong” denotes the bow-like block for supporting the load. Fig. 1 shows these two components in a 3-D model of a typical dougong structure made in Autodesk 3DS MAX. In the structure of ancient buildings, dougong are constructed on multiple levels to support the superstructure including beams, girders and roofs. Fig. 2 shows an archway with several levels of dougong in Yingxian Wooden Pagoda, Shanxi Province, China. The dougong was invented during the Han Dynasty (BC 206 – 221
AD), initially as a vertical placement of connection parts between beams and pillars in levels. After evolving for hundreds of years, however, the *dougong* has become a unique, sophisticated, and complex system of components in ancient Chinese construction. **Fig. 3** shows what may be the earliest depictions of *dougong*, found in the mortuary objects in the Han Dynasty (BC 206 – 221 AD), taken in the Metropolitan Museum of Art in the New York City.

![Fig. 1: A 3-D model of the typical structure of dougong](image1)

**Fig. 1: A 3-D model of the typical structure of dougong**

![Fig. 2: An archway with several levels of dougong in the Yingxian Wooden Pagoda in Shanxi Province, China](image2)

**Fig. 2: An archway with several levels of dougong in the Yingxian Wooden Pagoda in Shanxi Province, China**
Fig. 3: Supposedly earliest *dougong* ceramic model from the Han Dynasty, BC 206 – 221 AD (Metropolitan Museum of Art in the New York City).

The major functions of *dougong* in ancient Chinese buildings are the following: 1) to transfer the weight of the beams and roofs to pillars as a connector, because of its unique level-like structure, it can significantly reduce the moment loading on the beams and girders and then protecting the building from excessive load; 2) to absorb seismic energy into their mortise-and-tenon connection structure and timber materials, owing to their anti-seismic performance; 3) to extend the eaves of roofs and avoid the rainwater pouring into the portico of the building, and thus prevent the structural components from deterioration due to excessive humidity; and 4) to provide an aesthetically pleasing element to the building structure. The nomenclature of *dougong* is complicated, in which each and every component, type of *dougong*, configuration and even decorative style have been assigned a unique name. In general, *dougong* can be sorted into two main categories: Song-style *dougong*, from the ancient building specification known as the *Yingzao Fashi*, published in the Song Dynasty (960 – 1279 AD), and Qing-style *dougong*, recorded in the *Gongcheng Zuofa* published in the Qing Dynasty (1644 – 1912 AD)\textsuperscript{12}. Historically, descriptions of *dougong* mostly occurred in the form of hand-drawn engineering drawings in ancient books, 2-D plane drawings, photographs and textural statements, meaning readers may not fully understand the design, structure, construction processes and aesthetic value of *dougong* without professional training and related knowledge. Therefore, the objective of this
paper is to represent *dougong* in the form of 3-D graphics and *virtual reality* (VR), to educate general audiences about *dougong* structures and construction via 3-D graphical models in a VR environment, and to establish an interactive and immersive learning platform which can be used as a tool to introduce the engineering of *dougong* into modern educational practices.

For the graphical simulation aspects, the modeling work of *dougong* in this research are mainly based on the *Yingzao Fashi*, the *Gongcheng Zuofa*, and more recently, *Dougong* by Dehua Pan. The graphical simulations of *dougong* were conducted by using Autodesk Inventor and Intelligent *Dougong* System (IDS) has been developed as a learning tool to review the detailed construction process of Song-style *dougong*. As one of the most promising candidates among man-machine interactive techniques, VR has been used in the engineering education field to simulate the construction of the Roman Colosseum, forestry protection, and engineering manufacturing streamlining and optimization.

The application of virtual modeling of ancient Chinese architecture for educational purposes has been discussed previously, including the tools, methods and advantages and limitations. Other systematic graphical simulations of ancient buildings, such as the Temple with the Wudian Roof, the Great Wild Goose Pagoda, the Great Wall, and the monolithic Rock Hewn Church in Lalibela in Ethiopia, provide a number of explorations and paradigms with which to simulate the construction of ancient buildings with modeling software in 3-D graphics.

This research will continue this trend by not only creating a graphic modular database of Song-style *dougong* for educational purposes, but also using these models to reconstruct the Yingxian wooden pagoda, also called the *Sakyamuni Pagoda*, which is the oldest and highest wooden currently preserved structure in the world, located in the Yingxian, Shanxi province in China, originally built in AD 1056, during the Liao Dynasty (AD 907-1125). The Yingxian Wooden Pagoda is the only building constructed with wood as its only construction material, including the connection parts, making it a prime candidate for a digital *dougong* reconstruction model. In the Yingxian Wooden Pagoda especially, the major structural components, including the pillars, *dougong*, girders and beams, and mortise-and-tenon joints, were all made of local timbers. Due to its unique structural characteristics, the Yingxian Wooden Pagoda has survived
several relatively severe earthquakes in history and still stands today. The reason for selecting the Yingxian Wooden Pagoda as the representative ancient Chinese architecture with *dougong* is that it is well-known for its intensive use of *dougong* in the construction of each level, as shown in Fig. 4., reflecting the first peak in the development history of *dougong* in that time.

Fig. 4: Intensive *dougong* used in the levels of the Yingxian Wooden Pagoda

II. Methods --- Graphics Pipeline

The methods of establishing the VR simulation of *dougong* in this paper, known as a *graphics pipeline*, consist of four stages: (1) initial modeling, (2) advanced modeling, (3) VR production, and (4) dissemination for education, as shown in Fig. 5.
Fig. 5: Graphical pipeline to establish the VR simulation

In the initial modeling stage, the primary objective was to build the basic 3-D models of the components, and to assemble these components into the individual structures of 20 different types of Song-style *dougong* and 18 different types of Qing-style *dougong* (Pan 2006). Then, based on the created models, the advanced modeling stage entailed multiple methods of presentation, including multi-view engineering drawings, exploded views, and rendered pictures, being produced and compiled. After the initial modeling stage was finished, the files of these models and assembly parts needed to be transformed into a file format that could be imported into the VR environment, in which the parameters of light, textures, shadow, materials, event setup and hierarchy of all of the objects would be configured to establish an immersive and interactive VR environment.

In the VR production stage, a head-mounted display (HMD) device was connected to the virtual environment to test and modify its compatibility, usability and efficiency. To optimize the final interactivity, the tasks of debugging and refinement are indispensable. Finally, these graphical objects were integrated into a multimedia system: the Intelligent *Dougong* System with Virtual Reality, an integrated learning system designed as a comprehensive and accurate browser to review all of the information about *dougong* in multiple forms. In terms of software chosen for this study, Autodesk Inventor and Autodesk 3DS MAX were used to conduct the initial and advanced modeling work, Unity 3D in the VR production stage, and Microsoft Visual Studio in the dissemination stage. The Oculus Rift Development Kit 2 was used as the hardware to implement the VR simulation in this graphics pipeline.
While an educational analysis has yet to be officially conducted, the end result of this process has been well-received by both graduate and undergraduate construction students. The next logical step in this process, and the subject of a possible future study, would be to create and distribute formal surveys to these students regarding the realism, interactivity, and efficacy of the simulation and the models presented, using the feedback garnered from these surveys to help improve the model for future use in the construction classroom setting.

III. Initial Modeling

In order to let students understand the complex structure of dougong components in detail, several types of graphical simulation have been made, as shown in Fig. 6, for each type of dougong, including basic 3-D model, multi-view engineering drawing with dimension, engineering drawing with three primary view, 3-D model on orthographic or perspective on each level, exploded view on each level, illustration of component on each level dougong and rendered finished structure.

The motivation for creating the graphical simulation is twofold. When the concept of dougong firstly introduced to students, pure 3-D models of components and dougong is the best way to help to establish the subjective and qualitative perception of this complex architectural components, as illustrated in Fig. 6a and 6b. Next, from the perspective of education in engineering, engineering drawing of three primary views with dimensions can help students understand the details of component and configuration of dougong precisely and quantitatively, as shown in Fig. 6c and 6d. One expected aim of this project is that, by using other 3-D modeling software based on engineering drawing, such as SolidWorks, students can fully recreate their own 3-D model of dougong by referring the engineering drawings provided, which will definitely facilitate their recognizance and understanding of a complex system of building component as dougong shown in this paper. After knowing the dimension and configuration of dougong, students may explore how such a complex structure can be built and what is the construction process. To this end, the exploded view of dougong on each level can clearly show which components will be placed on which level (Fig. 6e), and illustration of every components can show the step-by-step construction process on each level ((Fig. 6f). Last, the rendered finished structure of dougong with multiple angles can give students a comprehensive view of
this structure, as shown Fig. 6g and 6h. The graphical simulation is intended to introduce dougong to student from simple to complex, from qualitative to quantitative, from non-professional to professional and from visual perception to full understanding in the process of education practice.

Fig. 6: Graphical simulation of dougong made in initial modeling process.
IV. Advanced Modeling

As defined in the graphics pipeline, the second stage is advanced modeling, in which two major tasks were conducted: the animation and the modeling of an ancient building. Unlike the static manner of presenting the assembly sequences of *dou-gong* as shown in the initial modeling stage, the intention of the manufacturing animation was to show the step-by-step construction process of *dou-gong* in a dynamic way, by which the student could review more details of the assembly process by watching a series of videos. The software used in the second stage is Autodesk 3DS MAX.

On the level of engineering education, the animation produced in Autodesk 3DS MAX is a good way to show the construction process of an entire structure *dou-gong* fluently and dynamically. Unlike the static pictures shown in Fig. 6, many construction details, such as the assembly sequences and connection, are self-evident when they are played in the form of a video. Fig. 7 shows the animation to showcase the construction process of a Song-style *dou-gong*, Bujian Puzuo of eight levels, from which the relative position of components and connection details can be reviewed even at first glance.

![Fig. 7: Animation of the construction process of *dou-gong*: Bujian Puzuo of eight levels](image)
The second educational meaning in the advanced modeling stage is to create a 3-D model of an entire ancient building with *dougong* by using Autodesk 3DS Max, such as the Yingxian Wooden Pagoda model produced in this paper. The reasons for using a digital reconstruction are based on two aspects. Firstly, the *dougong* conducted in the initial modeling stage are merely the ones recorded in the *Yingzao Fashi* and *Gongcheng Zuofa*, which are different from the *dougong* built on the existing building, so based on the information available such as photographs taken from field trips and other documents, models of existing ancient buildings could be used as references to show the differences, evolution and design ideas between the *dougong* recorded in the ancient books and the ones which were actually built.

In addition, during the aforementioned teaching phase, 3-D models of *dougong* can help students understand the style and detail as well as the assembly of *dougong*. However, by reviewing a 3-D model of the entire building, rather than merely the *dougong* itself, students will have an overview of *dougong* as a functional structural component, and thereby broaden and deepen their understanding of the structural features of *dougong*. For example, after viewing the *dougong* placed upon the pillar on each level of Yingxian Wooden Pagoda, as shown in Fig. 8, students can find answers to the following questions: “Why does *dougong* have so many levels? It can distribute the bearing moment when transferring the load.” or “Why do the components of *dougong* connect in the form of mortise-and-tenon joint? It can absorb considerably the dynamic energy by translations between components and deformation of wooden material, thereby protecting the building during an earthquake.” As demonstrated above, the digital reconstruction of the entire building with *dougong* structure can help student understand this component in a higher level.
V. VR Production

The aim of the third stage was to produce an immersive and interactive VR environment as a multimedia learning platform, in which students can explore and study the knowledge of dougong by reviewing the 3-D models, assembling the dougong by themselves, conducting a virtual tour and experiencing a walk-through in a real-time rendering environment. Rather than merely depending on the 3-D graphics created by software on a computer, a complete VR user experience expected to be accomplished in this stage also needs to connect with a VR hardware, such as VR glasses with game controller. As for the software, Unity 3D and Lumion were used in this stage.

Unity 3D is an increasingly popular game engine for which some interactive actions can be programmed based on the C# language. The major advantage of employing Unity 3D to build an educational platform is that it has specific add-ons which are highly compatible with the Oculus VR products. Once the 3-D models of the dougong and ancient building made in the previous two stages have been imported, setting some parameters in Unity 3D allows the VR headset to be easily connected with the 3-D graphical simulation made in Unity 3D. The interactivity is implemented by programming the C# scripts which are attached to the game objects in the Unity 3D scenes, in which the users are allowed to interact with the virtual world via multiple ways, such as clicking a button, moving around, touching the objects and even giving orders by
speaking. A demo of importing the Yingxian Wooden Pagoda in Unity 3D is shown in Fig. 9. In this demo program, by wearing VR glasses and headset, students can walk through the virtual site and interact with virtual objects (e.g. dougong, stairs and other pagoda components) by using mouse and keyboard or VR game controllers. For example, students can walk into the pagoda to view the inner structure of this building, learn the basic knowledge of *dougong* by reviewing the floating slides on the sides, or observe the *dougong* on each level in free flying mode.

![Fig. 9: A demo of Yingxian Wooden Pagoda in VR made by Unity 3D](image)

Additionally, to inspire students to participate in the learning process of dougong installation, an educational program in which students can assemble the *dougong* in Unity, as shown in Fig. 10. By using a mouse or other input device, students can pick up virtually the components and placed them in the correct position under the instruction provided. In a VR environment, such simulated assembly process can highly inspire students’ interest to know the complex structure and construction process of *dougong*, just like they played with a big puzzle when they were children, which is much more acceptable for the learners compared with the conventional text-and-graphics education method.
The second software package used in this project, Lumion, is a professional architecture design software which can provide real-time realistic rendering. An advantage of adopting Lumion to implement the simulation is that it can simulate scenes with many objects quickly and vividly, such as trees, grass, wind, sunshine, cloud, water, people flow, cars, traffic facilities and indoor interior decorations. A scene from the Yingxian Wooden Pagoda VR simulation made by Lumion is shown in Fig. 11. Thus, as demonstrated by state-of-the-art computer graphics techniques, Lumion can be used to construct an exceedingly immersive VR simulated scenes, which is higher level graphical simulation with much more details and realistic effects. On the perspective of the application of VR in engineering education, higher rendering quality, quicker rendering speed, more realistic and vivid details can definitely improve the students’ using experience, and great user experience can foster the learning effects on this point.

Fig. 10: A demo of assembly of dougong made by Unity 3D
VI. Dissemination for Education

The final stage of the graphics pipeline is to create an integrated learning platform to introduce the graphical simulations made in the previous phases as a means of education dissemination. The integrated learning platform is a C#-based intelligent system, named the Intelligent Dougong System with Virtual Reality (IDSVR), is an extension of the Intelligent Dougong System (IDS) launched in the lead author’s MS thesis project. In this new version, several significant updates have been developed, such as:

- Adding the graphical models of 18 types of Qing-style dougong
- Extending the decision tree possible paths up to 350 possibilities
- Including 20 new dougong sites in the form of photographs from field trips
- Adding the VR interactive programs
- Correcting some errors in the previous models

The decision tree in the IDSVR has been extended up to 350 possible paths, as shown in Fig. 12., including the 3-D graphical simulation of the structure and construction processes of
both Song-style and Qing-style *dougong*, as well as photographs from 28 field trips, so students can use this system to search and review any specific type of *dougong* as they wish. Thus, theoretically, a total of 350 different types of *dougong* would be available in this system. In fact, for some *dougong* that are identical except for their dimension grading system, only one set of graphical models were made for such *dougong*. Hence, 20 different types of graphical models of Song-style *dougong* and 18 different types of Qing-style *dougong* were modeled and integrated into the IDSVR.

![Extended decision tree in IDSVR](image)

**Fig. 12: Extended decision tree in IDSVR**

The working procedure of the IDSVR is as follows: After entering the welcome scenes shown in **Fig. 13**, a student can review the introduction information of the *dougong* in both textual and graphical form, as shown in **Fig. 14**. Next, the student is asked to answer a series of questions about the categories and features of *dougong* as per the decision tree defined above, as shown in **Fig. 15**. After all the questions for each category have been completed, by clicking the NEXT button, the IDSVR finds the type of *dougong* requested. For every type of Song-style or Qing-style *dougong*, the complex structure and construction processes are presented in the form of 3-D graphical models, multi-view engineering drawings, exploded views, illustrations, rendered final result pictures, and textual descriptions for each level, as shown in **Fig. 16**.
Additionally, the for the selected type of *dougong*, the student can check the dimensions of its major components in the DIMENSIONS tab page, review the *in situ* photographs in the PHOTOGRAPHS tab page, and view the assembly animation in the ANIMATION tab page. Finally, in the VR tab page, the student can enter a VR simulation environment made in Unity 3D and Lumion, by clicking the button with illustrations to learn the knowledge of the *dougong* in an immersive and interactive manner. All the graphical simulation and interactive programs in the VR environment are integrated in IDSVR in this tab page.

For the time being, the IDSVR remains an off-line standalone *dougong* learning tool produced by Visual Studio based on C#, which can only be run on the Windows computer platform. By contrast, the trend of online mobile programs is fast becoming mainstream in the era of the internet. Compared to traditional programs installed on computer hard drives, these new types of applications, or “APPs,” have smaller sizes, save memory resources, and offer multi-platform availability. In addition, portable smartphones and tablets are replacing traditional desktop computers as the major medium for information dissemination thanks to the development of CPU and GPU on mobile devices; more education might be more depending on popular mobile operation systems such as Android and iOS in the future teaching practice.

Therefore, one of the potential improvements of the VR implementation may include expansion to multiple platforms and operation systems, optimized graphics engines for fast real-time rendering, more versatile interactivity methods via touchscreen, and audio and gesture-based input for the VR experience. To attain these objectives, the IDSVR may need to be reprogrammed in other languages such as Java or Python, and other specified development tools may also be needed to meet the requirements of multi-platform expandability and even for other types of virtual environments, such as Augmented Reality (AR), a combination of real environment feedback and virtual objects, and Mixed Reality (MR), a mixture of VR and AR.

To test the performance of the IDSVR in terms of engineering education practice, a beta-testing process may be warranted, wherein students are invited to use the system and provide feedback via questionnaires including measurement of variables such as education efficiency, user-friendliness, ease of use, VR experience, rendering speed and quality, controller setting, accuracy of model and other aspects of the IDSVR. By collecting and analyzing the first-hand
user experience from the students, the current problems of the IDSVR can be identified, and more improvements can thus be conducted to further enhance the teaching effectiveness and usability of the IDSVR in educational activities.

Fig. 13: Interfaces of IDSVR: Welcome

Fig. 14: Interfaces of IDSVR: Introduction
Fig. 15: Interfaces of IDSVR: Question interfaces

Fig. 16: Interfaces of IDSVR: Construction Process
Although no formal surveys have been implemented as of the time of writing (and a formal survey will likely be the next step in this process as well as the subject of a future paper), the IDSVR has been presented to a seminar body of 15 graduate civil engineering students as well as multiple undergraduate students in the construction field. The program has been well-received as an educational tool with particular praise for the visuals and extensive attention to detail, providing the step-by-step process for *dougong* creation needed to understand the overall construction process. An official, quantified analysis of the efficacy of the project is a logical follow-up to the creation and demonstration of the program itself, thus enabling the authors to further judge the efficacy of the IDSVR in the classroom environment.

As it stands, the IDSVR appears to be a capable and sophisticated educational tool which could be highly beneficial to students intending to learn about *dougong* and their various components. The program renders and presents these components in a comprehensible manner and with many variations and details it is relatively engaging and flexible within its topic of focus. *Dougong* are, of course, a specific albeit important subject in a broader field of Asian architectural components and of architecture in general, but the authors also believe that the same educational principles behind the IDSVR can be applied to other modular engineering features to the same effect, allowing such a system to be used for a variety of engineering and architectural topics and courses.

**VII. Conclusions**

The research conducted in this paper resulted in a comprehensive, complete and accurate 3-D graphical database of Chinese *dougong*, which has been integrated into a knowledge-based system known as the Intelligent *Dougong* System with Virtual Reality (IDSVR) as a learning platform, in which students can examine the complex structures and construction processes of an ancient heritage, such as *dougong* via multiple methods, including: 1) static images, such as 3-D graphical models, multi-view engineering drawings, exploded views, and illustrations; 2) dynamic videos, such as animation clips of assembly procedures; and 3) VR interactivity, such as a virtual tour of the Yingxian Wooden Pagoda and the assembly of the components of *dougong* models in the VR environment. As expected of the application of VR in education, the authors believe that employing VR techniques to create a new path of engineering education with more immersive and
interactive user experience to facilitate students’ understanding and participating in the education practice is a promising new path for researchers and instructors alike.

The tasks accomplished in this research follow a graphics pipeline which consists of four stages: initial modeling, advanced modeling, VR production, and dissemination. The graphics pipeline can be used as a guidance to develop more VR-based teaching and learning applications in educational practice, facilitating the effectiveness of instruction and inspiring students to learn about complicated procedures and structures in the field of engineering education, as in the prototype of IDSVR conducted in this paper. In the future, additional simulation methods, such as AR or MR, can also be explored and applied in more engineering education curriculums, a particularly promising endeavor in light of the ongoing development of computer graphical software and hardware.

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