A Multimedia User-experience System with 3-D Simulation for the Construction Process of Nanwang Water Diversion Pivotal Project on China’s Grand Canal

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Abstract

Three-dimensional (3D) simulation is used to display projects over a large area to help users develop a comprehensive understanding of an overall project more efficiently compared to traditional photos and slides frequently used in an educational setting. It allows users around the world to observe synchronized work between various elements in the system both simultaneously and independently. With respect to ancient facilities that have been destroyed over time, 3D simulation provides users with a valuable means to observe and learn how ancient facilities functioned, and also furnishes valuable insights on ancient engineering designs and methods. Combining the most up-to-date information for a sample structure with the ease of use offered by 3D simulation, a Multimedia User-experience System with three-dimensional Simulation (MUSSN) has been developed that allows users to virtually construct an ancient sluice gate on China's Grand Canal in the region of Nanwang Water Diversion Pivotal (NWDP) project in Shandong province. The MUSSN walks students through an interactive series of topics that introduce them to the construction sequence and engineering required to build the NWDP. The combination of a 3D simulated model and a multimedia user-experience system will not only provide students an interactive platform to comprehensively understand the NWDP and the construction sequence of a sluice gate, but also train and improve students’ spatial recognition.

Introduction

The Grand Canal of China is the longest ancient artificial canal in the world, reaching a length of approximately 1800 km. It significantly contributed to ancient China’s economic, cultural and industry development by connecting south and north China as well as by providing a convenient watercourse for water transportation across the nation. Corresponding to the great significance of China’s Grand Canal is the difficulty to design and construct such a long canal that traverses a considerable number of provinces. Different terrain characteristics, uneven distribution of water resources, and precipitation also exacerbated this difficulty. In order to successfully build China’s Grand Canal to satisfy the requirement of connecting south and north China, ancient
civil engineers employed various skills and techniques in the design and construction process. As one of the most outstanding projects in ancient China, demonstrating the highest achievement of the construction techniques of the time, the Nanwang Water Diversion Pivotal project (henceforth NWDP) is introduced to students in detail with the help of a combination of 3D simulation models and a multimedia user-experience system.

The NWDP warrants this case study because of Nanwang’s unique location and the sophistication of the construction involved. Nanwang is a town located in Shandong Province and it is the highest location on China’s Grand Canal with an elevation of 38 m [1]. Considering elevation differences along the canal, the first challenge in the design of this sectional canal is how to overcome the influence of gravity, in order to allow the water to flow smoothly. The second challenge is the water shortage in northern China due to an uneven precipitation distribution. To solve both of these problems, the ancient engineers in the Ming Dynasty presented the following three solutions [2].

The first solution was to construct artificial watercourses to lead the water flow from natural water systems to the canal. There were four main natural water systems, respectively named Wen River, Ji River, Si River and Sha River, that provided water resources to the partial canal located in Shandong province. The artificial watercourse cut for the canal at Nanwang is known as the Little Wen River, which channels water flow from the Wen River to the canal. The direct distance between the Wen River and the canal is 38 km with a 13-m elevation difference [3]. In order to slow down water velocity to better control water flow, there were more than 80 curves constructed for the watercourse of the Little Wen River.

The second solution was to set up reservoirs by expanding natural lakes around the watercourse of the canal and reinforcing them. As discussed above, precipitation in Shandong province, especially at Nanwang, is relatively small, and is not evenly distributed in different seasons [4]. This seasonally uneven distribution of precipitation caused difficulties for navigation on the canal. There were three reservoirs built for the canal at Nanwang location, which were the Nanwang, Mata, and Shushan lakes.
The third solution was to construct sluice gates on the canal. The Shili and Liulin gates were constructed north and south of Nanwang, respectively, to control water flow at the NWDP (Figure 1).

The NWDP is the system designed to solve both of the primary difficulties at Nanwang (high elevation and water shortage). The system scope is limited by the authors to the section of the canal between Shili and Liulin gates, which consists of the gates plus the canal between them, especially including the intersection of the canal and Little Wen River (Figure 2). The Shili and Liulin gates were later reconstructed into bridges for contemporary transportation, which has resulted in increased difficulty in studying the original structures and construction materials of the ancient gates. Only a small trace that indicates the original shape of the gates was observable during the site visit. The distance between the two gates is 5 km, with the river intersection being
approximately in the middle [5]. The intersection of the canal and the Little Wen River was reconstructed in 2010, as part of the creation of the Nanwang Water Diversion Pivotal Site Park. The cleared watercourse, reconstructed retaining walls and the boundary of the site park are readily observed. There is an approximately 390-m long retaining wall, as measured by Google Earth, reconstructed on east bank. On west bank, the reconstructed water retaining wall is 510-m long.

Figure 2: The NWDP depicting the Shili and Liulin Gates
The Simulation

The combination of 3D simulation model and multimedia user-experience system is conducted in this research for several reasons: (1) Because structures of sluice gates and retaining walls at Nanwang location are seriously damaged by local residents or even disappeared, and remains of the NWDP cover at least a 5-km-long area. Both of these facts make it inconvenient and unsafe for students to visit the overall remains at one time. Three-dimensional simulation models of the NWDP provide an opportunity to students to visually observe the structures in the NWDP efficiently and conveniently. What is more, 3D models assist students to build a comprehensive understanding over the NWDP and decrease students’ difficulty of mentally transferring 2D photos and images into 3D structures. (2) The multimedia user-experience system is developed by the authors as it offers a knowledge-based environment and platform where students are able to experience and interact with the NWDP. This kind of participation would enhance student’s intellectual excitement and retention, which makes this system an efficient and enjoyable tool for education [6]. (3) The 3D simulation models are able to improve students’ spatial ability, which is reported to be critical for success in Science, Technology, Engineering, and Mathematics (STEM) education [7].

Numerous applications of graphical simulation for educational purposes have been discussed and conducted previously, including the graphical simulation of the Temple with the Wudian Roof [8], the Great Wild Goose Pagoda [9] and the Great Wall [10] in China. These explorations have indicated the feasibility of the graphical simulation application in education domain. Knowledge-based systems have been applied for educational purposes as well, such as Intelligent Dougong System with Virtual Reality (IDSVR), which is developed to introduce a structural component Dougong [11], and Multi-media Graphical System to teach students about St. George’s Church [12].

The research conducted in this paper is composed of two stages: (1) modeling and (2) dissemination for education. In the initial modeling stage, Autodesk Inventor and 3DS MAX were used to build the basic 3D models for the NWDP, including sluice gates and watercourses. When building the 3D model for a sluice gate, the authors followed the construction specification and simulated the construction sequence step-by-step, which assures that the 3D
model satisfies the accuracy requirements for simulation and educational purpose. In the second stage, a Multimedia User-experience System with three-dimensional Simulation for the NWDP (MUSSN) was developed for education using Microsoft Visual Studio. There are three main functions designed for students: learning, applying and reviewing. In the “learning” stage, students are able to learn the characteristics of China’s Grand Canal from the video, such as the evolution history, advantages and disadvantages of it. After having a general understanding of the overall China’s Grand Canal, the system provides a section canal in Shandong province, which is the canal at Nanwang location. After reading a text describing Nanwang’s unique location and the resulting difficulties to construct this section canal, students would comprehend why the NWDP is necessary and how did ancient engineers design this system. Later, MUSSN provides students an opportunity to learn specific construction technology regarding a sluice gate in the NWDP.

In the “applying” stage, MUSSN creates an interactive environment for students to simulate the construction process of a sluice gate. Students are required to answer related questions to simulate certain construction process, where significant participation of students is involved. This interaction between students and MUSSN considerably helps students develop a comprehensive understanding on a dynamic process to a degree where tradition educational methods are difficult to reach (due to the lack of interaction between the knowledge and students).

In the “reviewing” stage, students are able to reflect on what they have learned with the help of intuitive illustrations and convenient operation of MUSSN. While no surveys have been officially conducted as of this writing, the program has been presented to a seminar of 10 civil engineering graduate students. The next step of the research would be to distribute formal surveys to undergraduate, graduate students and experts to evaluate the effectiveness of the program. After analyzing the feedback, further improvements of MUSSN will be made for the future use in the classroom setting.
MUSSN

Students are first greeted by a Welcome Screen tab when they use the MUSSN (Figure 3). The background is a 3D graphical simulation of the NWDP. In the lower right corner is a “Next” button which takes students to the next tab. In the Introduction tab, students can find a brief introduction of China’s Grand Canal in the upper left Textbox (Figure 4). In Figure 4, the map was retrieved on February 8th, 2018 from [13]. Just below this Textbox is a video which would lead students to YouTube website to develop a more comprehensive understanding on the overall canal by watching it. On the right is an illustration of China’s Grand Canal, where students would be able to get familiar with the provinces and their locations that China’s Grand Canal flows through. In the lower right corner are the “Back” and “Next” buttons, which lead students to previous and next tab respectively.

Figure 3: MUSSN Welcome Tab Screenshot
The NWDP tab reveals the position of Nanwang Water Diversion Pivotal (Figure 5). On the left is a Textbox introducing two main problems that prevents the canal from flowing smoothly through Nanwang, which are the elevation and water shortage. Corresponding to these two problems, two illustrations on the right intuitively demonstrate the high elevation and lack of precipitation at Nanwang.
The Solutions tab in Figure 6 shows how the ancient engineers overcome the difficulties at Nanwang location discussed in previous tab and conducted their creative and effective design for the NWDP. Students would read three solutions in detail from the textbox in the upper left corner. Just below the textbox are two questions and drop down selection menus. The “Back” and “Next” buttons work same as those on previous tabs. On the right is an illustration of how ancient engineers designed the NWDP as a comprehensive system, and three solutions, which are utilizing natural and artificial watercourses, expending reservoirs, and constructing sluice gates, are observable in this illustration. This illustration is not visible until students have read the Textbox, correctly chosen the right answers and clicked “Show the design” button. The illustration was designed to enhance students’ self-thinking process based on given information, instead of directly providing an ancient design. In this tab, students will learn the idea of how to design a system to solve existing problems by taking advantage of natural resources combined with manmade projects.
The Construction Material tab in Figure 7 shows four illustrations of materials that are used to build a sluice gate. There is a button below each illustration that takes students to an information tab for the exact material they have selected. At the same time, the buttons below the illustrations of stone blocks and green (not fully baked) bricks provide the dimensions of standard unit of corresponding material.

When students click the “Stone blocks (0.8 m * 0.4 m * 0.4 m)” button, they will see an Introduction to Construction Material tab which has a detailed description of stone masonry on it (Figure 7a). On the left is an illustration of a section view of a sluice gate, where students can see the dimensions for stone block walls. On the upper right, there is a table where students learn how many columns and layers of stone blocks are placed to construct a sluice gate. In the upper right corner is a “Return” button which takes students back to the Construction Materials tab (Figure 7c).
Figure 7: MUSSN Construction Materials Tab Screenshots
If students click the “Green bricks (0.5 m * 0.167 m * 0.1 m)” button, they will be lead to Introduction to Construction Material tab which introduces brick masonry work (Figure 7b). Similar with the previous tab, an illustration of a section view is available on the left so that students learn the dimensional data of brick walls at this time. On the upper right is an illustration that indicates the placement pattern of the brick masonry work. Below this illustration is a table of showing how many wythes (vertical rows of one unit thickness of bricks) and courses (horizontal layers) of green bricks are used to construct a sluice gate. The “Return” button leads students back to Construction Materials tab (Figure 7c). In Figure 7c, the photo showing stone blocks, green bricks, sanhe earth and wood piles is taken from [15][16][17] and [18], respectively.

The “Sanhe earth (rammed earth)” button takes students to Introduction to Construction Material tab where students are able to learn about the earthwork of a sluice gate (Figure 7d). In the upper left corner is a Textbox where introduces how ancient engineers produced sanhe earth, the two ingredients they used, and what ratio was used in the production of sanhe earth. In the lower tab are the illustrations of section and top views of a sluice gate from which students can learn the construction information of earthwork for both superstructure and substructure. The left and right tables show the production ratio of sanhe earth for superstructure and substructure respectively. As with the previous tabs, the “Return” button takes students to Construction Materials tab (Figure 7c).

The “Wooden piles” button takes students to a tab that enables them to learn about the pile foundation of a sluice gate (Figure 7d). In the upper left corner, there is a Textbox introduces three types of piles, which are stone-supporting, brick-supporting and earth-supporting piles (Figure 7e). On the right is an illustration of the distribution modes of piles. The type and distribution mode of the piles are determined by their location and what construction materials are they supporting above. Below are two illustrations and two tables. Left illustration and the table below it introduce the type, distribution mode and density of the stone-supporting piles. Right illustration and table show the same information for the brick-supporting and earth-supporting piles. The “Return” button works the same as the previous “Return” buttons.
After reviewing above tabs, students have learned construction information of a sluice gate from perspective of construction materials, masonry work, earthwork and foundation. In the following tabs, students will experience the construction process of a sluice gate by virtually building a sluice gate by themselves. The Construction Process Simulation tab is unique to the previous tabs. There are seven sub-tabs under this tab, which are Start, Construction Plan, Foundation, Bottom Layer, Middle Layer, Top Layer, and Finish, working as a step-to-step process to build a sluice gate. Figure 8 shows the Start tab and Construction Plan tab.

![Construct a sluice gate on your own!](image)

Figure 8: MUSSN Construction Process Simulation Tab and Construction Plan Tab Screenshot

In the Construction Process Simulation - Foundation tab, students find four questions on the left side of the application (Figure 9a). First three are about pile foundation while the last question is for earthwork. The “Recommendation for piles” button and “Recommendation for earth work” button take students to Introduction to Construction Material tab that introduces wooden piles and *sanhe* earth respectively. For example, when students click “Recommendation for earth work” button, they are led to Introduction to Construction Material tab which offers their required information (Figure 9b). In the lower right corner, there is a “Back to construction” button which takes students back to the previous construction process where they have trouble. This button is not visible when students just want to review construction materials, so students won’t become confused by MUSSN. There are similar designs in the following tabs which assist students when they have questions while not confuse them by offering too much information at one time.
In the Construction Process Simulation - Foundation tab (Figure 10), when students start to choose answers, there are 4 possible outcomes: (1) answers for both piles and earth work were incorrect, (2) answers for earth work were correct, but those for piles incorrect, (3) answers for piles correct, but those for earth work incorrect, and (4) answers for both piles and earth work correct. Since in the construction process, piles were driven before constructors began ramming earth, both outcomes 1 and 2 would lead to the failure of the whole foundation. So if outcome 1 or 2 has been selected when students click the “Construct” button, the message “There is something wrong with the pile distribution, please try again” will be displayed, suggesting that students should enhance their understanding on pile foundation (Figure 10a). If outcome 3 has been selected, students show basic understanding on piles, so after they click “Construct” button, an illustration of the process of driving piles appears on the upper right (Figure 10b). If outcome 4 has been selected when students click the “Construction” button, a Message Box with “Congratulations! Foundation of your sluice gate is successfully built” appears, along with two illustrations of driving piles and completed foundation for a sluice gate (Figure 10c). The “Back” and “Next” buttons in this tab work in the same way as those in previous tabs.
Figure 10: MUSSN Construction Process Simulation - Foundation Tab Screenshot
In the Construction Process Simulation – Bottom Layer tab, there are two Textboxes for displaying questions, two Combo boxes for displaying multiple options for students, and four buttons (Figure 11a). In this tab students are required to answer questions about stone masonry, thus “Recommendation” button will take students to Introduction to Construction Material tab for them to acquire related knowledge. Similar to what has been discussed above, only if students have both questions correct and click the “Construct” button, two illustrations for simulating the construction sequence of the bottom layer of a sluice gate appear on the right (Figure 11b).

The Construction Process Simulation – Middle Layer, Construction Process Simulation – Top Layer, and Construction Process Simulation – Finish tabs follow the same pattern as the Construction Process Simulation – Bottom Layer tab, where there are two Textboxes for displaying questions, two Combo boxes for displaying multiple options, and one or two illustration(s) for simulating the construction sequence of a sluice gate (Figure 12). “Recommendation” buttons in these three tabs allow students to review the construction materials as well as related construction techniques. After finishing with the questions on the left, students click “Construct” button to simulate certain construction step. The “Back” and “Next” buttons bring students to previous and next tab, respectively. To be specific, as the Construction Process Simulation – Finish tab is the last sub-tab under the Construction Process Simulation tab, “Next” in this tab takes students to next tab, the Review on Construction Process tab.
Figure 11: MUSSN Construction Process Simulation – Bottom Layer Tab Screenshot
Figure 12: MUSSN Construction Process Simulation – Middle Layer, Construction Process Simulation – Top Layer and Construction Process Simulation – Finish Tabs Screenshots
The Review on Construction Process tab (Figure 13) enables students to recollect the overall simulation steps of the construction process, and provides an overview of the knowledge learned. This tab works as a clear and simple conclusion to this experience to assist students with enhancing their memory retention. Finally, the Data Source tab (Figure 14) demonstrates all beneficial data sources the authors have used to develop this system. For students with a desire to learn more about the construction process of China’s Grand Canal or the NWDP, data sources in this tab might be a start for further study.
Conclusions
The research conducted in this paper resulted in an interactive platform which is known as a multimedia user-experience system with 3D simulation for the NWDP, where students can learn about China’s Grand Canal, its highest point Nanwang, and which was designed and constructed by ancient engineers to overcome the problems resulted from high elevation and water shortage at Nanwang location. Simultaneously, students’ spatial ability is trained and improved by observing 3D models. The MUSSN provides students with a platform to examine the structure and construction process of a sluice gate. In addition, students can interact with the MUSSN by simulating the construction process of a sluice gate in this system.

Furthermore, the multimedia user-experience system provides users with access to Nanwang, helping users to develop an understanding of the NWDP, by allowing users to
construct a sample sluice gate (using a 3D simulation model of the sluice gate). The various tabs in this system enable users to experience how ancient engineers designed the NWDP and how workers constructed sluice gates. Based on this step-by-step process, users can freely explore the construction process of the Grand Canal as well as the function of the completed structure, and researchers can use the research methods employed for this study as a starting point for similar educational analyses of other such structures in both antiquity and the modern era.

The applicability and flexibility of graphical models and user-experience systems allows this type of research to be applied to educate a variety of ancient facilities. The authors believe that developing an interactive educational environment and platform for students is a promising path in education domain as it is efficient in both facilitating students’ understanding and enhancing student’s intellectual excitement. At this stage, the modeling progress and application in educational settings have been favorably reviewed by graduate students (over 10 students) in weekly seminars of the authors’ construction program. In order to improve the MUSSN, it is recommended to test the effectiveness of this model in the classroom environment by undergraduate and graduate students.

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