Digital Reproduction and Virtual Simulation System Design of Astronomical Clock-tower

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ABSTRACT-The author designed and developed a virtual simulation system to introduce people to the great astronomical installations called astronomical Clock-tower of the Song Dynasty in China. In this paper, the operation data of the replica of the Astronomical Clock-tower was studied and defined, the digital replication and working principle of each part of the astronomical clock tower platform are studied, the dynamic flow physical simulation was carried out by using the Obi fluid plug-in, and the user experience system was improved by the design of virtual reality. Based on the interaction design analysis and usability research analysis, the user learning test table is formulated. The statistical data illustrates the advantages of the system in terms of learning and user experience.

1. INTRODUCTION

The Astronomical Clock-tower also called Water Transport Observatory, is a large-scale astronomical device invented by Song Su and Gonglian Han during the Northern Song Dynasty [1]. It uses a variety of instruments and technologies such as leak pots, water wheels, scale leaks, connecting rods, roller coasters, transmission chains, gears, transmission cams, barrel trucks, HunXiang and Armillary sphere, and a series of escapement control pivots. The transmission speed of the wheel is an unprecedented system innovation [2]. Since the founding of New China, Chinese and foreign scholars such as Xianzhou Liu, Zhenduo Wang, Needham Lee, Yanhang Chen and Xiao Chen, Chengxue Guan, and lots of museums have studied the restoration of the waterway instrument platform [3]. In recent years, Beijing China Science and Technology Museum, Taichung Museum of Natural Science, Suwa Lake Time Science Museum in Japan, and other institutions have also restored and produced waterborne instrument platforms. There are advantages and disadvantages in these structure and design of waterborne instrument platforms. But none of them departed from the basic description of Song Su's "Hsin I Hsiang Fa Yao" [4].

With the continuous development of virtual reality technology in recent years, the application of virtual simulation technology to the reproduction of ancient scientific and technological relics is becoming more and more common. Especially in some museums of science and museums of technology, people can use the virtual reality interactive system to more rationally display the ancient science and technology cultural heritage that has not existed or been destroyed in a digital and interactive image [5]. The digitized ancient artifacts in the virtual reality system can facilitate visitors to observe its details in detail and interact with visitors, which greatly improves the experience of
traditional museum exhibition viewing [6]. By using virtual reality technology to restore its operation process, users can browse the progress of the process step by step, which is easier to understand and more interesting than the existing Museum Tour methods such as video reviews [7].

The Astronomical Clock-tower VR system can introduce the history of the Astronomical Clock-tower and analyze its operation methods, so that people can understand the way of this great ancient scientific and technological relic more conveniently and clearly. This paper focuses on the derivation of the transmission mode and completes the digital reproduction. The Obi Fluid plug-in and particle system are used to perform the physical simulation of the water flow dynamics, to achieve a good interaction effect and to analyze its usability.

2. ANALYSIS OF DIGITAL MODEL OF THE ASTRONOMICAL CLOCK-TOWER

2.1. Power System
The power system is divided into three parts: the water transport system, the pivot wheel, and the transmission system. The specific movement principle of the escapement mechanism is not described in detail in the "New Instrument". During the restoration work, domestic and foreign experts gave different Solution [8]. The rotation of the pivot shaft drives the ground hub to rotate, and the ground hub meshes with the lower wheel of the pillar to push the entire pillar to drive. The upper wheel of the Tianzhu directly promotes the rotation of the armillary instrument and the Tianyun ring on the armillary instrument; the middle wheel and the teether wheel are engaged, pushing the timing system and HunXiang to run, as shown in Figure 1.

![Figure 1 Transmission flowchart](image)

The water transport system is composed of river car, Upper water-raising tank, Lower water-raising tank, Upper noria, Lower noria, Water-with-drawing tank, Water-receiving scoop, Upper flume and Upper reservoir. The water transportation route is shown in Figure 2: when the lifting water tank is full of water. The water-man moved the river vehicle. After the river vehicle was turned, the lifting boat lifted the water into the lifting water pot. After the lifting water pot was full, the Lower noria lifted the water into Upper water-raising tank and then flowed into Upper reservoir. Upper reservoir water naturally flows into the Constant-level tank, and the special flow of the Constant-level tank is used to pour the water into the kettle with a uniform speed. After the kettle is moved to the designated position due to gravity, the water in the kettle is poured into the retreating kettle, then flows into the submerged kettle, and then is lifted into Upper reservoir to circulate.

![Figure 2 Water transport route](image)
2.2. HunXiang and Armillary Sphere
The horoscope rotates in the opposite direction to the rotation of the earth. It rotates one day a day. The gears on the equator ring on the equator are called equatorial teeth. The equator teeth are engaged with the sky wheel driven by the gear wheel to drive the horoscope. Armillary sphere and HunXiang are shown in Figure 3.

![Figure 3](image)

**Figure 3** (a) Armillary sphere (b) HunXiang

Armillary sphere which is at the highest position of the waterborne instrument platform is an instrument for observing and calculating the movement of celestial bodies. It is composed of Liuheyi, Sanchenyi, Siyouyi, and telescope. The front hub and the Tianyun ring are engaged to complete their own rotation.

2.3. Timekeeping system
Tianzhu's middle wheel drives an eight-wheel reporting system to operate, which is covered by a five-story wooden pavilion inside the instrument. There are three puppets on the "Floor Bell and Drum Wheel" on the first floor: every hour starts, the red puppet rattles, and the purple puppet buckle clock. The green puppet beats the drum every 15 minutes; the second and third layers are different colors. The puppets tell the time and the time respectively; the fourth and fifth layers are the night time system [9]. IGS files generated by Solid Work were imported into Unity3D through PiXYZ to facilitate subsequent model material production [10].

3. ANALYSIS OF THE PRINCIPLE OF THE ASTRONOMICAL CLOCK-TOWER

3.1. The operating principle of the Astronomical Clock-tower
In order to animate the model, this system focuses on clarifying the transmission sequence of each link and the moving direction and speed of each element. The driving process of the power system combed from the second section, and the actual records recorded in "The New Instrumental Method", can be summarized as shown in Figure 4 of the entire Astronomical Clock-tower.

![Figure 4](image)

**Figure 4** Transmission chart of the platform

3.2. System transmission data analysis
There are some omissions in the records of gears and transmission data of the Waterborne Instrument Platform in the New Instrumental Method. After examining the waterborne instrument platform
reproduced by the Beijing Science and Technology Museum in Beijing, the number of gears in this system was corrected and confirmed.

Through the transmission process in Figure 5, and the correction of the number of gears of each component in Table 1, and the known and determined data (bold display): the horoscope, the horoscope and the earth rotate at the same speed in reverse; the speed of the gear wheel is 1 day / Cycle, etc., the speed of other components can be inferred from the number of gears.

When the gears are driven by gears, the linear speeds of the two gears are the same, that is \( V_1 = V_2 \), the angular velocity is inversely proportional to the number of gears, that is \( V = R \omega, \omega = \frac{1}{n} \), the remaining component speed is obtained. After finishing, the number of gears and speeds of all the components involved in the transmission are shown in Table 1.

| Element                        | Number of gears / number of buckets | Rotating speed |
|--------------------------------|-------------------------------------|----------------|
| Pivot wheel                    | 36 (buckets)                       | 15min/turn     |
| Ground Hub                     | 22                                  | 15min/turn     |
| Lower, middle, upper wheel     | 176, 50, 60                         | 2h/turn        |
| Rear, front hub                | 20, 30                              | 1h/turn        |
| Tianyun ring, armillary sphere | 480                                 | 1day/turn      |
| Tooth wheel                    | 600                                 | 1day/turn      |
| Sky Wheel                      | 488                                 | 1day/turn      |
| North and south bridge wheel   | 32                                  | 1.6h/turn      |
| Equatorial teeth               | 487                                 | 1day/turn      |

4. SIMULATION INTERACTIVE SYSTEM PRODUCTION

4.1. Water Flow physics simulation

Water is an important element of the driving force of the power system in the water instrument platform. For the part of the water current driving pivot wheel in this system, the water flow simulation is performed by the particle system in Unity3d. The motion of water flow can be simulated by the movement of multiple fluid particles to simulate its overall momentum and shape. The motion of each particle can be adjusted by the particle emitter, animator, and renderer to obtain a physical simulation of the overall water flow [11].

In order to make the movement of the water flow more natural during the movement of the pivot wheel, this system uses the Obi Fluid plug-in to perform dynamic simulation of the movement of the pivot wheel and a small part of the water flow on each lifting wheel. Obi Fluid is a plug-in that uses particles' physical effects to simulate liquid effects. It has a real physical performance for the interaction between fluid particles and the interaction with colliders. Emitter emits particles and adds them to the scene as components. You can drag the Obi Emitter Shape component to the emitter in the scene (the water pipe of the kettle in this system), and then assign the Obi Emitter component to the The Emitter attribute of the camera that needs to render the water flow can be used. Due to the binocular nature of the VR system, both the left and right cameras need to be rendered.

By adjusting the maximum number of Num particles to 3000, the life cycle of Lifespan particles to 10, and the flow rate to 2, the most suitable water flow effect can be simulated. The simulation effect is shown in Figure 5. When the pivot is turned down, water flows into the water tank When the water reaches a certain weight, it will rotate the pivot wheel to form a splash effect, and then continue to flow into the next sink.
4.2. Interactive functions and interface design

The main purpose of this system is to allow users to understand the operation principle of the water transport instrument platform. Therefore, in terms of interaction design, this system aims to make the user understand the water transport instrument platform more conveniently, quickly and comprehensively.

This interactive system is composed of Google VR glasses, Android phone and gamepad. You can switch the floor, view the operating principle, and jump to the specified element by operating the layer information on the buttons on the handle. It is suitable to do too much interesting interactive design for its virtual reality interactive system, so add voice explanation and video playback modules. When the character enters the target object, call the interface of playing audio source and video file to realize the playback of music, sound effects and video.

Some components of the water meter platform are relatively small and scattered on various layers, and it is difficult for tourists to accurately understand the driving process. Therefore, the function of zooming in and playing out several animations together allows tourists to understand each of them faster in this huge machine. Partial transmission mechanism principle.

According to the requirements, the gamepad buttons have been redefined, as shown in Figure 6.

In summary, the content that needs to interact is the following:

1. The handle and the headset control the first person to walk and tour freely.
2. The b button on the handle executes the function of jumping to the designated floor, as shown in Figure 7.
3. After the line-of-sight collision detects a specific component, the video playback mechanism is implemented by the x key of the handle, as shown in Figure 8.
4. The character enters the designated place to trigger the audio playback of the explanation.
4.3. System availability research

The purpose of this system is to allow users to understand the operating principle of the water tanker platform more intuitively. In order to ensure that the system is available and the effect is higher than other browsing methods, the user test method is used for usability evaluation. Due to the strong learning nature of the system, a questionnaire method was used for user testing.

This test experiment randomly divided 10 volunteers who did not know about the Water Transport Instrument Observatory into two groups. These 10 volunteers were students of the same age and education of different professions. The first group was visited by computer game version, and the second group passed VR system tour, the same audio and video played in the system, each person using the system to roam is limited to 8 minutes. Stay for 10 minutes after the end of the experience, complete the test questions in Table 2, and record the completion time and score for each question.

Table 2 Test of the platform operation

| Serial number | Topic                                                                 |
|---------------|------------------------------------------------------------------------|
| 1             | What is the instrument on the second floor?                            |
|               | A. Armillary sphere B. HunXiang C. Pivot wheel                         |
| 2             | What drives the gear wheel?                                            |
|               | A. Medium wheel B. Timing system C. Tianzhu                             |
| 3             | Armillary sphere is driven by which of the following parts?            |
|               | A. Pivot wheel B. HunXiang C. Upper wheel                              |
| 4             | What is the instrument located at the highest position of the watercraft instrument platform? |
|               | A. Armillary sphere B. HunXiang C. Water transport system              |
| 5             | How many layers does the timekeeping device have?                     |
|               | A. Three floors B. Five floors C. Eight floors                         |

One correct answer plus 1 point, the wrong answer gets 0 points out of 5 points, the first group of volunteers are numbered A1-A5, the second group is B1-B5. The test time statistics are shown in Table 3; the test score statistics are shown in Table 3.

Table 3 Statistics table of 10 volunteers' time for completing the test questions (unit: second, s)

| No. | A1  | A2  | A3  | A4  | A5  | B1  | B2  | B3  | B4  | B5  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| time| 45  | 68  | 55  | 60  | 66  | 43  | 60  | 56  | 39  | 50  |

Table 4 10 volunteer test scores

| No. | A1  | A2  | A3  | A4  | A5  | B1  | B2  | B3  | B4  | B5  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   |
| 2   | 1   | 0   | 1   | 0   | 1   | 1   | 0   | 1   | 1   | 1   |
| 3   | 1   | 1   | 0   | 1   | 1   | 1   | 1   | 1   | 1   | 1   |
| 4   | 0   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   |
| 5   | 1   | 1   | 1   | 1   | 0   | 1   | 1   | 1   | 0   | 1   |
According to the test results, $t_A$ is 58.8s and $t_B$ is 49.6s; the total number of 5 questions in group A is 20 points, and that of group B is 23 points. According to the experimental data, it can be considered that the VR system mode of the watercraft instrument platform can help the user to master the knowledge of its various components and operating principles more than the ordinary computer game mode.

5. CONCLUSION
The design of the VR system of the Astronomical Clock-tower has a very important role in popularizing the scientific and technological status of the water transport instrument and displaying the operation principle of the water transport instrument. This article introduces the production points and analysis of the usability of the VR system of the Astronomical Clock-tower platform, and explores that compared with other forms of knowledge transmission, it can improve the user's interactive experience, the efficiency of knowledge control and the pleasure of browsing. In the follow-up work, the accuracy of digital restoration and the fidelity and diversity of virtual interactions should be further improved.

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