Expert Systems With Applications 217 (2023) 119502

Contents lists available at ScienceDirect

Expert Systems With Applications

journal homepage: www.elsevier.com/locate/eswa

Immersive virtual reality as a tool to improve bridge teaching communication

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ARTICLE INFO

Keywords:
Immersive virtual reality
Bridge teaching
3D modeling
Teaching communication
Participation and interactivity

ABSTRACT

The objective of bridge teaching is to provide students with knowledge of bridge construction and lay a solid foundation for further in-depth study and work practice. However, the current bridge teaching has the following limitations: (1) the "spoon-feeding" teaching is dominated by teachers; (2) the teaching material lacks intuitiveness, practice, and interactivity. Immersive virtual reality (IVR) enables the possibility of representing abstract bridge concepts in a 3D manner while stimulating student engagement and motivation in the learning process. In this article, we attempt to use IVR as a tool to improve the student's engagement and teaching communication. The automatic generation of bridge scenes in 3D, immersive interaction, and teaching communication evaluation are discussed in detail. Finally, a mega suspension bridge under construction is selected as a case for experiment analysis. The results of the experiment show that the combination of IVR and bridge teaching can effectively improve the students' learning interests and teaching communication. The percentages of students who were very satisfied and satisfied with the immersive bridge teaching were 39.6% and 54.2% respectively, which proves that IVR has great potential and positive outcomes in education.

1. Introduction

As an integral part of education, teaching is the knowledge and skills training deemed necessary in the form of lectures among a large group (Blumenfeld et al., 1991; Udeozor et al., 2021). Bridge teaching is a very important course in civil engineering and related engineering disciplines and aims to provide students with knowledge of bridge construction, mechanical behavior, and construction processes, thus providing a solid foundation for further in-depth study and work practice (Kim, 2012; Magdalene & Sridharan, 2018; Wei & Ju, 2018).

However, the current bridge teaching is mainly dominated by teachers, which conduct "spoon-feeding" teaching for students. "spoon-feeding" means that students passively absorb large volumes of information passed by the teacher in short amounts of time, without active thinking and practice, which will affect their motivation and interest in learning and loses the innovative abilities. Overall, there are three major current challenges for bridge teaching communication:

(1) Lack of intuitiveness: Bridge structures are more complex than building structures (Huang et al., 2022), and students with weak spatial imagination have difficulties understanding the bridge structure if they only rely on textbooks or two-dimensional (2D) drawings.
(2) Lack of practice: Bridge teaching is a course that emphasizes both theory and practice. Due to most of the construction parties being reluctant to accept students for internships (Sun et al., 2018), students generally do not get enough practical exercise, which leads to a decoupling of theory and practice.
(3) Lack of interactivity: In a bridge teaching course, most of the information is presented through paper-based textbooks or slides, teaching is mainly narrated by the teacher and there is a lack of substantive interaction between students.

To maximize the improvement of teaching and learning, we should strive to engage students in a way of personal experience with the course (Morélot et al., 2021; Nadan et al., 2011; Slavova & Mu, 2018). Over the last decades, the 3I's (immersion, interaction, and imagination) of virtual reality (VR) have driven its shift from gaming to more diverse applications, such as tourism (Talwar et al., 2022), fire protection (Cha et al., 2012; Lorusso et al., 2022), disaster management (Sermet & Demir, 2019), and particularly the increasing use in education (Kamińska et al., 2019; Liu et al., 2017). VR applications that are typically used for education could be regarded as games with a serious purpose, named serious games (Imlig-Iten & Petko, 2018; Udeozor et al., 2021). VR serious games are believed to have many positive effects on learning outcomes, such as improving intrinsic

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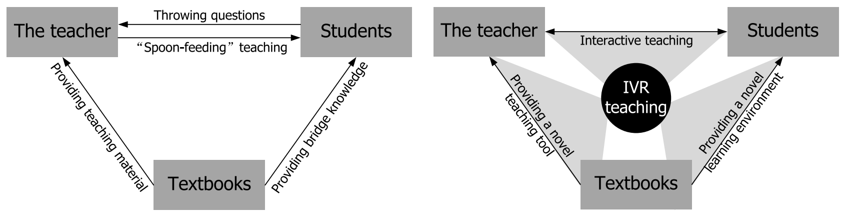
https://doi.org/10.1016/j.eswa.2023.119502
Received 24 May 2022; Received in revised form 1 January 2023; Accepted 2 January 2023
Available online 7 January 2023
0957-4174/



(a) Traditional communication cycle. (b) New communication cycle with IVR.

Fig. 1. Communication cycle in bridge teaching.

motivation, increasing the level of interest in learning, and improving problem-solved skills (Araiza-Alba et al., 2021; Checa et al., 2021; Morélot et al., 2021). While some researchers are negative towards the application of VR serious games in education (Dimitriadou et al., 2021; Fernández-Manjón et al., 2015), one aspect is that they question the real educational value of VR serious games and whether the students can actually learn from them. Another aspect is that VR serious games implementation is limited due to the hard accessible hardware, which results in the educators reluctant to put in the extra effort integrate the VR serious games into the time-pressed curriculum.

Nevertheless, most researchers are still optimistic about the value of using VR serious games in education. Many surveys concluded that VR serious games are a more memorable environment than slides-based demonstrations, which could facilitate a visual understanding of complex concepts and improve student attitudes toward learning, therefore, knowledge acquisition (Checa & Bustillo, 2020; Kamińska et al., 2019; Ladendorf et al., 2019; Villena Taranilla et al., 2019; Wu et al., 2021; Zhu et al., 2022).

In terms of supported devices for VR serious games, which can broadly be classified into two main categories: desktop VR (DVR), and immersive VR (IVR) (Hamilton et al., 2021; Peixoto et al., 2021). DVR is characterized by being less immersive and the least expensive, which only allows the participant to manipulate the three-dimensional (3D) virtual environment on a monitor utilizing a traditional keyboard and mouse hardware. Nevertheless, DVR plays an important role in improving the intuitiveness of teaching content in the classroom. For example, Ausburn and Ausburn (2004) mentioned DVR can produce a virtual environment on the computer, the industrial educators can add this powerful technology to their classroom portfolios and create a unique research base in the field. Glick et al. (2012) used 3D computer models in the classroom to increase student understanding of complex construction systems and components. Goedert and Rokooei (2016) proposed a novel approach to virtual interactive construction education, which is a project-based pedagogical approach delivered in a simulated and virtual environment.

With the advances in computer graphics and the rise of consumer-grade VR devices (e.g., HTC Vive, Oculus Quest, etc.), IVR technology is gaining attention for its potential use in education and is increasingly being adopted as a learning tool in the classroom (Araiza-Alba et al., 2021). IVR offers students a visuospatial perspective (Chen & Lin, 2018), which allows students to learn by performing activities in a high-fidelity environment and increases self-efficacy compared with the DVR (Chang & Hwang, 2021; Chen & Lin, 2018; Ladendorf et al., 2019; Makransky et al., 2020; Zhao et al., 2020). Furthermore, interactivity is believed to be the most fundamental aspect of effective learning, the natural interaction of IVR can enhance student engagement and interaction in the classroom (Martirosov & Kopecek, 2017). At present, IVR has been applied in many fields related to education, such as chemical engineering (Udeozor et al., 2021), fire safety training (Morélot et al., 2021), foreign language education (Peixoto et al., 2021), psychology education (Kamińska et al., 2019).

However, there is little study on the application of IVR to education in engineering disciplines, particularly there is no work addressing the utilization of IVR in the case of bridge teaching. To the authors' knowledge, the introduction of IVR into bridge teaching can help students perceive and recognize the surrounding environment of bridges from an all-around perspective, and allow students to experience the bridge components and construction process in an immersive way, the purpose is to improve student's motivation in learning and teaching communication (Mulders et al., 2020). Wang et al. (2018) revealed five future directions for VR-related education in construction engineering, one of which is the rapid generation of scenes for virtual training or teaching. In this context, one objective of our work will focus on the automatic generation and immersive interaction of bridge scenes in 3D, and introduce such an IVR scene as a tool to improve bridge teaching communication. To this end, we will also quantitatively evaluate the impact of IVR on bridge teaching and learning.

The remainder of this article is organized as follows: Section 2 discusses the communication cycle in bridge teaching. Sections 3.2, 3.3, and 3.4 introduce the semantic hierarchy of bridges, automatic generation of bridge scenes, and immersive interaction, respectively. Sections 4 and 5 give insight into the implementation of the prototype system and experiment analysis. Sections 6 and 7 present the discussion and conclusion.

2. Communication cycle in bridge teaching

In the field of engineering, Lai et al. (2011) point out that communication between decision-makers, engineers, and the public was tenuous due to excess engineering details and a lack of integrated presentations. Likewise, there is also a communication gap between teachers and students in bridge teaching.

Fig. 1(a) shows the traditional communication cycle in bridge teaching. Textbooks are used as a medium of communication between the teacher and the students, sometimes textbooks are made into a slide show, then the teacher takes the lead in transmitting the bridge knowledge to the students through "spoon-feeding" teaching. To decrease communication gaps, some teaching reforms have been proposed, such as the use of more pictures of the construction sites and video of the construction process, which can enhance the student's interest to some extent, but participation and interaction are still insufficient. Taking suspension bridges as an example, there are thousands of components with complex interrelationships involved. Relying on textbooks, 2D images, and computer-aided design (CAD) drawings, it is difficult for students to imagine how the bridge components are assembled and how the bridge is constructed in dangerous mountainous areas.

Fig. 1(b) illustrates a new communication cycle that incorporates IVR into the teaching process. The bridge knowledge in textbooks and the teacher's teaching theory are abstracted to form an IVR teaching environment. Using virtual environments in bridge teaching, the teacher can demonstrate some abstract concepts more concretely (e.g., wind load, mechanical behavior). In particular, such an immersive learning environment can trigger students' interest and motivation, thereby reducing cognitive load and stimulating the imagination. Therefore, the communication between the teacher and students is greatly enhanced by using an immersive 3D virtual environment for bridge teaching, which can transform knowledge acquisition from one-way communication guided by teachers to two-way communication with student's participation.

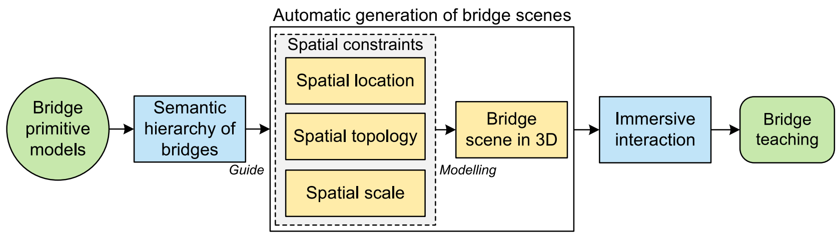
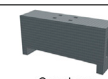
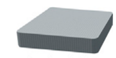
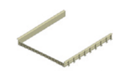
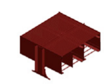


Fig. 2. Overall research framework.

Table 1
Contents of bridges and their descriptions.

Number	Term	Description	Example
1	Superstructure	The portion of the bridge that supports the deck and connects one substructure element to another	 Crossbeam
2	Substructure	The portion of the bridge that supports the superstructure and distributes all bridge loads to below-ground bridge footings	 Bearing platform
3	Foundation construction aids	Facilities to assist in the construction of bridge foundations	 Protective wall
4	Passenger tunnel	Underpass for pedestrian traffic only	 Passenger tunnel
5	Culvert	A pipe or small structure is used for drainage under a road, railroad, or other embankments	 Culvert
6	Ancillary facilities	All of the equipment, buildings, structures, and improvements associated with or required for the construction of bridges	 Inspection walkway

3. Methodology

3.1. Overall research framework

The overall research framework of this article is shown in Fig. 2. We start with the bridge primitive models, which are organized by ontology to form the semantic hierarchy of bridges. Then, spatial constraint rules are used to guide and constrain the automatic generation of bridge scenes in 3D. Lastly, we design immersive interaction to increase students' participation and interactivity.

3.2. Ontology-based semantic hierarchy of bridges

As mentioned before, bridge construction involves the assembly of a large number of components with complex interrelationships. To enhance the student's overall understanding of bridge composition, the bridges are abstracted from a conceptual level with reference to Railway Building Information Model Delivery Accuracy Standards,[1] which mainly include six parts: superstructure, substructure, foundation construction aids, passenger tunnels, culverts, and ancillary facilities. More details as shown in Table 1.

Ontology can conceptualize and clearly define objects and express their relationship in a unified and formal way (Fox, 2021; Li et al., 2021). Subsequently, Protégé is used to create and edit the ontology of bridges, which is an open-source ontology tool developed by Stanford University. Ontology-based semantic hierarchy of bridges is shown in Fig. 3. On the one hand, such a semantic hierarchy helps students to better understand the bridge structure, and on the other hand, it can be used to guide the automatic generation of bridge scenes in 3D.

[1] https://www.11bz.com/a/631375.html

3.3. Automatic generation of bridge scenes with spatial constraints

3.3.1. Modeling framework of bridge scenes

The application of 3D visualization technology provides a more intuitive interface for teaching (Chen et al., 2013). Bridge scenes in 3D are the basis for immersive teaching and learning, so how to quickly and automatically generate the bridge scene is a key problem that needs to be solved. Therefore, we propose an automatic generation method of bridge scenes with spatial constraints, the process is shown in Fig. 4. By designing spatial constraint rules to guide and constrain the primitive model of bridges, to achieve the automatic matching and combination of primitive models in the modeling process of bridge scenes in 3D.

3.3.2. Spatial constraint rules

Spatial constraint rules include spatial location, spatial topology, and spatial scale. Spatial location rules include the position alignment and orientation consistency of bridge primitive models in geospatial space. Spatial topology rules enable the spatial layout of bridge scenes correctly represented. Spatial scale rules ensure seamless integration between bridge primitive models.

(1) Spatial location rules

Spatial location rules include spatial position and orientation, as shown in Fig. 5. The spatial position is used to achieve the positioning of bridge primitive models in geospatial space, and the three types of orientation are yaw, pitch, and roll, which represent rotation about the Z, Y, and X axes respectively. Unlike the railway scene modeling, bridges do not involve superelevation information (Difference in height between the inside and outside of the model on the line), so we do not consider the roll parameter of bridge primitive models in this article.

① Pitch parameter

As shown in the bottom right corner of Fig. 5, the pitch parameter reflects the alignment of the bridge primitive models in the XZ plane.

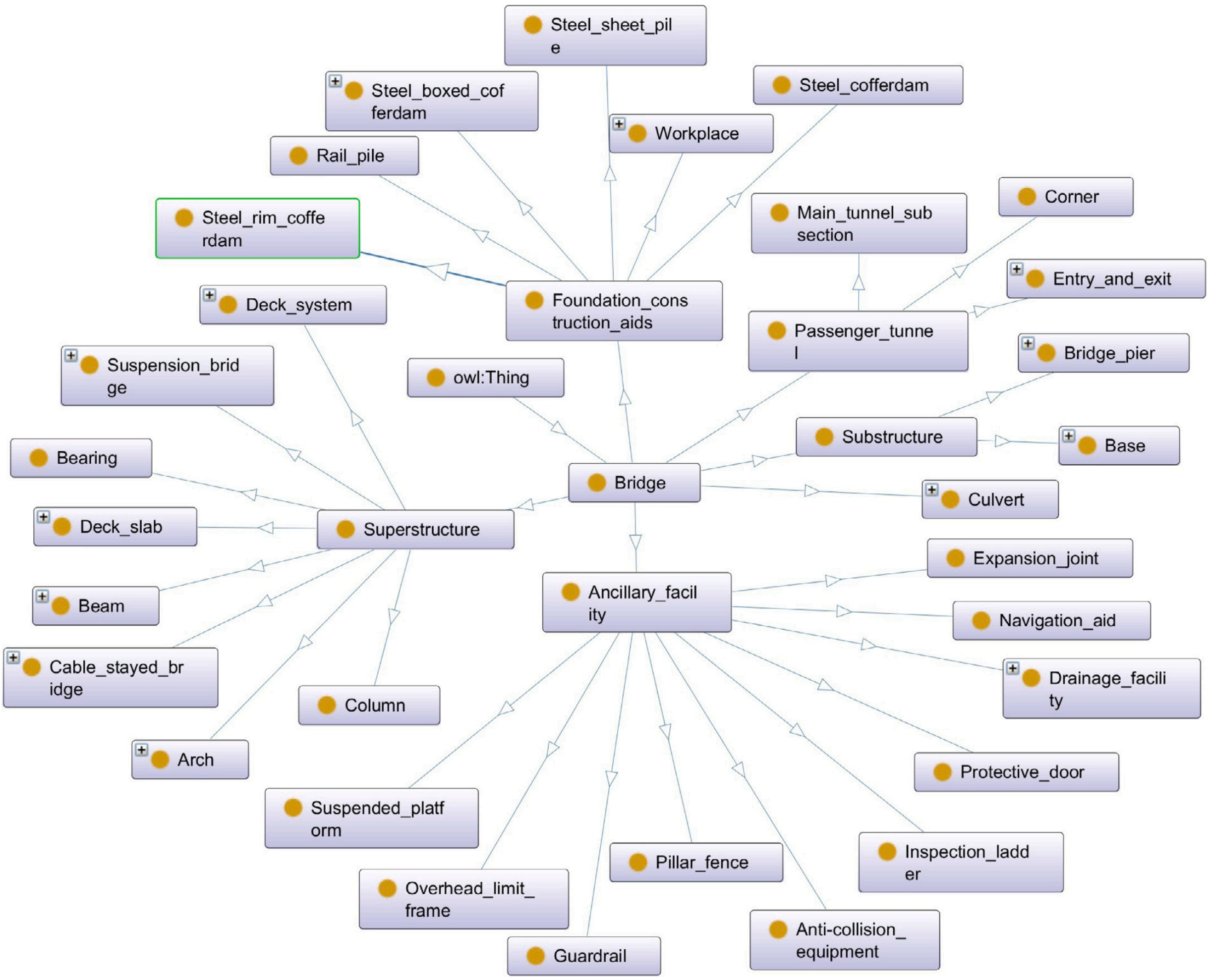


Fig. 3. Parts of ontology-based semantic hierarchy of bridges.

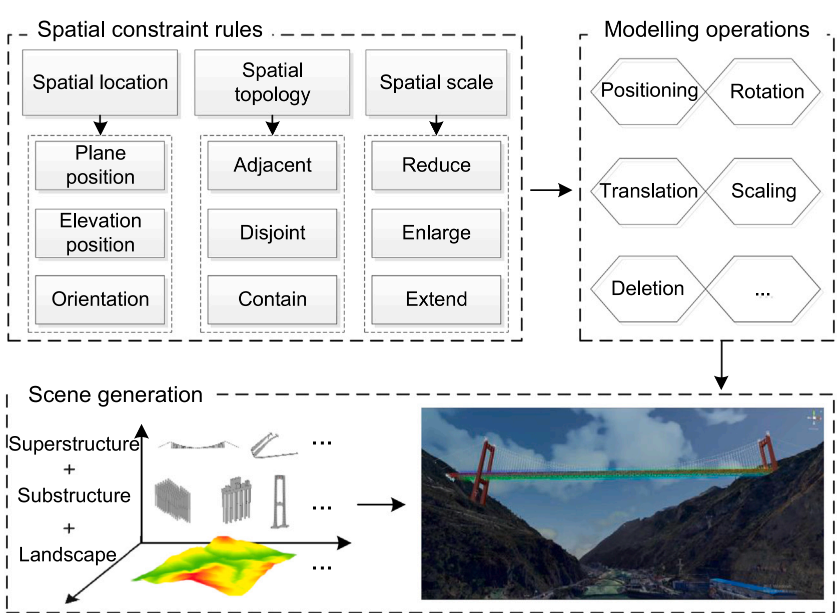


Fig. 4. Modeling framework of bridge scenes with spatial constraint rules.

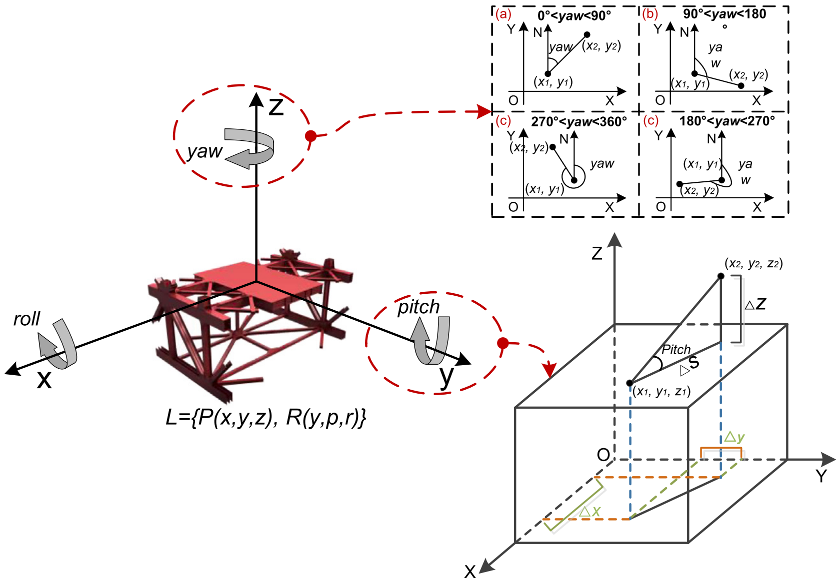


Fig. 5. Spatial position and orientation.

We assume that the first model is $M(x_1, y_1, z_1)$ and the second one is $N(x_2, y_2, z_2)$. Eq. (1) can be used to calculate the pitch parameter P.

$$P = \arctan \frac{z_2 - z_1}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \tag{1}$$

② Yaw parameter

The yaw parameter reflects the alignment of the bridge primitive models in the XY plane. We project the 3D coordinates of primitive models onto the XY plane and then use Eq. (2) for the yaw parameter calculation.

$$Y = \begin{cases} \arctan \left| \frac{x_2 - x_1}{y_2 - y_1} \right| & (x_2 > x_1, y_2 > y_1) \\ 180^\circ - \arctan \left| \frac{x_2 - x_1}{y_2 - y_1} \right| & (x_2 > x_1, y_2 < y_1) \\ 180^\circ + \arctan \left| \frac{x_2 - x_1}{y_2 - y_1} \right| & (x_2 < x_1, y_2 < y_1) \\ 360^\circ - \arctan \left| \frac{x_2 - x_1}{y_2 - y_1} \right| & (x_2 < x_1, y_2 > y_1) \\ 90^\circ & (x_2 > x_1, y_2 = y_1) \\ 270^\circ & (x_2 < x_1, y_2 = y_1) \end{cases} \tag{2}$$

In this equation, Y indicates the yaw parameter of bridge primitive models, $M(x_1, y_1)$ and $N(x_2, y_2)$ indicate the coordinates of the two models on a 2D plane respectively.

(2) Spatial topology rules

Spatial topology rules are used to describe connectivity, regionality, and adjacency between primitive models. In this article, we consider three spatial topology rules, namely adjacent, disjoint, and contain. Adjacent indicates that primitive models M and N are adjacent to each other, e.g., Stiffening beams. Disjoint indicates that primitive models M and N are disjoint, which means that there is no common intersection between the two models, e.g., anchorages. Contain indicates that model M is inside model N, e.g., tower column. In Fig. 6, we give examples of these three relationships between the primitive models for readers.

(3) Spatial scale rules

When combining different types of bridge primitive models, we scale the size of the intersecting models to achieve the best spatial scale, to ensure the seamless integration between the primitive models. For example, when the bridge deck meets the roadbed, we scale the geometrical size of the last stiffening beam model to avoid the intersection or separation between the bridge model and the roadbed model.

3.3.3. Automatic generation of bridge scenes in 3D

The bridge ontology stores the id, position, size, and other relevant information of the primitive models, the spatial constraint rules restrict the logical judgment and coupling operation of the primitive models in the process of combination. First, the ontology structure is used to guide the sequence of each scene object combination. Second, the location information of each primitive model is resolved and the corresponding model at each point is instantiated. Finally, the spatial constraint rules constrain and adjust the primitive model position, size, and orientation parameters, to realize the automatic generation of bridges from a conceptual level to realistic 3D scenes, as shown in Fig. 7.

3.4. Immersive interaction to improve teaching communication

Immersive interaction can increase students' participation and interactivity with the teacher, thus improving the efficiency of teaching communication. Zhu and Fu (2017) stated that people's demand for cognition is from viewing, to analyzing, and to the acquisition of spatial knowledge. In this context, we design immersive interaction modes of bridge scenes from three levels: view-only interaction, analytical interaction, and explorative interaction.

In view-only interaction, the user can automatically navigate the bridge scene in multiple views along a fixed route without any additional operations. Analytical interaction detects the collision with bridge primitive models via handle rays and then matches the bridge model id with the database to query for information, such as name, position, size, description, etc. Explorative interaction allows the user to assemble bridge components in a virtual scene via the VR handle. We pick up the bridge model through the VR handle and release the gravity of the models, then the bridge model is accurately assembled by matching the position of the target.

4. Data description and prototype system implementation

As mentioned before, we intend to use immersive bridge scenes in teaching to enhance students' understanding of the bridge construction process. In this article, a mega suspension bridge under construction was selected as a case for experiment analysis. The digital surface model (DSM) with a spatial resolution of 0.5 m obtained by drones was used to create the 3D virtual landscape. The bridge primitive models

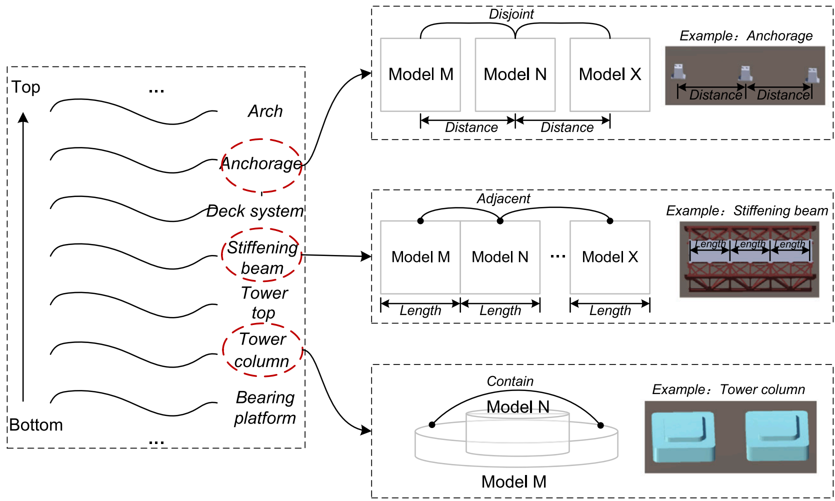


Fig. 6. Topological relationships between bridge primitive models.

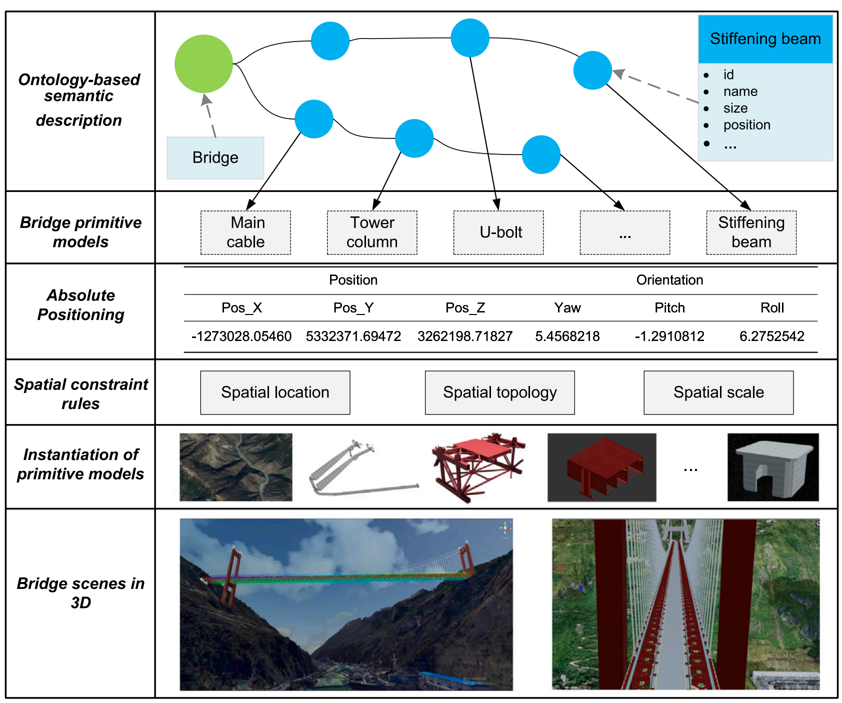


Fig. 7. Automatic generation of bridge scenes in 3D.

are based on the geometric and attribute parameters in the CAD design drawings, and modeled by using Bentley MicroStation, the material, appearance, and size were given as well, as shown in Fig. 8. To achieve the integration of bridge models and geographic scenes, we transformed the projection of bridge models from the local coordinate system to the global coordinate system and coded for each model.

Based on IVR and 3D visualization technology, we developed a prototype system for immersive bridge teaching. Fig. 9 shows the interface of the system. The 3D rendering engine used Unity 3D v2020.3.8, Steam VR, and VRTK were used to drive and configure the Oculus quest 2 VR device. The prototype system was run and tested on Lenovo Legion R9000P2021H. The processor was an AMD Ryzen 7 5800H with Radeon Graphics, with 16 GB memory, and NVIDIA GeForce RTX 3060 Laptop GPU with 6 GB.

5. Experiment analysis

5.1. Generation of bridge scenes in 3D

The generation process of bridge scenes in 3D mainly includes three parts, as shown in Fig. 10. First, we constructed and encoded a top-down directory tree of bridge primitive models based on ontology. Each primitive model has data properties and object properties, where the data properties store the id, position, orientation, and attributes of the model, and the object properties have the relationships of the models

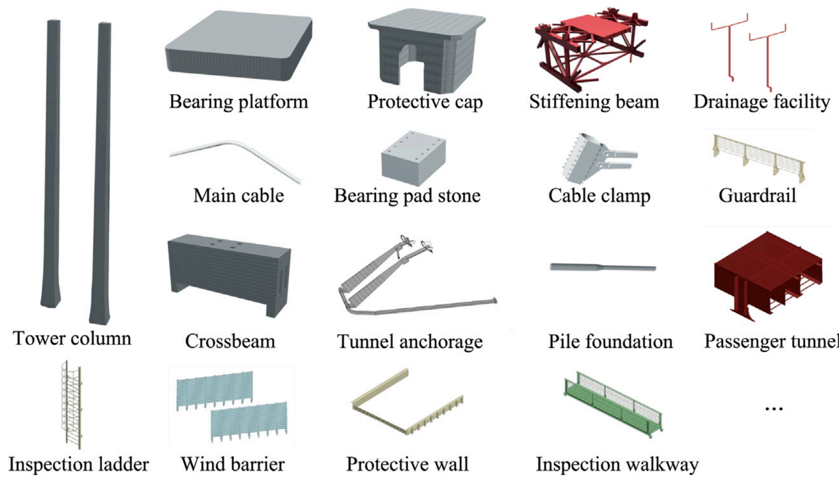


Fig. 8. Parts of Bridge primitive models.

Fig. 9. The interface of the IVR system for bridge teaching.

(e.g., Is-a, HasPart). Second, each id has a corresponding instanced bridge primitive model. For example, the pile foundation model was loaded through the "id = Pile foundation", and the model was reproduced according to the preset number, as shown in the pile foundation part (①) of Fig. 10. Lastly, the bridge models were positioned in the geographic scene based on the coordinates and orientation parameters (e.g., pitch, yaw.), and the spatial topology and scale rules adjusted the layout of bridge models in the geographic scene. In summary, the above-mentioned generation process of bridge scenes was guided by the ontology-based semantic hierarchy and constrained by the spatial constraint rules, which reduced the difficulty and complexity of bridge scene construction and further improved the automation of bridge scene generation to a certain extent.

5.2. Immersive interaction

5.2.1. Background learning and scene roaming

The immersive scene allows students to overview the bridge construction project, they can access bridge information (e.g., main tower, steel beam) and view construction content, construction schedule, and construction difficulties, as shown in Fig. 11(a). In the roam experience part, the students can easily observe 3D bridge models and the landscape from various perspectives, to feel the difficulties and spectacular of bridge construction in such a complex mountainous area in an immersive way, as shown in Fig. 11(b). The teachers can also teach bridge knowledge to students more easily, rather than praying for poorly written texts or oral descriptions to resonate with them.

5.2.2. Construction process simulation and information query

The construction process simulation was based on a timeline that dynamically presents the virtual construction process of the bridge, allowing students to intuitively and truly understand the bridge structure and the whole process of "growing" from substructure to superstructure, as shown in Fig. 12(a), and more detailed experiment results of construction process simulation was presented in a video that was available on Youtube[2] and Bilibili[3]. In the interactive query part, the students can use the handle ray to query the information of each primitive model. For example, they can get information about the stiffening beam, such as size, id, and construction status, as shown in Fig. 12(b).

5.2.3. Interactive virtual assembly

Interactivity was believed to be the most fundamental aspect of effective learning, and the practical and interactive part had been made a priority (Kamińska et al., 2019; Martirosov & Kopecek, 2017; Udeozor et al., 2021). The left handle was tied to the bridge model library, the students can use the right handle to grab and assemble bridge components, to perceive the process of bridge components assembly and surrounding environments through 3D objects, rather than viewing traditional drawings, as shown in Fig. 13.

To make it easier for readers to understand the interaction of the IVR-based bridge teaching system, we have recorded the whole

[2] https://www.youtube.com/watch?v=zwj451U7sn4
[3] https://www.bilibili.com/video/BV13B4y1172R/

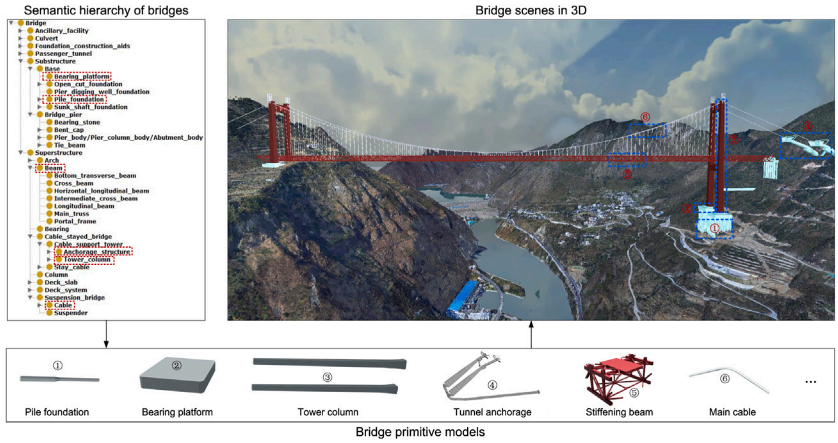
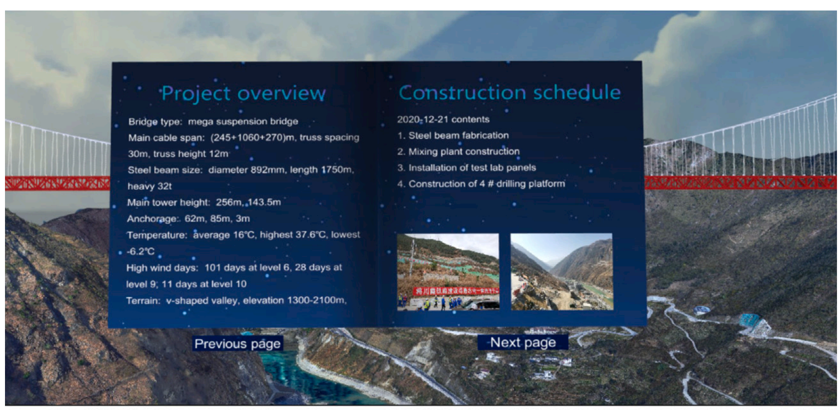


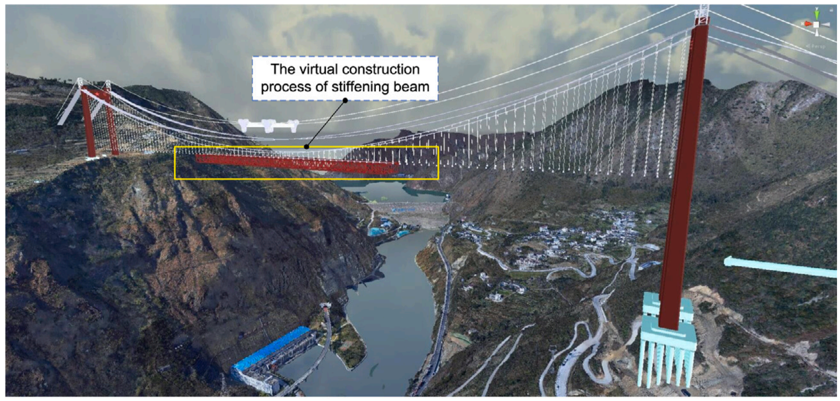
Fig. 10. The IVR scene of the bridge in 3D.



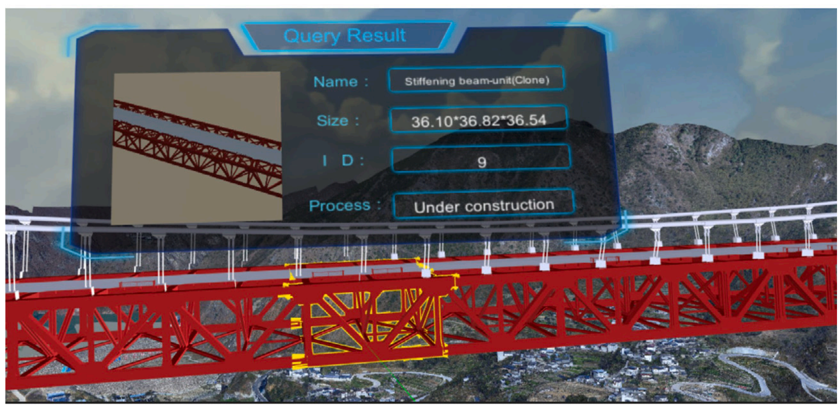
(a) Background learning.

(b) Scene roaming.

Fig. 11. Representation of the background information and scene roaming.



(a) The virtual construction process of stiffening beam.



(b) The information on stiffening beam-unit.

Fig. 12. The construction process simulation and information query.

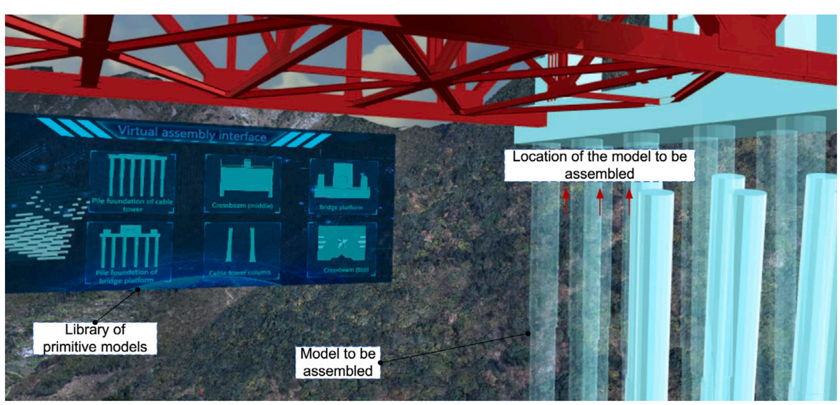


Fig. 13. The interactive virtual assembly of pile foundation.

process of 3D representation and immersive interaction into a video and uploaded it to YouTube[4] and Bilibili[5].

5.3. Teaching communication evaluation

5.3.1. Design of the evaluation procedure

Teaching communication evaluation is carried out according to the procedure shown in Fig. 14. The test environment is the bridge scene in 3D mentioned before, the high-performance computer is used

[4] https://www.youtube.com/watch?v=c5gnH7xithw
[5] https://www.bilibili.com/video/BV1Ju411C7xM/

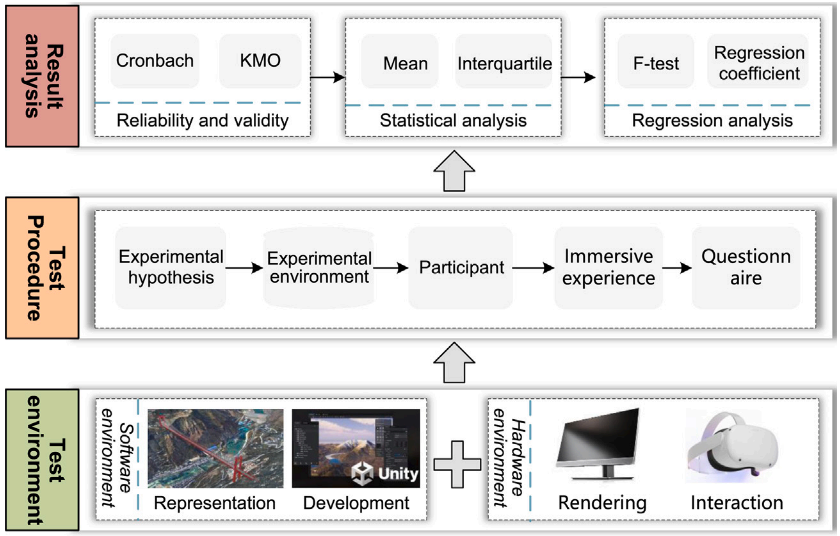


Fig. 14. Design of the evaluation procedure.

Table 2
List of preset questions.

Terms	Description of questions
Interaction	① By using this system, I can easily observe 3D bridge scenes from various perspectives ② By using this system, I can easily query the corresponding information of bridge primitive models ③ By using this system, I can easily grip bridge primitive models and complete reassembly ④ This system can enhance teacher–student interaction
Immersion	① The IVR bridge teaching system creates a realistic-looking learning environment ② I pay more attention when using the IVR bridge teaching system ③ This immersion brings me a spectacular that is difficult to express in textbooks or slides
Imagination	① The system gives me more engagement to help me understand bridge components ② I feel the system improves my understanding through the imagination of bridge construction ③ The system makes me understand the enormous difficulty of building bridges in complex mountainous areas
Interest and motivation	① It is impressed using the IVR bridge teaching system for learning purposes ② The system can enhance my learning interest ③ The system can enhance my learning motivation ④ The system can enhance my practical ability
Satisfaction	① Are you satisfied with the IVR bridge teaching system

for the efficient rendering of bridge scenes in 3D, and the VR device is used for participants to develop immersive experiences from a first-person perspective. The test follows the process of experiment hypothesis, experiment environment, participants, immersion experience, and questionnaire.

We analyze the participants' feedback from three aspects. Cronbach's α, which is the most commonly used reliability coefficient, is used to reflect the consistency and reliability of the questionnaire results. Kaiser–Meyer–Olkin (KMO) and Bartlett tests are used to evaluate the structural validity of the questionnaire (Ao et al., 2020). The indicators such as the mean, interquartile and standard deviation are used to analyze the participants' feedback. The regression analysis (Yang et al., 2022, 2023) will be performed to check the effects of interaction, immersion, imagination, interest, and ability.

5.3.2. Implementation process

(1) Experiment hypothesis

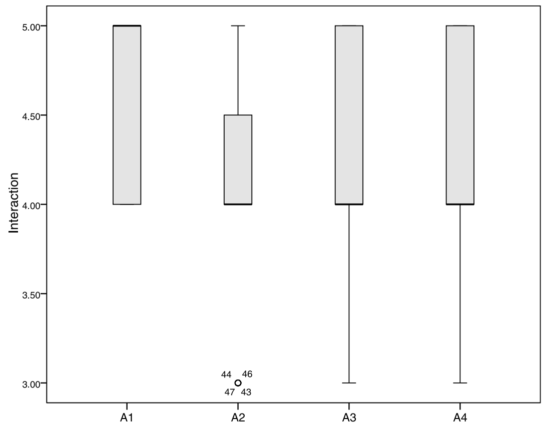
The three key factors of applying IVR to bridge teaching are interaction, immersion, and imagination. We aim to improve students' interest and motivation in bridge courses through the interplay of these three factors. Therefore, we first verify whether immersive bridge teaching meets the requirements of the above factors. Inspired by Huang et al. (2010), we make the following hypothesis: as interaction, immersion, and imagination increase, the student's interest and motivation in bridge course increase.

(2) Participants

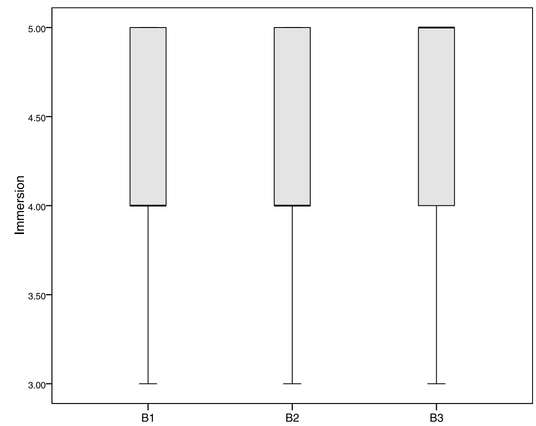
We recruited 44 students (aged between 23 and 28 years old) from the digital bridge construction course to participate in this experiment, 24 males and 20 females, with a background in bridge engineering and geographic information system (GIS). Most of the participants had map reading experience and only 3 participants had previous experience using a head-mounted display (HMD) VR device.

(3) Test

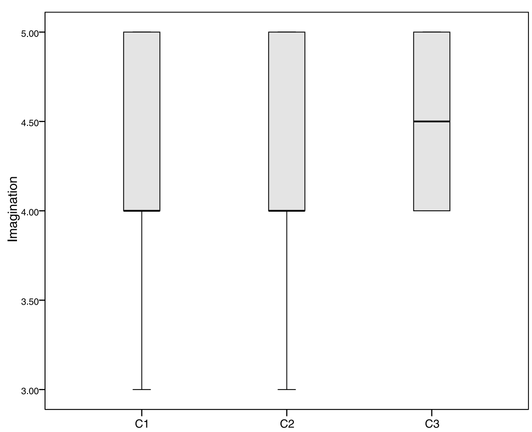
The above-mentioned 44 participants were invited to experience the IVR bridge teaching system and then they were asked to complete the questionnaire shown in Table 2. The questionnaire has 17 questions that are to be evaluated using a 5-point Likert scale (with 5 being the highest rating, corresponding to "1: Not at all", "2: Not much", "3: Normal", "4: Somewhat", "5: Very"), Some questions were based on the work of Huang et al. (2010). One point we would like to note is that



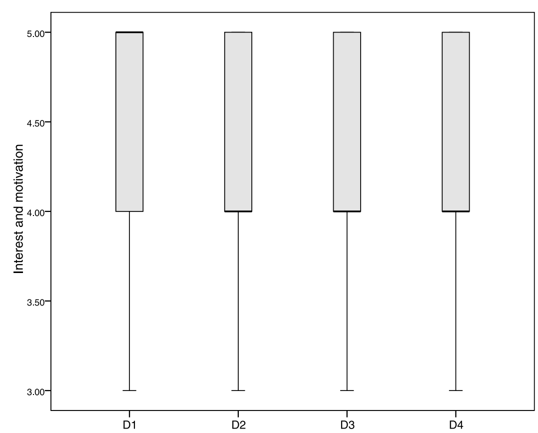
(a) Interaction.



(b) Immersion.



(c) Imagination.



(d) Interest and motivation.

Fig. 15. The statistical analysis of the participants' feedback.

Table 3
Reliability and validity of test results.

Cronbach's α for reliability	KMO for validity	Bartlett's test for significance		
		Approx. chi-square	df	Sig
0.816	0.743	275.841	91	0.000** < 0.01

the IVR bridge teaching system and the questionnaire are in Chinese as all participants are Chinese students, but we have translated the system and questionnaire into English for the reader to better understand the work of this article.

5.3.3. Results analysis

(1) Reliability and validity analysis

As shown in Table 3, Cronbach's α value for reliability was determined to be 0.816, which was greater than 0.8. The KMO value for validity was 0.743 and Bartlett's test results reached an extremely significant level. All of the above statistics indicated the questionnaire results were valid and reliable, which can be further analyzed.

(2) Statistical analysis

As shown in Table 4, the mean value for each question was higher than 4.0, which indicated that all participants believed that the IVR bridge teaching system had a positive effect on improving the interactivity and engagement of teaching. In particular, the mean value of the first question in the interaction item and the third question in imagination were higher than 4.5, which highlighted the advantages of the IVR bridge teaching system in terms of intuitive visualization compared with textbooks and slides.

Fig. 15 shows the statistical analysis of the participant's feedback. In terms of the interaction, the MD value of A1 was 5.0, the IQR was distributed in the interval (4.0, 5.0), the MD value of A2 was 4.0, the IQR was distributed in the interval (4.0, 4.5), the MD values of A3 and A4 both were 4.0, the IQRs were also distributed in the interval (4.0, 5.0). In summary, most of the participants believe that the system could support multi-angle viewing, virtual assembly, and teacher–student interaction, but there is room for improvement in the handle-based information query.

In terms of the immersion, the MD values of B1 and B2 both were 4.0, the IQRs were also distributed in the interval (4.0, 5.0), the MD value of B3 was 5.0, and the IQR was distributed in the interval (4.0, 4.5). These results indicated that immersion can give the students a spectacle in the teaching that textbooks cannot provide and make them more focused.

In terms of the imagination, the MD values of C1 and C2 both were 4.0, the IQRs were also distributed in the interval (4.0, 5.0), the MD value of C3 was 4.5, and the IQR was distributed in the interval (4.0,

Table 4
The means and standard deviations of each question.

Terms	Description of questions	M	S.D.
Interaction	① By using this system, I can easily observe 3D bridge scenes from various perspectives	4.54	0.50
	② By using this system, I can easily query the corresponding information of bridge primitive models	4.06	0.67
	③ By using this system, I can easily grip bridge primitive models and complete reassembly	4.15	0.74
	④ This system can enhance teacher–student interaction	4.29	0.62
Immersion	① The IVR bridge teaching system creates a realistic-looking learning environment	4.35	0.60
	② I pay more attention when using the IVR bridge teaching system	4.33	0.63
	③ This immersion brings me a spectacular that is difficult to express in textbooks or slides	4.42	0.77
Imagination	① The system gives me more engagement to help me understand bridge components	4.29	0.65
	② I feel the system improves my understanding through the imagination of bridge construction	4.17	0.63
	③ The system makes me understand the enormous difficulty of building bridges in complex mountainous areas	4.50	0.51
Interest and motivation	① It is impressed using the IVR bridge teaching system for learning purposes	4.42	0.71
	② The system can enhance my learning interest	4.25	0.67
	③ The system can enhance my learning motivation	4.27	0.61
	④ The system can enhance my practical ability	4.29	0.65
Satisfaction	① Are you satisfied with the IVR bridge teaching system	4.33	0.60

Table 5
Regression analysis results.

H	Dependent variable	Independent variables	β	R^2	P	F
Hypothesis	Interest and motivation	Interaction	0.222	0.086	0.671	F(3, 44) = 29.929 p = 0.000
		Immersion	0.401	0.000**		
		Imagination	0.218	0.050*		

5.0). The combination of 3D terrain and bridge models, coupled with immersion, stimulates the students' imagination through an immersive experience that is not available in traditional 3D visualizations or slideshows.

In terms of the Interest and motivation, the MD value of D1 was 5.0, the IQR was distributed in the interval (4.0, 5.0), the MD values of D1, D2, and D3 both were 4.0, the IQRs were also distributed in the interval (4.0, 5.0). The statistics showed that such an IVR bridge teaching system enhances students' learning interests and practical skills. The percentages of participants who were very satisfied, satisfied and normal were 39.6%, 54.2%, and 6.2% respectively.

(3) Regression analysis

For investigating hypothesis H, the regression analysis was performed to check the effects of immersion, interaction, and imagination on interest and motivation of using IVR, The statistical results are shown in Table 5.

The results showed that the model passed the F-test ($F(3, 44) = 29.929$, $R^2 = 0.671$, $p = 0.000$), which indicated that at least one of the independent variables influences the dependent variable. The regression coefficient value β for the interaction factor was 0.222 ($t = 1.754$, $p = 0.086 > 0.05$), which meant the interaction factor did not influence interest and motivation. The immersion and imagination factors both were predictors and the immersion factor ($\beta = 0.401$, $t = 4.436$, $p = 0.000^{**} < 0.01$) had more prediction and positive effects than the imagination factor ($\beta = 0.218$, $t = 2.018$, $p = 0.050^{*} < 0.05$).

6. Discussion

In this article, we have made some attempts to introduce IVR technology into bridge teaching. Here, we would like to underline the strengths and limitations of our work, we also propose some suggestions and hope the readers to apply further creative thinking to address the challenges raised here.

6.1. Strengths

Wang et al. (2018) stated that one of the future challenges for VR-related education in construction engineering is the rapid generation of 3D scenes. Following this idea, we proposed an automatic generation method of bridge scenes with spatial constraints, which addressed the difficulty of 3D scene generation in virtual teaching. This is a significant practical contribution of this article to promote the IVR application in construction engineering education, enabling educators to shift the focus of IVR-based teaching from scene modeling to pedagogy design. Specifically, the practical contribution has two aspects. First, an ontology-based semantic hierarchy of bridges was constructed, which could enhance the student's overall understanding of bridge composition and be used to guide the automatic generation of bridge scenes. Second, the spatial constraint rules were designed to achieve the automatic combination of primitive models in the generation process of bridge scenes, which has improved the automation of bridge scene generation to a certain extent.

We innovatively introduced IVR technology into the bridge discipline intending to improve student engagement and teaching communication. Checa et al. (2021) have argued that the strong sense of presence and immersion created by IVR could provide higher satisfaction and learning rates than conventional teaching. The same conclusion was reached in our case, the percentage of participants who were satisfied with IVR-based bridge teaching was more than 90%, indicating that we can still be optimistic about the value of IVR applications in education. Furthermore, the visual representation of IVR allows more degrees of freedom (DoFs) to be integrated (Wang et al., 2018), thus the students can perceive different bridge construction spaces from an all-round perspective, rather than viewing textbook or traditional CAD drawings, such a vivid and immersive experience induces more interest and motivation in the students and increases the effectiveness of the teaching communication. The results of our regression analysis also confirm this above. Among the 3I characteristics of IVR, both immersion and imagination are predictors and positively contribute to learning interest and motivation, and the immersion factor has more prediction and positive effects.

In addition, Martirosov and Kopecek (2017) and Udeozor et al. (2021) stated that interactivity is believed to be the most fundamental aspect of effective learning, and that immersive interaction can indeed increase interactivity in bridge teaching. However, from the authors' perspective, immersive interaction is a double-edged sword. On the one hand, it allows the use of a handler to grip and pull the bridge primitive objects to complete the assembly, which indeed promotes practical and problem-solving skills in students that are not possible with traditional interaction (Araiza-Alba et al., 2021). On the other hand, compared with the keyboard and mouse, handle-based interaction is a bit difficult for students who have never used VR, which could affect their motivation during practice. Checa and Bustillo (2020) also highlighted that user interactivity with the VR environment is critical to achieving high learning rates. Hopefully, readers should also be aware of this point when designing IVR interactions. Therefore, it is necessary to design a user-friendly interaction to make the most of IVR in teaching and learning, which is one of the priorities for future work.

6.2. Limitations

Taking bridge teaching as a case, we introduced IVR as a tool to improve student engagement and teaching communication, but we did not carry out a rigorous pedagogy design that is suitable for IVR teaching in our case. As Huang (2002) and Huang et al. (2010) argued, all worthwhile educational innovations must begin with solid pedagogy. Educators who apply the new IVR technology to teaching, need to consider carefully how a pedagogy or a learning theory may influence the learning process. We are considering designing an IVR-based pedagogy that shifts teacher-centered passive teaching to student-centered active learning.

Due to the specialized and specific nature of bridge teaching, we recruited only 44 participants to complete the experiment of teaching communication evaluation, the whole experiment was finished in about one week. However, the promotion of new technology for teaching communication should be a long-term process, the small sample size and short duration of the experiment in our case will affect the generalizability of the proposed methodology and results to a certain extent.

6.3. Suggestions

The balance between immersion, representation, and fidelity. Realistic representation and a high-fidelity virtual environment can increase the attraction of bridge teaching, but unnecessary fine details may distract students' attention and lead to a higher cognitive load. In addition, highly realistic environments can influence rendering efficiency, thereby reducing immersion and inducing dizziness. Therefore, it is important to find the right balance between quality of immersion, representation, and fidelity when designing IVR teaching pedagogy (Udeozor et al., 2021). The combination of some new technologies (e.g., eye tracking, brainwave sensing) with IVR can record information such as students' areas of interest and gaze direction, which has great potential in quantifying students' spatial cognitive abilities and further refining immersive teaching pedagogy design.

Systematic teaching practice based on IVR. Numerous studies have shown an extremely high level of interest in the use of IVR for teaching and learning, which shows IVR could be a promising learning tool for higher education. Although some researchers revealed the future directions for VR-related education, the maturity of using IVR in teaching and learning is still questionable, most research is still in an experimental state without large-scale applications in terms of performance and usability, these facts can hinder the rapid adoption of immersive VR technologies into teaching regularly (Radianti et al., 2020; Wang et al., 2018). Therefore, more practical IVR teaching tools should be developed for the needs of teachers and students, we know that these tasks will be difficult and tedious to execute, but they are also an essential step towards systematic teaching practice and large-scale application based on IVR technology.

7. Conclusion

IVR produces a rich and high-fidelity environment that provides a fully immersive and interactive experience for use in teaching (Ferguson et al., 2020). In this article, we introduced IVR as a tool to improve bridge teaching communication, and some key technologies were discussed in detail. We first created the ontology-based semantic hierarchy of bridges. Then, the spatial constraint rules were designed to guide and constrain the automatic generation of bridge scenes in 3D, we also designed three immersive interaction modes to improve teaching communication. Finally, we selected a mega suspension bridge under construction as a case for experiment analysis, and the positive contribution of IVR to teaching was verified in a digital bridge construction course. In summary, we aim to use IVR in bridge teaching to increase student engagement, motivation, and interest, thereby enhancing teacher–student communication and student problem-solving skills.

In the future, we have two main tasks that need to be addressed as a priority, besides the suggestions proposed in the discussion section. First, a pedagogy applied to IVR-based bridge teaching should be rigorously designed. Second, exploring a more efficient immersive interaction method for IVR-based bridge teaching.

Funding

This paper was supported by the National Natural Science Foundation of China (Grant Nos. U2034202, 42201446 and 42271424), the Sino-German (CSC-DAAD) Postdoc Scholarship Program (Grant No. 2021(57575640).

CRediT authorship contribution statement

Weilian Li: Methodology, Software, Experiment, Writing. **Jun Zhu:** Conceptualization, Reviewing, Editing. **Pei Dang:** Software, Experiment. **Jianlin Wu:** Software, Experiment. **Jinbin Zhang:** Software, Reviewing. **Lin Fu:** Data collection. **Qing Zhu:** Reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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