



# An augmented reality-based multimedia environment for experimental education

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## Abstract

Over the last few years, there has been a growing interest in augmented reality (AR) technology for education. However, current AR education applications are often used as a new type of knowledge display platform, and they cannot fully participate in educational activities to improve educational results. To enable AR technology to participate in educational activities more effectively, according to learning-by-doing theory, we explore the form of a future experimental course and propose a new AR-based multimedia environment for experimental education. The framework of the multimedia environment consists of three components: the AR experiment authoring tool, the AR experiment application, and the management application. In this AR-based multimedia environment, teachers can independently create AR experiments using the what you see is what you get (WYSIWYG) editing method. Students can manipulate the AR-based experimental object to complete the experiment in class. Moreover, teachers can observe students' experimental behaviour, obtain evaluations in real time, and even guide students remotely. We also present an application case of a chemistry experiment and obtain results of the usability test, demonstrating improvements in AR technology participation in educational activities.

**Keywords** Augmented reality · Experiential learning · Experimental education · Multimedia environment

## 1 Introduction

Augmented reality (AR) is a multimedia technology in which 3D virtual objects are integrated into a 3D realistic environment in real time [3, 17]. Recently, researchers have given

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the concept of AR a broad meaning. AR systems have also been designed and implemented by new technologies, such as various high immersion technologies, intelligent mobile technologies, and new human-computer interaction technologies [12, 15]. With the development of AR technology, researchers also noticed that AR enables seamless connection of the digital and physical domains, offering excellent potential in the educational field [20, 23]. Educational activities are learner-centred activities [5, 10]. AR technology has already begun to show promise in helping students to learn more effectively and to increase knowledge retention relative to traditional methods of learning [5].

The application value of AR in education requires relying on the innovations of not only new AR technology but also educational theory and technology. However, developers of AR education applications are largely educators pursuing ad hoc creation, educators with little understanding of the technology or developers with little understanding of education [2, 7, 10]. Current AR education applications are often used as a new type of knowledge display platform, and they cannot fully participate in educational activities to improve education results. Furthermore, there are few multimedia tools that provide educators with assistance in carrying out teaching activities [6, 14, 15, 21].

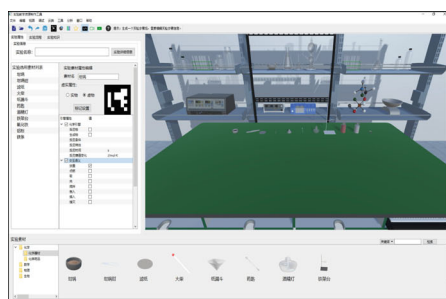
Middle school educators believe that the classroom is the first place for education and teaching activities. The classroom is a simple environment with few external interfering factors and a strong overall learning atmosphere [5]. Moreover, classroom teaching is generally used for large-scale university education. In the meantime, we notice that students are more interested in STEM experiment courses. AR environments offer better opportunities for learning by doing through physical movements in rich sensory spatial contexts [9, 11, 18, 23]. The main advantages of AR applications in the education domain are the activity of learners, cost, and safety [2, 13, 15]. With AR technology, students can manipulate the virtual and real equipment and materials in the experiment classroom, attempt experiments that are dangerous in the traditional classroom, and perform experiments that cannot be realized because of financial conditions.

Based on the fact that AR technology cannot effectively participate in educational activities, we proposed a multimedia form of AR technology and educational technology. With reference to the advantages of AR technology in STEM experimental education, we built an AR-based multimedia environment. The AR-based multimedia environment consists of the following three parts:

- 1) AR experiment authoring tool;
- 2) AR experiment application;
- 3) Management application.

In the AR-based multimedia environment (Fig. 1) for experimental education, teachers can use the AR experiment authoring tool to create AR experiments. Using the AR experiment application, students can manipulate the experimental equipment and materials via two possible methods of interaction and finally complete the AR experiment. The reaction between equipment and materials happens between real objects and virtual objects or between virtual objects and other virtual objects, while in class, teachers can use the laboratory management tool to guide the manipulation behaviour of students and evaluate the performance of students. The AR-based multimedia environment can support learning of multiple students at the same time. The hardware of the multimedia environment is low-cost and straightforward. Moreover, the software of the AR-based multimedia environment is easy to use.

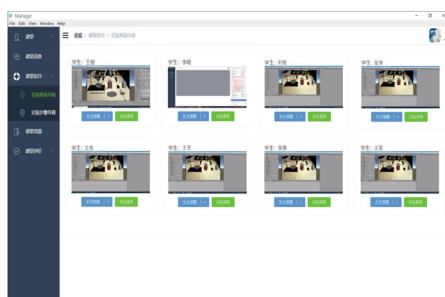
The rest of the paper is organized as follows. Section 2 reviews some related work. Details of the multimedia environment are described in Section 3. The case study and



(a) AR experiment authoring tool



(b) AR experiment application



(c) Management application

**Fig. 1** AR-based multimedia applications of the environment

discussion of results are presented in Section 4. We conclude the article and point to the main directions of future research in Section 5.

## 2 Related work

Augmented reality (AR) is a 3D technology that enhances the user's sensory perception of the real world with a contextual layer of information [2]. In recent years, AR has become a popular technology with an important focus on research education.

There are several current AR applications for education. The ARIES system [22] is an e-learning system that enables teachers to actively participate in the authoring process of interactive educational scenarios. It has been built as an implementation of the Augmented Reality Environment Modeling (AREM) approach. The AREM approach enables teachers to design and create learning scenes for augmented reality environments. There is another AR-based authoring tool [16] for education applications, where applications authorized by this tool interact with the user in order to increase the learner's interest and reflect various desires of a dynamic environment. Users can fine-tune the AR content in a very intuitive manner. Recently, another low-cost virtual studio called ARStudio [1] has been presented. Similar to professional virtual studios, ARStudio allows content refinements to be carried out quickly; however, ARStudio is not aimed at education. It would be hard for educators to author an AR experiment.

Moreover, there is much AR content for education. The DiedricAR [8] application allows students to learn in an autonomous way by using their own mobile devices. DiedricAR has potential benefits for students' spatial ability, the relationship between application design

and user experience. There is another application [4] that uses various training kits available in laboratories with operating manuals and teachers to assist the students. To evaluate the attitude of learners toward learning in ARIES [22] augmented reality environments, a questionnaire was designed based on TAM enhanced with perceived enjoyment and interface style constructs. The BumbAR [19] approach is used for composing multimedia presentations and evaluates them through a qualitative study based on the TAM. The AR content for education benefits student learning motivation, but teachers cannot participate in students' learning behaviour. In addition, an AR-based multimedia environment for educational activities is uncommon. Meta-AR-App [23] realizes collaboration, which enables students to become active promoters of the learning process.

According to the review of the previous research work, there are still disadvantages of the state-of-the-art research with respect to supporting AR technology to improve educational activities in class. The goal of the AR-based multimedia environment is to enable AR technology to better participate in educational activities. Moreover, this multimedia environment adopts the idea of learning by doing and is aimed at the domain of experimental education in middle school.

### 3 System overview and implementation

The AR-based multimedia environment for STEM experimental education consists of an AR experiment authoring tool, an AR experiment application, and the management application for the laboratory. Teachers can use the AR experiment authoring tool to design AR experiments and export a configuration file of the AR experiment. The AR experiment configuration file can be loaded and implemented by the AR experiment application. In the AR experiment application, students can manipulate experimental equipment and materials in two interactive ways following the requirements of the experiment and finally complete the AR experiment. Teachers can distribute the experiment in class, watch and guide students, and obtain evaluations of student performance using the management application. The authoring tool and the AR experiment application are developed with the support of Unity3D, Qt and OpenCV. The hardware of the AR experiment application is composed of a PC, a Leap Motion sensor, and two RGB cameras. The multimedia environment framework is shown in Fig. 2 below.

#### 3.1 AR experiment authoring tool

We developed an AR experiment authoring tool for experimental education. Considering that the users of the authoring tool are educators, this tool is a GUI-based non-programming authoring tool. Users can use this tool to design AR experiments with WYSIWG editing.

To enable middle school teachers to independently create AR experiments with teaching targets, we propose a general framework of the AR experiment authoring tool to meet the teaching needs of middle school education. The authoring tool consists of the following four parts: 1) AR attribute editing module, 2) experiment simulation engine, 3) experiment workflow engine and 4) the AR experiment configuration file.

##### 3.1.1 AR attribute editing module

The AR experiment authoring tool includes an AR attribute editing module, which is mainly revealed in the experimental equipment and material attributes. The AR engine of the AR

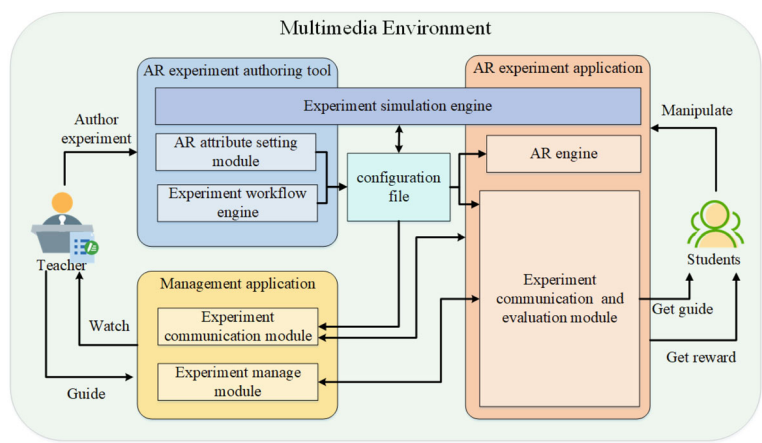


Fig. 2 AR-based multimedia environment framework

experiment application realizes the tracking registration, the interaction between virtual and real experimental equipment and materials, and multi-modal human-computer interaction channels under the condition of limited computing resources. If the experimental equipment and materials are “virtual” equipment and materials, the marker enables the “virtual” experimental equipment and materials to be displayed in the correct places. If the experimental equipment and materials are “real” equipment and materials, then the marker provides the position information of the equipment and materials, and an invisible model is built in the virtual space. While selecting markers for the experimental equipment and materials, we can set the interactive ability of the experimental equipment and materials, which is enumerated in an interactive semantic manner. Educators need only to focus on semantic-level interaction capabilities and do not need to understand the details of the interaction implementation (Fig. 3).

3.1.2 Experiment simulation engine

For middle school experiments, a real-time, open, unified and extensible simulation engine is developed. Combined with classical physical, chemical, biological and mathematical

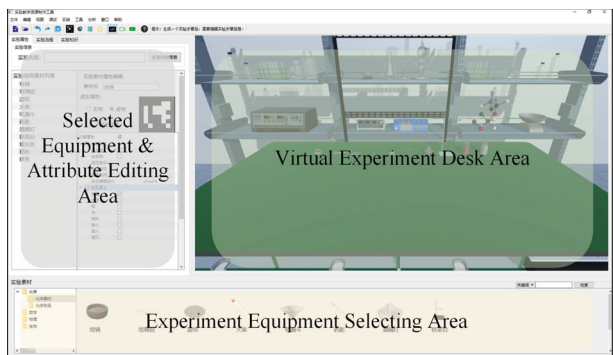


Fig. 3 The interface for equipment selection and editing

experiments, the engine supports real-time simulation of fluids (fire, smoke, water, etc.), materials (cloth, metal, etc.), and abstract concepts (geometric surface, electromagnetic field, molecular structure) and supports the generation of different experimental operation modes for simulation of different experimental results. The experiment simulation engine supports personalized exploratory experiments, and it solves the problem of how to maximize the real-time efficiency in the case of acceptable authenticity and how to realize the open experimental environment while maintaining real-time efficiency.

The experiment simulation engine provides the simulation function for middle school experiments. In the multimedia environment for experimental education, the experiment simulation engine supports physical simulation, chemical simulation, and biological simulation. The physical simulation engine supports basic simulation of mechanics and electromagnetic experiments, the chemical simulation engine realizes the simulation of chemical reactions with reactants and reaction conditions as essential variables, and the biological simulation realizes the biological observation method using time as a control method.

While editing the experiment workflow, the tool user can manipulate the experimental object in the virtual experiment desk area and edit the experiment simulation attributes of the step. Taking the chemical reaction as an example, the tool users can set the experimental reagent concentration and experimental reaction conditions. With different reactant concentrations or reaction conditions, the experiment presents different reaction results.

### 3.1.3 Experiment workflow engine

The key points of middle school experimental education are the steps and operation of the experiment. Educators design AR experiments according to the requirements of experimental education. They are asked to define the experimental steps of the experiment. By defining and dividing experimental steps, experimental simulation attributes can be edited in the experimental steps, and experimental evaluation rules can also be defined. A fixed number of serial and parallel experimental steps constitute an AR experiment. The experimental evaluation rules include various evaluation requirements such as step execution time, step execution order, and experimental simulation requirements.

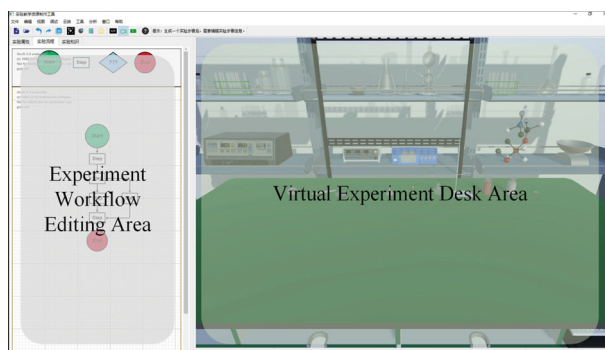
While using the AR experiment application, students can manipulate the experimental equipment and materials to trigger an experiment event. The experiment workflow engine provides the workflow information for the AR experiment application to judge and constrain the students' behaviour during the experimental steps in this multimedia environment (Fig. 4).

### 3.1.4 AR experiment configuration file

The configuration file completely describes an AR experiment, including the properties of the selected AR experiment equipment and materials, the interactive information of the AR experiment, the simulation properties, the workflow of the experiment, and the evaluation rules of the experiment.

The configuration file is exported by the authoring tool. The AR experiment application implements an AR experiment by loading an AR experiment configuration file. Other AR resources are shared between the authoring tool and the AR experiment application.

We use JSON as the descriptive language to define the description of the AR experiment, providing a standardized description. The configuration file is an educational resource that can be appropriately modularized to enable easy sharing among teachers. The resources



**Fig. 4** The interface for experiment workflow editing

should be treated as regular digital products that are produced and distributed. Table 1 gives the definition of each node tag in the configuration file description.

### 3.2 AR experiment application

The AR experiment application implements an AR experiment by loading an AR experiment configuration file. Students are the most common users in the multimedia environment. The AR application consists of 3 modules: 1) the AR engine, 2) the experiment simulation engine and 3) the experiment communication and evaluation module. With the support of the AR engine and experiment simulation engine, students can manipulate virtual or real objects to trigger a reaction or explore the laws of different subjects. Moreover, teachers are able to watch the students' behaviour through the management application, which involves transmitting information from the AR experiment application.

#### 3.2.1 AR engine

Under the condition of limited computing resources, the AR engine realizes the tracking registration, the interaction between virtual-real experiment equipment and materials, and multi-modal human-computer interaction channels.

##### 1) An framebuffer-based occlusion handling method

The AR engine establishes unified spatial coordination for the real and virtual space based on recognition and tracking markers to display the virtual experiment equipment and materials and the interaction with the real experiment and real space. To establish a realistic experimental learning environment, the occlusion between virtual and real experiment equipment and materials is realized by the framebuffer-based occlusion algorithm.

The flow of the framebuffer-based occlusion algorithm can be described as follows:

Firstly, the Marker is detected and tracked, the transformation relationship from the marker coordinate system to the camera coordinate system and the image coordinate system is determined, and the depth information of the occlusion pixel is calculated to establish the occlusion relationship between virtual and real objects.

Then, the frame is drawn by graphics buffer technology: in the color buffer, the area where the occlusion is located is filled with a certain color to generate the occlusion pixel,

**Table 1** Definition of each node tag in configuration file description

Nodes	Sub-nodes	Sub-sub-nodes
Object	Type_Id	
	Object_Id	
	Name	
	RealorVirtual	
	Marker_Id	
	Marker_Path	
	Model_Id	
	Model_Path	
	InteractionMode_List	
	SimulationProperty_List	
FlowGraph	Graph_Node	Node_Id
		Text
		Color
		Figure
	Graph_Link	From_List: vector (Node_Id*) To_List: vector (Node_Id*)
Step	Step_Id	
	Node_Id	
	Object1_Id	
	Object2_Id	
	Step_Score	
	Simulation_Behaviour	Physical_Behaviour
		Biological_Behaviour
		Chemical_Behaviour
	Evaluation_Rules	Correct_Step
		Correct_Behaviour
		Step_Time
		Guidences

and the full transparent effect of the occlusion is achieved by alpha blending, At the same time, the template of occlusion pixel is generated in the template buffer.

Finally, the virtual object is drawn into the color buffer, and the invisible part of the virtual object is culled by template buffer method, and only the visible part is sent to the graphics drawing pipeline, and fused with the video image to obtain the realistic occlusion effect.

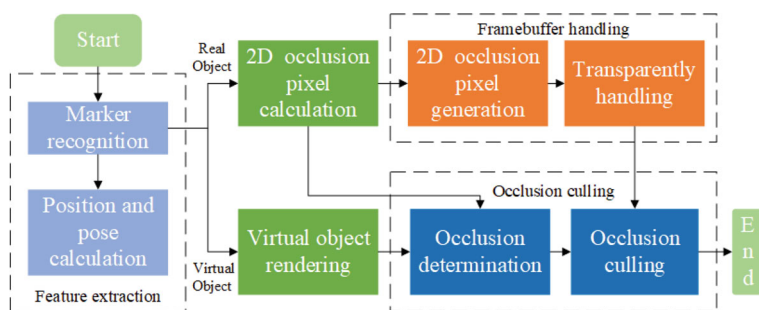
The overall flow of the algorithm is shown in Fig. 5.

Depending on the features of the real objects, the occlusion between virtual and real objects happens in the virtual space (see Fig. 6). In the models of the real objects, the occluded parts are invisible.

## 2) Multi-modal human-computer interaction channels

The embedded experiment interaction interface in the AR engine accepts multi-modal human-computer interaction channels. The interaction interface combines two interaction



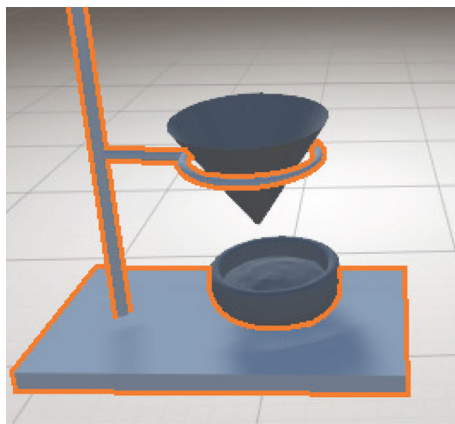


**Fig. 5** The flow of the framebuffer-based occlusion algorithm

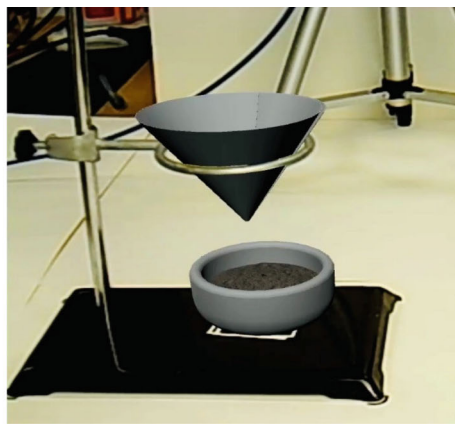
methods: marker-based interaction and gesture-based interaction (see Fig. 7). Gesture-based interaction is realized by a Leap Motion sensor. Students can manipulate the AR experiment with the support of the interaction interface.

### 3.2.2 Experiment simulation engine

With the support of the experiment simulation engine, the AR experiment application can present a mixture of virtual and realistic experimental phenomena in real time, including the more dangerous phenomena in daily life, such as explosions, and present the characterization of experimental mechanisms and elaboration of scientific principles (such as magnetic lines and molecular knots). Moreover, experimental phenomena such as explosions, smoke and other special effects are supported by advanced theory and technology. Through the simulation engine, we can realize realistic experimental effects, such as the flow of liquid and the collisions between objects. At the same time, we can visualize some abstract objects, such as the visualization of light paths and electric fields in physics, to exploit the advantages of augmented reality technology (see Fig. 8).

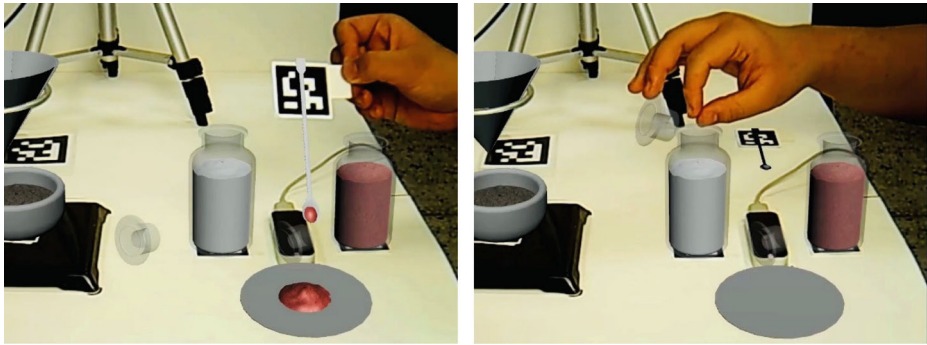


(a) Occlusion in virtual space



(b) Occlusion in real space

**Fig. 6** Framebuffer-based occlusion



(a) Interaction channel based on markers

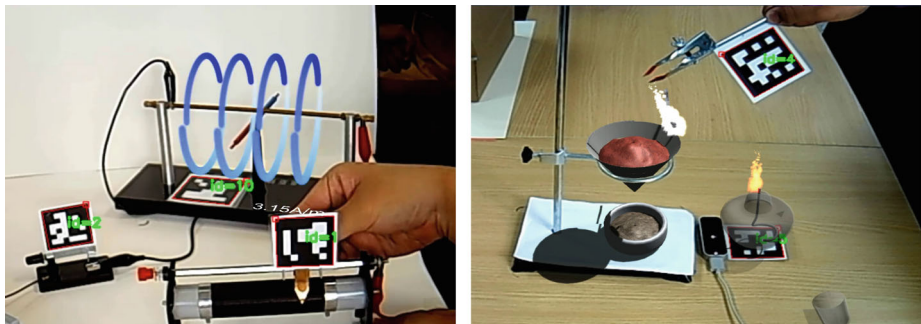
(b) Interaction channel based on gestures

**Fig. 7** Two interaction channels

The experiment simulation engine in the experiment multimedia environment is embedded by the AR experiment authoring tool and the AR experiment application. The difference between these two situations is that in the AR experiment application, the visualized effects are displayed in a mixed virtual and augmented reality environment with the combination of the AR engine. The experiment simulation engine supports the simulation of different subjects.

### 3.2.3 Experiment communication and evaluation module

The experiment communication and evaluation module records the step execution time, step execution order, and experiment simulation requirements and compares them with the evaluation rules. The AR experiment application can evaluate the experimental performance of students according to the evaluation rules. In the classroom teaching environment, the AR experiment application can not only transfer the experiment progress, the results of evaluation, and the students' experiment interface to the management application in real time but also send guidance from teachers and rewards from the evaluation module to students.



(a) Augmentation of the experiment visualization

(b) Manipulation of AR experiment equipment

**Fig. 8** AR experiment application

### 3.3 The management application

In the laboratory, to make our AR experiment application participate in experimental education more effectively, the management application of the experiment assists teachers in providing teaching guidance to students. The management application uses multiple network protocols (WebRTC and HTTP) to achieve the real-time information exchange of students' AR experiments, such as observing students' behaviour, controlling steps, and giving guidance (Fig. 9).

#### 3.3.1 Communication module

It is advised to run this multimedia environment in a LAN network environment. Teachers can use the management application to distribute AR experiment configuration files to students' AR multimedia environments at the start of the experiment class. While students are manipulating the experiment, teachers can watch the students' behaviour and obtain their experiment progress information in real time using the management application. When one student requires experiment guidance, guidance can be sent to the student's terminal to be displayed on the student's desktop through the AR method.

#### 3.3.2 Manage module

The manage module is the core module of the application. This module has two main functions: managing students in class and after class.

In class, teachers must manage the students in the classroom. Focusing on the teaching interaction, teachers can control the steps of the students' experiments. The step information and the evaluation rules can be analysed and acquired from the AR experiment configuration file. Teachers can reset a step in the student experiments or make a particular student's experiment jump to a specific experimental step. After completion of each step, the student receives the evaluation of the step. According to the evaluation, teachers can offer guidance to the student if necessary.

After class, teachers can obtain a collection of information of students' performance, including the details of the experimental workflow and the students' experiment scores. All of these datasets can be analysed in personalized fashion, and the knowledge can be recommended to students.

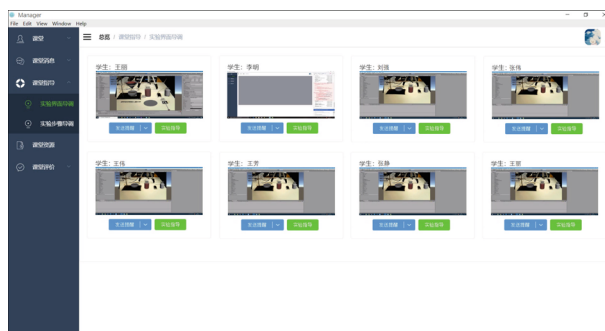


Fig. 9 The management application

## 4 Results

### 4.1 Application case study

Following the teacher's suggestion, we choose "Thermite Reaction" as an application case of AR experiments. The "Thermite Reaction" proves that using this multimedia environment can allow for implementation of dangerous experiments with limited equipment or materials.

We introduce this AR-based multimedia environment to ten middle school teachers and thirty middle school students who are participating in the research program and guide them to use this multimedia technology.

#### 4.1.1 Authoring an AR experiment

Using the AR experiment authoring tool, a teacher selects the experiment equipment and materials that will be used in this experiment: aluminum powder, iron oxide, magnesium ribbon as a fuse, alcohol lamp, crucible, clamp, filter paper, match, spatula, iron sheet, and paper funnel (Fig. 10).

During the selection workflow, the selected equipment and materials will be generated in the virtual experiment desk. Teachers edit the properties of the experiment equipment and materials, choose "real" or "virtual" and select a marker as spatial location mapping in the real world. For "virtual" experimental equipment and materials, teachers need to select methods of interaction and the reaction in the experiment simulation engine.

Next, teachers can manipulate the experiment equipment and materials in the virtual experiment desk and realize the whole workflow of the "Thermite Reaction". Note that each

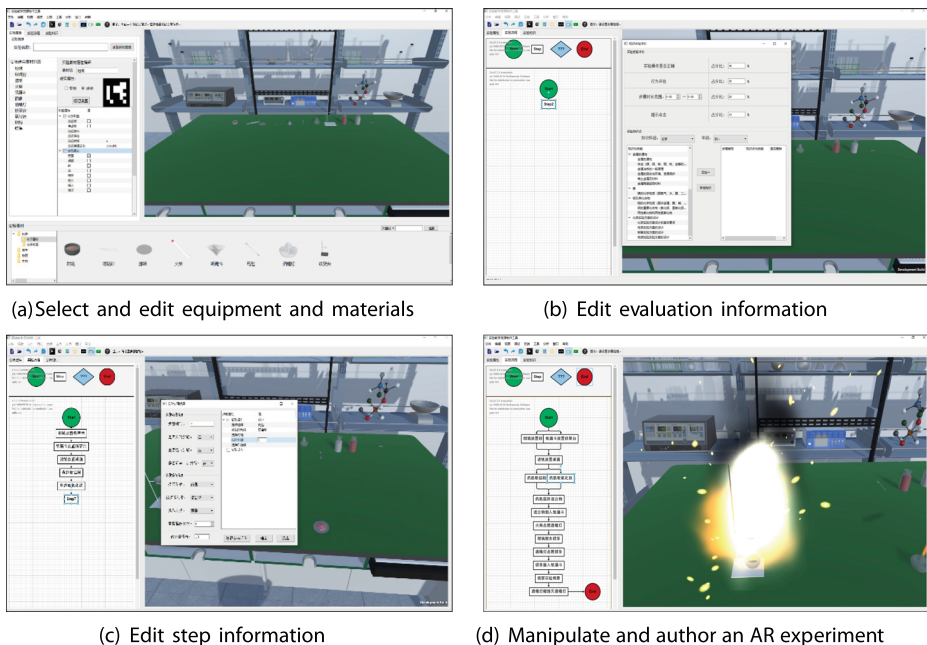


Fig. 10 Interface of authoring an AR experiment

time an experiment step is generated, the brief information of this step is shown as a triple: (Object1, Behaviour, Object2). Object1 is the equipment and materials that actively interact with Object2. Behaviour is the semantics of the interaction action. Object2 is the equipment and materials that are passively being interacted with by Object1. For example, when we use the match to light the alcohol lamp, the triple is (match, light, alcohol lamp).

In consideration of the requirements of experimental education, teachers are asked to write the details of the simulation properties and the evaluation rules of the experiment. If this step involves an experiment simulation engine, for example, in this chemical reaction, teachers should also record the experimental reactants, reactant concentrations, and reaction conditions. The flow chart of authoring the AR experiment is shown in Fig. 11.

#### 4.1.2 Laboratory learning and teaching

After authoring the AR “Thermite Reaction” experiment, teachers export the configuration file and distribute it to the students’ AR experiment application through the management application. Students start the experiment under the guidance of experiment requirements and then manipulate experimental equipment and materials using markers and gesture interaction. (Fig. 12)

The first task for students is to identify the virtual equipment represented by the markers. Students can place the markers under the webcams, and the virtual equipment is shown on the screen. Then, it is easy for students to manipulate the markers to move virtual objects. We define a gesture interaction method to open the wide-mouth bottle by removing the cap, which students would be notified of in advance.

With the assistance of the management application, teachers can watch the behaviour of the students, check the progress of the students’ experiments through the flowchart, and give guidance. Guidance is shown as text on a student’s desk. After the students complete the experiment, teachers can receive the evaluations of the students (Fig. 13).

#### 4.2 Usability test

To evaluate this multimedia environment, we designed two questionnaires for students and teachers. These questionnaires are designed on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The statement and results of the questionnaire are shown in Tables 2 and 3.

Regarding the effects of using the multimedia environment in the experimental class, both teachers and students consider this multimedia environment to be helpful for teaching and learning. Teachers considered this multimedia environment as easy to use and learn. The teachers are willing to try to use this multimedia environment in the future. Moreover, students think that AR technology can arouse their interest in experimental learning. Students are willing to use AR technology for experimental learning and think that using AR

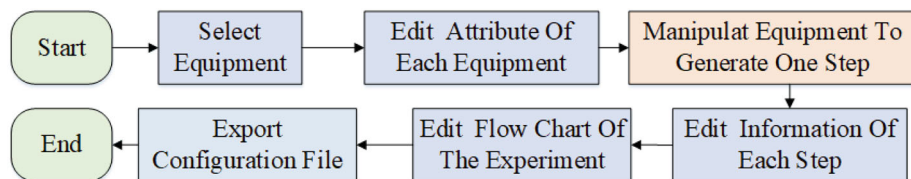


Fig. 11 The flow chart of authoring an AR experiment



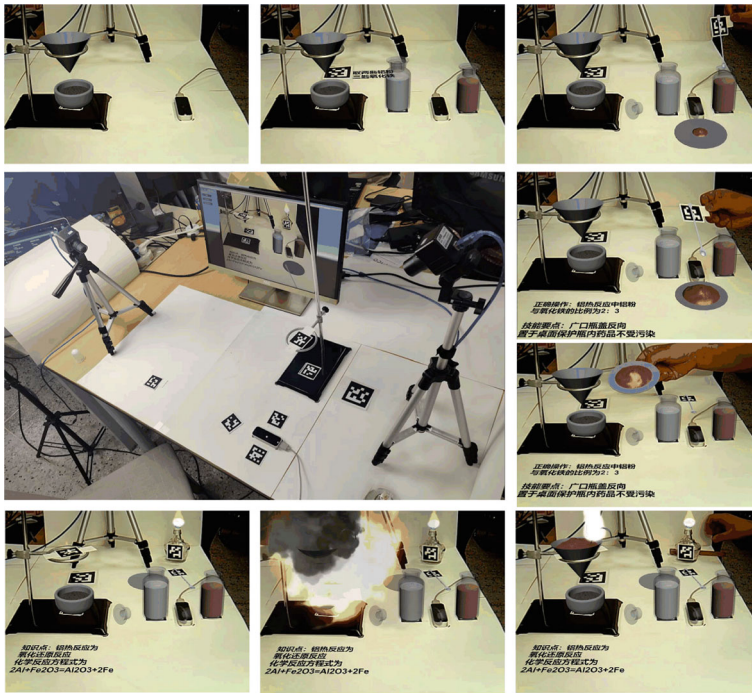


Fig. 12 AR experiment environment

technology could help them to complete experiments that could not be previously achieved. On the other hand, to make the teaching content more meaningful, it needs to be produced by educators using teaching theories.

## 5 Discussion and future work

This paper introduces an augmented reality-based multimedia environment for experimental education. AR technology is beginning to be applied in the field of education, and current

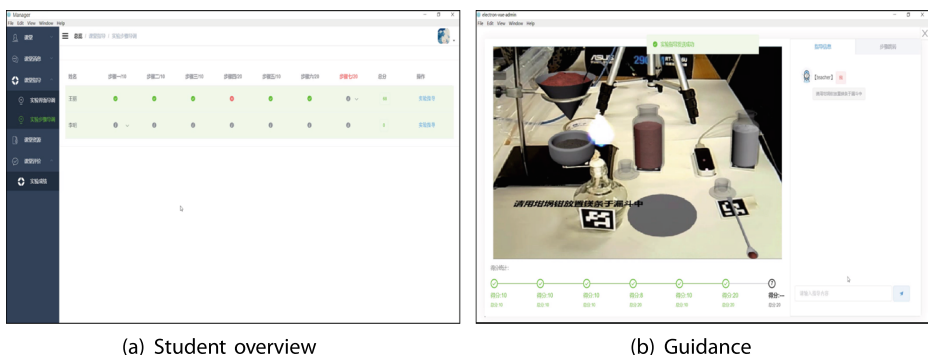


Fig. 13 Managing laboratory learning and teaching

**Table 2** Research questions for teachers

Research Questions for teachers	Mean	S.D
Q1. The multimedia environment improves experimental education	4.3	0.67
Q2. I could easily manage the class using the multimedia environment	4.4	0.52
Q3. The multimedia environment is easy to use	4	0.82
Q4. Learning to use these multimedia applications is not a problem.	4.2	1.03
Q5. Operation with these multimedia applications is clear and understandable	4.3	1.06
Q6. Using such a multimedia environment makes learning more interesting	4.3	0.82
Q7. Using such a multimedia environment in the experiment classroom is a good idea.	4.4	0.7
Q8. I would like to use the authoring tool to create AR experiments	4.5	0.71
Q9. I would like to use the multimedia environment in the future if I had the opportunity	4.3	0.82

AR educational applications are often used as a new type of knowledge display platform and cannot participate in teaching and studying. In consideration of this problem, we have combined AR technology and experimental education to build a multimedia environment for experimental education. The AR experiment authoring tool in this multimedia environment is easy to use to create AR experiments. Students can manipulate AR experiments in a natural, interactive way, and in the meantime, teachers can watch and guide the behaviour of students through the management application.

In this multimedia environment, AR technology, as a new type of multimedia, exhibits interactive technology that has contributed to the teaching of experiments in class. In addition, the results proved that the multimedia environment based on AR can effectively improve educational activities and improve the teaching effects. The interaction of the real and virtual objects provides a new direction for the educational multimedia environment.

The main challenge in multimedia education is determining how to combine multimedia technology with educational theory. In future research, we hope to create experimental equipment and materials in the manner of crowd-sourcing in order to extend the interface of experiment equipment and materials production, establish a free sharing community for AR experimentation, and improve the applicability of experimental teaching. In terms of the function of multimedia experimental teaching, we hope to analyse the cognitive level of students according to their experimental behaviour and recommend the knowledge points that students need to master with machine learning. We hope that we can better use this new multimedia technology to build a learner-centred multimedia environment.

**Table 3** Research questions for students

Research Questions for students	Mean	S.D
Q1. I think the AR technology in the experiment is interesting	4.83	0.38
Q2. I enjoyed doing the AR experiment	4.37	0.49
Q3. I think it's easy to manipulate the AR experiment	3.97	0.61
Q4. Using the system during lessons would facilitate understanding of certain concepts	3.83	0.59
Q5. I think learning with this multimedia environment is helpful to master experimental skills	4.33	0.8

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