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A novel animation authoring framework for the virtual teacher performing experiment in mixed reality

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Abstract

Virtual teachers embedded into reality enable the transfer of skills and knowledge to students by demonstration. However, authoring the animation of virtual characters aligned with real environments is difficult for educators. In this study, a novel animation authoring framework for demonstration teaching is proposed based on human–computer interaction and intelligent algorithm, and its application is demonstrated in mixed reality experimental education. We developed a simulation experiment environment; users could operate equipment using gestures by a Leap Motion controller. The interaction trajectory can be adaptively adjusted by the dynamic motion primitives algorithm to generate a virtual teacher demonstration trajectory aligned with real environments. For the details of the virtual teacher animation, the deep reinforcement learning algorithm performed the adaptive grabbing for objects of different shapes and sizes. Our experimental results showed that the framework is easy to use; users are able to easily author a natural animation of a virtual teacher performing a chemical experiment aligned with real environments. Also, the user feedback showed that the virtual teacher's demonstration animation in MR is impressive, and students can learn from the animation by observation and imitation.

KEYWORDS

animation authoring, experimental education, human–computer interaction, mixed reality, virtual teacher

1 | INTRODUCTION

Over the last few years, there has been growing interest in mixed reality (MR) technology for education. As a new multimedia technology, MR has better demonstration teaching potential than traditional multimedia forms (e.g., text and video). Embedding virtual humans in educational settings enables the transfer of the approved concepts of learning by observation and imitation of experts to extended reality scenarios [23].

In the educational field, the role of teachers is irreplaceable and important. However, for teachers, authoring MR content is a complex task, especially when it comes to three-dimensional (3D) objects, due to this, the use of MR in teaching is markedly limited [9]. Furthermore, virtual humans in MR need to be aligned with real environments at different moments, making the reuse of existing animations difficult.

To address this issue, we explore the use of a human–computer interface as a simulation experiment environment to author the animation of virtual teachers. Our key idea is to mimic the operational interaction behavior of the users to generate the animation of virtual teacher in MR. However, there is a huge gap between the operational interaction behavior and the animation of virtual teacher in MR. This motivates us to solve two technology issues. The first technology issue is that the animation in MR should be aligned with real environments. The second technology issue is that the gesture-driven interaction data captured by sensor are not a good motion template to generate virtual teacher animation.

Thus, a novel authoring framework (Figure 1) is designed and proposed, which allows casual users to directly operate equipment using gestures in a simulation experiment environment by a Leap Motion controller. The interaction trajectory can be adaptively adjusted by the dynamic motion primitives (DMPs) algorithm to generate a virtual teacher performing trajectory aligned with real environments. For the grab motion of the virtual teacher, the deep reinforcement learning (DRL) algorithm is used to realize the adaptive grabbing for objects of different shapes and sizes. With the support of this framework, casual users could quickly author virtual teacher animations without lots of training or hardware setup.

We demonstrate the usefulness and effectiveness of our framework for a typical experiment "Thermite Reaction." Our qualitative evaluation shows that our authoring framework provides users with an intuitive, easy-to-use and effective way for authoring the animations of a virtual teacher in MR. The structure of this paper is shown in Figure 1.

2 | RELATED WORK

In this section, we briefly review two categories of work related to ours: MR applications in education and virtual human animation. Research papers are categorized into these two specific areas and are presented in Table 1 as

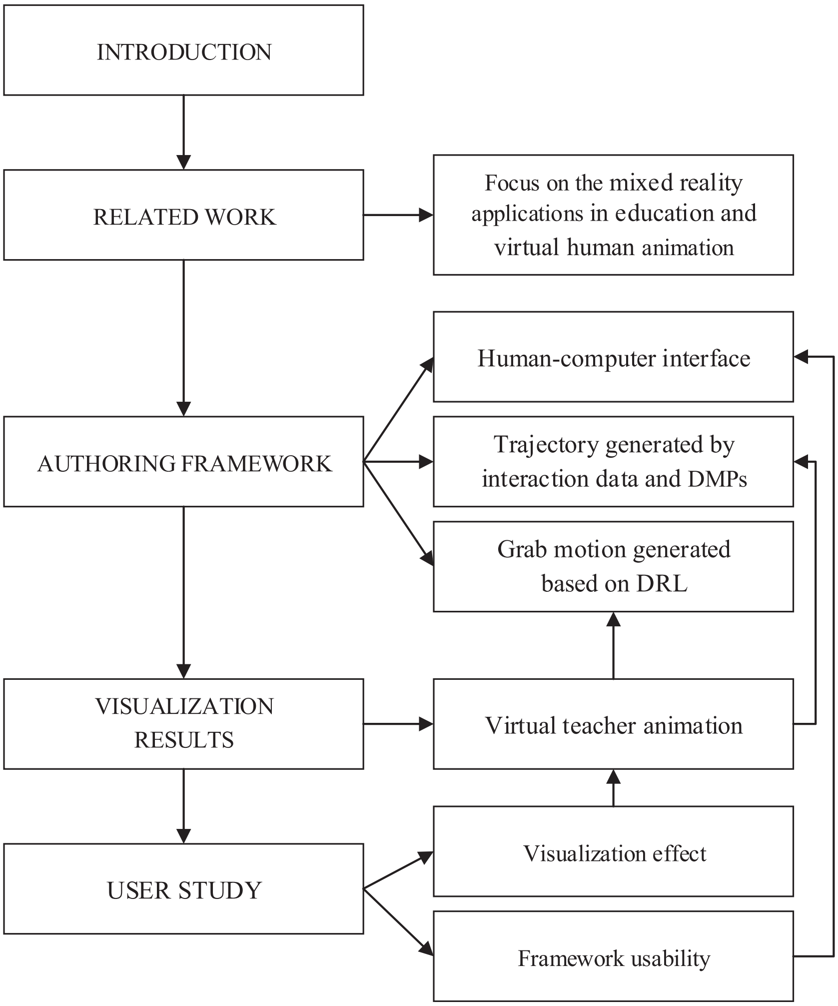


FIGURE 1 Structure of this paper. DMP, dynamic motion primitive; DRL, deep reinforcement learning

TABLE 1 Publications that focus on the MR applications in education, ordered by the name

Reference	Topic	Approach and activity	Findings
Billinghurst et al. [3]	Augmented Reality in the Classroom	Evaluations of AR experiences in an educational setting provide insights into how this technology can enhance traditional learning models and what obstacles stand in the way of its broader use.	Research results and classroom studies of educational AR applications strongly suggest that the technology can be a valuable teaching tool.
Dream-Experiment [27]	An MR User Interface for Virtual Experiments	Develops a multi-channel MR user interface called Dream-Experiment.	Improved the traditional MR user interface, users can have a real, natural 3D interactive experience like real experiments, but without danger and pollution.
Frank et al. [12]	Mixed-Reality Learning Environments	Discussed the efforts to integrate vision-based measurement and control, augmented reality (AR), and multi-touch interaction on mobile devices in the development of Mixed-Reality Learning Environments	Enhance interactions with laboratory test-beds for science and engineering education.
Ke et al. [20]	Mixed-reality learning environment	Simulations and immersive teaching practices for university teaching assistants; studied the design of an MR integrated learning environment (MILE) and its potential impact	The MILE reinforced the sense of presence and supported the performance of an ample range of virtual teaching tasks/actions with avatar-embodied live gesturing.
Lindgren et al. [25]	Mixed-reality simulation for learning	Applied MR to teach scientific content for STEM subjects.	The experiment proves that MR enhances the learning of scientific concepts and improves student participation and positive attitudes toward science.
Lugrin et al. [26]	VR-assisted training	A low-cost collaborative immersive VR training system; this system was applied for teacher training	The experiments proved that the VR system can more effectively improve the teaching level of teachers.
Singh et al. [35]	AR on electronics laboratory skills of engineering students	The participants of the experimental group were provided ARLE treatment, while the participants from the control group were provided traditional teaching treatment.	The experimental results suggest that the AR intervention has a significant positive impact on student laboratory skills.

use of MR applications in education and in Table 2 as virtual human animation authoring.

2.1 | MR applications in education

With the development of MR/AR/VR technology, researchers noticed that MR/AR enables seamless connection of the digital and physical domains, offering excellent potential in the educational field [3,19,28,31,40]. Taking advantage of MR, researchers developed many educational applications based on MR technology (Table 1). These applications focus on different cognitive enhancement fields with MR technology. However, these applications are developed by engineers or scholars with programming skills, and teachers cannot participate in the educational activities well.

Educators are encouraged to develop MR content with cognitive enhancement ability [1]. However, it is still a challenge for teachers to design and author complex and interactive MR content. In this study, a framework to author the virtual teacher animation for the chemical experiment demonstration teaching is proposed.

2.2 | Virtual human animation

Research shows that creating virtual human as teaching agent in computer-based learning environment is benefit to learning [5-7,14,21,38] and could improve social

TABLE 2 Publications that focus on the animation authoring, ordered by the name

Reference	Animation authoring method	Domain	Aligned with reality	Application
Chiang et al. [4]	RGBD capture	MR	Unaligned	Sports learning
Hamanishi et al. [15]	Motion capture	MR	Unaligned	Sports learning
Heloir et al. [17]	Motion capture	3D	Unaligned	Sign language
Lampen et al. [23]	Real-time motion capture	MR	Aligned	Industrial Assistance
Liang et al. [24]	Gesture-based interaction and animation data	2D	Unaligned	Chinese traditional shadow play
Sakai et al. [33]	Spring-damper dynamical model	3D	Unaligned	Conversational android
Tanaka et al. [36]	Semiautomatic 3D reconstruction	3D	Unaligned	Karate training
Tsuchiya et al. [37]	Video capture	VR	Unaligned	Human interactions
Ye et al. [41]	User-defined Motion Gestures	MR	Aligned	Mini character animation authoring

existence and cooperation [2,16,32]. Researchers developed many applications [13] with virtual human animation. However, most of the animations in MR did not align with reality, and were not fundamentally different from video education. In the robotics field, Robots can be aligned with reality in real time. Robots can learn various human-like skills in a more efficient and natural manner through human–robot interaction [11,22,39]. Peng et al. [29] propose a method that enables physically simulated characters to learn skills from videos (SFVs). Imitation learning techniques aim to mimic human behavior in a given task. An agent (a learning machine) is trained to perform a task from demonstrations by learning mapping between observations and actions [8,10,18]. By combining a motion-imitation objective with a task objective, Peng et al. [30] can train characters that react intelligently in interactive settings.

Inspired by imitation learning, a novel authoring framework for the virtual teacher animation is proposed in this study. Casual users could author the animation through simple HCIs. The virtual teacher in the MR scene would change the operation trajectory adaptively depending on the real environment.

3 | FRAMEWORK OVERVIEW

The overall framework of the animation authoring is summarized in Figure 2. Casual users could directly operate equipment using gestures in the simulation experiment environment by a Leap Motion controller (Figure 2, top left). Start and end points are recognized and located in real time (Figure 2, bottom left). The interaction trajectory can be adaptively adjusted by the DMPs algorithm to generate a virtual teacher performing a trajectory aligned with real environments (Figure 2, top middle). Also, adaptive grabbing for operational equipment is generated by DRL (Figure 2, bottom middle). The operation trajectory and the adaptive grab motion would be blended to generate the virtual teacher animation in the MR scene (Figure 2, right).

3.1 | Human–computer interface

We developed a 3D human–computer interface as the simulation experiment environment based on a Leap Motion controller. The human–computer interface environment is composed of an experimental table and experimental equipment, where users can choose the required experimental equipment independently. The human–computer interface is shown in Figure 3.

The Leap Motion controller was placed on the desktop in reality. Within the effective range of the controller, the user could use a simple gesture to grab and operate the experimental equipment in the 3D human–computer interface. The operation scenario is shown in Figure 3b. To create the virtual teacher animation, we record the position of the object being grabbed and the operation trajectory starts at the time of grabbing and ends when the hand releases the equipment.

3.2 | The trajectory aligned with real environments

To ensure that the trajectory of the virtual teacher's hand is aligned with real environments, we use the RGB

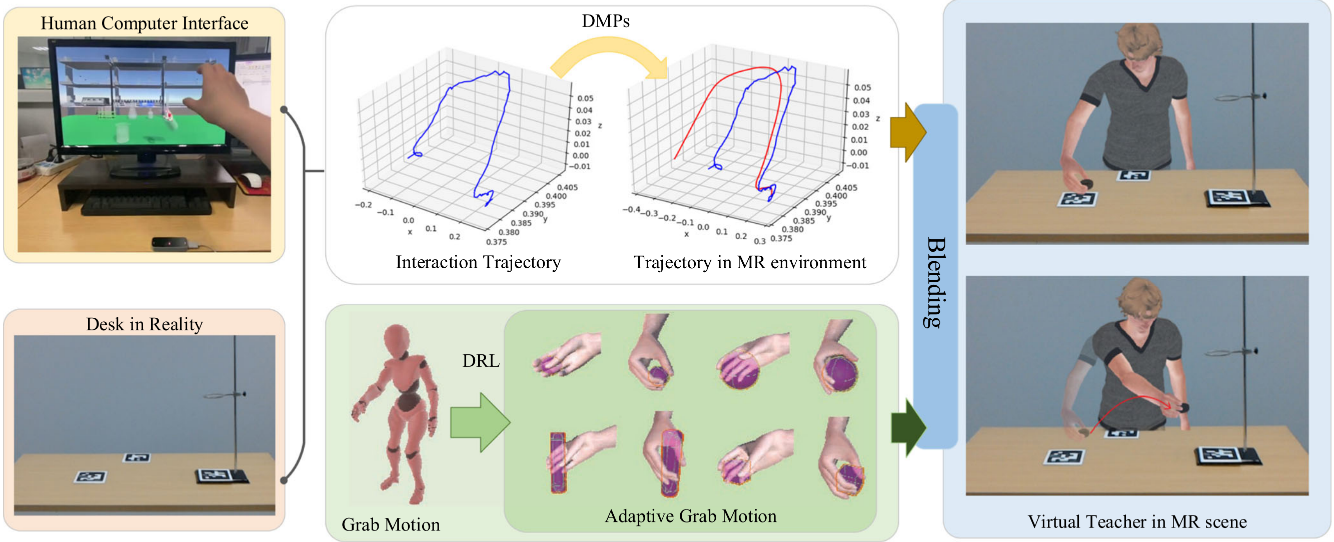


FIGURE 2 Virtual teacher animation authoring framework. DMP, dynamic motion primitive

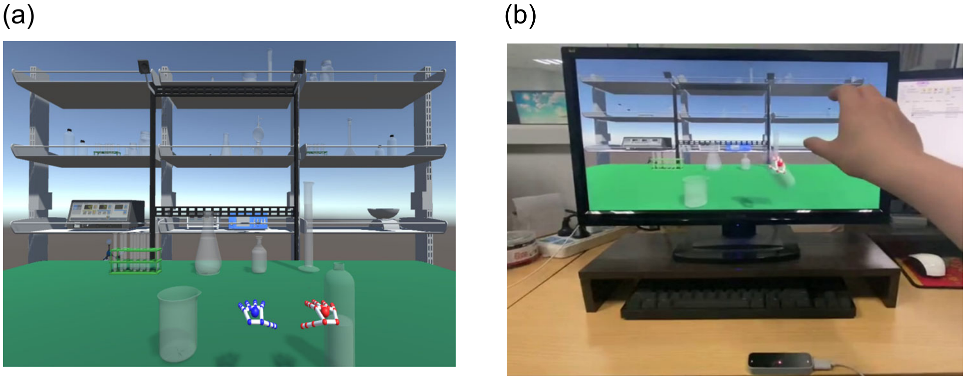


FIGURE 3 3D human–computer interface. (a) Simulation experiment environment and (b) user Interaction scene

camera to recognize the marker and obtain the starting and ending positions and rotation of the operation. We have noticed that it is important for workers to teach robots operating skills through demonstration. DMPs [34] allow multi-DOF humanoid robots to learn new motion quickly and simply. These trajectories can be adjusted flexibly without manual adjustment of parameters, and there is no need to worry about instability. In this framework, the virtual teacher will learn the trajectories' template and generate the operation trajectories aligned with real environments via DMPs in MR.

Complex motion could be considered a set of basic motions executed in sequence or in parallel. DMPs are mathematical formal representations of these basic motions. DMPs are composed of nonlinear dynamic systems. The desired trajectories are generated by combining the asymptotic stability of the dynamic system and the forcing function, which can change the trajectory. The dynamic system used in DMPs is a second-order dynamic system based on a spring damping system

$$\tau\ddot{y} = \alpha(-\beta(y^g - y) - \dot{y}), \tag{1}$$

where y is the position, $\dot{y}$ is the velocity, and $\ddot{y}$ is the acceleration. y^g is the expected target state, that is, α and β are the parameters of the dynamic system. The current second-order dynamic system can guarantee that the trajectory converges to the target point y^g in a specific simple form, but it does not have the ability to generate an arbitrary trajectory. To make the system converge to the target point with the expected shape set by humans, the forced term function f is added

$$\tau\ddot{y} = \alpha(-\beta(y^g - y) - \dot{y}) + f. \tag{2}$$

The forcing term function f is the key to generating arbitrary trajectories via DMPs. The forcing function f is defined as a function of the canonical system:

$$f(x, g) = \frac{\sum_{i=1}^{N} \psi_i w_i}{\sum_{i=1}^{N} \psi_i} x(g - y_0). \tag{3}$$

where y_0 is the initial position of the system, and the parameter in the mandatory function is the weight vector w. Through the combination of the basis function and the weight vector w, arbitrary trajectories can be obtained. This is why DMPs coupled with forced term functions can generate arbitrary expected trajectories, where N is the number of basic functions and w is the weight vector. Although the system is no longer expected to converge to the state of the system, y^g is no longer expected to be able to generate the desired trajectory. Therefore, the canonical dynamic system is introduced

$$\dot{x} = -\alpha_x x. \tag{4}$$

By importing the canonical dynamical system into the mandatory function, the effect of the forcing term can be guaranteed to disappear at the end of time. Thus, the dynamic system will not be affected in terms of converging to the attractor. To ensure the spatial scaling ability of the trajectory, the trajectory scaling factor $x(g - y_0)$ is imported. Therefore, we could obtain the operation trajectory aligned with real environments via DMPs.

3.3 | The adaptive grab motion based on DRL

Stable grabbing is the basis for humans using tools. For humans, the eyes can accurately discern inconsistencies in human-like movement. However, the grab motion captured by the Leap Motion was unnatural. On the one hand, the motion noise was caused by the sensor. On the other hand, the human–computer interface was driven by gesture and the users have no real object to grab.

To make the virtual teacher grab objects more naturally, we use the DRL method to train the model by combining the motion target and the grab task target to generate an adaptive grabbing animation of the virtual human hand and replace the captured unnatural animation.

DRL [18,29] provides a model agnostic method to control complex dynamic systems, which enables virtual humans to imitate various actions, adapt to changes in tasks, and achieve the goals specified by users. DRL is an end-to-end perception and control system that has strong generality. The reward function is an index function that needs to be maximized in the training process of the reinforcement learning strategy. On the basis of Deepmimic [30], a reward function for hand adaptive grabbing is as follows:

$$R_t = w^I R_t^I + w^G R_t^G. \tag{5}$$

We define R_t^I and R_t^G as the imitation reward and task reward, respectively, where w^I and w^G are the weights. The reward function means that the agent's strategy needs to make a trade-off between the imitation task and the adaptive task, and finally generate a natural grabbing animation.

1) Imitation reward

   The imitation reward is the idea of inverse reinforcement learning, which enables the agent to imitate the reward function of the reference motion sequence of the hand. Compared with the simple grabbing task, the introduction of the reward makes the grab sequence of the generated hand closer to the human demonstration and more natural. Specifically, these are as follows:

$$R_t^I = w^p r_t^p + w^v r_t^v + w^e r_t^e, \tag{6}$$

where r_t^p and r_t^v represent the angle reward and the speed reward of the agent, respectively

$$r_t^p = \frac{\max(\|\Delta \boldsymbol{p}\|) - \sum_i \|\Delta \boldsymbol{p}\|_t^i}{\max(\|\Delta \boldsymbol{p}\|)}, \tag{7}$$

$$r_t^{\mathrm{v}} = \frac{\max(\|\Delta \boldsymbol{v}\|) - \sum_i \|\Delta \boldsymbol{v}\|_t^i}{\max(\|\Delta \boldsymbol{v}\|)}. \tag{8}$$

Only when the t angle deviation $\Delta \boldsymbol{p}$ between each joint i of the hand and each joint i in the reference motion sequence is small and the velocity vector deviation $\Delta \boldsymbol{v}$ is small can the two reward functions obtain higher reward values.

r_t^e represents the end coordinate reward of the agent. Since the hand is a hierarchical structure with a parent–child relationship, the closer to the end of hand (e.g. fingertips), the easier deviation occurs. We define:

$$r_t^e = \frac{\max(\|\Delta \boldsymbol{\rho}\|) - \sum_i \|\Delta \boldsymbol{\rho}\|_t^i}{\max(\|\Delta \boldsymbol{\rho}\|)}. \tag{9}$$

$\boldsymbol{\rho}_t$ is the coordinate matrix of the five distal finger segments at the end of the finger at time t. At each time t, the five fingertips of the hand are as close as possible to the reference motion sequence fingertips in the relative coordinate system.

2) Adaptive reward

It should be noted that if only an imitation reward is adopted, that is, only the reference motion sequence is imitated, the final generated grabbing posture cannot meet the above adaptive ability. The reward function of the adaptive grabbing task is to meet the requirement of stable grabbing for different shapes and sizes of objects under the grabbing task. Specifically:

$$R_t^G = w^\rho r_t^\rho + w^c r_t^c + w^a r_t^a. \tag{10}$$

r_t^ρ is the reward of the distance between the fingertips of the agent at time *t*. We only calculate the distance between the preset point at the end of the finger and the object. The existence of the reward function makes the fingertip of the agent contact the target object to the greatest extent possible, instead of completely imitating the reference motion sequence. For the fingertip *i* of each finger of the agent:

$$r_t^\rho = \begin{cases} -\frac{\|\Delta\boldsymbol{\rho}\|_t^i}{\max(\|\Delta\boldsymbol{\rho}\|)}, & \text{Fingertips have not touched the object,} \\ 0, & \text{Fingertips have touched the object.} \end{cases} \tag{11}$$

r_t^a is the reward of avoiding hanging in the air at time *t*. To further ensure contact between the fingertip and the surface of the object and avoid an unnecessary hanging phenomenon, for each fingertip, we take

$$r_t^a = \begin{cases} 0, & \phi_t \le 0.6, \\ -0.2, & 0.6 \le \phi_t \text{ and finger tips have not touched the object.} \end{cases} \tag{12}$$

r_t^c is the centroid reward of the agent's fingertips at time *t*. However, the contact distribution with the fingertip is still more heuristic than that with the fingertip distribution. We believe that "stable grabbing" requires that the space distance between the five fingers' centroid and the object's centroid be as small as possible:

$$r_t^c = -\frac{\|\Delta\boldsymbol{c}\|_t}{\max(\|\Delta\boldsymbol{c}\|)}. \tag{13}$$

3.4 | Inverse kinematics (IK)

The virtual teacher animation is mainly composed of virtual human upper limb animation. By specifying the position of the end joint, the position of each intermediate joint could be calculated using the IK algorithm. Use of the IK algorithm, in terms of the virtual human operation trajectory generated in the MR environment as the time series of its upper limb end movement position and posture, can drive the virtual human upper limb movement in real time, and rotate the head and gaze to follow the interactive object to generate a virtual human demonstration animation.

4 | EXPERIMENT OVERVIEW

4.1 | Adaptive operation trajectory

In the adaptive operation trajectory experiment, we use the "water pouring operation" (pick and roll) in the 3D human–computer interface as the trajectory template, and generate the 6DOF operation trajectory via DMPs. The trajectory is shown in Figure 4.

4.2 | Adaptive grabbing animation

We use the DRL to generate adaptive grabbing animation. Under the effect of an imitation reward, the grab motion can maintain the original human motion characteristics. We select objects of random size to adaptively grab and record the movement displacement of the five fingers at the same time.

The adaptive grabbing task is divided into two aspects: the adaptive grab of the size of the object and the adaptive grab of the shape of the object. We set the size factor to 0.5 and 1, and test the spherical grab animation with different sizes. The effects of two sizes for sphere grabbing tasks are shown in Figure 5a,c. For the shape adaptive grabbing, we tested the size factor of 0.5 for cube and cylinder grabbing animation generation. The effect of grabbing the cube and cylinder is shown in Figure 5.

4.3 | MR visualization

We apply the authoring framework of virtual teacher demonstration animation in the field of middle school experimental education. In the virtual teacher demonstration teaching scene, we determine the position and rotation of the virtual experimental equipment (crucible, iron stand) in an MR environment by recognizing the markers. On the basis of the trajectory provided by users in a 3D HCI, the 6-DOF experimental operation trajectory aligned with the real environment is conducted by combining the position and pose of the starting and end points. Also, the captured grab motion was replaced by the adaptive grabbing animation that is generated based on the shape and size of the virtual experimental equipment. Additionally, the IK algorithm is used to drive the upper limb and head movement of the virtual teacher, and the crucible is placed at the bottom of the iron platform. All of these virtual human animations are presented in the MR environment, and the animation sequence is shown in Figure 6.

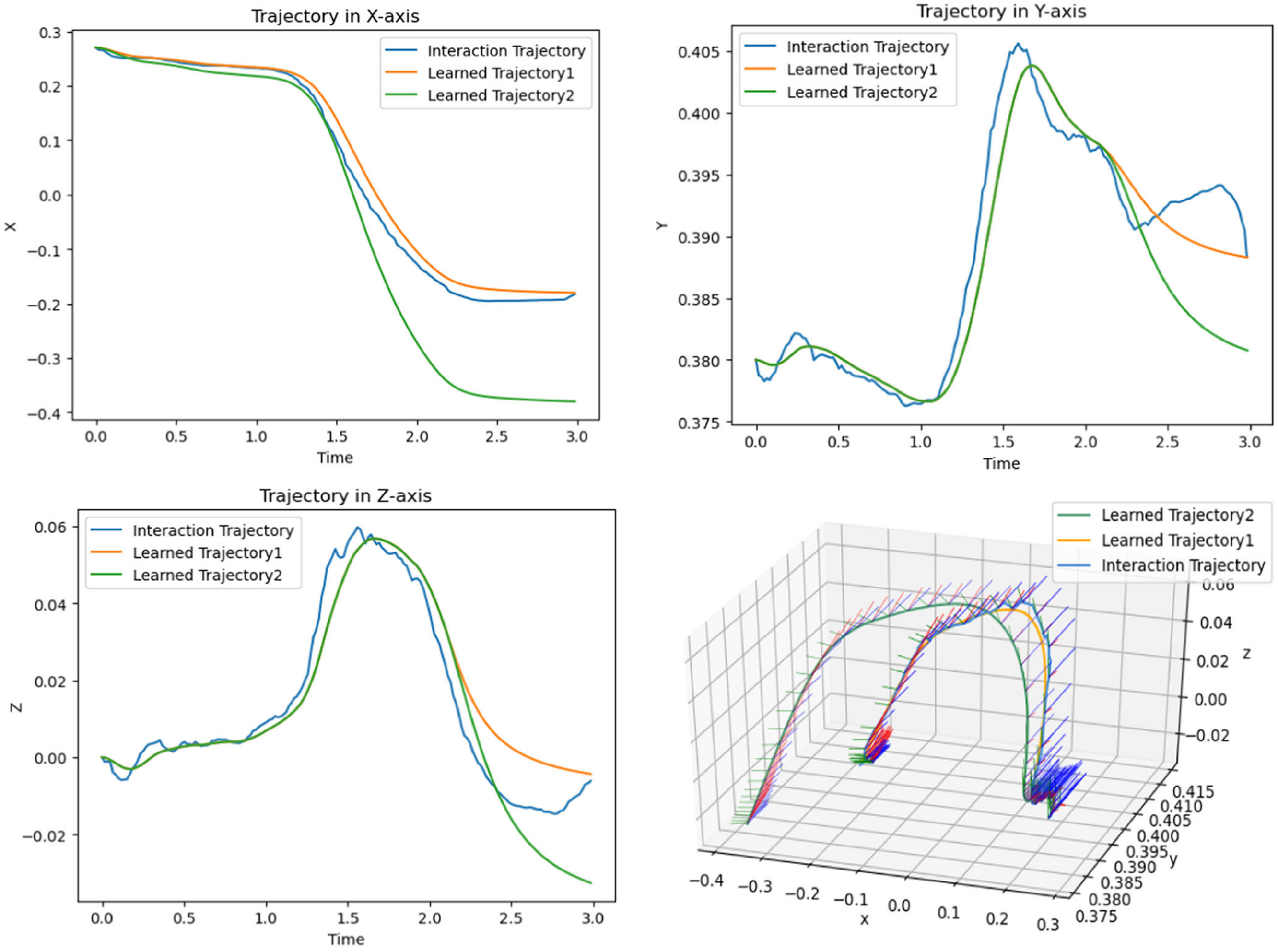


FIGURE 4 6-DOF adaptive operation trajectory

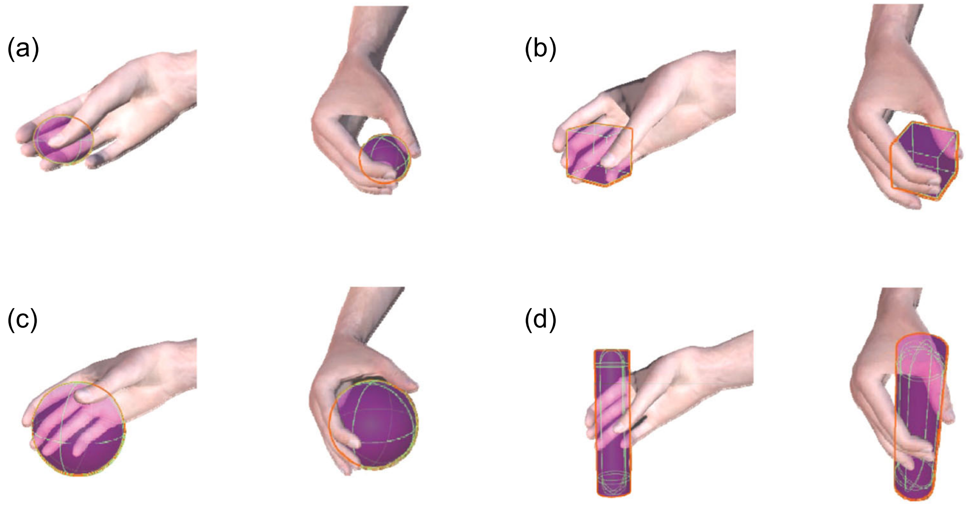


FIGURE 5 Effect of adaptive grabbing of object size and shape. (a) 0.5 size spherical grab, (b) 0.5 size cube grab, (c) 1 size spherical grab, and (d) 0.5 size cylinder grab

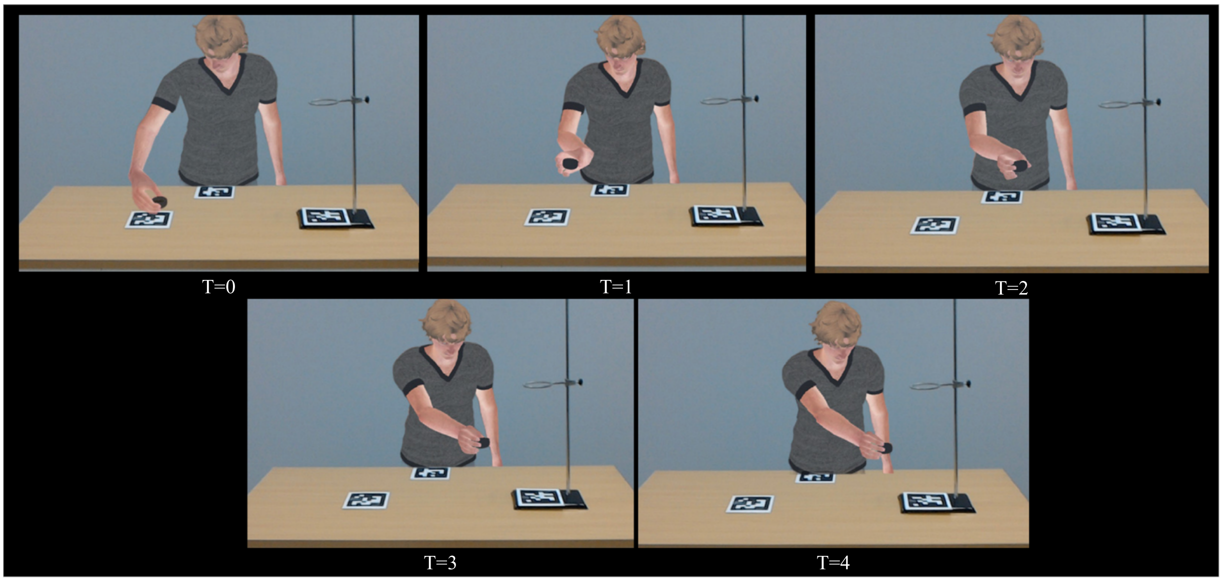


FIGURE 6 Sequence of virtual teacher demonstration

5 | USER STUDY

We used our animation authoring framework of the virtual teacher demonstration in middle school experimental education, focusing on the usability of the authoring framework and the visualization effect of virtual teacher animation. A formal user study is designed in this section.

5.1 | Apparatus

Figure 7 shows a snapshot of our experimental setup. The subjective evaluation of the framework mainly focuses on the usability of users using the system framework to record the interaction motion of specific operation tasks. The configuration of the system consists of a PC and a Leap Motion controller. The experiment is constructed by unity3d. The subjective evaluation of virtual human visualization mainly focuses on users' evaluation of virtual human animation. The equipment consists of a HoloLens 1, a PC, and network communication equipment.

5.2 | Participants

We recruited 18 volunteers (6 females, 12 males) from college to conduct the test. Participants ranged in age from 21 to 31 years ($\mu_{\text{age}} = 24.5$). Most volunteers claimed to have good or very good HCI skills ($\mu = 3.27$), and had a certain understanding of MR technology ($\mu = 3.0$) on a 5-point Likert scale. All of the volunteers were right-handed.

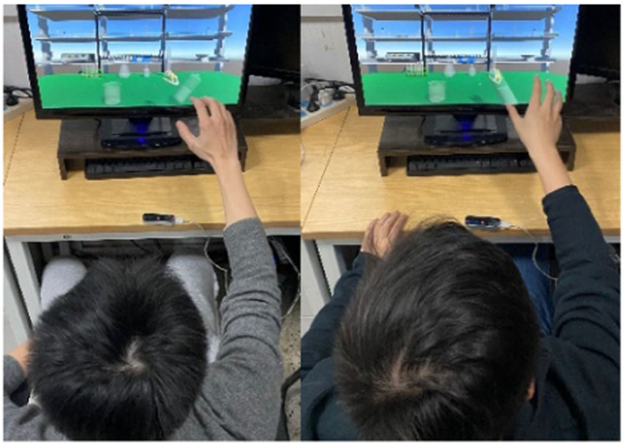


FIGURE 7 User study scene

5.3 | Experimental design

Participants needed to complete one random experimental task in the simulation experiment environment. In the experiment, the participants used a sitting posture, and used their dominant hand to grab experiment equipment by the Leap Motion controller. Also, participants released the equipment to finish the task. After all the participants finished the task, they watched the virtual teacher animation authored by themselves and others using HoloLens.

FIGURE 8 A gallery of virtual teacher animation results of the "Thermite Reaction"

5.4 | Procedure

Before the experiment, participants were given 10 min to become familiar with the Leap Motion and the simulation experiment interaction method. Each time participants completed an experiment task, we recorded the data of the 6-DoF operating trajectory. For each equipment task, participants were asked to pick, place, and roll the experimental equipment in the correct place. During the experiment, the experimental platform did not provide any experimental feedback. After the interaction task in the simulation experiment environment, according to the position and pose of the marker in real space, the participants watched the virtual teacher animation, and provided the evaluation.

5.5 | Results

We mainly evaluated the usability of the system framework and the effect of virtual teacher animation. Figure 8 shows sample frames of the authored representative virtual teacher animation results. Usability is one of the common perspectives for subjective evaluation. In the subjective evaluation of the system framework, participants mainly play the role of teachers, and authoring specific operating trajectory independently, watching the virtual teacher animation in the MR scene. All pictures were captured by HoloLens 1.

We used a 5-point Likert scale (from 1 [*very poor*] to 5 [*very good*]) to record users' subjective evaluation. It can be seen from Figure 9 that the participants provided positive comments on our framework. Participants are willing to accept the demonstration teaching of the virtual teacher with the least disagreement (Q6, mean = 4.5, *SD* = 0.69). Due to the noise of the sensor, some participants were unable to control the virtual equipment well in the simulation experiment (Q3, mean = 3.5, *SD* = 1.07). The start and point end points may be inaccurate, resulting in an error in the operation (Q4, mean = 3.72, *SD* = 1.10).

We discuss the results of the subjective evaluation in relation to our observations and the comments received from the participants during the interview. We categorized and divided these comments into two parts: human–computer interface and virtual teacher animation, and selected representative comments for analysis (*Italicized text* represents user feedback).

(1) Human–computer interface

Before the experiment, we instructed the participants on how to choose the virtual equipment and operate it in the interface. After free practice, all the participants agreed that it was an interesting way to operate the chemical experiment and author animation.

1. I think I can operate the experiment easily, and the interface could be used as teaching software for students.
2. I think my suspended upper limbs will become tired after a long time operation.

However, the range of user motion has certain sensor limitations. The location of the Leap Motion needs to be explored further.

(2) Virtual teacher animation

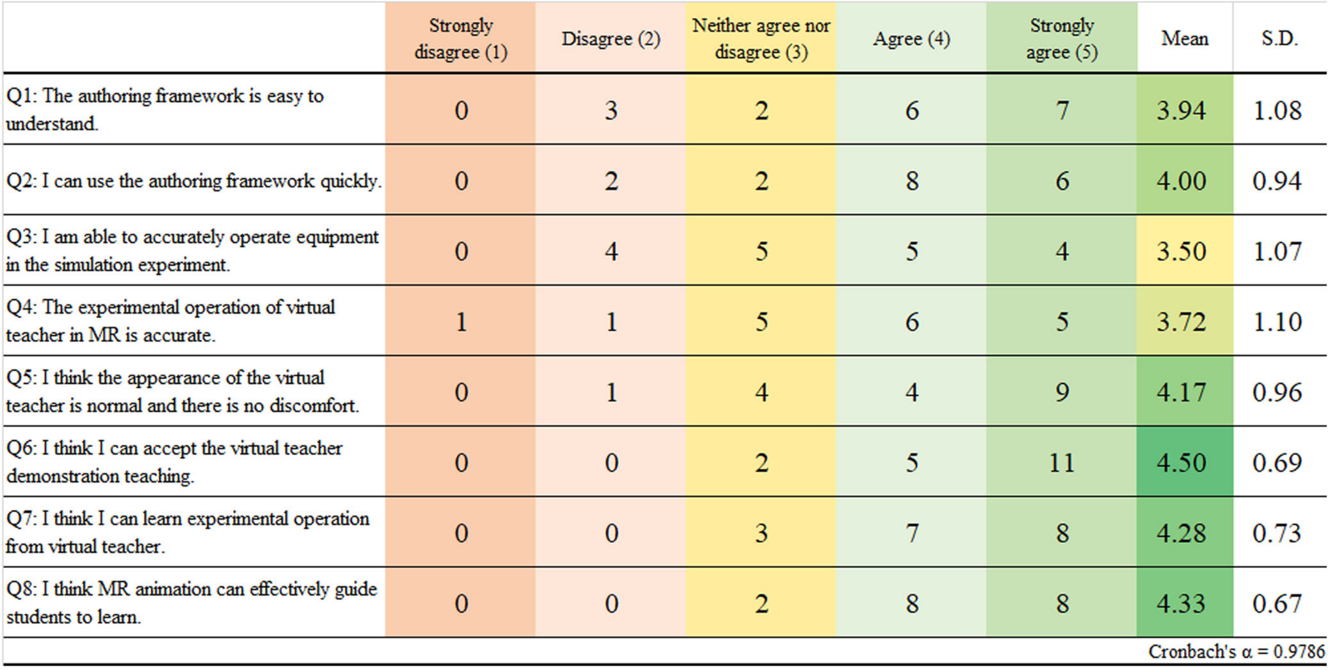
The location of the virtual teacher is defined by the Marker. After all the Marker location information was obtained, users could click the play button. Participants could watch the animation of the virtual teacher in 360°.

1. The effect of virtual teachers and virtual experiment are impressive.
2. I find it interesting that virtual teachers can contact with real equipment.
3. In some cases, the animation of virtual teacher is short.

All participants agreed that virtual teachers can provide users with impressive experimental education effects.

6 | DISCUSSION

In this paper, we focus on providing a human–computer interface for teachers to author experimental operations, and for authoring the animation in MR of virtual teachers for demonstration teaching. We use the DMPs algorithm to solve the aligned issue between virtual teachers animation



	Strongly disagree (1)	Disagree (2)	Neither agree nor disagree (3)	Agree (4)	Strongly agree (5)	Mean	S.D.
Q1: The authoring framework is easy to understand.	0	3	2	6	7	3.94	1.08
Q2: I can use the authoring framework quickly.	0	2	2	8	6	4.00	0.94
Q3: I am able to accurately operate equipment in the simulation experiment.	0	4	5	5	4	3.50	1.07
Q4: The experimental operation of virtual teacher in MR is accurate.	1	1	5	6	5	3.72	1.10
Q5: I think the appearance of the virtual teacher is normal and there is no discomfort.	0	1	4	4	9	4.17	0.96
Q6: I think I can accept the virtual teacher demonstration teaching.	0	0	2	5	11	4.50	0.69
Q7: I think I can learn experimental operation from virtual teacher.	0	0	3	7	8	4.28	0.73
Q8: I think MR animation can effectively guide students to learn.	0	0	2	8	8	4.33	0.67

Cronbach's α = 0.9786

FIGURE 9 Result of the subjective evaluation and real environments, and use the adaptive grab motion to replace the unnatural gesture motion. This framework has been verified. We conducted a user survey on the usability of authoring experimental animation and the visualization effect of virtual teachers. According to the results of the user study, users who play as teacher role, believe that the 3D human–computer interface based on Leap Motion is easy to learn, easy to remember, easy to use, has a low error rate, and high overall satisfaction. Users believe that the finger movements of virtual teachers generated by the framework are more fluent and natural, and that the demonstration teaching of virtual teachers is acceptable. For our selected virtual teacher model, most users believe that the appearance is normal, and there is no "valley of terror" effect.

6.1 | Limitations

Although our research has shown application potential in STEAM education, limited by the FOV and brightness of the existing head-mounted display device, the user's evaluation with the display device is not considered. Considering interactive MR experiment education, we believe that normal-size virtual teachers can imitate the relationship between teachers and students in the real world to guide and demonstrate, which is of great significance in the future. The operation track of the virtual teacher is generated by the DMPs algorithm. In the normal-size virtual teacher demonstration animation, the accuracy of the starting and ending points of the track depends on the accuracy of the marker location. In this paper, we determine the position and pose of the starting point and the end point by identifying the marker. If the recognition error of the starting point is large, then the end point of the trajectory will have a large error with the marker of the end point. In a 3D human–computer interface, the data obtained from Leap Motion also have noise or loss. In the future, we can consider a crowdsourcing-based method, combining multiple motion tracks of the same operation, and generate an experimental operation trajectory in MR via a probabilistic DMPs algorithm. In the user study, the usability of our animation authoring framework has been verified, but it is still in the prototype system stage, and the user guidance and experimental teaching resources still need to be improved.

7 | CONCLUSIONS

In this paper, we have proposed a novel authoring framework for virtual teacher animation. To the best of our knowledge, this is the first MR virtual human animation authoring framework for educators. Any complex experiment is composed of several simple experimental steps; we decomposed the simple experimental steps into grabbing operations and 6-DOF trajectory operations. A 3D experimental interface based on Leap Motion is designed and implemented. Teachers and other nonprofessionals can provide virtual humans with operation trajectory templates through simple HCIs. To ensure that the animation is aligned to the interactive MR environment, we used the DMPs algorithm to adaptively generate the virtual teacher motion trajectory in the MR environment. The adaptive grabbing animation is generated by DRL algorithm and replaced the captured hand animation. User evaluation showed that our framework is easy to use, and the virtual teacher's experimental demonstration animation has a certain education significance.

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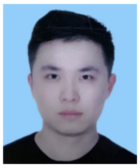

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