An Interactive Mixed Reality Platform for Inquiry-Based Education

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***Abstract*—Mixed reality technology presents new opportunities for educational applications through its combination of real and virtual worlds. Recently, a growing interest has been noted in inquiry-based learning that emphasizes active learning and personalized education. Accordingly, this paper proposed a mixed reality-based interactive media platform for an inquiry-based learning environment in which the users were able to explore a wide range of optional experiments under the instruction of the inspectors. A sequence of mixed reality technologies are combined in this environment. Users became immersed in an interactive media space, while the environment responded with the user via interactive displays fitted on the experimental utilities and furniture. User behavior was instantly recorded and interactively visualized for the inspector to make decisions on the instructions. A prototype was then designed for this environment, and an evaluation was conducted to test its applicability. Overall, the participants revealed that the 3D printing experimental utilities were effective in enhancing their sense of reality, while the virtual interactive 3D scene played a key role in extending the inquiry base. Furthermore, it enabled users to have more freedom in conducting exploration compared to traditional experimental environments.**

Keywords—mixed reality, inquiry-based learning, user experience, interactive design, touchdesigner

I. INTRODUCTION

In recent years, due to the rapid development of mixed reality (MR) technologies, integrated environment designs connecting real and virtual worlds have been applied in the education sector. Limits imposed by location, teaching resources and facilities are being released nowadays due to the development of the Internet, computer graphics and mixed reality technologies.

In many studies, mixed reality has been shown to increase the sense of immersion, presence and reality for students, thereby increasing concentration, integrity and performance in their studies. In such applications, the virtual scenes are created by graphics engines simulating and recreating various education scenarios, including abstract figures, animations, and realistic physics-based simulation. In addition, with mixed reality technology, collaboration both remotely and on-site are combined, and the boundary between the real world and virtual world studies is blurred.

Inquiry-based learning (IBL) is of notable interest in education as a methodology that is known to enhance interest and engagement in study, thus improving a user's experience, activeness, intellectual ability, collaboration, and performance, especially in scientific study and experimental practice. IBL emphasizes certain learning activities such as active participation, self-driven exploration, formative discussion and collaboration. Effective IBL is conducted under the teacher's instruction; therefore, it is highly dependent on the teacher and teaching environment.

Though mixed reality technology has been applied in various education settings, the combinatory design of real-virtual worlds for IBL presents new challenges. The user becomes immersed in an open environment accessible for student groups. The exploratory scene and storyline could branch with multiple solutions with hierarchical or even looping structures according to the course syllabus and student discussion. As a result, adequate experiment options of trial and error are required for students, simulating the real-world experimental procedure. Personal interest, knowledge base and background can exert influences on student inquiry behavior; therefore, learning activities can be personalized. A situation=aware instruction inspires the student more accurately in conducting scientific exploration. While the teacher's instruction in inquiry-based learning is essential, the role of the teacher or inspector is under-investigated and lacks support in mixed reality environment design.

In this paper, an interactive mixed reality platform is proposed for inquiry-based education with the following contributions.

1. The framework proposes a design strategy integrating course syllabus, branching tasks, task workflow with the media

space design. Specifically, a sequence of mixed reality techniques are mapped with module breakdowns, including motion capture, physics sensors, and interactive projection.

2. The inspector's role was explicitly supported as an independent component in the environment. An inspection module is designed to enable the teacher in keeping track of user behavior and providing effective feedback instructions.

3. The design framework is demonstrated by taking middle school chemistry reactions as an example. Notably, the framework can be extended to many other IBL applications. According to the present user study, the system supports a wide range of exploratory virtual reactions.

II. Related Works

Mixed reality technology has introduced new means, approaches and experiences in engagement, collaboration, and inspiration [1], [[2].

Recent advances in mixed reality technology have fostered the rapid creation of virtual content and applications in education. Hughes et. al. proposed that MR applications in education enhance the overall experience and encourage repeated visits, thus stimulating curiosity and forming a positive attitude towards content [3]. Mateu et. al. developed a software package, Virtual Touch, in order to connect the virtual world with the real world and help teachers create teaching syllabi conveniently [4]. MiRTLE is a partially physical and virtual conference space where students both in the classroom and remotely may interact with the teacher in the real and virtual worlds [5].

Collaborative mixed reality environments join distant learners together and enable them to share their experiences. SMALLable is a mixed reality framework allowing students and teachers to collaboratively design course syllabi incorporating both visual and audio information [6]. MARVEL is a virtual mechanics and electronic laboratory that employs mixed reality to connect the real and virtual worlds, allowing students to join the real lab in a virtual environment [7]. TIWE Languastico is a mixed reality environment for an English competition where virtual and real players compete in a game [7]. Nikolakis et. al. proposed a mixed reality system using touch gloves to manipulate virtual 3D geometries, which was proven to be effective for geometry in several rounds of evaluation in secondary schools [9].

Augmented reality is represented by image registration and the tracking of real-world objects, which presents natural approaches in interaction. Fjeld et. al. presented an augmented reality system for users to interact with the virtual view of chemicals' microscopic structures via models with markers [10], [11]. This system improved students' interests and performance in understanding abstract concepts. Iordache et. al. developed a platform for learning chemistry elements, in which students were able to demonstrate a better understanding with a reduced workload [12].

Recently, Inquiry-Based Learning (IBL) has established improvements in fostering a better understanding of scientific thinking as well as a positive and sustainable learning attitude [13]. Abdi et. al. suggested that students receiving inquiry-based education exhibited better performance compared to traditional education [14]. Hmelo-Silver et. al. found that IBL is a powerful study methodology known to reduce cognitive load, which may achieve comprehensive teaching targets, such as knowledge, collaboration and self-driven study [15]. Pedaste et. al. raised the importance of teachers in IBL in guiding students to define questions, further analyze problems and solve problems in order to deepen their impressions and establish a meaningful level of learning [16]. Lin et. al. pointed out that tracing and recording learners' learning behaviors and states would benefit teachers in adjusting their teaching strategies and methods while enhancing learners' learning performance [17].

Mixed reality has also been used to support IBL [18][19]. Kang et. al. presented and evaluated a new mixed reality tool called SharedPhys, which tightly integrates real-time physiological sensing, whole-body interaction, and responsive large-screen visualizations to support new forms of embodied interaction and collaborative learning [20]. Dunleavy et. al. collected data through formal and informal interviews, direct observations, web-site posts, and site documents [21]. Kaufmann et. al. presented a fully functional educational AR application for mathematics and geometry education [22]. Kang et. al. also proposed a multi-stage, mixed-methods approach in order to evaluate the potential of live physiological sensors, whole-body interaction, and large-screen visualizations to engage children in playful, collective inquiry [20].

III. Environment Design

The present design combined real components and virtual components in order to satisfy several target goals. A task flow was designed as a storyline of our environment, and the target application represented an interactive environment that can be portable to accommodate various teaching environments.

A. Design Strategies

Inquiry-based education attaches importance to the balance between student-oriented active exploration and instructions from teachers. This designed real-virtual environment adhered to the following principles:

1. Creating content supporting an exploratory environment. The virtual content should support an exploratory scene. The users are then immersed in an environment where they can try different operations by following similar rules. For example, in a chemistry laboratory environment, students are expected to be able to explore different chemicals and apply utilities to conduct tests on different reactions. As they develop their hypothesis, they may repeat the same reaction or similar reactions to reach their own conclusions.

2. Fostering an immersive experience, both from virtual generative digital images and from the real-world environment. Although virtual scenes enhance inclusive content and promote free inquiry, in pure virtual immersive environments, certain unnatural manipulations have to be superimposed and present a challenge in more realistic user experiences. Using real-world replications instills a sense more similar to the real-world and increases user engagement. For example, the physics sensors attached to real objects allow the user to operate on a real object, while operational information gets passed to the system in order

to interactively generate images consistent with the user's operation.

3. The environment should generate an adequate user experience for inspectors. The inspector needs to check the user's behavior, research the user's experiences, and provide instructions and feedback to the user. There needs to be an inspection module included in the system to facilitate first-hand, yet easy to parse, data presentation for the inspector.

4. Our target teaching environment is a collaborative space with a size that is typical for inquiry-based teaching. It could be taken as a classroom group discussion site or a public space, such as an experimental booth in a museum. Collaboration with virtual users has been investigated in many previous studies. However, concept discussion and collaborative communication are difficult to practice within the virtual world. Group effects such as a study atmosphere, the actions of peer review, peer discussion and even the sense of peer pressure and stimulation are difficult to deliver simply through language, text and voice communication.

Thus, our environment is designed for the user, system, and inspector as integrity (see Fig. 1).

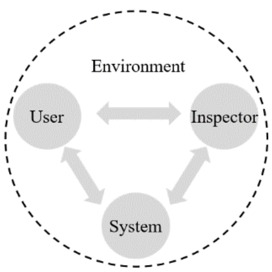

Fig. 1. Real-virtual environment

B. System Framework

In the target environment, real components and virtual components are designed in combination. Real components include real objects that can interactively influence and respond to virtual content. They also hold responsibility for the connection between the real environment and virtual digital content.

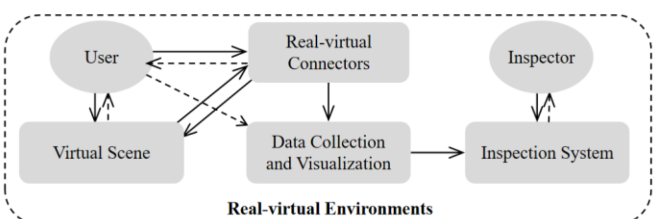

Fig. 2. System framework supporting the environment with real-virtual world contents, and fostering inspection work.

Virtual components are comprised of the virtual scene for the users as well as data collection and representation for the inspectors to capture a user's behavior. The virtual scene is created to extend the limitation via real-world objects. The user's behaviors, including all manipulations made to the virtual scene objects and real objects, are collected by the recording module. The recorded data is then parsed, visualized and presented for the inspector. The corresponding framework is illustrated in Fig. 2.

Mixed reality technology integrates the presence of the real world with digital content created using computer graphics and animations. The knowledge bank supporting reasonably wide exploration options is ensured by the generative scene in line with the scientific rules.

C. Task Design

Inquiry-based education activities follow the sequences of an integrated procedure, which is generally comprised of five groups: orientation, centralization, experiment, conclusion, and discussion. Fig. 3 depicts the workflow of an inquiry-based teaching course syllabus with the exemplary tasks of orientation, instructed exploration, and free exploration.

First, the orientation and introduction present a procedure for the users to immerse themselves in the learning context and connect with the environment both physically and conceptually. Then, an instructional orientation, inspirational questions and introduction are presented to promote the core question or study topic. This is followed by an experiment conducted through exploration, experimentation, or data analysis. Finally, conclusions are drawn pertaining to the raised questions following a thorough discussion and communication. The discussion may also involve a test and evaluation.

In an IBL procedure, there may be steps that do not have to be necessarily completed prior to moving on to the next step. The student may disengage from an ongoing task in order to pursue another one, speculate on the questions proposed, or come to a conclusion before the experiment is accomplished. One may also repeat any conducted experiments for further confirmation, better understanding, or closer inspection. Their behavior serves as the evidence essential for teachers to understand their level of study. The system should also be made open to branching other options in the environment.

Throughout the process, the student's activity is supposed to be inspected by the teacher either directly or indirectly. The platform should automatically record the user's behavior and reflect it in a meaningful manner for the teacher.

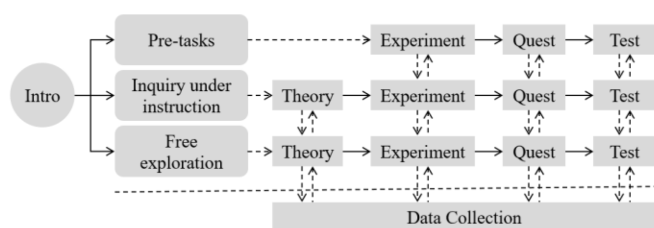

Fig. 3. Task flow, structure and groups with 3 example learning tasks.

IV. Media Space Design and Prototype Setup

As mentioned before, an inquiry-based course is designed in line with the teaching goal and the designed syllabus. To better illustrate the platform design and environmental design, we take the middle school chemistry reactions as an exemplary course.

Our designed environment is demonstrated in Fig. 4. The space is comprised of the user zone and the inspector zone. In the user zone, large-area planar projection is combined with a small area LED display to present the virtual digital scene. Large space projections on e.g. desktop and walls give comfortable and natural view, and benefit for the sharing of information among the study group. A small size display with a higher resolution is fit for a realistic view rendered for a more focusing zone, such as the actual phenomenon to observe.

With the assistance of motion capture technology and physics sensor, the user's behavior is captured to exert influence on the interactive scene. The generative scene is rendered to digital images and then projected on an experiment desk for sharing on the display attached to real physics media suites, turning them into connectors between the real and virtual world. In this way, the user zone is transformed into an interactive space.

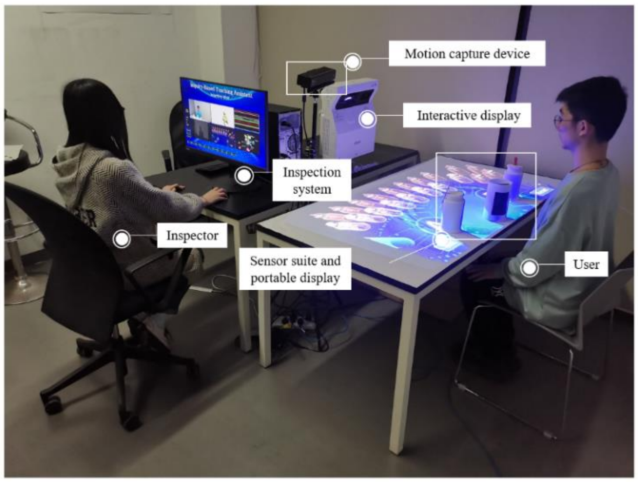

Fig. 4. Mixed reality environment with virtual displays.

A. System Implementation

We implement the prototype system with TouchDesigner. TouchDesigner is an interactive media art creation platform that supports a complete graphics engine and a variety of multimedia devices. The system is composed of web pages to present and connect the course workflow, and task interfaces, the virtual scene to render the experimental space, the interactive display and sensor suite to connect the virtual scene with real-world manipulators, the physics-based simulation for the generative phenomenon, and the data collection and visualization for the instructors. The data flow and system architecture are illustrated in Fig. 5.

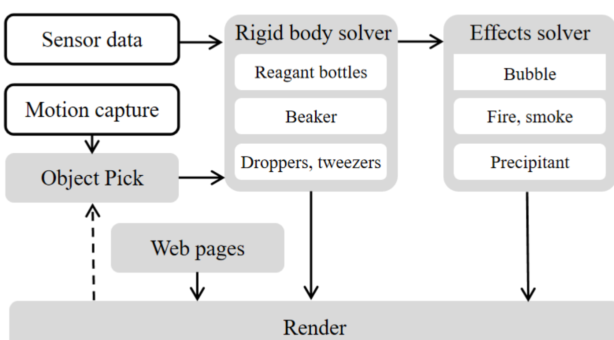

Fig. 5. The data flow and system hierarchy.

B. Workflow and Task Interface

The teaching syllabus is presented as web documentation. Web pages are efficient in creating the structured digital content including texts, images, and videos. Among the task components, the orientation and introduction(a), the pre-tasks(b-c), the inspiration(d-e), the discussion, test and evaluation(f-h), and the conclusion(i) are presented as web pages. The web pages are rendered to our virtual scene and displayed with the desktop projection as illustrated in Fig. 6.

Fig. 6. Web pages for workflow and task interfaces.

C. Virtual Scene

The essential virtual experiment is presented with a realistic graphical scene comprised of an experiment desk, 20 reagent bottles, a reaction beaker, several droppers and tweezers, and a trash can, as illustrated in Fig. 7. With these representative reagents of metal, metal oxide, acid, and alkali, over 20 middle school chemistry reactions are supported for exploration. The soluble liquids are kept in bottles with droppers, while the insoluble solids are contained in the bottles with tweezers.

In the bottom part of the scene, there is a "Reset" and "Return" button, enabling the students to actively redirect from the experiment scene back to the main course.

All objects are simulated as rigid body actors, meanwhile, they are influenced by user manipulation. The users explore by picking, dragging and opening bottles to observe the chemicals inside in the virtual scene.

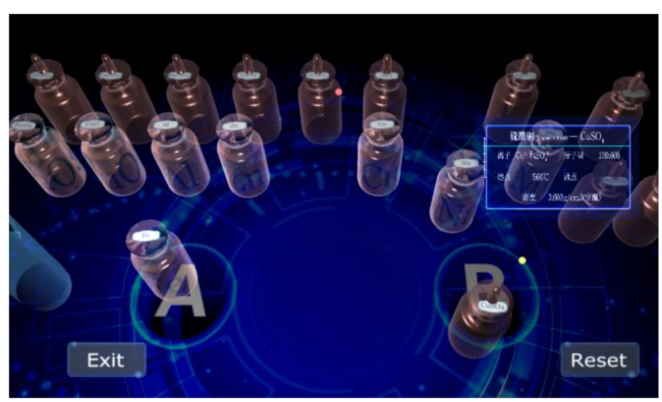

Fig. 7. Virtual scene and interactive display.

The center part of the scene is left empty, and it is the zone for real-virtual connector utensils in the real-world. The replicas of chemical reactant bottles are placed on the circles marked with "A" and "B", while the reaction beaker is placed on the center circle. The users may drag one bottle from the virtual scene to the real reactant zone A or B, indicating that the chemicals represented by that virtual bottle are "transformed" into the corresponding real reactant bottle. The real bottle becomes an avatar for an arbitrarily chosen chemical bottle, and the manipulations on these avatars are mapped to their virtual equivalents.

D. *Interactive Display and Sensor Suite*

Motion capture combines technologies to reconstruct the joint positions and orientations of the users that can be used to reconstruct the user poses and motion. We used Kinect V2 to capture the user gestures without wearing any electronic device. Through an analysis of the infrared image and the depth image, the 3D positions of character joints are captured and used to record and reconstruct the user behavior. As an image-based solution, the resolved 3D positions are sensitive to the image quality and the environment complexity, inaccurate and sometimes ambiguous. It is especially challenging to capture fine motor actions, such as web page clicking and reagent bottle picking, leading to hopping joints and gestures. Therefore, we used a more accurate infrared multi-touch to trace clicking and dragging events.

In the design of environments combining real and virtual worlds, the sense of reality is an important factor to consider. Although the 20 chemicals in the virtual scene potentially satisfy the requirement of free exploration over an extensive amount of representative chemical reactions and various phenomena, the sense of holding real bottles and manipulating with real equipment is different from virtual scene operations. Moreover, realistic challenges are presented only in real-world operations. For the chemical experiment training, a critical task to evaluate is to correctly manipulate the real-world experimental equipment. Virtual world operations cannot achieve this goal.

Therefore, we used 3D-printing techniques to create models as the real-world replica of utensils in the virtual scenes. The design is demonstrated with 3 implementations representing a dropper bottle for soluble chemicals, a bottle with tweezers for insoluble chemicals and a reaction beaker for demonstrating the reaction phenomenon.

For the reactant bottles, a series of user operations needs to be captured, including opening the bottle, squeezing and releasing the dropper, and pressing the tweezers. We develop utensil suites combining pressure sensors and light sensors. To simulate the real-world bottles, a Wi-Fi module and batteries are encapsulated inside the bottle. We used Arduino to send and receive sensor data from the suite. The electronic structure, the real-world suite and the application scene are illustrated in Fig. 8.

For the beaker, an LED display and an accelerometer are attached to the 3D printing model of the beaker. The kinematic pose of the real beaker is resolved from the accelerometer signals, and the virtual beaker is driven by both the resolved real beaker pose and the interactive collision with other virtual objects in the scene. In combination with the simulated chemical fluid dynamics and reaction phenomena, the generative scene is eventually rendered to images and shared on the LED display.

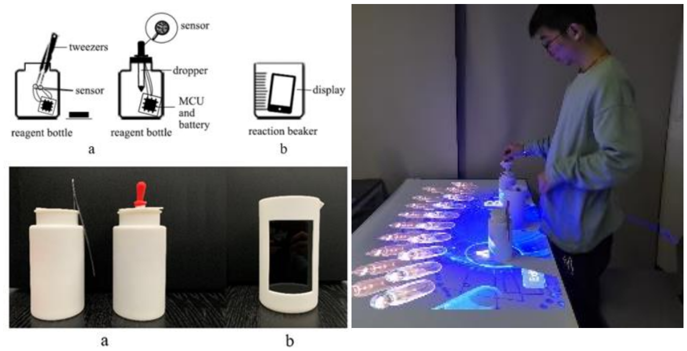

Fig. 8. Sensor suite design and in the environment.

E. *Simulated Scene*

In our demonstrated application, the major generative scene is the chemical reactions with soluble liquids and insoluble solids. The chemical reactions lead to such phenomena as combustion, gas bubble generation, precipitant generation and solution color change. The liquid chemical solutions are simulated using a turbulence fluid field. The gas bubbles and precipitant are simulated as light particles in the liquid. The interactively generated images inspire the students to take active participation and encourage them to conduct further inquiry and exploration.

Due to the limited simulation accuracy and rendering quality in a real-time scenario, generative images are not as realistic as live images. Therefore, the live video, along with the chemical reaction equation and explanations is presented as an attached reference to the students for more comprehensive and accurate delivery of the knowledge, as shown in Fig. 9.

Fig. 9. Chemical reaction simulation(up) and comparison with real world phenomenon(bottom).

Our design is carried out to create an environment with components utilizing virtuality where abstraction and extension are necessary, and using reality, where sensory realism, naturalism and intrinsic shareability are more important considerations.

F. Data Collection and Visualization

User behavior is recorded for the benefit of inspectors. Operation log plays an essential role in automatically recording the user's behavior. While the recorded data is precise in reflecting the detailed operations, it also contains the sequential patterns and variations, behavioral repetition and preferences. Due to the amount of quantitative data, it is often challenging to parse the information.

Experienced teachers intensively observe the student behavior and capture the student actions as well as psychological hints. Decisions are made based on the student behavior, and instructions are provided, leading towards a personalized inquiry path. This procedure requires a high cognitive workload and a low student-to-instructor ratio. Part of the instruction could be automated with design, while others are related to the teachers' experience, on-site decision, teaching style and intermediate targets. Therefore, the instruction is a complex and mixed procedure that cannot ignore the role of the teacher.

Therefore, the inspector in IBL environment plays an important role by observing the user behavior, speculating on the study procedure, and giving instant feedback. More advanced tools are model-dependent and algorithm-dependent. Extensive study is required to correctly parse the analysis results and especially, to match up with personal teaching experience. In the inspection system, we instead visualize the raw data faithfully and release the decision-making to the teachers. To facilitate teaching and instruction, we record the user behavior details and reappear from various perspectives for the teachers to view the students with multiple optional focus and a more efficient way.

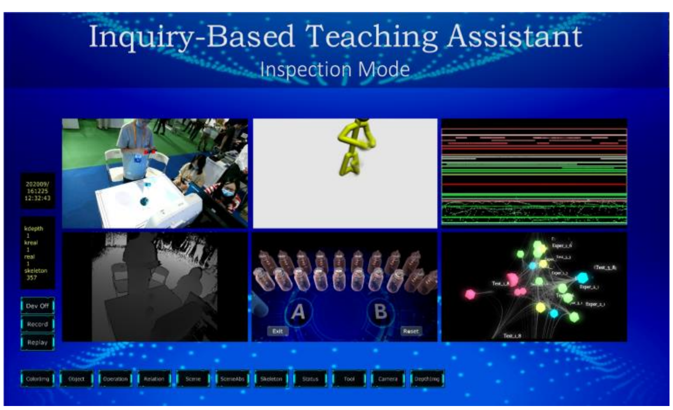

Fig. 10. Inspection system and visualization

In the inspection system, the following images are displayed (see Fig. 10).

1) the real image and depth image of the real environment scene,

2) the virtual scene and the reconstructed user skeleton,

3) the visualization of user operation data including the web page manipulation, the virtual scene operation, and the sensor feedback,

4) the visualization of a knowledge graph.

The knowledge graph demonstrates the structures of the task components. Each component is indicated by a node. The task group is distinguished by the node color. The activity frequency is mapped to the node size, and the transition probability between each pair of web pages is indicated by the thickness of the connecting wires.

Our presented visualization clearly illustrates the operation log and facilitates the teachers to visually and directly capture the students' operation with less workload.

V. User Experience

In the present study, to evaluate the design and validate its implementation, a user study was carried out by interviewing five users. Each user possessed experience in usability tests and evaluations, while three were experienced in using head-mounted mixed reality devices. None were experienced in educational applications for experiments.

Most users were excited about testing in an experiment. We collected the most frequently proposed comments and responses as follows.

1) The 3D-printing chemical reagent bottles provided a smooth sense of touch. Their outlooks were different from traditional fragile glass ware and presented a degree of freshness, attracting students to be involved in a safe and broad exploration. Their conformal geometric shape and opaque material implied an extensible chemical connotation as well as a potential variation for the materials inside. This also fostered the students' active imagination and recollection of related knowledge. Some students felt that the action of operating on real chemical bottles increased their interest, and they became more engaged in the study.

2) The interactive display transformed a regular laboratory desk into a study environment. The transformed desk with a blue background design rendered a mysterious and focusing atmosphere.

3) Some users liked the introduction web pages as it enabled complete storytelling and introduces the users to be involved within the unfamiliar environment. The users preferred to continue their exploration before jumping to a conclusion or test. They preferred to communicate with a real teacher towards the end of the exploration, especially in the case when conclusions with multiple perspectives are derived.

4) Some users felt that the LED display in a beaker was an interesting idea. Interacting by shaking the bottle seemed interesting to them and attracted them to conduct further observations. Some students stated, "People have been wondering about the amazing real chemistry phenomenon, and it has inspired the scientists for deeper and continuous study. I guess wondering about the virtual vision could have a similar effect on the students, and it is fun too."

The first round of tests used a Kinect only to capture operations, such as clicking on a web page and grabbing a virtual bottle. Some users said that it took several tries and that the bottles could lose track of the bottle in the middle. The later version of the infrared frame was much smoother and was more accurate in its operation.

In the conducted study, users experienced with head-mounted displays, such as Oculus Rift, HTC Vive, or HoloLens, preferred the feeling of directly interacting with real objects. Projected display on stable desks gave a stable sense without dizziness. Some users appreciated the spacious feeling with the information seamlessly presented with the surrounding environment, such as enlarged pages on the table or posters on the wall. In addition, several users considered it friendly to share their experiences openly with others nearby without any device control and limitation. One user expected to share the beaker display with a surrounding view. One also suggested a more immersive environment.

Some testers felt that although the real objects and virtual extension of the lab desk shared the same space, switching from hand gestures to grabbing real bottles was somehow making the users feel distant. However, once they figured out this connection, they felt it natural to continue the same interactivity in more experiments. Some users complained that the bottle was too big to hold and was somehow heavy. They expected the electronic suites to be more streamlined. We are working on further compacting the test suites.

One chemistry teacher was interviewed. She was worried that this suite may not fully hold capacity for classroom teaching, but could be used in experimental classes with groups, in which a single student's inquiry would arouse other students' reflections and discussion. She felt it would be very interesting to have it in a science museum and that it could accommodate table games. She also suggested that this reaction was not as realistic as there was no respect for the actual quantities of the chemicals and their changes. She suggested to more accurately simulate the phenomenon based on the number of chemicals inside. It would also be beneficial to display such information. The visualization of student behavior was helpful but somehow lacked a more meaningful analysis. A comparison between different students could also have been helpful.

VI. CONCLUSION AND DISCUSSION

This paper presented a mixed reality environment and interactive platform for inquiry-based education. Accordingly, this design addressed several issues that were proposed but were not limited to an educational environment. By emphasizing hybrid real-virtual environment design, the demonstrated example system was evaluated with a user study and received positive feedback on the real-virtual connector design, storyline design, the inspector's interface and support to the teacher's engagement.

Although the proposed design was shown to be effective in increasing learning interests, concentration and fostering group collaboration, teacher evaluation and teacher-student collaboration, certain challenges remain. In a mixed reality platform design, content creation and system design are inseparable. Moreover, the traditional iterative design implementation has some challenges. In this regard, the present paper put forward an attempt to incorporate the inspection component within the early design process. A more advanced visualization tool would require more work and requires an independent component in the framework.

The electronic suite is too big for holding and is heavily used. For a better collaborative effect, using additional suites on surrounded tables may be better for small user group discussions. The inspector should be able to view all users' operation data and parse peer comparison. Although the teaching strategy was designed as a web page, the structure and teaching content design was not visualized.

In a mixed reality environment content and system design, technical rehearsal and comparison require more rounds of implementation. Although the replacement of components was designed, it was not demonstrated, except for the desktop interaction approaches. As a result, we would like to further investigate the influence of component replacement along the virtuality continuum.

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REFERENCES

[1] A. Ali, G. A. Dafoulas, and J. C. Augusto, "Collaborative educational environments incorporating mixed reality technologies: A systematic mapping study," IEEE Trans. Learn. Technol, vol. 12, pp. 321–332, 2019.

[2] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays," IEICE Trans. Inf. Syst, vol. 77, pp. 1321–1329, 1994.

[3] C. E. Hughes, C. B. Stapleton, D. E. Hughes, and E. M. Smith, "Mixed reality in education, entertainment, and training," IEEE Comput. Graph. Appl, vol. 25, pp. 24–30, 2005.

[4] J. Mateu, M. J. Lasala, and X. Alamán, "Developing mixed reality educational applications: The virtual touch toolkit," Sensors, vol. 15, pp. 21760–21784, 2015.

[5] M. Gardner, J. Scott, and B. Horan, "Reflections on the use of Project Wonderland as a mixed-reality environment for teaching and learning," in Proceedings of the ReLIVE 08 Conference, Milton Keynes, UK, 2008, pp. 130–138.

[6] L. Tolentino, D. Birchfield, and A. Kelliher, "SMALLab for special needs: Using a mixed-reality platform to explore learning for children with autism," in Proceedings of the NSF Media Arts, Science and Technology Conference, Santa Barbara, CA, USA, 2009, pp. 29–30.

[7] D. Mueller and J. M. Ferreira, "MARVEL: A mixed-reality learning environment for vocational training in mechatronics," in Proceedings of the Technology Enhanced Learning International Conference (TEL 03), Milan, Italy, 2003, pp. 25–33.

[8] A. Fiore, L. Mainetti, and R. Vergallo, "An Innovative Educational Format Based on a Mixed Reality Environment: A Case Study and Benefit Evaluation," in International Conference on E-Learning, E-Education, and Online Training, 2014, pp. 93–100.

[9] G. Nikolakis, G. Fergadis, D. Tzovaras, and M. G. Strintzis, "A mixed reality learning environment for geometry education," in Hellenic Conference on Artificial Intelligence, 2004, pp. 93–102.

[10] M. Fjeld, P. Juchli, and B. M. Voegtli, "Chemistry Education: A Tangible Interaction Approach," in Proc, INTER4CT, 2003, pp. 287−294.

[11] M. Núñez, R. Quirós, I. Núñez, J. B. Carda, E. Camahort, and J. Mauri, "Collaborative augmented reality for inorganic chemistry education," in

WSEAS international conference. Proceedings. Mathematics and computers in science and engineering, 2008, vol. 5, pp. 271–277.

[12] D. D. Iordache, C. Pribeanu, and A. Balog, "Influence of specific AR capabilities on the learning effectiveness and efficiency," Stud. Inform. Control, vol. 21, pp. 233–240, 2012.

[13] R. W. Marx et al., "Inquiry-based science in the middle grades: Assessment of learning in urban systemic reform," J. Res. Sci. Teach, vol. 41, pp. 1063–1080, 2004.

[14] A. Abdi, "The Effect of Inquiry-Based Learning Method on Students" Academic Achievement in Science Course," Univers. J. Educ. Res, vol. 2, pp. 37–41, 2014.

[15] C. E. Hmelo-Silver, R. G. Duncan, and C. A. Chinn, "Scaffolding and achievement in problem-based and inquiry learning: a response to Kirschner, Sweller, and," Educ. Psychol, vol. 42, pp. 99–107, 2007.

[16] M. Pedaste et al., "Phases of inquiry-based learning: Definitions and the inquiry cycle," Educ. Res. Rev, vol. 14, pp. 47–61, 2015.

[17] F.C. Lin, C.M. Chen, and W.F. Wang, "Learning process analysis based on sequential pattern mining and lag sequential analysis in a web-based inquiry science environment," in 2017 6th IIAI International Congress on Advanced Applied Informatics (IIAI-AAI), 2017, pp. 655–660.

[18] L. Johnson, A. Levine, R. Smith, and S. Stone, The 2010 Horizon Report. ERIC, 2010.

[19] B. E. Shelton, "Augmented reality and education: Current projects and the potential for classroom learning," New Horiz. Learn, vol. 9, 2002.

[20] S. Kang, L. Norooz, V. Oguamanam, A. C. Plane, T. L. Clegg, and J. E. Froehlich, "SharedPhys: Live physiological sensing, whole-body interaction, and large-screen visualizations to support shared inquiry experiences," in Proceedings of the The 15th International Conference on Interaction Design and Children, 2016, pp. 275–287.

[21] M. Dunleavy, C. Dede, and R. Mitchell, "Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning," J. Sci. Educ. Technol, vol. 18, pp. 7–22, 2009.

[22] H. Kaufmann and D. Schmalstieg, "Mathematics and geometry education with collaborative augmented reality," in ACM SIGGRAPH 2002 conference abstracts and applications, 2002, pp. 37–41.