Virtual and Augmented Reality for Teaching Materials Science: a Students as Partners and as Producers Project

Marie-Luce Bourguet
School of Electronic Engineering and Computer Science
Queen Mary University of London
London, UK
marie-luce.bourguet@qmul.ac.uk

Yaxin Ran
International School
Beijing University of Posts and Telecommunications
Beijing, China
y.ran@se16.qmul.ac.uk

Yue Zhang
International School
Beijing University of Posts and Telecommunications
Beijing, China
yue.zhang@se16.qmul.ac.uk

Xiangyi Wang
Queen Mary Engineering School
Northwestern Polytechnical University
Xian, China
xiangyi.wang@se17.qmul.ac.uk

Zeyu Zhou
Queen Mary Engineering School
Northwestern Polytechnical University
Xian, China
z.zhou@se17.qmul.ac.uk

Maria Romero-Gonzalez
School of Engineering and Materials Science
Queen Mary University of London
London, UK
m.romero-gonzalez@qmul.ac.uk

***Abstract*—Two visualisation techniques have recently gained great momentum in education: virtual reality (VR) and augmented reality (AR). In materials science education, VR and AR are potentially very useful when teaching about a topic that is difficult to experience due to being abstract or invisible, or when availability of equipment and space is a limitation. In this paper, we describe a co-creation and multidisciplinary project between students and staff in two University departments for the design and prototyping of VR and AR simulations to teach materials science. The VR prototype is a virtual laboratory where the classic Rockwell hardness test can be experienced; and the AR prototype simulates the optical transmittance properties of some transparent materials.**

Keywords—materials science, students as partners, students as producers, virtual reality, augmented reality

I. Introduction

Virtual Reality (VR) and Augmented Reality (AR) relate to visualisation, where images, diagrams, or animations are used to communicate a message. *Scientific visualisation* is the use of interactive and visual sensory representations of abstract data to reinforce cognition, hypothesis building, and reasoning [27]; *educational visualisation* typically uses simulations to create images of a subject so it can be taught about [22]; and *knowledge visualisation* refers to the use of visual representations to transfer knowledge between at least two persons by using computer and non-computer-based methods complementarily [8,19]. In this paper we report work at the intersection of scientific, educational and knowledge visualisation with the aim of supporting teaching and learning in the domain of materials science.

In materials science, visualisation is potentially very useful when teaching a topic that is difficult to experience due to being abstract or to a lack of physical interaction. In our university programme, one of the main challenges teaching material science to year 1 and year 2 undergraduate students is the large number of students (ca. 300). For these large cohorts, experiencing fundamentals of elastic and plastic deformation, fracture mechanics and fabrication processes of materials in a laboratory environment is not feasible. The amount of equipment and space facilities is a limitation when teaching these aspects. Our aim is thus to use visualisation techniques and simulations to create a virtual laboratory where students can perform short experiments on examining mechanical properties of materials, for example, stress-strain behaviour of metals, hardness test and fracture toughness testing. We also aim to develop experiences for enhancing the understanding of physico-chemical properties of materials such as optical and electrical properties, thermal ability and magnetic susceptibility. These properties arise at atomic and electronic level and are often difficult for students to grasp due to their 'unseen' nature. Therefore, establishing relationships between properties at atomic level that result in the behaviour of a material at the macro level becomes the main learning outcome when using simulation techniques.

In order to achieve best results, we adopted the "students-as-partners" [6,14,15] and "students-as-producers" [10,16] models, making this a co-creation and multidisciplinary project between students and staff. In this paper, we describe the design and prototyping of the VR and AR simulations, but more importantly, we describe the roles and processes followed by the students and their experience and collaboration while participating in the project.

In section II of the paper, we present some related work on the use of VR and AR in STEM education. In section III, we explain our staff-student partnership model. In section IV and V, we present the VR and the AR prototypes' design and development processes. In section VI, we evaluate our staff-student partnership model, and in section VII, we conclude the paper with a discussion on the lessons learned from the project and our future work.

II. Related Work

Two visualisation techniques have gained great momentum in education in the past few years: virtual and augmented reality [9,13,21]. VR is a simulated experience that can be similar or completely different from the real world. It can be used to immerse viewers in a completely virtual world where the usually invisible is made visible (e.g. inner materials structure) [1,2,17,29]. AR is an interactive experience of a real-world environment where the objects that reside in the real-world are enhanced by computer-generated perceptual information [3,4,5,20]. It can be used to superimpose the invisible to the visible (e.g. mechanical forces).

In engineering education, the use of 3D virtual laboratories has been popular as a resource for providing students with practical experiences that sometimes remove the dangers associated with the use of harmful chemicals or the operation of large machines [22,29]. According to [25], the engineering education applications based on VR cover approximately half of the total number of VR resources: VR for teaching engineering subjects have been shown to provide technical results like those obtained in a real practice, while allowing the inclusion of questions and exercises to evaluate the teaching-learning process and enabling kinaesthetic learning. VR learning environments have also been used in gamification, providing opportunities to enhance student engagement [24]. From the students' point of view, the most important features of VR applications are their interactivity, realism, ease of use and educational usefulness [23].

Different from VR, AR-based systems superimpose data analysis and simulation results directly on real-world objects, augmenting a user's perception and cognition of the world and offering the ability to explore data and numerical simulations interactively [12]. Building AR environments as classroom resources, contribute to facilitating the learning process through the exploration and analysis of physical phenomena, often described using mathematical models. AR allows the students to continue interacting with both the virtual simulations and the real objects around them, which has been shown to have good potential in making the learning process more active, effective and meaningful [28]. In [26], it is suggested that the quality of experience of the learning process can be increased even more greatly by introducing elements of popular augmented reality games in education using mobile phones, and enabling context-aware learning experiences.

III. Students as Partners and as Producers

Our multidisciplinary staff-student VR and AR co-creation project involved two teams of students and staff from two of the Queen Mary University of London (QMUL) transnational educational programmes in China. The team at the Queen Mary Engineering School, Northwestern Polytechnical University (QMES-NPU) is based in Xi'an, and their primary expertise is on Materials Science and Engineering. The team at the QMUL School of Engineering and Computer Science and at the International School of the Beijing University of Posts and Telecommunications (BUPT) in Beijing are experts in Multimedia Engineering. The transnational programmes are collaboratively designed to equip Chinese students with a combination of the best aspects of two different education systems (from the UK and from China). Students receive two separate degree awards, one from each partner institution; teaching is done entirely in English and is shared equally between professors of the host university in China and Queen Mary professors.

The two *student-partners* in the project, from the School of Engineering and Materials Science, have an academic understanding of the subject area and a firsthand experience of the limitations in the delivery of the Materials Science module. They brought their own perspectives about what may be easy or difficult to understand by their peers, and helped academics identify common misconceptions held by undergraduates. They also helped academics identify incorrect assumptions they had about students' needs and prior knowledge. They acted as "clients" of the VR and AR applications, guiding the needs and requirements for the simulations and helping present resources in more accessible or "student friendly" formats to their peers when seeking feedback for evaluating the design of the prototypes.

The two *student-producers* in the project, from the School of Electronic Engineering and Computer Science, designed and implemented the VR and AR prototypes. They are finalist students on our University's multimedia undergraduate transnational programme, well equipped with all necessary pre-requisites to tackle this project, having taken courses on Interactive Media Design and Production (which covers topics such as user requirements gathering, elements of cognitive psychology including human vision, and design techniques), 3D Graphics Programming (which covers 3D modelling, rendering and programming), and Image and Video Processing. They worked part time from October to December 2019, and then full time from January to May 2020 (from home, as this fell within the COVID-19 lockdown period) and used the project as their final year project main output.

At the start of the project, the student-partners contributed to the elicitation of both systems' user requirements, in collaboration with the student-producers and one member of academic staff. User requirements describe what users expect from a system and what the system should do to meet the users' needs. Given the importance of user involvement in the system design, defining a proper and detailed statement of user requirements helps developers set a correct research direction. Student-partners and producers had a first face-to-face meeting in November 2019 (this required the team to travel from Xi'an to Beijing), which was followed by several online meetings. Through discussions, ideas were exchanged about what the VR and AR applications should and can do, and the product specifications were agreed amongst the group. Throughout the project, every discussion and progress made were logged and shared in an online portfolio hosted on the University Learning Management System (LMS).

The requirements were then refined further and made explicit with the help of storyboards drawn by the student-producers. Storyboards are sequences of graphic representations that guide potential users through the various interaction steps with the application. They are used as a communication tool between users, designers and developers. They help users understand how the system will be used and what it will give them.

Finally, the student-partners and the student-producers prepared presentations of the prototypes and designed evaluation questionnaires to collect feedback from their peers.

IV. The VR Prototype

The VR prototype focused on simulating a classic and important experiment in materials science: the Rockwell hardness test. The purpose of using VR is to palliate the lack of availability of laboratory equipment and facilitate the amount of contact time that students can spend learning how to use the instrument. The VR prototype was built using an Oculus Rift VR headset [18] and a Leap Motion sensor [11].

A. The Rockwell Hardness Test

The Rockwell hardness test provides an indication of metal hardness by measuring the permanent depth of indentation produced by a force or load applied on an indenter of the tester. Several different scales may be used from possible combinations of various indenters and different loads, a process that permits the testing of virtually all metal alloys. The specifications for this project included performing this test to measure the hardness in three metal alloys - Low carbon steel: AISI 316L annealed stainless steel, Medium carbon steel: AISI 1045 annealed carbon steel, and High carbon steel: AISI 404C annealed stainless steel. These alloys have different chemical compositions and microstructures enabling the collection of clearly different test result. From a materials viewpoint, this allows the demonstration of how the amount of carbon in an alloy sample affects the mechanical properties of steel.

To perform the hardness test, materials science students need to operate a Rockwell type-tester step by step in a laboratory. For the design of the VR prototype, the process can be divided into 7 steps: Step 1 is to select a test material. Step 2 is to rotate the test force dial. Step 3 is to rotate the lifting handwheel. Step 4 is to adjust the hardness indicator to zero. Step 5 is to push the pressure applying wheel backward and then pull upward after 5 seconds. Step 6 is to read the result. And the final step is to rotate back the lifting handwheel in the anti-clockwise direction.

B. *Requirements and VR System Design*

The functional and non-functional requirements for the VR simulation can be summarised as follows: the system should help students gain a thorough understanding of all the operational steps of the Rockwell hardness test; it should contain (1) an introduction to the Rockwell hardness test, (2) a tutorial on the tester operational steps, and (3) hands-on experimentation and manipulation of the tester; the interaction should be based on 3D hand gesture recognition; three kinds of test metal materials should be proposed (Low carbon steel: AISI 316L annealed stainless steel, Medium carbon steel: AISI 1045 annealed carbon steel, and High carbon steel: AISI 404C annealed stainless steel).

The VR application storyboard sets the usage environment and describes a fictive user named Tom and his goals whilst using the VR system. In addition to introducing the content of the hardness test, the storyboard also describes what items (button, text box, hand icon and instructions) will be displayed in each part of the system and how users can interact with them. Fig. 1 illustrates the first step of the hardness test, which consists in selecting one test material, and check its properties. Students have the option for choosing 3 different samples that represent the different steel alloys available in the demonstration.

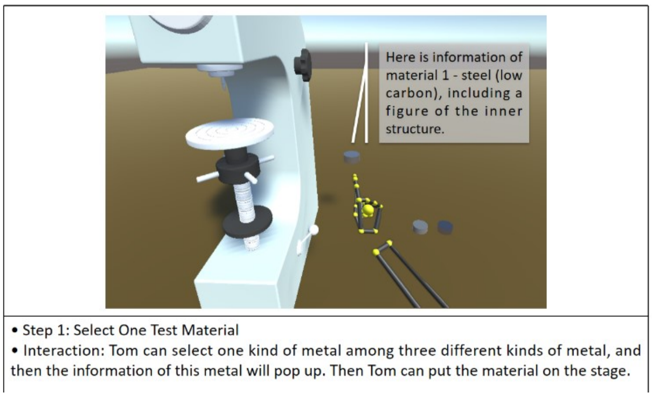

Fig. 1. VR storyboard operating instructions: chosing test samples.

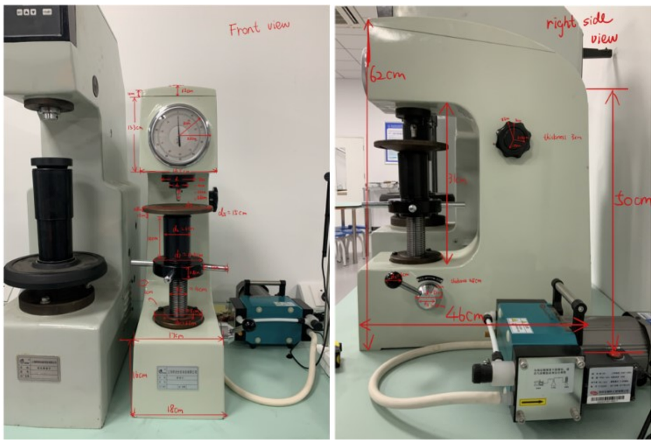

Fig. 2. The Rockwel hardness test physical equipment.

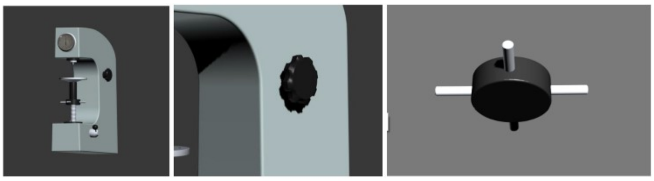

Fig. 3. Perspective view on the Rockwel hardness tester virtual model, and texture.

C. *Implementation*

The 3D models for the Rockwell test equipment and the test materials were realised in 3D Max, after carefully observing the physical objects' appearance and actual measurements. The student-partner provided pictures of the equipment to the student-producer (see Fig. 2). These pictures were taken from different viewpoints and were carefully annotated with precise information about each part of the equipment, providing sufficient information to the student-producer for grasping the dimensions and operative parts of the equipment, the shape and size of each of its component, and create realistic 3D virtual models. The final model is essentially a composition of regular-shaped 3D objects, such as cubes, cylinders, circles and spheres. Some more complex-shaped components were modelled using Boolean calculations, a built-in function in 3D Max to create irregular objects by combining two or more regular-shaped objects.

The next step in 3D Graphics is the rendering of the models, which includes selecting a view and a projection mode, such as perspective, and adding texture to the surfaces (see Fig. 3). Mapping a 3D object with different materials can produce very different visual effects. For example, in the real equipment, the material of the pedestal is metal. Therefore, a metal-like material was chosen in the simulation for its specular reflection properties (to make this part look shiny and hence metallic), whereas the material on the plastic pressure applying wheel, was chosen for its diffuse reflection properties. The interactive functions were implemented in Unity 3D after importing the 3D models in the FBX format. Importing the models into Unity 3D also required embedding the texture materials in binary form, and some geometric transformations of the X, Y, Z axes.

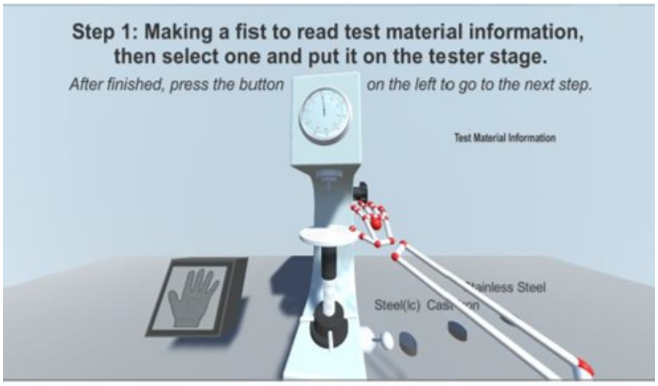

Fig. 4. Various objects rendering in Unity 3D.

Fig. 5. Oculus Rift VR headet and mounted Leap Motion controller for hand tracking.

In Unity3D, by default, there is a main camera and a model of the user's hands for gesture-based interaction with the 3D objects. A UI (User Interface) canvas was added to display UI objects such as buttons and text. The model of the Rockwell hardness tester and of the test materials are placed onto a uniform grey plane area, which simulates a laboratory bench (see Fig. 4). To accurately show users' hands and the UI objects (buttons, etc.), the canvas must be situated in front of the main camera, while leaving some suitable distance (using the Screen space camera mode), so the UI objects don't block the users' view of their hands. The UI objects are important because they are used to provide instructions and prompt the user about how to move on to the next operation step using the tester.

Users' hands are tracked using a Leap Motion controller device mounted on the Oculus Rift VR headset (see Fig 5). The Leap Motion asset package includes plugin files for using the Leap Motion device with Unity 3D on Windows and Mac computers. This package includes scripts and demo scenes to help develop Leap Motion applications quickly, but additional C# scripts had to be written to link hand gestures to 3D objects. Two kinds of interactive functions were implemented: one is using hand gestures to select UI options and navigate through the VR application ("UI interaction"); the other implements hand gesture interaction to manipulate the Rockwell hardness tester and test materials ("test interaction").

UI interaction is achieved through two basic hand gestures from the Leap Motion core assets: making a fist and opening the palm. The test interaction requires recognising different gesture types, such as hovering, contacting and grasping, which were attached through scripting to all interactive 3D objects in the 3D scene. Individual scripts had to be written for object manipulation, for example to rotate the tester's handwheel or to place a test material onto the tester. The rotation function of the pressure applying wheel uses the velocity and angle of the hand palm's movement to control the wheel's transformations and real time changes of position and orientation. As a result, the wheel rotates by the same angle as the user's hand, which provides a genuine sense of direct manipulation.

Unity's Prefab system allows the creation and configuration of "GameObjects" complete with all their components and property values, as reusable assets. The "OVRCameraRig" prefab was used to replace the original camera. With this prefab, users can turn their heads to view the virtual world from different viewpoints rather than from a fixed point. As a basic VR principle, the user's view of the 3D world follows the headset's movements, contributing to the sense of immersion. This was successfully implemented in the Rockwell hardness test VR prototype.

After launching the application and wearing the Oculus VR headset, users automatically enter the first screen, which displays the title and instructions about how to navigate to the Introduction part. The users must go through the Introduction and Tutorial parts before they can enter the laboratory environment and start the experiment. In the virtual lab, there are three test materials to choose from (step one). Once users have completed an experimental step, they can press a button to move on to the next step. Step two for example requires users to rotate the test force dial.

D. *Evaluation of the VR Prototype*

The evaluation of the VR prototype had to be done remotely following the closure of all University campuses and the impossibility to travel during the first part of 2020. Using online communication programmes and social media, the student-partner and the student-producer prepared a presentation video and designed an evaluation questionnaire for the materials science students. The questionnaire contained 10 questions, including multiple-choice and free comment questions: (Q1) Have you ever experienced or used a VR application? (Q2) Do you believe the use of VR can improve your learning of materials science? (Q3) How much do you think the VR application can improve your understanding of the Rockwell hardness test? (Q4) Do you think the VR application can enhance your study experience? (Q5) Do you like the virtual hand model, or do you think the application should include a more realistic hand model? (Q6) About the use of the virtual hand, do you think it would be necessary to include various interactive hand gestures, or would it be easier to have few simple gestures? (Q7) About the background images, would you like to see the surrounding environment simulated as a laboratory? (Q8) Do you understand the steps required to complete the Rockwell hardness test using the VR application? (Q9) Is there anything you would like to suggest for improving the design of the VR application? (Q10) Can you think of any other area of materials science that could be taught using VR? The video and questionnaire were presented to the students during a live online lecture session, and 75 students participated in the evaluation of the project idea.

The results show that only just over half of the students (53.33%) have used a VR application before (Q1), and about 80% of them believe a VR application can improve their understanding of materials science in general (Q2) and of the Rockwell hardness test in particular (Q3). Over 85% of the students think VR can enhance their learning experience, as a faster and easier way to acquire knowledge (Q4). 60% of the students wish the virtual hand to be more realistic (Q5), and 64% would like the 3D environment to be highly interactive using various hand gestures (Q6). An interesting feedback (77.33% of the students) was that a more realistic design of the lab environment (such as the lab space and desk) would improve the quality of the VR experience (Q7). An exact reproduction of the school laboratory that students are familiar with would in fact be the best. 81.33% of the students found the required steps to complete the Rockwell hardness test highly intuitive and understandable (Q8). Finally, an interesting suggestion was to implement a simplified version of the Rockwell hardness test itself (Q9).

Finally, the student-producer created a video of the prototype, which showed the immersive view one would have wearing the VR headset. All interaction was performed by the student-producer herself and covered every step of the virtual Rockwell hardness test lab experiment. The immersive video was shared with the student-partner so he could provide in depth comments and feedback about the VR prototype. In the student-partner's opinion, the VR prototype largely meets all the initial user requirements of a virtual lab that simulates the Rockwell hardness test equipment and experimental steps. It can successfully contribute to improving his peers' understanding of metal hardness. In addition, he judges the prototype easy to use and attractive, and he believes that the smooth and logical system flow, as well as the interactive functions, can greatly help students gain an in depth understanding of the hardness test experiment.

V. THE AR PROTOTYPE

The AR prototype is dedicated to an optical experiment to test the optical properties of polymethyl methacrylate (PMMA) materials. The purpose of using AR is to make the invisible phenomena visible. The equipment used is a pair of Epson Moverio BT-300 smart eyeglasses [7].

A. *PMMA Optical Properties*

Optical transmittance describes the ability of light to pass through some material. It is calculated as the ratio of the amount of transmitted light to the amount of incident light. When a parallel monochromatic beam of light passes through a uniform medium, part of the light is absorbed, part passes through, and part is reflected on the medium's surface. Light has different wavelengths, with visible light ranging between 380 and 780 nm; and ultraviolet light (UV) ranging between 10 and 380 nm. Different materials have different transmittance properties when illuminated with a given light wavelength, and a given material has different transmittance properties depending on the incoming wavelengths. The study of materials optical transmittance is important for the large number of applications that depend on it, from window coatings to computer display equipment, e.g. touch screens.

Most of the mechanism of optical transmittance phenomena are invisible to the naked eyes. This is something that can be addressed with AR technology, by combining real-world physical materials with computer generated virtual interactions between light and materials. The objectives are to help students get a better grasp of the phenomena by making them visible. The AR prototype aimed to help students understand the spectral transmittance of both UV and visible light using polymethyl methacrylate (PMMA) material boards. PMMA is one of the most common types of plastic material, readily available and cheap, that is used in numerous domains, from car windows, smartphone screens to aquariums.

B. *Requirements and AR System Design*

As with the VR prototype, the student-partner and the student-producer cooperated closely during the requirements and design phases of the project via numerous discussions, online meetings and exchange of information and materials (data, illustrations, storyboard, etc.).

Since the main aim of the application is for students to understand optical transmittance in relation to materials properties, the AR system should be able to recognise the different types of materials. The student-producer proposed the use of QR codes, attached to the PMMA boards, and to link these QR codes to stored information such as the material name and the size of the boards (see Fig. 6). This will inform the user about the type and basic characteristics of the material that they are holding in their hands. Another important function of AR is object tracking to combine real-world objects with virtual simulations (see Fig. 7).

Finally, the various functions of the AR system and the interaction flow of optical transmittance experiment were captured in a storyboard, illustrated in Fig. 8. In scene 3.1, students choose the light source (UV or visible light). In scene 3.3 (the 'Optical experiment-UV light wavelength' scene), students choose the wavelength of the UV light, and in scene 3.4 they can observe the resulting spectrum of light interacting with the PMMA board. Scene 3.2 is a simulation of visible light interacting with the material.

Fig. 6. QR code scanning.

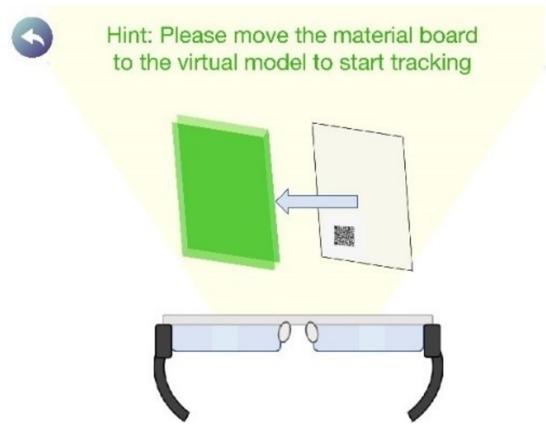

Fig. 7. Object tracking.

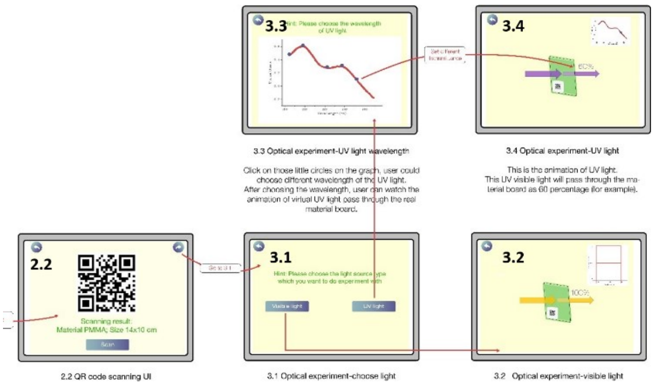

Fig. 8. AR optical transmittance experiment prototype storyboard. The text is kept for illustration purposes and not intended to be readable.

C. Implementation

The Epson Moverio BT-300 eyeglasses (see Fig. 9) use the Android mobile operating system, and their Unity Plugin was set on Unity 3D for the creation of the virtual objects. The Moverio AR SDK provides image capture tools, object recognition training tools, and a tracking engine for the object tracking function. The QR code recognition function was implemented using the ZXing library and the UnityEngine.UI was used to connect with the UI interactive elements, controlled using the remote controller. 3d Max was used to build the 3D models of the material boards and of the light beams.

Object tracking with the Moverio AR SDK is implemented in several steps. The first step is a training process to teach the system to recognize the 3D objects. It starts with capturing images of the target object (the PMMA boards) using the SDK Capture Tool. The capture tool offers a “with marker” option designed to deal with transparent objects and improve foreground/background segmentation in the images. The training process itself is performed using Visual Studio and the Microsoft .Net Framework 4.5.1. (see Fig. 10). Fig. 11 shows the result of visible light transmittance through the PMMA board, as seen through the eyeglasses.

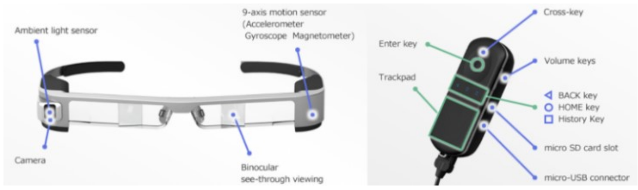

Fig. 9. The Epson Moverio BT-300 eyeglasses and UI controller.

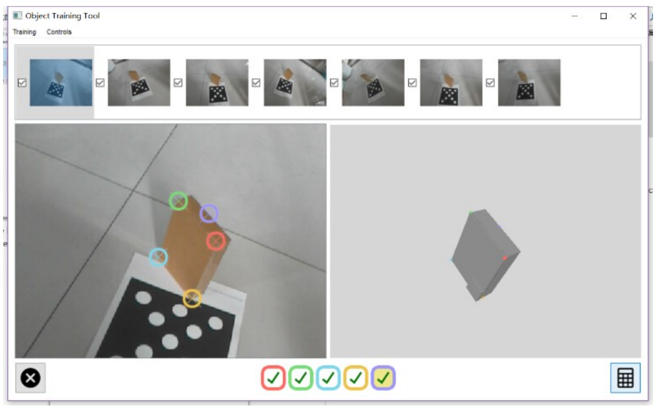

Fig. 10. System training for object recognition and model alignment.

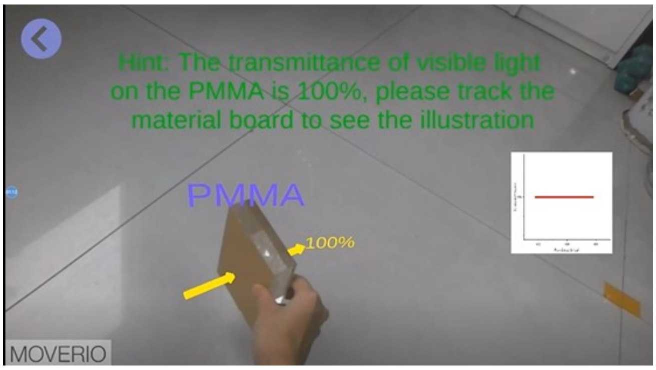

Fig. 11. Visible light transmitttance simulation.

D. Evaluation of the AR Prototype

The evaluation of the AR prototype was done remotely and followed the same methodology as for the VR prototype, using a video and a similar questionnaire: (Q1) Have you ever experienced or used an AR application? (Q2) Do you believe the use of AR can improve your learning of materials science? (Q3) Do you think an AR application can improve your understanding of the optical properties of materials? (Q4) Do you think the AR application can enhance your study experience? (Q5) Do you think the user interaction with the AR application looks easy? (Q6) Do you understand the steps required to complete the optical experiment using the AR application? (Q7) Is there anything you would like to suggest for improving the design of the AR application? (Q8) Can you think of any other area of materials science that could be taught using AR? 87 students participated in this evaluation.

The results show that about half of the students (52.27%) have used AR before (Q1), and 96.59% of them believe that AR can be useful, to various degrees, in their study of materials science (slightly useful: 15.91%, moderately useful: 31.82%, very useful: 36.36%, extremely useful: 12.5%) (Q2). 89.55% of the students think that AR can significantly improve their understanding of the optical properties of materials (Q3), and 90.91% think that the AR application can enhance their study experience (Q4). 84.09% of the students think the AR prototype is easy to use (Q5) and 78.41% think that the experiment workflow (Introduction → Start → Scan code → Select type/wavelength of the light → Track the object → Watch the Animation) is clear and logical (Q6).

In response to Q7, several students reported that using more affordable and widely available equipment, such as a tablet or a mobile phone, would be preferable to the eyeglasses. This is an important feedback as it shows students' readiness to use the technology if they can access it easily. Comments were also received about the need for better and smoother object tracking, which students considered an important contributing factor to the quality of the learning experience. This has since been addressed by reducing the level of transparency of the objects, adding some textured signs on the boards. Transparency is indeed a problem when detecting and tracking objects. Several suggestions were also made about other Materials Science experiments and phenomena that students would enjoy studying using AR, for example transformations on the micro-structures of various types of materials (Q8).

Finally, the student-producer interviewed the student-partner and the materials science teacher to collect their feedback on the completed prototype. Despite some important limitations of the system (e.g. lack of interactivity and lack of variety of materials that can be tested), most of the initial requirements have been met. The prototype helps them understand how AR can be used to simulate phenomena that cannot be directly demonstrated and observed in the school laboratory. They suggested how the current prototype could be made more engaging by offering more options to interact with both the light and the material parameters, or by running several tests in parallel for easier comparison between different optical transmittance properties.

The initial choice of equipment (eyeglasses) implied many constraints during the implementation phase of the project, which had not been foreseen. Both the teacher and the student-partner think that eyeglasses are not the best AR solution for large classes and that simpler solutions that can run on personal mobile devices may be more appropriate and convenient for simple experiments like the optical transmittance experiment. Similar remarks have been made by some of the participant students who responded to the evaluation questionnaire. More complex experiments (e.g. micro properties transformations) would still benefit from eyeglasses technology though as these would provide higher simulation quality and better learning experiences. Whether the school would be ready to invest in rather expensive AR equipment would depend on how much benefits AR brings to the students and how frequently it would be used (according to the teacher, the more complex the experiments and phenomena simulated in AR, the more extensive and frequent the use of the equipment would be).

VI. Evaluation of the Staff-Student Partnership

The students that participated in the partnership were asked to evaluate their experience by considering what they found beneficial and challenging from working in this project. A consensus from the students was that they all agreed to have gained a lot from participating in the project and that they were very happy about the impact the project would have on their peers. Comments from the students-partners included: "*I had never imagined that the materials science knowledge I had learned could be applied in such a novel way, nor had I ever imagined that the ideas could be implemented so quickly ..*"; "*...AR/VR will bring teaching to a new level, where students can study independently with more interactions with the knowledge."* The students believe they have acquired a deeper understanding of the subject, new experimental skills, and insights into new domains, such as product development: "*It strengthens my understanding of ... how to create a product, which is an essential ability in my future career.*" Students also valued developing new transferable skills, including research and data collection, teamwork, interdisciplinary collaboration and presentation skills "*... such a great opportunity to train myself and apply my knowledge to creating such an advanced product.*"

The student-producers believed the project offered a chance to practice professional skills by working with "clients" for their final year project. They mentioned having gained technical skills, insights into another scientific domain and hands-on experience with product development. The comments reflected their appreciation of the partnership: *'...this brand-new experience greatly improves my multimedia design and implementation skills.' '... [participation] in the whole process of producing a VR prototype ... made me deeply understand that user is one of the most important part in product design and development.*"

The students also recognised they acquired new transferable skills, such as problem solving, communication and interdisciplinary collaboration, and a deep understanding of the benefits and the limits of the technologies that they worked on *'VR has some limitations for usage. The high expenses and strict usage environment are the problems for VR's widespread use in education.*" "*…[the] AR equipment is heavy, prolonged use might cause dizziness… has very high requirements for object tracking and real-time interaction'.* Despite the technical and economic challenges of using these techniques in the classroom, the students are very aware of its benefits: "*… VR technology ... can express almost anything that is invisible or difficult to understand…';'…implementing AR technology in learning is ... useful as long as we properly design and implement the product…*".

From the viewpoint of the academic partners, this partnership was very meaningful. Although we are in a different position within the organisational structure, we addressed this issue by creating space for the students to contribute and develop ideas, empowering them to take ownership and responsibility for driving the project. This was facilitated by the interdisciplinary nature of the problem, the final product could not be realised without the contributions of all project partners, since we were all in a position of learners in the project. This experience has transformed the way we establish relationships with students, making learning a successful collaborative process.

VII. Conclusion

This work has revealed several lessons that can inform ongoing and future student-staff co-creation projects for the development of teaching and learning resources in materials science and beyond. It confirms the benefits of virtual and augmented reality technologies for teaching and learning in materials science; it shows the importance of involving students when developing learning resources; and it demonstrates the benefits of interdisciplinarity in teaching and learning. Very importantly, from the students' own voices, it enabled them to gain new valuable technical and transferable kills. The next step in this project is to test the prototypes created in a classroom setting. This will allow a refinement and evaluation of the product and their implementation as routine class activities.

The partnership model successfully demonstrated that interdisciplinary projects bring additional pedagogical benefits to co-creation; by working on complex issues that require different levels of expertise for providing solutions, both students and staff play the role of experts and learners at different stages of the project, balancing the power relationships, rewards and recognition and enriching the learning experience.

In order to apply this model, partnerships must be built on the assumption that all the partners equally bring valuable knowledge and contribution to the project and therefore have a lot to learn from each other. It is crucial to set expectations and establish responsibilities early in the project. This will guarantee investment and commitment in producing results from all project partners.

To move this area of research forward, it would be necessary to further explore the sense of community of learning during the process and design formal mechanisms for critical reflection on relationships, identities, processes and structures that can potentially transform the learning experience.

Acknowledgment

The authors would like to acknowledge the funding support from the International Centre for Teaching and Learning at Queen Mary Engineering School from Queen Mary University of London.

References

[1] A.G. Abulrub, A.N. Attridge, M.A. Williams (2011). Virtual reality in engineering education: The future of creative learning. IEEE Global Engineering Education Conference (EDUCON) – "Learning Environments and Ecosystems in Engineering Education".

[2] B. J. Andersen, A. T. Davis, G. Weber, B. C. Wünsche (2019). Immersion or Diversion: Does Virtual Reality Make Data Visualisation More Effective? International Conference on Electronics, Information, and Communication (ICEIC), Auckland, New Zealand, 2019, pp. 1-7, doi: 10.23919/ELINFOCOM.2019.8706403.

[3] R. Barmaki, K. Yu, R. Pearlman, R. Shingles, F. Bork, G.M. Osgood, N. Navab (2019). Enhancement of Anatomical Education Using Augmented Reality: An Empirical Study of Body Painting. Anat. Sci. Educ., 12(6):599-609, Jan. 2019, doi: 10.1002/ase.1858

[4] J. Barrow, C. Forker, A. Sands, D. O'Hare, W. Hurst (2019). Augmented Reality for Enhancing Life Science Education. VISUAL 2019 - The Fourth International Conference on Applications and Systems of Visual Paradigms, Rome, Italy.

[5] D. Behmke, D. Kerven, R. Lutz, J. Paredes, R. Pennington (2018). Augmented Reality Chemistry: Transforming 2-D Molecular Representations into Interactive 3-D Structures. Proc. Interdiscip. STEM Teach. Learn. Conf., vol. 2, no. 1, Jan. 2018

[6] C. Bryson (2016). Engagement through partnership: students as partners in learning and teaching in higher education. International Journal for Academic Development, 21:1, 84-86, doi: 10.1080/1360144X.2016.1124966

[7] Epson Moverio https://tech.moverio.epson.com/en/bt-300/ Last accessed 08/08/2020

[8] O.A. Fadiran, J. van Biljon, M.A. Schoeman (2018). How can visualisation principles be used to support knowledge transfer in teaching and learning? Conference on Information Communications Technology and Society (ICTAS), Durban, 2018, pp. 1-6, doi: 10.1109/ICTAS.2018.8368739

[9] M.-J. Garcia-Bonete, M. Jensen, G. Katona (2019). A practical guide to developing virtual and augmented reality exercises for teaching structural biology. Biochem. Mol. Biol. Educ., vol. 47, no. 1, pp. 16–24, Jan. 2019.

[10] K.E. Hubbard, R. Brown, S. Deans, M. Paz García, M.G. Pruna, M.J. Mason (2017). Undergraduate students as co-producers in the creation of first-year practical class resources, Higher Education Pedagogies, 2:1, 58-78, doi: 10.1080/23752696.2017.1338529

[11] LeapMotion https://developer.leapmotion.com/ Last accessed 08/08/2020

[12] W. Li, A. Y. C. Nee, S. K. Ong (2017). A State-of-the-Art Review of Augmented reality in Engineering Analysis and Simulation. Multimodal Technologies and Interactions. 1(3), 17. doi:10.3390/mti1030017.

[13] J. Martín-Gutiérrez, C.E. Mora, B. Añorbe-Díaz, A. González-Marrero (2017). Virtual Technologies Trends in Education. EURASIA Journal of Mathematics, Science & Technology Education, v13 n2 p469-486.

[14] K.E. Matthews, A. Dwyer, L. Hine, J. Turner (2018). Conceptions of students as partners. High Educ 76, 957–971 (2018), doi: 10.1007/s10734-018-0257-y

[15] L. Mercer-Mapstone, S.L. Dvorakova, K. Matthews, S. Abbot, B. Cheng, P. Felten, K. Knorr, E. Marquis, R. Shammas, K. Swaim (2017). A Systematic Literature Review of Students as Partners in Higher Education. International Journal for Students As Partners, 1(1), doi: 10.15173/ijsap.v1i1.3119

[16] B.L. Nielsen, H. Brandt, H. Swensen (2018). Students developing representational competence as producers with and of augmented reality in science. NorDiNa vol. 14 No. 2, doi: 10.5617/nordina.6163

[17] M.M. North, S.M. North. (2019). Dynamic Immersive Visualisation Environments: Enhancing Pedagogical Techniques. Australasian Journal of Information Systems, 23, doi: 10.3127/ajis.v23i0.2109

[18] Oculus Rift https://www.oculus.com/ Last accessed 08/08/2020

[19] C. Onime, J. Uhomoibhi, R. Austin and V. McNair (2017). Smart technologies and applications for visualisation in higher science and Engineering education: Issues of knowledge integration and virtual experimentation. IEEE Global Engineering Education Conference (EDUCON), Athens, 2017, pp. 1070-1077, doi: 10.1109/EDUCON.2017.7942981

[20] C. Paulus, N. Haouchine, D. Cazier, S. Cotin (2015). Augmented Reality during Cutting and Tearing of Deformable Objects. The 14th IEEE International Symposiumon Mixed and Augmented Reality, Fukuoka, Japan, Sept. 2015.

[21] E.Y. Putra, A.K. Wahyudi, C. Dumingan (2016). A proposed combination of photogrammetry, Augmented Reality and Virtual Reality Headset for heritage visualisation. International Conference on Informatics and Computing (ICIC), Mataram, 2016, pp. 43-48, doi: 10.1109/IAC.2016.7905687

[22] A. Sivanand, B. Frank (2016). Information Visualisation in education: a Review of Current Tools and Practices. Proceedings of the Canadian Engineering Education Association (CEEA) Conference- Dalhousie University June 19-22, 2016.

[23] D. Vergara, M. Lorenzo, M.P. Rubio (2015). Virtual environments in materals science and engineering: the students'opinion. In Handbook of Research on Recent Developments in Materials Science and Corrosion Enginering Education. Lim, H., Ed.; IGI Global: Hershey, PA, USA, 2015; Chapter 8; pp. 148–165.

[24] D. Vergara, M.P. Rubio, M. Lorenzo (2016). Enhancing the teaching/learning of materials mechanical characterization by using virtual reality. Journal of Materials Education. Vol 38, 63-74.

[25] D. Vergara, M.P. Rubio, M. Lorenzo (2017). On the Design of Virtual Reality Learning Environments in Engineering. Multimodal Technologies and Interactions. 1, 11. doi:10.3390/mti1020011

[26] M. Videnovik, V. Trajkovik, L.V. Kiønig,T. Vold (2020). Increasing quality of learning experience using augmented reality educational games. Multimed Tools Appl (2020). doi: 10.1007/s11042-020-09046-7

[27] C.H. Wang, D. Han, W.K. Chou (2018). Overview of information visualisation in science education. International Journal of Computational Science and Engineering (IJCSE), Vol. 17, No. 1, 2018.

[28] Y. Wen, C.K. Looi (2019). Review of augmented reality in education: situated learning with digital and non-digital resources. In learning in a digital world. pp. 179-183. doi: 10.1007/978-981-13-8265-9_9

[29] M. Won, M. Mocerino, K.S. Tang, D.F. Treagust, R. Tasker (2019). Interactive Immersive Virtual Reality to Enhance Students' Visualisation of Complex Molecules. In: Schultz M., Schmid S., Lawrie G. (eds) Research and Practice in Chemistry Education. Springer, Singapore.