Virtual Reality Prototype of a Linear Accelerator Simulator for Oncological Radiotherapy Training*

Vei S. Chan[1], Andrés Iglesias[2,3], Habibollah Haron[1], Pedro J. Prada[4], Samuel Ruiz[4], Akemi Gálvez[2,3], Lihua You[5], Faezah M. Salleh[6], Farhan Mohamed[1,7]

[1] School of Computing, Faculty of Engineering, University of Technology Malaysia, 81310 Johor Bahru, Malaysia
vschan2@live.utm.my, habib@utm.my
[2] Dept. App. Maths. & Comp. Sci., University of Cantabria, 39005 Santander, Spain
[3] Faculty of Sciences, Toho University, 2-2-1 Miyama, 274-8510 Funabashi, Japan
{iglesias,galveza}@unican.es
[4] Hospital Universitario Marqués de Valdecilla, 39008 Santander, Spain
jpedraja@hvvaldecilla.es, samuel.ruiz@scsalud.es
[5] National Center for Computer Animation, Faculty of Media & Communication, Bournemouth University, Poole BH12 5BB, UK
lyou@bournemouth.ac.uk
[6] Dept. of Biosciences, Faculty of Science, University of Technology Malaysia, 81310 Johor Bahru, Malaysia
faezah@utm.my
[7] Media & Game Innovation Centre of Excellence, 81310 Johor Bahru, Malaysia
farhan@utm.my

Abstract. Learning to operate medical equipment is one of the essential skills for providing efficient treatment to patients. One of the current problems faced by many medical institutions is the lack or shortage of specialized infrastructure for medical practitioners to conduct hands-on training. Medical equipment is mostly used for patients, limiting training time drastically. Virtual simulation can help alleviate this problem by providing the virtual embodiment of the medical facility in an affordable manner. This paper reports the current results of an ongoing project aimed at providing virtual reality-based technical training on various medical equipment to radiophysicist trainees. In particular, we introduce a virtual reality (VR) prototype of a linear accelerator simulator for oncological radiotherapy training. The paper discusses the main challenges and features of the VR prototype, including the system design and implementation. A key factor for trainees' access and usability is the user interface, particularly tailored in our prototype to provide a powerful and versatile yet friendly user interaction.

Keywords: Virtual reality · Linear accelerator · Medical simulator training · Oncological radiotherapy · Head-mounted display · User interface

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1 Introduction

With the increasing number of cancer cases worldwide, there is urging need for highly-skilled specialists from the various disciplines involved in the prevention, diagnosis, monitoring, and treatment of cancer. An illustrative example is given by oncological radiotherapy (ORT), a field where different types of oncologists work in close cooperation with radiophysicists, a type of medical physicists with the technical ability to operate medical radiation equipment efficiently [1, 4].

Radiophysicists typically work with linear accelerators (LINAC), sophisticated devices used to speed up charged subatomic particles or ions through a series of oscillating electric potentials. Oncological radiotherapy linear accelerators (ORTLINAC) are used for procedures such as intensity-modulated radiation therapy (IMRT), a level-3 high-precision technique that combines the use of computer tomography (CT) imaging and multileaf collimators. In IMRT, CT is used to get a volumetric representation of the tumor, while the collimators use a set of individual "leaves" equipped with independent linear in/out movement (orthogonal to the radiotherapy beam) to fit the treatment volume to the boundary shape to the tumor and vary the radiation signal intensity accordingly. In this way, IMRT is used to deliver precise radiation doses at targeted areas within the tumor, thus reducing the radiation impact on healthy organs and tissues.

Unfortunately, IMRT requires a lot of expertise and considerable experience for optimal performance. For instance, an individual radiation treatment planning (RTP) must be set up for each patient before the therapy sessions. The plan needs to consider several factors and parameters, such as the region of interest (ROI) where the radiation beam will focus, the most suitable beam type, the energy to be applied, the appointment schedule of therapy sessions and many others. The RTP is intended at maximizing the treatment effectiveness while minimizing the physical strain upon the patients. Once all details of the RTP are agreed, radiation sessions are set on place. During the radiotherapy session, the practitioners arrange the patients on a motorised table with six degrees of freedom. Then, they use remote controls to move the table and match the tumor location and orientation to the radiation beam's focal point of ORTLINAC. The whole procedure is highly-demanding in terms of concentration and skills to get the precise position. As a result, intensive practising is required for the medical trainees to master the positioning of the patients to the precise radiation beam's focal point by using the remote controls. However, the ORTLINAC therapy schedule is often full due to its high demand [1]. The medical trainees have scarce time to access the facility for practising [5]. Moreover, it is not affordable to allocate ORTLINAC rooms for training purposes owing to their high costs [1, 4]. In this context, virtual reality (VR) emerges as a suitable technology to simulate the real medical environment in the virtual world, allowing the trainees to conduct hands-on practice and let them accustomed to the environment.

Previous studies explored the usage of VR in training and education in various domains [14, 19, 20]. These works show that VR technology contributes to psychomotor or technical skills development, knowledge transfer, and social skills. In the radiotherapy field, there is also research work using VR technology for training the novice to operate the medical equipment [24]. VR is also used to inform the patients about the therapy session and reduce their anxiety [15, 23]. Nevertheless, realism is still an issue because most studies visualise the virtual operation in the ORTLINAC room. In contrast, the practitioners in real-life situations are also involved in operating the equipment remotely in another control room. Therefore, both the ORTLINAC room and the control room must be fully integrated and coordinated in the VR simulator for realistic training. In addition, the user interaction in the VR simulator must be as similar as possible to that in the real-world setting. These are the goals of the present contribution.

This paper introduces a VR prototype of a unified system comprised of the ORTLINAC room and the control room along with their interactions. The paper describes the main tasks of the system design and implementation, including the research workflow to determine the user requirements and to address the user interaction issues. The structure of this paper is as follows: Sect. 2 reports previous work regarding VR for medical science. Sect. 3 describes the workflow for the design and implementation of the VR prototype introduced in this paper. Then, Sect. 4 shows the main results of the implementation. Lastly, Sect. 5 discusses the conclusions and future work in the field.

2 Previous Work

2.1 Virtual Simulation for Medical Science

The presence of virtual simulation is soundly significant in many areas of the medical science, such as radiation therapy [5], radiography [13], and surgery [24]. The 3D visualisation of a patient's body and internal organs is helpful for medical practitioners to make a treatment plan and discuss it with their peers. The large-size wall display can also help them present and collaborate effectively. In radiotherapy, most institutions use the virtual environment for radiotherapy training (VERT) system for such purposes [21]. Besides, the 3D view and virtual simulation can also benefit the teaching and learning process [9].

2.2 Oncology Radiotherapy Training Issues

To provide efficient treatment to the patients, quality and effective medical education are of utmost importance. Training is also essential in solving the shortage of qualified staff operating the medical equipment for radiotherapy [6, 21]. Here we discuss some issues found in conventional ORTLINAC radiotherapy training.

Need to learn diverse skills. Radiotherapy workflow involves many medical knowledge and skills [10]. According to [2, 4], the workflow includes: (a) CT scanning to obtain the imaging data of patient's anatomy; (b) segmentation to extract the region of interest (organ, tumor); (c) treatment planning and evaluation; (d) quality assurance to avoid patient injury; (e) image-guided to place the patient on the ORTLINAC; and (f) perform the radiotherapy. Aside from the technical skills, the novice also needs to learn to communicate with patients and provide patient-care service [4]. These factors require the trainees to spend much time mastering these skills. However, the ORTLINAC equipment is often in high demand, giving the trainees sparse access for practising [1, 5, 13].

Patient care issues. The need to ensure patient safety and well-being during the ORT sessions is a big concern, as it may cause psychological pressure for the trainees [5, 16]. Using phantoms might help minimize this issue [8]. However, the limited access to the ORTLINAC still affects the training progress.

Limitations of the 2D medium. Conventional treatment planning and demonstration use 2D media to explain the concept, such as 2D imaging slice view and printed medium. Previous studies found it challenging to visualise and explain the spatial relationship between organs and anatomy and how the radiation beam affects these organs [9]. Therefore, 3D and immersive techniques can help effectively explain these spatial concepts to the trainees.

2.3 VR for Radiotherapy Education and Training

Several research works addressed the use of VR technology for RT training, including skin apposition application [3], medical imaging [13], breast cancer [15], prostate cancer [18], medical dosimetry [9, 17], and brachytherapy [24].

The VERT system. Most of the VR training approaches make use of the VERT system, consisting of a wall-size display and an actual hand pendant controller to operate the virtual ORTLINAC. The studies show that VERT provides an optimal environment for hands-on practice [4, 21]. The virtual simulation can offer a safe working environment where the trainees can practise by trial and error without the fear of injuring the actual patients [4, 12]. The work in [5] reported that most of the trainees utilised VR simulation training significantly whenever it is available. This study is consistent with the high level of satisfaction and enjoyment among the trainees, as reported by [3, 9, 10, 22]. These results showed that VR simulation could provide a conducive environment and a valuable opportunity for practice, which can help the trainees to master the skills effectively and in shorter time [9]. Besides, the large screen display of VERT helps the educators to demonstrate and explain therapy concepts in a classroom setting [17, 21]. This display can help the trainees understand the spatial relationship between the radiation beam and the target organs [21] and allow more engagement and discussion of learned knowledge into the professional conversation [10]. These results provide evidence that VR-based training fosters the trainees' development and confidence in operating the radiotherapy equipment.

However, previous studies reported several limitations of the VERT system. First is the realism issue. Most users stated that the VERT lacks immersion and does not provide tactile feedback when the collision occurs [3, 12]. A few studies showed that the students obtained less performance and task accuracy in actual treatment planning after practice using virtual simulation units compared to conventional simulation practice by using the actual unit or the treatment planning software [12, 17]. Some users also criticised the complex control of the VERT system as a limiting factor for their training and skill development [4].

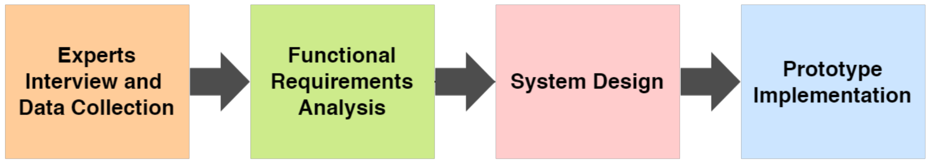

Fig. 1. Our design and implementation flowchart.

Secondly, [10] revealed the lack of autonomous and self-directed learning in their blended learning framework. This issue is possibly caused by the large display unit where the student has less opportunity to conduct the practice by him/herself. Moreover, the COVID-19 pandemic also caused the cancellation of many on-site clinical practices [5], which further exacerbates the usual access limitation to the learning facility. Clearly, there is a need to explore an alternative immersive technology that can allow distance learning but without these issues.

Head-mounted displays. The advancement of VR technology allows the increased affordability of small-size equipment. The head-mounted display (HMD) is one such VR equipment that can solve the issues found in large 3D displays. Authors in [1] created an HMD VR application for ORTLINAC training, resulting in better learnability and effectiveness in training radiotherapy compared to VERT. The work in [24] utilised the room-scale VR headset HTC Vive for brachytherapy training to improve the trainees' technical skills. With the recent research trend in collaborative VR [11], HMDs can improve both autonomous and group learning environments.

Based on [10], medical practitioners and experts' involvement can help design the software and education curriculum to fulfil the real-life situation. Since the practitioners spend most of the time in the control room, there is a requirement to simulate the virtual embodiment in the control room where they have limited view and need to depend on the camera to operate the ORTLINAC. Accordingly, this paper emphasises the development of a virtual control room to train hand-eye coordination skills and spatial awareness in a limited viewing condition.

3 System Design and Implementation

This research work is part of an ongoing project aimed at providing VR-based technical training on various medical equipment to radiophysicist trainees. Although the full project is still a work in progress, we think that it has already reached significant results to justify publication. The work described in this paper concerns the development of a workable medical simulation training system to simulate the real-life working condition of ORTLINAC based on user requirements. In this context, this section focuses on the design and implementation workflow plan for creating a VR prototype of the ORTLINAC simulator for ORT training. Fig. 1 shows the main steps of the design and implementation flowchart. They are described in detail in next subsections.

3.1 On-site medical facility visits and meetings with experts

The first step of the process involves visits to medical facilities and meetings with medical practitioners to elicit the functional requirements of the system. Some authors visited the medical facilities in the oncology department of Hospital Universitario Marqués de Valdecilla, Santander, Spain, where they were presented the daily operation in both the ORTLINAC therapy room and the remote control room, including the features of ORTLINAC, how to control the ORTLINAC and some standard procedures in radiotherapy. The authors collected photos, videos and other materials to analyse and design the VR training system.

3.2 Functional Requirements

After the visits to the medical facilities and meetings with experts, the authors analysed the collected materials (video transcripts, photos, printed materials, and others) to extract the functional requirements for the VR ORTLINAC training system. Fig. 2 shows the use case diagram of the VR medical simulation training system.

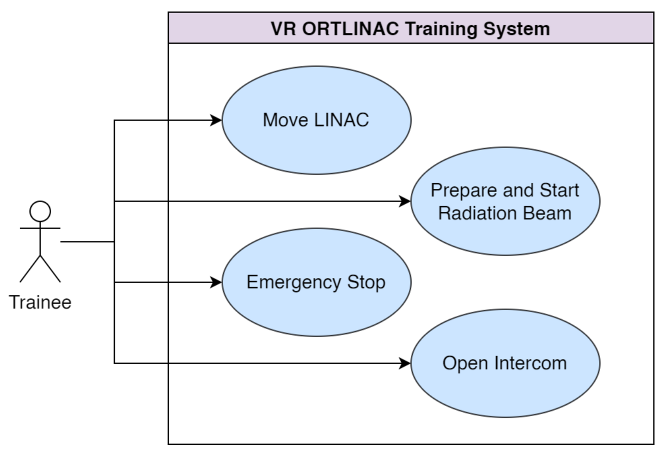

Fig. 2. The use case diagram of the VR ORTLINAC training system.

The trainee is the primary use case actor to use the VR ORTLINAC training system for practising. Table 1 shows the analysed functional requirements and their description.

3.3 System Design

As indicated above, there are two rooms for our VR-based training system: the ORTLINAC radiotherapy room and the control room. During the radiotherapy

Table 1. Functional requirements and their description.

ID	Requirement	Description
RQ1	Move LINAC	Trainee can move the position of table and gantry by pressing the button in the remote control panel.
RQ2	Prepare and Start Radiation Beam	Trainee can choose, prepare, start and stop the radiation beam.
RQ3	Emergency Stop	Trainee can perform an emergency stop to shut down the ORTLINAC immediately.
RQ4	Open Intercom	Trainee can open the intercom and give instructions to the patient to adjust his/her position remotely during the radiotherapy session.

session, the practitioners in the radiotherapy room place and fasten the patient on the motorised table of ORTLINAC to stabilise and fix the patient' position. In some cases, an individually customized plastic mask is provided to the patient to wear during treatment. After this, any other person than the patient should leave the room to avoid the harmful effects of the radiation. The LINAC machine is operated from the control room, where the patient can be tracked through a window and/or one or several cameras. There is also an intercom for oral communication with the patient. The practitioners in the control room use different controls to guide the motion of the table and gantry and align the tumor's region of interest to the centre of the radiation beam's focal point. This external radiotherapy procedure is typically applied in several sessions distributed over days and weeks according to the patient's RTP.

In this paper, we will focus on the design and development of the virtual control room. Firstly, we designed and created the control room simulation according to the real-life situation. According to the experts' feedback, the practitioners spent most of their time in the control room. Therefore, this simulation can provide more exposure for the novices to the environment. To furnish the virtual scene, the authors utilised Blender and SketchUp software to create the 3D model of the furniture, electronic devices and medical equipment, such as the camera display of the ORTLINAC device room and control panels.

The user interface (UI) is also an essential element for interacting with the virtual world. For example, to operate the ORTLINAC using the control panel and view the camera display. We identified several design considerations, leading to different versions throughout the design process. The first design version relied on virtual buttons for user interaction, allowing the users to click on the buttons of the 3D model to perform different actions. However, this feature may cause navigation difficulties for the trainees because they may accidentally click on another nearby button. The alternative solution of increasing the size or changing the buttons' orientation may reduce the realism and familiarity to the actual control panel. Therefore, this work proposes sign-posting and annotation above the 3D models to attract the users to click on the button in the VR world. Once clicked, it will open a larger user interface panel that displays the camera view and control panel layout for easy viewing and selection, respectively. In this way, the 3D medical equipment can be displayed in VR at its original real-life size scale, thus improving the realism of the system.

3.4 Implementation

The VR ORTLINAC training system was developed in Unity3D with the Oculus Integration package. This package provides various templates and prefabs to develop a VR application in Unity3D, including an avatar framework and customised configurations. This work also used the Oculus Quest as the VR head-mounted display (HMD) with two Oculus Touch controllers for user interaction. The reason to use Oculus Quest is that it is a standalone system, requires fewer set-up procedures, and is very ubiquitous to carry around. In addition, Blender and SketchUp were used to create the 3D models of the medical equipment, electronic devices, furniture and room. Blender supports texture mapping on the 3D models to improve their visual realism. Table 2 shows the hardware and software specifications used in this work along with their versions.

Table 2. Hardware and software specifications.

Name	**Category**	**Specification**
Unity3D	Software -> Game Engine	Version: 2020.3.25f1
Oculus Integration	Software -> Unity Asset	Version: 37.0
Blender	Software -> 3D Modelling	Version: 3.0.0
SketchUp	Software -> 3D Modelling	Version: Pro 2022
Oculus Quest	Hardware -> HMD	Generation: 1 Software version: 37.0

After creating the 3D models in Blender and SketchUp, they were imported in Unity3D to build the virtual control room scene according to the sketch and requirements. The Unity UI can implement the UI design and user interaction based on our design considerations. Furthermore, the VR system included the room-scale locomotion feature to let the users physically walk around the virtual room. Another VR feature is to show the 3D models of users' hands with a Touch controller and cast a laser pointer from the right-hand controller to allow the users to point and click on the virtual button. The inclusion of virtual hands can also improve the users' perception of presence in the VR world. Lastly, the VR training system was built as an Android application package (APK) file and deployed in the Oculus Quest. Additional visualization on smartphones and tablets has also been developed and is fully supported.

4 Results

This section presents the results of the VR ORTLINAC training prototype. There are three main components: the virtual remote control room, the ORTLINAC radiotherapy room, and the proposed UI and user interaction.

4.1 Remote Control Room

Fig. 3 shows a scene comparison between the real (top) and virtual (bottom) environments. As the reader can see, the virtual simulation was created as similar as possible to the actual control room, including the furniture, electronic devices, and interior layout. Real-world textures were extracted from the photos and applied on the virtual surfaces to improve the overall realism of the scene.

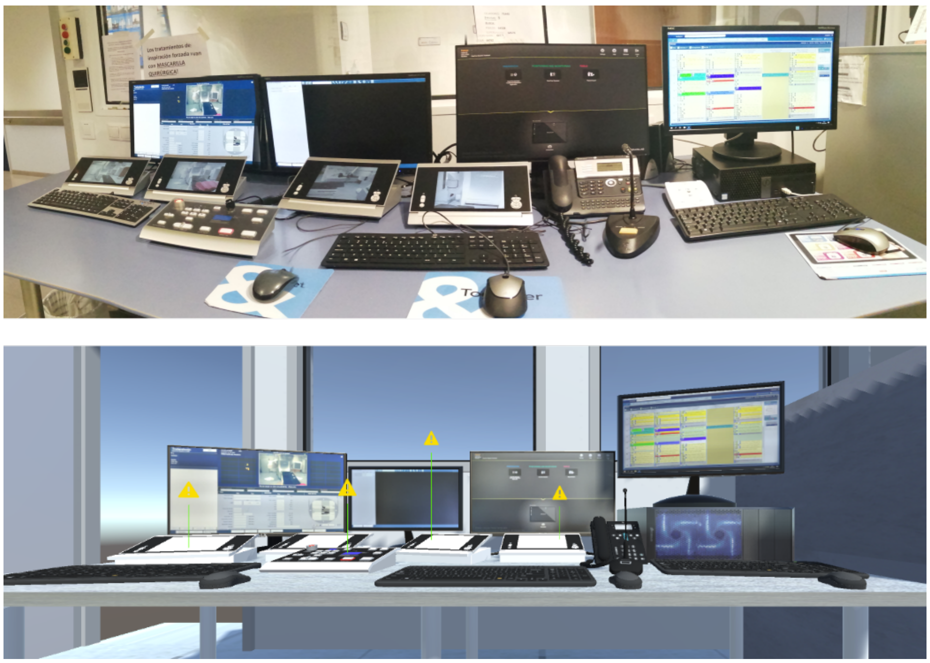

Fig. 3. Comparison of actual (top) and virtual (bottom) control rooms.

Fig. 4 shows the comparison of the 3D models of the camera display (left) and control panel (right). We also mapped the button icon and text annotation textures on the 3D models, based on their appearance in the actual equipment.

4.2 ORTLINAC Radiotherapy Room

For the ORTLINAC room, the current work focused on the 3D modelling of ORTLINAC equipment and the position of cameras. The authors edited and modified the 3D LINAC model created by [7] in SketchUp and Blender, and shown in Fig. 5(top). Meanwhile, we set the positioning of cameras in the radiotherapy room in order to project the camera view into the camera displays in the virtual control room by using render texture mapping in Unity3D. Based on these features, this work simulates the remote control room successfully. Fig. 5 shows the multiple camera positions and their displays in the control room.

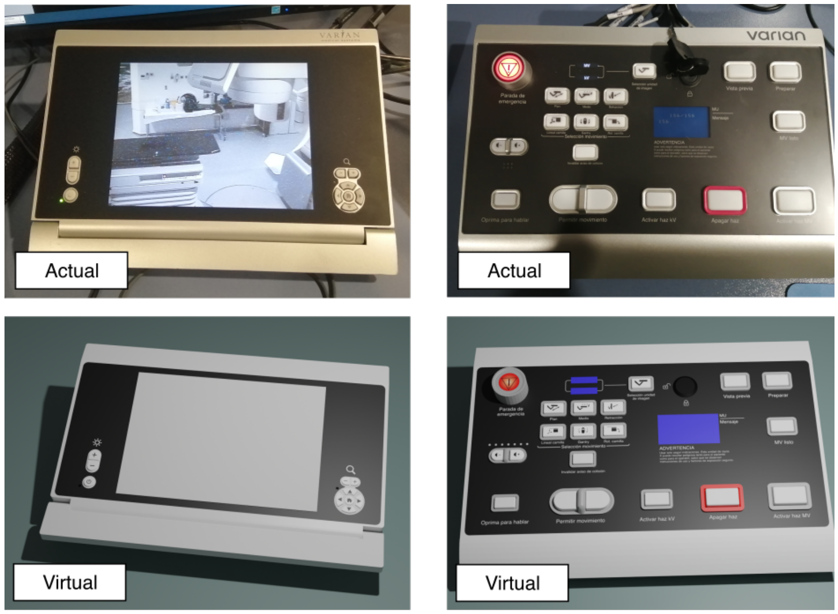

Fig. 4. The actual (top) and virtual (bottom) models of the camera display (left) and control panel (right).

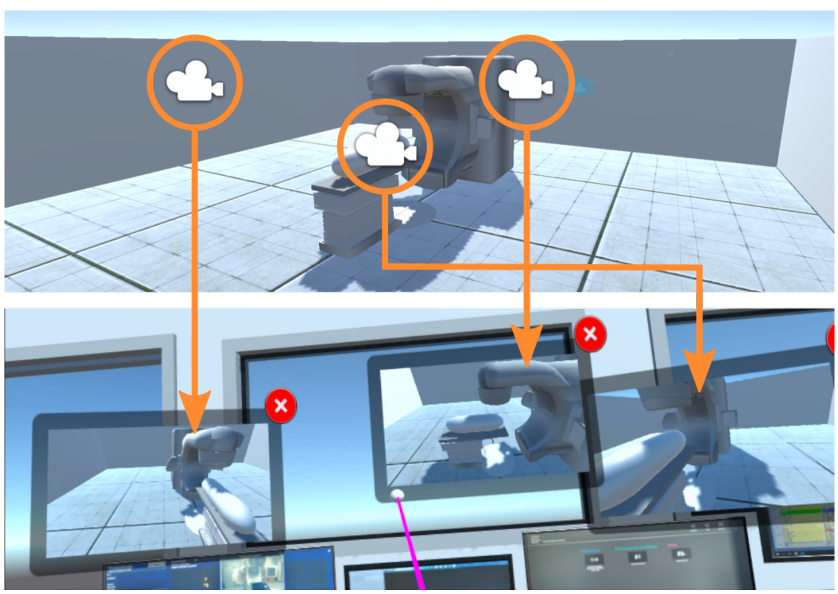

Fig. 5. The camera positioning in the ORTLINAC radiotherapy room (top) and their displays in the virtual control room (bottom).

4.3 User interface and Interaction

As mentioned above, this work implements the sign-posting UI displayed above the 3D models to attract the users to point the controller's laser to the button, as shown in Fig. 6(left). After pressing the "A" button, this action opens a larger UI panel that displays the camera view or control panel layout for the users to interact, as shown in Fig. 6(right).

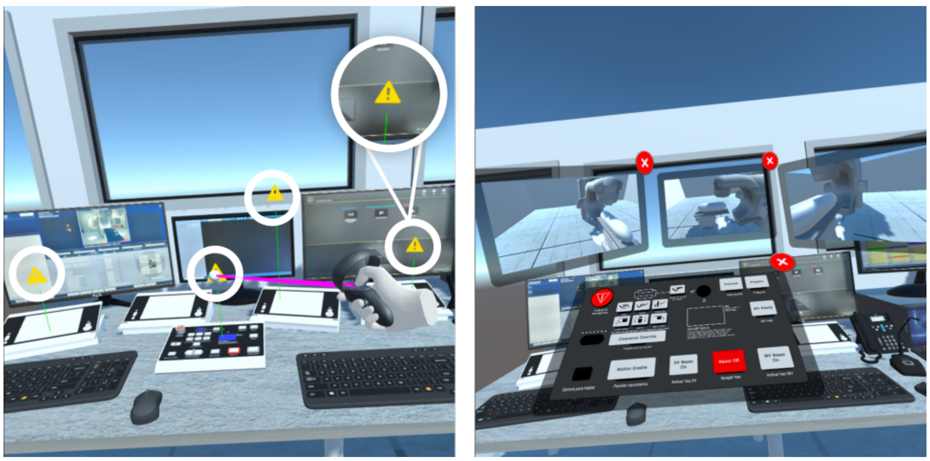

Fig. 6. The UIs presented in the VR ORTLINAC training system: sign-posting UIs (left); camera view and control panel layout UIs (right).

Besides, the users can point and click on the buttons in the control panel layout UI to control the movement of the ORTLINAC. Currently, this prototype only includes the functionalities to rotate the gantry and move the table linearly. The movement of ORTLINAC is reflected in the camera displays, as shown in Fig. 7. Hence, the users can observe the ORTLINAC position remotely. We also included the grab interaction by using the grip button in the left-hand controller when the virtual hand touches the UI. The users can grab any UI panel and place it in the desired location to customise their workspace, as shown in Fig. 8. The video demonstration can be found in this link: https://youtu.be/5YmY_0EsiLQ.

5 Conclusions and Future Work

This paper presents a VR prototype of an ORTLINAC system for oncological radiotherapy training. Based on the experts' feedback, the ORTLINAC room and the control room are now integrated within a unified framework. Unity3D's render texture mapping functionalities are used to achieve the effect of the remote camera display for effective synchronization between both rooms. Also, several

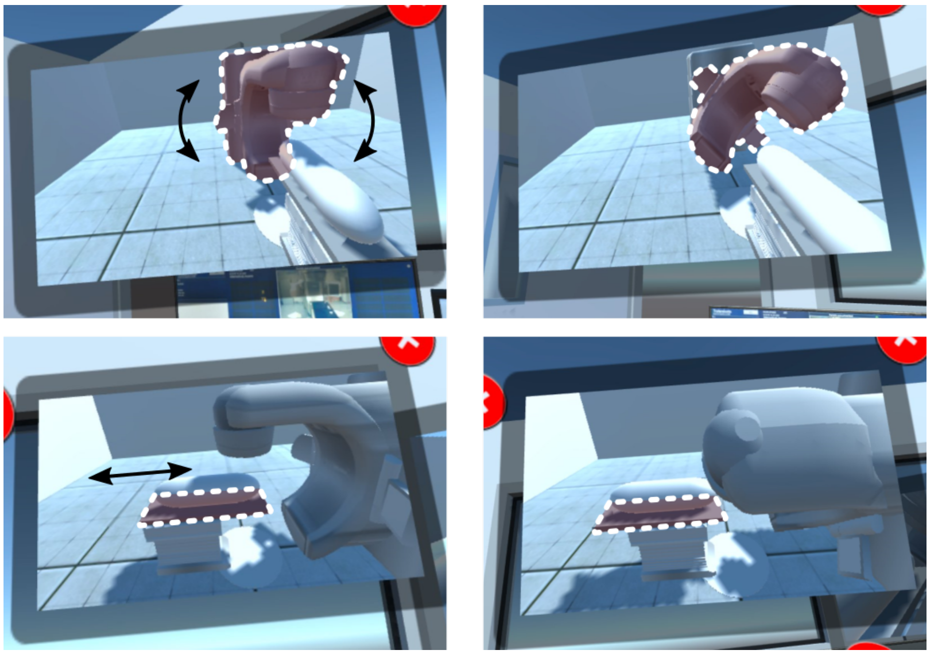

Fig. 7. The movement function for the rotation of the gantry and translation of the table before movement (left) and result after movement (right).

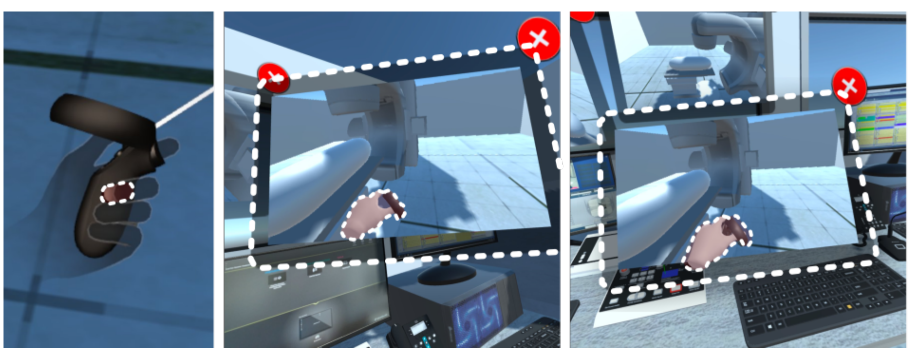

Fig. 8. The grab interaction to move the UI location: the grip button (left); the user activates his/her left hand on the UI panel (middle); using this feature to grab and drag the UI panel to other location (right).

UI design considerations are proposed for the VR world, including sign-posting and displaying a larger UI button layout for easier user interaction.

We will continue improving the prototype in terms of functionalities, graphics, and user experience (UX) for the next step. Furthermore, 3D reconstruction of imaging data that shows a patient's body with internal organs and tumor regions should be included in this system. This feature can challenge the trainees to practice operating the ORTLINAC correctly and avoid collision between the patient and the gantry. In addition, we wish to evaluate the efficiency and effectiveness of using this VR system for training medical practitioners and compare it with the traditional pedagogical approach.

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