VR Isle Academy: A VR Digital Twin Approach for Robotic Surgical Skill Development

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Abstract. Contemporary progress in the field of robotics, marked by improved efficiency and stability, has paved the way for the global adoption of surgical robotic systems (SRS). While these systems enhance surgeons' skills by offering a more accurate and less invasive approach to operations, they come at a considerable cost. Moreover, SRS components often involve heavy machinery, making the training process challenging due to limited access to such equipment. In this paper we introduce a cost-effective way to facilitate training for a simulator of a SRS via a portable, device-agnostic, ultra realistic simulation with hand tracking and feet tracking support. Error assessment is accessible in both real-time and offline, which enables the monitoring and tracking of users' performance. The VR application has been objectively evaluated by several untrained testers showcasing significant reduction in error metrics as the number of training sessions increases. This indicates that the proposed VR application denoted as *VR Isle Academy* operates efficiently, improving the robot - controlling skills of the testers in an intuitive and immersive way towards reducing the learning curve at minimal cost.

Keywords: Digital Twin · Medical Training · Virtual Reality · Inverse Kinematics · Surgical Robotic System

1 Introduction

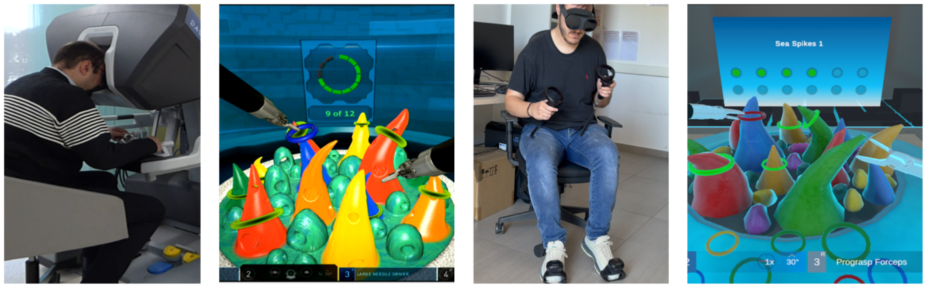
In recent years, the trajectory of medical training has significantly shifted, incorporating the latest technological advancements. However, this transition is not extensively adopted in universities or other institutions that focus on medical training, primarily due to the limited availability of market products and the high cost of the required training equipment. To this day, due to the aforementioned reasons, the majority of surgical training courses still adhere to a pattern of the 16th-century training procedure [15] where the trainees simply observe the expert-surgeon/tutor perform surgery.

Contemporary advancements in the field of robotics have established robotic surgical systems as a viable option for performing highly precise minimally invasive operations enabling the surgeon to operate while seated. Some of the surgical robotic systems that are out in the market are the da Vinci surgical system (`https://www.intuitive.com/en-us/products-and-services/da-vinci`), Senhance surgical system (`https://www.asensus.com/`) and Flex robotic system (`https://novusarge.com/en/medical-products/flex-robotic-system/`). The da Vinci Surgical System [13] has is one of the most widely used robotic surgical systems [20]. This system has been used for many different operations such as cardiac, colorectal, general, gynecologic, head and neck, thoracic, and urologic surgeries [20]. In 2021, 6500 da Vinci Surgical system were installed in 67 different countries and 55.000 doctors were trained to use it [2,21]. The cost of acquiring and maintaining the above Surgical System is significant. Due to cost considerations of acquiring it and the low amount of systems around the world, various companies have capitalized on private training courses tailored for doctors and surgeons.

The field of Virtual Reality (VR) has undergone major advancements with powerful VR headsets being able to render entire worlds in real-time. This has introduced a new market for VR, in medical training. VR training offers an immersive experience for the trainees who enhance their hard-skills inside the virtual world and gain experience by training their hard-skills. Researchers across the globe have directed their efforts towards enhancing the scientific domain of VR medical training by introducing innovative solutions to address existing challenges, such as those highlighted in [16], [10].

Recognizing the necessity for a more convenient, affordable, and portable approach to utilize SRS, we suggest an advanced VR Ultra Realistic training simulation for surgical robotic systems. Figure 1a illustrates the user utilizing the machine that controls the robotic arms, with figure 1b depicting the view from the simulated training scenario. Figures 1c and 1d respectively demonstrate a user being trained in the same scenario using our application along with his view within VR. This VR simulation democratizes the training of these systems with a "device-agnostic" strategy by reducing the cost of training and smoothing out the learning curve. The incorporation of feet tracking enhances user immersion, providing an authentic training experience for a surgical robotic system.

The main contribution of this work is to present a complete digital-twin of the SRS training process. To the best of our knowledge, VR Isle Academy is the first approach that provides the full training experience entirely in VR. In this paper, we selected da Vinci as the reference point due to its renowned reputation within the global community of surgeons. However, the work accomplished can be adapted to replicate any SRS system and not just the mechanics and training scenarios of the reference SRS. By leveraging available tools, we've developed a VR simulation enabling trainees to undergo SRS training conveniently, irrespective of location or time constraints. This addresses the challenge posed by the limited availability of SRS training devices in certain geographical areas, thereby saving both time and expenses associated with traditional training methods.



(a) (b) (c) (d)

Fig. 1: An actual Surgical Robotic System (SRS) simulation in comparison with its digital twin, VR Isle Academy. In images (a) and (b), a modern SRS simulator is depicted, showing a user operating from the surgeon's console. In contrast, images (c) and (d) showcase VR Isle Academy, where the user controls a simulated SRS digital-twin using an inside-out VR HMD, controllers and feet trackers.

2 Related Work

2.1 Digital Twin

A Digital Twin is a virtual representation, mirroring a physical object or process in the digital realm with a high-fidelity resemblance. The term was publicly introduced by Michael Grieves for a product lifecycle management [6].

In the modern age, digital twins are extensively utilized across various sectors including power generation equipment, structures, manufacturing operations, automotive industry, healthcare services, and urban planning [5]. Specifically, in domains such as SRS training, digital twins offer opportunities to simulate either real-life procedures, like laparoscopic surgery using the SRS, or typical training scenarios utilized for doctor training in SRS procedures. Within the framework of our project, we've developed a digital twin of the SRS training simulator, which can simulate real surgical operations when necessary.

2.2 Medical Training in VR

Numerous efforts have been made to expedite the training and education process in the medical field using VR. Recently, the cost of acquiring and maintaining commercial VR head-mounted displays (HMDs) has decreased. Furthermore, the contemporary advancements in HMD technology significantly enhance the overall performance of standalone applications. To this end, VR technology has been widely adopted for facilitating medical training not only for students but also for health care professionals. Several research papers and examples have demonstrated that VR training in the medical field reduces malpractices, training time, and the learning curve [9,7,19,14]. To facilitate the development of medical training scenarios, several software development kits (SDK) have been released.

MAGES SDK [23] is an innovative SDK that empowers developers with numerous tools to efficiently create fast and effective medical training scenarios. Paul Zikas *et al.* [23] highlight the latest advancements in the aforementioned SDK, including 5G edge-cloud remote rendering, a physics dissection layer, real-time simulation of organic tissues as soft-bodies within 10 ms, a highly realistic cutting and tearing algorithm, neural network assessment for user profiling, and a VR recorder for recording, replaying, and debriefing training simulations from any perspective.

Fundamental Core [1] is an all-in-one SDK for Unity game engine. The developer has the capability to establish a scoring system for real-time results at the end of a playthrough. Additionally, they provide a ready-to-use multiplayer service enabling users to connect and train together, complete with voice communication. Lastly, the SDK is device-agnostic and compatible with various VR headsets.

2.3 The da Vinci Surgical Robotic System

The da Vinci machine, a Surgical Robotic System developed by Intuitive(`https://intuitive.com`), stands as the most widely utilized SRS globally. This surgical system provides the surgeon with an advanced set of instruments for conducting robotic-assisted minimally invasive surgery. It consists of a surgeon's console, the four robotic arms that are scissors, scalpel, 3D cameras and forceps that are connected and moved from the surgeon's console and the vision cart which makes the connection between the surgeon's console and the robotic arms.

Moreover, the surgeon is provided with a superior vision, through the 3D real-time high-definition view with a magnifier that can reach up to 10 times more than the human eye can see. Moreover, the ergonomic design of the surgeon's console allows the surgeon to operate while seated for extended periods, ensuring high efficiency in incisions. The design also provides the surgeon with the capability to utilize hand controllers and foot pedals for the machine's various functionalities.

Lastly, the machine offers various functionalities triggered by pedals, masters, or the touch screen. The Camera Pedal allows adjustment of the position and orientation of the camera attached to a robotic arm. The Clutch Pedal is used to extend or shorten the robotic arm. Four energy pedals control the electro-surgical instruments. The 30-degree view pedal toggles between different camera views.

2.4 Previous Work

The current bibliography includes numerous VR training simulations incorporating advanced cognitive and psychomotor techniques aimed at maximizing educational advantages for trainees, exemplified by references such as [22] and

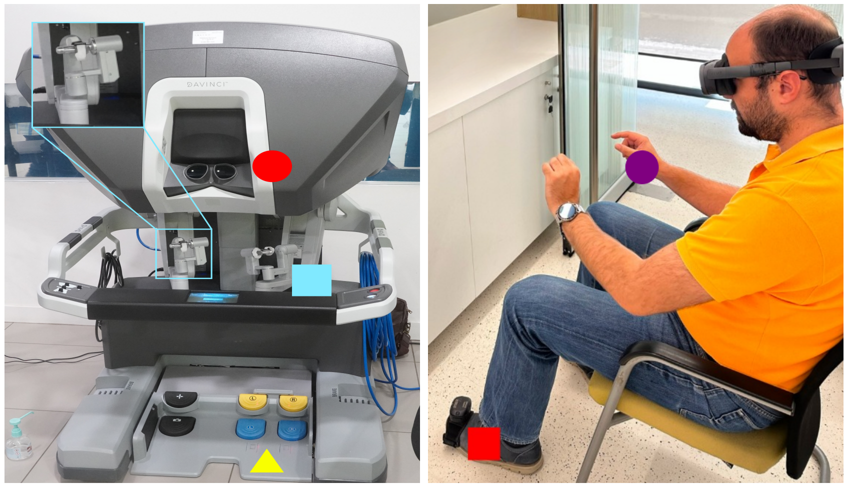


Fig. 2: (Left) The da Vinci surgeon's console features distinct elements. The yellow triangle represents the machine's pedals, whereas the red circle indicates the output of the cameras. The light blue square denotes the masters, each featuring two rings, into which the surgeon places their fingers in order to control the rotation and movement of the robotic arms. Original image from [3]. (Right) A user engages in exercises using hand tracking for controlling the robotic arms and HTC Vive Ultimate Trackers to operate the pedals on the surgeon's console. HTC Vive Ultimate Trackers are represented by red squares, while the user's hand, governing the console's masters, is depicted by a purple circle.

[14]. However, despite this proliferation, simulations tailored for training in SRS within XR environments remain relatively scarce.

Sketchy Neurons created a VR game called *Minimally Invasive* (`https://store.steampowered.com/app/2331420/Minimally_Invasive/`) where users act as transplant surgeons operating on aliens using a surgical robotic system. The game claims realistic physics and tools developed by actual surgeons. It includes a menu for training on robotic arms and six scenarios to teach functionalities like clutch and camera use. Despite using SteamVR, the game requires tethering, reducing portability, while also lacking realism in hand restrictions and physics implementation.

Surgical Robot Simulator (`https://store.steampowered.com/app/1727070/Surgical_Robot_Simulator/`) is another VR game that teaches SRS fundamentals. It offers tutorials and scenarios, featuring deformation algorithms for cutting and manipulating meshes. However, its control scheme for forceps and robotic arms is neither optimal nor intuitive, making seamless manipulation difficult.

Xiaoyu Cai *et al.* [8] proposed a robotic minimally invasive surgical simulator based on VR digital. In their research they used Pimax(`https://pimax.com/`) for the VR headset and two 3DSystems (`https://www.3dsystems.com/haptics-devices/touch`) Touch devices and two UR5 robots (`https://www.universal-`

robots.com/). While they have successfully linked the virtual and physical realms, there are still certain elements they are missing. Primarily, the application lacks portability, as it necessitates the presence of the robotic arm, touch devices, and the large machine designed to simulate the SRS. Furthermore, they do not incorporate any pedals, whether virtual or physical, to activate essential functions such as the clutch and camera. Finally, their solution is not cost-effective, mainly due to the necessary equipment required for the system to function effectively.

Marco Ferro *et al.* [11] proposed a portable da Vinci simulator in VR using cheap haptic interfaces and an Oculus Rift(https://www.oculus.com) to replicate the master console of the da Vinci. Despite its affordability, the system lacks portability due to the use of two styluses and a tethered connection to a desktop PC. Additionally, immersion is constrained, with users confined to a training scene, while clutch functionality is implemented through stylus' buttons

3 A digital twin for the surgical robotic system

3.1 The Unity Game Engine and the MAGES SDK

Unity (https://unity.com/) is a cross-platform game engine that can be used to create two-dimensional and three-dimensional games. The engine offers a primary scripting API in C#. We used a variety of external plugins in order to create this digital twin environment. The core plugin we used in order to create each training scenario is MAGES SDK, a robust tool enabling the creation of immersive XR simulations. From this kit, we used the analytics engine in order to capture the events needed to provide the user with realtime and offline feedback, and scores depending on their performance.

Also, the VR editor facilitates the quick and straightforward development of scenarios. Using scenegraph, a virtual editor that lets you create action nodes and modify existing ones in order to form a training scenario, we were able to create some of the basic scenarios of a SRS. More about them in the section 3.3.

Action nodes correspond to a certain task that has to be completed in VR. The developer can either use one of the predefined action types, such as insert action, remove action, use action, or create his own action type.

Although our implementation is Unity-based, our approach can be leveraged and implemented into any modern game engine.

3.2 Robot Description

The surgical robotic system employed in the VR environment consists of two parts, which are commonly coined as *master and slave* [17]. The master platform is controlled by the user with two-joystick-like controls (Fig. 3) and two pedals that can be utilized for changing functionalities when necessary. On the other hand, the slave is located in a different area within the scene and consists of two 6-Degrees of Freedom (DoFs) robotic arms. Each robotic arm is equipped with a 1-DoF two-jaw gripper end effector (the tool mounted at

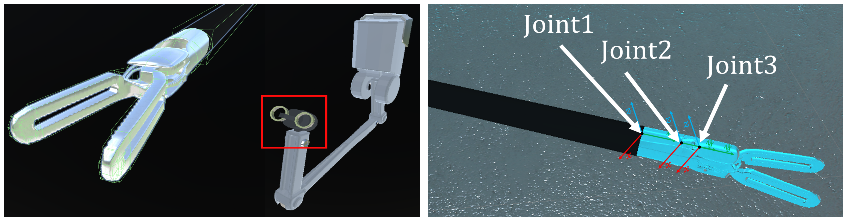


Fig. 3: (Left)The digital-twin robotic arm's end effector and the master control of the machine. The master controls the end effector in the digital-twin VR Isle Academy. The red box highlights where the doctor's fingers should be placed in the master during the operation. (Right) Three revolute wrist joints of the digital-twin robotic arm with the corresponding axes at each center of rotation.

the end of the robotic arm) featuring multiple box collider (Fig. 3), enhancing the realism and physics accuracy of haptic interactions with objects of various shapes within the scene. The master platform was acquired from [4] and it was modified appropriately to improve rendering speed and the overall efficiency of the model. The robotic arm was designed entirely by our team while drawing inspiration from the specifications of the da Vinci surgical robot(`https://www.intuitive.com/en-us/products-and-services/da-vinci`), the most widely utilized robotic system for minimally invasive surgeries [21]. Moreover, we aimed to replicate the surgeon's console, allowing users to customize the head height of the machine and adjust the position of the pedals to optimize ergonomic posture. Users can also re-calibrate the trackers to easily configure their height. These operations can be performed conveniently through the virtual tablet on the console.

3.3 Training Scenarios

In our application, we simulated eleven scenarios basic resembling those found in a modern SRS. These scenarios are designed to familiarize the user with the control of the robotic arms, the clutch pedal, the camera pedal, and the 30-degree camera.

The purpose of these activities is to provide the user with an interactive introduction to the surgical system's features. More precisely, some exercises try to mix various functionalities in a single scenario, while other lessons concentrate on a single one, such as the camera function in the Camera 0 scenario. For example, in the Sea Spikes exercises the user must learn how to manage delicate wrist movements while combining the camera and clutch functionalities effectively.

Through the User Interface (UI) menu, users can select from 12 training scenarios. Each scenario includes instructions outlining the exercise objectives and user responsibilities. For example, in Wrist Articulation 1, users must touch the ball inside a glass cube without breaking the exterior glass.

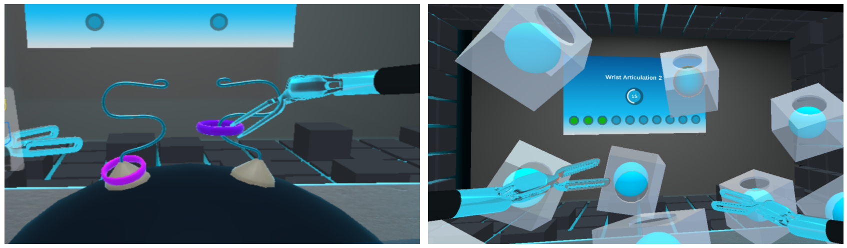


Fig. 4: Two of the 12 exercises implemented: the Ring Tower Transfer 1 (left) and the Wrist Articulation 2 (right).

The implementation of the exercises was carried out using the scenegraph framework from the MAGES SDK. In this framework, exercises can be seen as Actions that users have to perform. Exercises that require repetition, such as Wrist Articulation 1 or Camera 0, are implemented as one action that is repeated X times, where X is the amount of total iterations the scenario requires. To exemplify, in Wrist Articulation 1, the users have to perform two actions (in this case, place the instruments on a specific position and touch the glowing ball) ten times, but on a different angle. Lastly, more scenarios can be seamlessly added to the application in order to enhance the variety of the training options.

3.4 Error Detection and Analytics

In this section, we elucidate the scoring system we include in our application, used for the qualitative assessment of the users' performance. Through error detection and analytic metrics for each exercise, the users can monitor their progress and improve their skills. Each exercise contains a list of efficiency and penalty scores used to assess the overall score of the session. The scoring factors and analytics metrics of VR Isle Academy were designed and implemented based on the corresponding factors of a modern SRS, with a focus on retaining the different weight and importance of each metric to the final score of each exercise.

The main focus of VR Isle Academy regarding the scoring system is to retain the importance of each metric when providing user performance feedback. In order to extract information regarding the scoring factors and their importance, an iterative procedure was followed, where we carefully examined the scores and their breakdown in the actual simulation for each and every exercise. Each metric score is calculated using a weight factor. This weight factor varies from metric to metric.

The total score of an action is formed as such: $\text{Score} := \sum(\text{Efficiency Metrics}) - \sum(\text{Penalty Scores})$. As can be observed, the analytic metrics are split into two main categories: Efficiency Metrics and Penalty Scores.

For the implementation of the scoring system, we used the analytics framework from the MAGES SDK. Upon exercise completion a detailed breakdown of the score is presented to the user through a User Interface. Furthermore, MAGES automatically uploads analytics data for each exercise to a web browser portal in which users can log in using their credential and gain access to a detailed log.

4 Implementation Features & Novelties

4.1 Robot Control

The primary objective of this section is to present the control framework designed to guide the robot in accurately tracking the user's movements in an intuitive way. The user holds the VR controllers and by moving them, he can translate and rotate the two machine controllers within the virtual reality environment. These machine controllers, which will be referred to as "masters", directly control the robotic arms in the operation room. Each robot arm's end effector (EE) should achieve the corresponding desired pose (as extracted by the masters) accurately in real-time without significant delay. To this end, the computational complexity of the code is of pivotal importance when developing such a framework.

First, the 6-DoF pose (position and orientation) of each master is mapped into the desired pose for the corresponding EE (left and right). The mathematical expressions in this section will be formulated for one master and one EE since the left and right arms are considered equivalent. To prevent gimbal locks and other issues associated with representing rotations using Euler angles, rotation matrices are employed to express rotations, while transformation matrices are utilized for poses. Let $\boldsymbol{T}_W^M \in SE(3)$ be the pose of the master with respect to an inertial frame, or, world frame. $SE(3)$ is the *Special Euclidean* group in three dimensions, while $\boldsymbol{T}_W^M$ is a 4×4 homogeneous transformation matrix represents the translation and rotation from world frame (W) to the master frame (M) and it is defined as:

$$\boldsymbol{T}_W^M = \begin{bmatrix} \boldsymbol{R}_W^M & \boldsymbol{p} \\ \boldsymbol{0} & 1 \end{bmatrix} \tag{1}$$

where $\boldsymbol{R}_W^M \in SO(3)$ is the 3×3 rotation matrix which belongs to the *Special Orthogonal* group, $\boldsymbol{p} \in \mathbb{R}^3$ the translation part, $\boldsymbol{p} = [x, y, z]^T$ and $\boldsymbol{0} = [0,\ 0,\ 0]$. At each iteration, the orientation of the master is mapped to the EE's frame to extract the desired orientation (R_d):

$$R_d = R_{Wt}^M \times (R_{W0}^M)^T \times R_{W0}^{EE} \tag{2}$$

where, R_{Wt}^M is the current orientation of the master at time t, $(R_{W0}^M)^T$ is the transpose (or inverse) of the initial orientation of the master and, R_{W0}^{EE} is the initial orientation of the EE. For computing the desired position of the EE, $\boldsymbol{p}_d := [x_d,\ y_d,\ z_d]$, with respect to its own initial position, the following formula is utilized:

$$\boldsymbol{p}_d = \boldsymbol{p}_0^{EE} + \alpha \cdot (\boldsymbol{p}_t^M - \boldsymbol{p}_0^M) \tag{3}$$

where $\boldsymbol{p}_0^{EE}$ is the initial position of the EE, $\boldsymbol{p}_t^M$ is the current position of the master, $\boldsymbol{p}_0^M$ is the initial position of the master and finally α which denotes the translation sensitivity multiplier. Moreover, α is a hyperparameter that specifies the amount of change in the position of the EE for a certain displacement of the master. Given that this implementation is specifically tailored for surgical systems, enhancing the overall accuracy requires reducing the movement of the EE to considerably less than that of the master's displacement ($\alpha \ll 1$).

At every time step, after extracting the desired pose of the EE using equations (2) and (3), the corresponding control inputs ($u \in \mathbb{R}^6$) that achieve this pose are calculated using Inverse Kinematics (IK). To this end, we have developed a numerical-approximation IK solver that is utilized to determine the control inputs for each fully-actuated manipulator as follows. Consider the forward kinematics equation $\boldsymbol{x} = \boldsymbol{f}(\boldsymbol{\theta})$, where $\boldsymbol{f} : \mathbb{R}^6 \to \mathbb{R}^6$ is the forward kinematics function, $\boldsymbol{x} \in \mathbb{R}^6$ is the pose of the EE and $\boldsymbol{\theta} \in \mathbb{R}^6$ are the joint angles of the robot. The three wrist joint angles are depicted in Fig. 3. By deploying the *Newton-Raphson* method to solve the equation $\boldsymbol{g}(\boldsymbol{\theta}_d) = \boldsymbol{x}_d - \boldsymbol{f}(\boldsymbol{\theta}_d) = 0$, we extract the desired joint angles $\boldsymbol{\theta}_d$ that will result the desired pose for the EE $\boldsymbol{x}_d$ by using the 1^{st} order Taylor expansion [18]:

$$\boldsymbol{\theta}_d = \boldsymbol{\theta}_t + \boldsymbol{J}^{-1}(\boldsymbol{\theta}_t)(\boldsymbol{x}_d - \boldsymbol{x}_t), \tag{4}$$

where, $\boldsymbol{\theta}_t$ is the current state of the robot, $\boldsymbol{x}_d$ and $\boldsymbol{x}_t$ are the desired and current pose of the EE respectively. $\boldsymbol{J}^{-1}(\boldsymbol{\theta}_d)$ is the inverse Jacobian matrix that maps changes from the task space into joint space. Ultimately, after computing $\boldsymbol{\theta}_d$, we apply it to Unity's articulation drive component, which utilizes the information to extract the necessary forces for a smooth transition from the current to the desired joint angles.

4.2 Hand Tracking

All SRS machinery is typically controlled via hand movements of the user through a controller-like system, as depicted in Figure 2. Similarly, this approach can be adopted in the corresponding VR digital-twin, utilizing the HMD controller. However in order to increase the system's portability whilst enhancing the intuitiveness of controlling the robotic arms [12], we opt to explore replicating controller movements through hand tracking technology. This technology could enhance the training experience, particularly because the pitcher-like movement of the actual SRS cannot be replicated with a commercially standard VR controller. Therefore, hand gestures could be readily identified using hand tracking.

We aimed to replicate users' interactions and hand poses on the surgeon's console of an SRS, which led to the integration of hand tracking, as can be observed in Fig. 2, using the HTC Vive XR Elite and Quest 2/3 headsets.

Notably, hand tracking, by relying solely on onboard VR sensors, has limitations. For instance, the user's hands might exceed the Field of View (FOV) of the VR cameras which results in loss of tracking. Another significant issue is self-occlusion in instances that the user engages in intricate hand poses. This complication led to the VR system being unable to accurately recognize when the user was pinching, consequently preventing the forceps from closing in the digital twin.

While we successfully addressed the FOV problem by incorporating two HTC Vive Wrist Trackers on the user's wrists, the persistent self occlusion issue prompted. The hand tracking feature reserved solely for specific scenarios where pinch gesture is not required (such as Wrist Articulation). As a result, the pinch-like gesture that an SRS user would perform is instead performed via trigger buttons by the VR trainee.

4.3 Feet Tracking

Our primary objective was to implement a foot tracking solution to interact with physical pedals within the VR, which in turn would trigger specific functionalities of the surgical robot. We utilized the HTC Vive Ultimate Trackers (`https://www.vive.com/us/accessory/vive-ultimate-tracker/`), primarily due to their compatibility with standalone VR systems such as the HTC Vive XR Elite, and especially for Android applications. HTC Vive Ultimate Trackers are an enhancement of the standard model. They are distinguished by the inclusion of two 3D cameras, which significantly refine the mapping of the user's surroundings. This addition allows for a more nuanced interaction within virtual environments.

The Wave Tracker Manager from the Essence package is utilized in our application. The manager provides two key functionalities: activating the initial start tracker, triggering the tracker interface for direct communication when the API starts, and enabling the use of XR Device to retrieve tracker data. The script checks for instances where trackers may become stuck or lose connection, specifically when they have a valid rotation but no positional data, issuing warnings to the user. Once communication is established between the trackers and the headset, we implement the rotation and position data from the trackers onto the feet of the Full-Body avatar, ensuring an ongoing synchronization with the user's movements.

4.4 Feet tracker Mini-map

Mini-map in video games is a small heads-up display (HUD) map which is usually placed at the corners of the screen to help the player navigate inside the virtual world. Usually, the mini-map contains topographical information regarding key objectives and world features.

The utilization of feet trackers enables the user to literally press the pedals inside the virtual world. However, such action requires some form of feedback that will notify the user when the pedal has been pressed successfully. The HTC Vive Ultimate trackers do not provide a physical form of feedback (vibration). So, we propose a visual feedback scheme by utilizing the minimap. We created a User-Interface (UI) that represents the placement of the pedals and two UI elements, one for each foot. For the pedals, the user can see the Clutch, Camera, Switch and all the energy types. The user's feet UIs change position and scale. when the user moves his feet, the UI will change position. Then, by pressing one of the buttons, the UI icon of the particular pedal will turn black and an audible "click" sound will be triggered order to inform the user that he has pressed a pedal. Moreover, our approach solves another issue that corresponds to the height of the user's feet. If the user raises his leg, the feet UI will scale-up, signifying the foot displacement with the respect to the ground.

5 Results

To assess the effectiveness of our application and the impact on facilitating the medical training procedure, we conducted experiments involving 4 testers. The testers are medical students that do not possess any prior knowledge on operating an SRS. Each tester played 4 scenarios, repeating them 3 times. The order of scenarios was Wrist Articulation 1, Clutch, Camera 0, Sea Spikes 1, and Roller Coaster 1. Wrist Articulation 1 is the easiest scenario, whereas Roller Coaster 1 is the most challenging. The first three scenarios aim to familiarize the user with the core functionalities of the VR Isle Academy, namely, the control of the robotic arms, the clutch pedal and the camera movement. The remaining two scenarios involve a combination of robotic arms and camera movements, requiring users to execute precise actions.

The testers found it easy and intuitive to operate the surgeon's console for various training scenarios. The more they played, the easier it became for them to use. The most challenging concept to grasp was the feet trackers. Initially, users reported difficulty localizing their feet and whether they were pressing a pedal. This might stem from the fact that HTC Vive Ultimate trackers do not provide haptic feedback; hence, the mini-map and sound served as the only source of feedback. Upon familiarization, the users improved at controlling the trackers, getting accustomed to the mini-map.

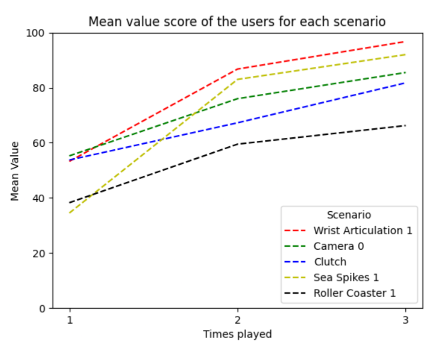


Fig. 5: The average score of four users in each scenario.

Even though the testers we selected are aspiring doctors, their background may not be fully aligned with the performance they achieved in the training scenarios. The ability to control a robotic arm should be intuitive and easy regardless of the user's background.

Lastly, users who have actually tried the VR Isle Academy prior to using the real machine have reported an intuitive transition between the two. The required training time with an instructor was significantly reduced and their score was higher than the average.

6 Conclusion

VR Isle Academy is a cost-effective solution that enables unsupervised training on operating an advanced SRS. Whether utilizing trackers, VR controllers, or Hand Tracking, the user enjoys the freedom to train in various settings. Thus, we minimized the need of using an explicit, bulky device. Also, the availability of the application is 24/7. Also, there's no need to schedule a slot or incur additional costs for a teaching service; the user can independently learn how to operate a SRS.

Moreover, the advancements in VR tracking technology, especially with the introduction of HTC Vive Ultimate Trackers, have substantially augmented the depth and breadth of virtual reality applications. These developments have not only heightened the immersive quality of VR but also expanded its practical applications across diverse fields. The ongoing evolution of VR technology promises further enhancements in tracking precision and user engagement.

Even as users strive to familiarize themselves with tracker usage, the inclusion of a mini-map depicting the position and orientation of the feet has proven highly beneficial. This approach effectively addresses the feedback-related challenges by providing visual and auditory cues, enabling users to orient themselves correctly and press the intended pedal.

The accurate error detection and comprehensive analytics are pivotal in such simulations. Surgeons undergoing training in this VR digital twin will benefit significantly from robust error detection mechanisms and detailed analytics. The user can check his analytics in real-time, while using the VR headset, or offline, by accessing a portal page.

Although we explored the Hand Tracking approach, we found it less suitable. The ergonomic design of the machine often led to hands going beyond the FOV of the VR cameras. Additionally, self-occlusion occurred when adopting unnatural hand poses. This presented challenges as the application couldn't accurately detect when the user was "tapping" or "closing" their fingers, impacting the simulation's fidelity. While we addressed the FOV issue by incorporating wrist trackers from HTC Vive, the problem of self-occlusion persisted. Although readily available tools were utilized for developing VR Isle Academy, the novelty lies in their effective integration. The combination of different features and techniques provides the users with a unique, immersive educational experience and value.

7 Future work

Development will continue, introducing an additional twelve scenarios aimed at training users in utilizing the energy pedals, the switch pedal, and a pedal facilitating the transition between two robotic arms. Additionally, there will be diversification in the types of forceps, incorporating both mono-polar and bi-polar options, enabling the utilization of different energy sources.

Currently, the sole method of employing the trackers independently is through the Wave SDK. However, there are plans to ensure compatibility of the Vive Ultimate Trackers with OpenXR. Preparations have been made, having already executed a port of the VR application to OpenXR for other HMDs like Meta Quest 2 and Meta Quest 3.

Finally, controlled clinical trials involving surgeons will be conducted to assess the fidelity and resemblance between the real and the digital twin SRS. Two groups will be formed. Both groups will use the real SRS while only one of them will have been trained using VR Isle Academy. Subsequently, we will compare the efficiency and time taken by each user, comparing the usage of our application and an SRS versus using only an SRS.

8 Acknowledgements

Heartfelt gratitude is extended to George Sofianos, Angeliki Karava and Alexandros Sgouridis for their generous provision of a modern SRS system and invaluable help and support throughout the learning journey. Lastly, special thanks to Pearly Chen and HTC Vive for providing us early access to the HTC Vive Ultimate body trackers.

This work is partially supported by the OMEN-E project (PFSA22-240), that have received funding from the Innosuisse Accelerator programme.

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