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ORIGINAL ARTICLE

Developing scalable hands-on virtual and mixed-reality science labs

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Abstract
Recent innovations in virtual and mixed-reality (VR/MR) technologies have enabled innovative hands-on training applications in high-risk/high-value fields such as medicine, flight, and worker-safety. Here, we present a detailed description of a novel VR/MR tactile user interactions/interface (TUI) hardware and software development framework that enables the rapid and cost-effective no-code development, optimization, and distribution of fully authentic hands-on VR/MR laboratory training experiences in the physical and life sciences. We applied our framework to the development and optimization of an introductory pipette calibration activity that is often carried out in real chemistry and biochemistry labs. Our approach provides users with nuanced real-time feedback on both their psychomotor skills during data acquisition and their attention to detail when conducting data analysis procedures. The cost-effectiveness of our approach relative to traditional face-to-face science labs improves access to quality hands-on science lab experiences. Importantly, the no-code nature of this Hands-On Virtual-Reality (HOVR) Lab platform enables faculties to iteratively optimize VR/MR experiences to meet their student's targeted needs without costly software development cycles. Our platform also accommodates TUIs using either standard virtual-reality controllers (VR TUI mode) or fully functional hand-held physical lab tools (MR TUI mode). In the latter case, physical lab tools are strategically retrofitted with optical tracking markers to enable tactile, experimental, and analytical authenticity scientific experimentation. Preliminary user study data highlights the strengths and weaknesses of our generalized approach regarding student affective and cognitive student learning outcomes.

Keywords No-code · Mixed-reality · Virtual-reality · STEM education · Science labs · Optical tracking · Multidisciplinary uses of XR

1 Introduction

Recent advances in virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies have enabled a wide range of novel training applications in fields such as dance/motion (Chua et al. 2003; Chan et al. 2011), psychological therapy (Pertaub et al. 2001; Anderson et al. 2003), construction/manufacturing (Seth et al. 2011), medicine/surgery (Lampotang et al. 2021; Freschi et al. 2015), and education (Chini et al. 2012; De Jong et al. 2013; Johnson-Glenberg 2018).

The immersion provided by VR head-mounted displays (HMD) coupled with the high precision of emergent motion tracking technologies makes MR especially well-suited for science lab education applications that require authentic hands-on tactile and kinesthetic force feedback. Virtual labs, in general, and immersive VR/MR science labs, in particular, have yet to enjoy widespread adoption as physical and life science laboratory instruction tools given the complexity of designing, implementing, testing, and maintaining such systems.

Most existing virtual science labs utilize 2D computer screens, keyboards, and mice as their main interaction devices. One major critique of such approaches is the inauthentic nature of the tactile user interactions/interfaces (TUIs) implemented in current generations of non-immersive 2D

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web-based virtual labs (i.e. a computer mouse) (Stephens et al. 2016). Even for immersive VR experiences that employ hand-held 6DOF controllers, the level of tactile authenticity required to teach lab-relevant psychomotor skills, to achieve effective learning outcomes such as a high level of motivation, or to build a user's sense of self-confidence and science identity remain limited. While many conceptual physical and life science learning tasks do not require tactile authenticity in lab tool manipulation and handling (e.g., understanding how to carry out calculations on datasets), students do enjoy, are far more engaged in learning, and show improved retention when concepts are learned and applied in a hands-on manner (Bigler and Hanegan 2011; Desai and Stefanek 2017; Catena and Carbonneau 2019). At the same time, authentic tactile psychomotor skills acquisition is essential to the real-life application of science in research and development settings.

Here we define VR experiences as those wherein the user is completely immersed within a physically non-existent digitally rendered 3D environment which they interact with indirectly using hand-held optically-tracked controllers. We define AR systems as non-immersive experiences where the user still sees the physical world around them and in which physically non-interactive digital content is spatially overlaid onto the physical world while the users' voice, eyes, and/or hand gestures enable non-tactile interactions with this digital content. We also define MR systems, generally, as VR systems in which one or more elements of the physical world (e.g. the user's hands and/or physical objects that are held and manipulated by the user) are spatially tracked and passed into the virtual world where they can interact non-physically with virtual objects even while they interact physically with each other and with the user. For the present purposes, it's also useful to further distinguish MR systems into those which "actively" provide tactile or kinesthetic force-feedback to the user from objects in the virtual environment using haptic components (i.e. gloves or suits with pressure sensors and/or actuators) from those which simply track the positions and orientations of hand-held physical objects in a "passive" manner (i.e. without returning any tactile or kinesthetic force feedback to the user through powered/actuated elements). While "active" MR hardware is more expensive and typically designed to be object-agnostic (i.e. able to emulate the feel of a broad range of different virtual objects on the user's body) at the expense of some elements of tactile authenticity, "passive" MR hardware can potentially be more cost-effective and provide more refined or accurate tactile/kinesthetic force feedback but for a narrower range of virtual objects.

"Active" MR hardware currently cannot provide for cost-effective and scalable reproduction of the hands-on "feel" of carrying out delicate scientific benchwork and experiments. Fortunately, in physical and life science laboratory settings, a user or trainee uses only a limited number of hand-held lab tools which must interact with each other and with the user's hands while the endless list of reagents theymanipulate must never actually touch their hands. The precise and refined manipulation of and interactions between these lab tools is what provides the user with the tactile and kinesthetic force feedback essential to psychomotor learning. Thus, one possible way to infuse tactile authenticity into VR/MR science lab learning systems without breaking instructional budgets would be the use of "passive" MR optical tracking technologies to spatially track sets of hand-held lab tools that are passed into the virtual world or "virtualized" such that their physical interactions with each other and with the user's hands in the real world can continue to provide fully authentic tactile and kinesthetic force feedback to the user even while the virtual instances of the tracked physical lab tools contain, transfer, and trigger reactions between virtual reagents and samples.

We have adopted this strategy while also tackling the remaining problem of how to create and iteratively optimize impactful MR lab experiences in a cost-effective manner using a no-code content development framework. This approach has already been adopted in some fields with great success (Lampotang et al. 2021), and will be essential in resource-limited applications such as STEM education.

To address the mentioned challenges in science lab education, we designed and implemented the Hands-on Virtual Reality (HOVR) Lab system with VR and MR modes. In this paper, we describe our current progress in developing a suite of HOVR Labs in the fields of chemistry and biochemistry as a proof-of-principle for a general framework for scalable and cost-effective construction of fully customizable HOVR Labs across the physical and life sciences. This system and framework were briefly introduced in a recent short paper (Hamadani et al. 2022). Here, we provide a detailed and complete description of our foundational software system—including the hardware-software integration required to support seamless switching between VR and MR TUI modalities with each lab tool as well as our structured spreadsheet approach to realizing a no-code content development workflow. In VR mode, the user interacts with the lab tool in question exclusively using VR controllers. In MR mode, selected sets of hand-held physical lab tools (which are carefully retrofitted with tracking markers) are optically tracked and rendered to the user's HMD to enable complete tactile authenticity in lab tool handling.

In our current work, we also provide a detailed analysis of a user study we conducted in the context of an analytical chemistry lab course which highlights both the strengths and weaknesses of our generalized approach. Through this user study we aimed to test the following hypotheses/questions:

1). Is authentic kinesthetic/tactile sensory feedback (i.e., the "hands-on" factor) a critical determinant of user interest and motivation to learn laboratory skills content? 2). Does this "hands-on" factor reinforce and enhance a user's ability to learn and retain STEM content knowledge? 3). Is it possible to reduce the complexity of developing customized VR/MR learning experiences so that resources can be put into content development instead of software development?

To address questions 1 and 2, we employed the VR TUI mode as a control and the "passive" MR TUI mode as an experimental intervention to test the impact of tactile authenticity on affective and cognitive learning outcomes. To address question 3, we employed structured Microsoft Excel spreadsheets to allow faculty content developers to create a fully prepared laboratory learning environments tuned to the needs of their students rather than the resource limitations imposed by software development costs. The key innovations of our work are summarized in Table 1.

Despite the limited course modules and lab tools implemented in the current system, it is suitable to be used in high school, lower division college, or continuing education introductory chemistry and biochemistry courses that contain introductory lab experiments such as pipette calibration. With more lab tools and lab modules, more courses will benefit from this approach in the future. The general framework we present which bridges no-code content development, cost-effective MR lab tool tracking, and authentic virtual science labs could benefit other science and engineering fields that require authentic hands-on labs. Section 2 presents a brief overview of prior related work. Section 3 provides an overview of the current HOVR Labs system and explains how its various sub-components are integrated. In Sect. 4, we provide a detailed description of the foundational software, its various sub-components, and the framework it implements. In Sect. 5, we present the user study design and our preliminary results. We discuss the overall system design, benefits, lessons learned, and future work in Sect. 6.

Table 1 Hands-on virtual reality lab (HOVR Lab) innovations

	HOVR lab (our work)	Existing VR labs
System TUI modality	Two modes per lab tool: VR and "passive" MR (authentic tactile kinesthetic feedback)	Single-mode: VR (inauthentic tactile/kinesthetic feedback)
Content development	Highly modularized, scalable, and iteratively optimizable no-code content development via structured spreadsheets	Fixed lab procedures or content development workflows that demand more software development resources to allow iterative optimization of the learning environment

2 Related work

In STEM fields, virtual labs complement and synergize with traditional face-to-face labs in many ways (Chini et al. 2012; De Jong et al. 2013). Animations that illustrate the microscopic or molecular basis for macroscopic experimental observations can be embedded into virtual experiments with positive outcomes for student learning (Moore et al. 2014). Real-time assessments with immediate responsive feedback are also beneficial for STEM learners. With advances in machine learning and artificial intelligence, adaptive learning experiences that model a user's knowledge state (Taagepera and Noori 2000; Stahl and Hockemeyer 2019) based on such real-time assessments and then offer them customized content tuned to their developmental stage have also demonstrated utility in specific contexts. Finally, our understanding of complex inquiry-based learning processes and mechanisms has been transformed by the application of the Knowledge Integration framework for technology-enhanced learning systems (Linn and Eylon 2011; De Jong et al. 2013; Linn et al. 2015; Linn et al. 2018).

Most existing virtual science labs or simulations are non-immersive and use monitor-based 2D displays, a keyboard, and a standard mouse to enable user interaction (UI) with digital content. However, the lack of immersion and tactile/kinesthetic authenticity in such 2D systems – which forgo all the advantages of spatial computing—limits their ability to engage and motivate STEM learners. Despite these limitations, such 2D non-immersive virtual science labs have demonstrated their impact on learning in various contexts (Bonde et al. 2014; Faulconer and Gruss 2018).

As computer graphics and spatial tracking/computing technologies have improved, it has become possible to create, implement, and examine the impact of more immersive 3D virtual science labs (Ali et al. 2014). In 2018, Schell Games released a gamified VR chemistry lab experience called "HoloLab Champions," to much acclaim (Shell-Games 2021). Notably, the ability to spatially track the hand-held controllers, headsets, and MR accessories of VR/MR systems using three degree-of-freedom (DOF) or six DOF tracking methods offers the prospect of applying the millimeter/millisecond spatiotemporal resolution of spatial computing to hands-on lab training applications and the provision of real-time feedback on psychomotor skills acquisition with a precision, accuracy, and scale that could never be achieved in a traditional lab training environment.

Though non-immersive 2D and immersive 3D virtual lab experiences both offer advantages for STEM learning (Bonde et al. 2014), the acquisition of practical hands-on skills requires – among other things- the proper manipulation of real lab tools and cannot be emulated using computer mice, keyboards, or even three DOF or six DOF VR controllers. Unfortunately, the costs of developing immersive VR or MR content currently limit the scale and scope of existing VR MR chemistry/biochemistry/science lab experiences. In addition, most current work employs VR (as opposed to MR) TUI modalities, in which interactions with virtual instances of lab tools and content are mediated solely by VR controllers. Such controllers do not give users an authentic tactile/kinesthetic sensory experience of holding and manipulating real lab tools.

3 Hands-on virtual reality (HOVR) lab system

The HOVR LAB system is comprised of a combination of commercial and home-built lab tool tracking hardware and software components; custom Unity3D foundational software; structured spreadsheets (called Lab Module Generators) that serve as sharable and editable no-code content creation tools; and a series of real-time, cognitive, and affective assessments that are used to iteratively improve and optimize the prepared virtual learning environment to maximize achievement of student learning outcomes.

3.1 System overview

As shown in Fig. 1, the front-end student-facing UI elements include three main classes of objects – lab tools, lab instruments, and a display for presenting instructions and feedback to the user. Lab tools function as simple virtual reagent containers and do not read or write information to or from the user. Each lab tool has a pre-determined fixed precision and a programmatically controllable accuracy. For example, micropipettes, beakers, reagent bottles, solvent dispensers, and graduated cylinders are lab tools and it's possible to purposefully and programmatically mis-calibrate the micropipette. In contrast to lab tools, lab instruments do read or write raw or analyzed data to or from the user. Such lab instruments include digital scales, calculators, pH meters, data analysis software/spreadsheets, and a lab notebook. Students read the step-by-step instructions on the display and use the lab tools and instruments to complete a series of tasks – which are further subdivided into milestones- while receiving responsive real-time feedback both during and after the completion of each individual milestone.

Fig. 1 HOVR Lab system user-facing front-end design. The virtual laboratory bench has a display for telling the user what tasks they need to perform, a submission area for submitting reagents or products for assessment, and lab tools that can be controlled via VR controllers (in VR mode) or MR handlers (in MR mode). The system also employs voice commands for various interactions

Each lab module can be experienced in either of two TUI modes: MR-mode or VR-mode. We will first explain the MR mode system flow. In the MR mode, a pre-selected set of physical lab tools (i.e. physical lab tool "handlers") are each spatially tracked while being physically manipulated by the user and interacting with each other to provide "passive" tactile and kinesthetic force feedback to the user. This tracking information is streamed into the main Unity simulation to update the positions of the rendered virtual instances of the lab tools within the virtual environment.

The tasks that the user must perform in a given module are broken down into "milestones". Each milestone is defined as a particular state of the virtual world and is specified by defining the value of one or more variables on one or more virtual objects being manipulated by the user or else placed by the user onto a designated "submission area" for assessment. The rows of the Lab Module Generation Spreadsheet define these milestones using drop-down menus and pre-formatted lists of variable and object names that content developers can easily select without prior game development or programming experience. By selecting from these drop-down lists of variables and objects and then specifying target values and acceptable tolerances, content developers can create and refine lab modules with great freedom and ease. The spreadsheets can also be freely distributed, shared, modified, and refined to create new experiences targeting more, less, or other learning objectives or user groups.

Figure 2 illustrates the flow of information between subcomponents of the HOVR Labs system. SteamVR tracking provides the positions and orientations of the VR controllers and HMD. In MR mode, customized 3-D printed adapters are mounted onto lab tools to rigidly hold sets of IR retroreflective beads/markers onto each physical lab tool in a non-perturbative fashion to enable passive optical tracking (Fig. 2, upper right). An Optitrack motion capture system (Natural Point, Inc. Corvallis, Oregon) stereoscopically triangulates the 3D spatial position of each marker and calculates the pose (position and orientation) of each lab tool being manipulated. This information is then streamed into the main Unity simulation via Optitrack Motive software and its Unity3D plugin. Active tracking of lab tools is also enabled using commercial or custom-built SteamVR

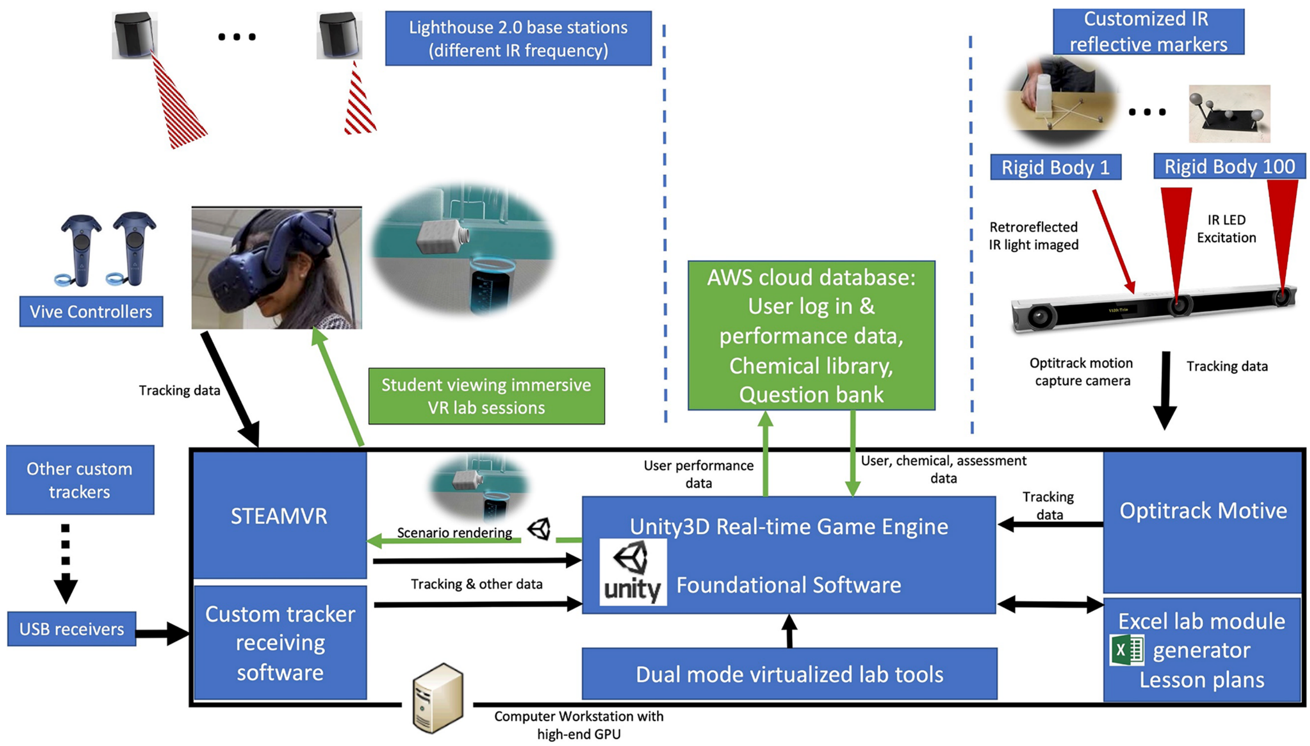

Fig. 2 The HOVR Lab system overview. Optical tracking hardware, lab module generator, dual mode (VR/MR) virtualized lab tools, Unity3D foundational software, and AWS cloud-based database are integrated together to provide scalable content development, smooth user interaction, and student performance evaluation capabilities

trackers (Gow et al. 2023) (Fig. 2, lower left). Optionally, passive optical tracking can also be achieved using less expensive fiducial markers and much simpler (i.e. webcam-based) imaging systems to further reduce hardware costs for passive MR implementation (Wu et al. 2017; Ahmadinia et al. 2022; García-Ruiz et al. 2023).

Only the critical lab tools that require authentic tactile feedback to promote learning are motion-tracked and presented in MR TUI mode. Interactions with lab tools and instruments that either don't require tactile authenticity for learning (e.g., notebooks, calculators, etc.) or which are not the focus of psychomotor skills acquisition in the present module are mediated by VR controllers.

In VR mode, students use object-agnostic HTC Vive VR controllers to interact with all objects in the virtual environment. The Optitrack motion capture streaming information is turned off and all the physical lab tools are cleared from the workbench. The virtual lab tools are generated like in MR mode, but they do not follow physical lab tools' movement and need the user to control them with VR controllers. This tunable tactile authenticity is a key element of our system design. The Lab Module Generation Spreadsheet functions independently from the TUI mode (MR or VR). After the tracking information is streamed into the system and the virtual lab tools are generated, subsequent stages of the software which control the lesson plan representation/implementation are the same.

3.2 Hardware and system performance

Our current system uses the Unity3D real-time gaming engine as the main platform for the simulation software. HTC Vive Pro HMDs render the virtual environment to the user, and 2 to 4 Light House 2.0 base stations are used for SteamVR tracking of the HMD and VR controllers. One Optitrack Trio camera is mounted to the wall in front of the lab bench for stereoscopic determination of retroreflective marker positions and passive optical tracking of the associated lab tools.

A desktop computer with an Intel Core i7 CPU and an Nvidia GeForce GTX 1080 graphics card powers the virtual/mixed reality experience. Currently, the VR/MR simulation runs at about 90 frames per second (fps) with 11.1 ms latency, which is sufficient to avoid VR motion sickness in most users. With roughly ten simultaneously tracked lab tool objects, the Optitrack motion tracking latency is currently around 11.6 ms observed from the Optitrack Motive software status panel. The Optitrack Motive software runs on the same computer as the Unity3D simulation software with a streaming rate of 120 fps. The Optitrack Motive software and streaming latency is thus estimated as 11.6 ms + 1000/1

20 ms = 20.03 ms. Chenechal et al. measured the HTC Vive Pro's Unity app-display latency at a mean of 31.33 ms with up to 1 million polygons rendered (Chénéchal et al. 2018). Our simulation has 210.7 k triangles, well within the range tested in Chenechal's work. Our system also uses a more powerful GPU. Thus, the total system latency from the optical tracking system to the virtual content displayed to the user in the HMD is estimated to be less than (20.03 + 31.33 ~) 51.36 ms. This is slightly higher than typical VR controllers' 'motion-to-photon' delays at 21-42 ms (Warburton et al. 2023). Since our user experience design requires users to stand in front of a lab bench without any need for sudden movements the simulation does not cause much motion sickness or sensation of motion delay in users.

We have developed and tested different science lab-tool tracking solutions. The design and optimization of both the active and passive tracking markers and adapters used in the HOVR Labs system are published in our recent hardware development papers (Ahmadinia et al. 2022; Gow et al. 2023).

3.3 Course integration and logistics

This system is designed to be used in secondary or post-secondary teaching environments. We put special effort into reducing the cost and system setup complexity. For each VR/MR station, the following equipment is required: a gaming computer with a GPU processor (~$500–1500); one ~2.5' x ~5' folding table (~$50); one consumer-level VR headset (ranging from ~$300 for a stand-alone Oculus/Meta Quest with controllers to $1200 for an HTC Vive Pro with base stations and controllers); one optical-tracking camera (ranging from ~$100 for a simple web-cam suitable for low-fidelity fiducial marker tracking to $4000 for an Optitrack Trio stereoscopic IR tracking camera suitable for high-fidelity optical tracking); a set of physical lab tools plastic beakers, pipettes, tip racks, plastic sample tubes, etc.) with marker-mounting adapters (HOVR Labs LLC) and tracking markers (retroreflective beads are ~$5 each from Natural Point or HOVR Labs LLC). Importantly, glass lab tools are replaced with plastic versions whenever possible to minimize the danger and liability of working with glassware. Notably, it's possible to repurpose mis-calibrated or otherwise inoperable lab tools that still have the feel of functional lab tools for our purposes. The optical tracking adapters can also be 3D-printed in-house and mounted onto the lab tools. Periodic calibration of the SteamVR tracking system and the Optitrack motive tracking system are necessary on a monthly basis. This system calibration takes only a few minutes and is automated in our protocol. A convenient workflow and user database are designed and implemented to store user information and facilitate course integration.

Implementation of the VR/MR lab experiences was designed to be minimally invasive to standard teaching environments. All the VR or MR lab experiences we've made (including the pipette calibration module described and tested here) can be easily shortened and simplified or made longer and more rigorous/demanding depending on the target audience and time restrictions. The experiences described here were hosted in a dedicated VR studio with two VR/MR lab stations. VR/MR gaming studios that are now commonly found at museums, malls, and many college campuses worldwide typically have 5 or more such VR/MR stations. Our VR/MR studio has trained staff who maintain the equipment and host the VR or MR lab experiences. Training of new staff members who were not familiar with our study or with VR/MR, in general, were held each semester as needed and took about two days. We are currently able to process students through VR/MR lab experiences at throughputs of about five 90-min labs per station per day. With 5 VR/MR stations, this would provide a throughput of about 125 experiences per week at maximum capacity.

At the beginning of the semester, class instructors informed the class roster and desired experimental module to the lab staff using a formatted Excel form. The staff then assigned and distributed user IDs and passwords to each student via a secure channel. In the case of the user study, the staff randomly assigned the students to different experiment or control groups. The file containing a mapping between the real student information (class, name, and email) and system ID and password was only accessible locally by the staff to protect student information. This roster Excel containing assigned user ID, password, and experiment groups (without real student information) was then uploaded to the cloud database integrated with the main simulation software to load the correct mode (VR or MR) and module of the experience upon student user login.

During the semester, students received an invitation to experience our platform and book VR lab time via a shared calendar. Students completed intake survey's and quizzes and watched preparatory tutorials via an online learning platforms. The lab staff set up the software and hardware before each batch of students came to the VR studio for sessions.

After all the students finish the experience towards the end of the semester, the staff can download student performance records from the cloud database and return the file to the instructor for grading purposes.

The main challenges we met were training lab staff, instructors, and students to use the system in an effective manner. To address these challenges, we made a series of tutorials for each user subtype. We have a "lab staff checklist" file and video tutorials to remind lab staff of the exact steps required to open, use, and maintain the system. We

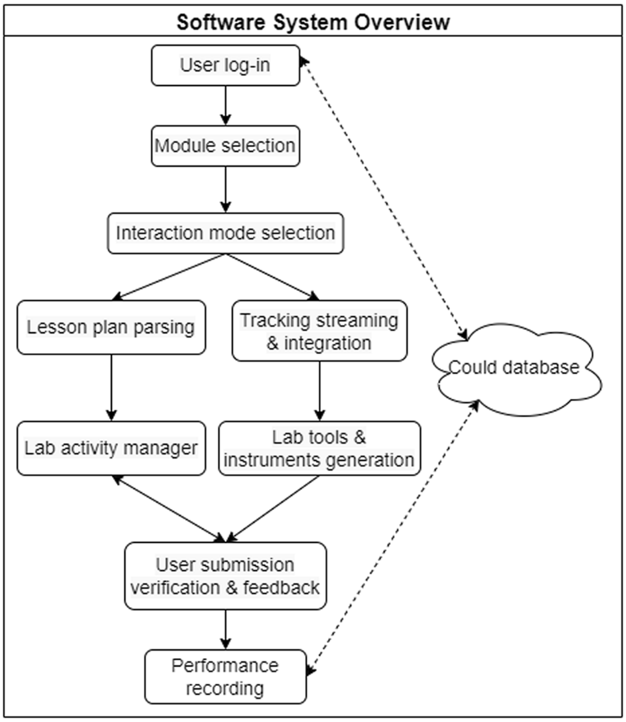

Fig. 3 Software system overview

also have a step-by-step tutorial to 3D print the needed marker sets and where to mount them onto the lab tools. A few backup lab tools with trackers are maintained in the lab for a quick change if any trackers break. The quizzes and VR studio booking system were implemented in our campus's learning management platform. We also designed a "welcome tutorial" video for students to watch before showing up to the lab. In the main virtual lab simulation software, we added many milestones to orient the student user, like which controller button to press and when. With these onboarding materials, we were able to quickly train lab staff across different semesters during the development and testing of the system and smoothly run user studies.

4 Software design

4.1 Software system overview

The HOVR Lab MR simulation software is designed to enable content developers to easily customize and optimize the lab experience while making interactions with the virtual lab environment intuitive for student users. The system was designed using an Agile development workflow, and the main software design patterns employed include the state pattern, coroutine, event handling, and singleton pattern.

The main foundational software system initializes the VR/MR experience using the following sequence (Fig. 3):

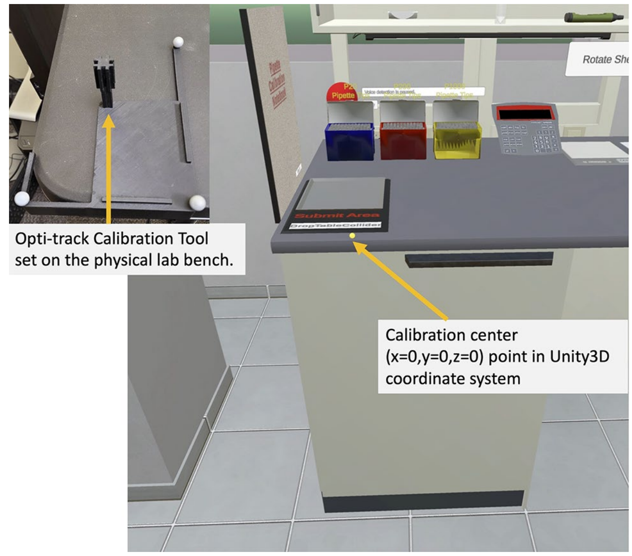

Fig. 4 Coordinate system registration and calibration procedures. The coordinate systems of the real, HTC Vive/SteamVR, Unity3D, and Optitrack worlds are aligned based on the calibration centers shown

User login, module selection, interaction mode selection, Lab Module Generator spreadsheet parsing, SteamVR and (when in MR mode) Motive optical tracking initialization, world calibration/registration, handler/tool/instrument instantiation, and finally lab activity management and user input verification components. Once the initialization sequence is complete, the instructions for each milestone are read/displayed on the task display screen. The user then completes the task, the user's submission is assessed against a target value (which can depend on the data acquired or submitted in prior milestones), and feedback is then provided based on whether the user adequately achieved the milestone. Real-time student assessment data is uploaded to the cloud database after the completion of each milestone to minimize database read–write call delays, which could otherwise impact system performance.

4.2 UI mode and global/local coordinate system registration processes

The HOVR Labs system has multiple coordinate systems that need to be calibrated with each other to meet the tracking needs of our application. For the most demanding science lab tool tracking applications we require sub-millimeter 3D spatial registration accuracy and precision for all these coordinate systems.

We defined a common global coordinate system with its origin near the front-left corner of the physical lab bench (Fig. 4, top left). We used a custom-made L-shaped 3D-printed calibration/registration tool containing three passive IR retroreflective beads to align the Optitrack coordinate system and origin to this common global coordinate system with sub-millimeter registration accuracy. The UNITY3D coordinate system is brought into registration with this common coordinate system by setting a "calibration center" object (located on the virtual lab bench where the L-shaped calibration/registration tool's corner would be) as the UNITY3D origin. The HTC Vive/SteamVR coordinate system is then brought into registration with the common coordinate system by mounting one or more fiducial HTC Vive trackers or controllers onto or beneath the custom-made 3D-printed calibration/registration tool (Fig. 4, top left).

Each of the 3D printed adapters used to mount passive rigid-body marker sets or active tracking markers onto a lab tool must also have its local coordinate system brought into registration with the common world coordinate system. This is achieved using a custom-designed 3D-printed orientational registration tool that positions each adapter in a defined orientation relative to the physical lab bench. This combined world/global and lab tool/local registration protocol enables the detection of even the most nuanced functional interactions between the various actively or passively tracked hand-held lab tools.

All the lab tools' rigid body names and initial orientations are predefined within the Motive software. Upon initializing the simulation within the Unity 3D environment, the algorithm pairs the virtual lab tool handlers with the correct rigid-body tracking data being streamed from Motive so that the virtual lab tool handlers are appropriately matched and registered to the real hand-held lab tools being manipulated by the user.

The entire world/global calibration/registration process takes 5–10 min and consists of: 1). the standard SteamVR room calibration process; 2). Calibration/registration of the Optitrack Motive world using the L-shaped calibration tool; 3). opening the main simulation software; and 4). single-click calibration/registration of the SteamVR world using the Vive tracker or controller. The local registration data for the tracked lab tools are saved in data files that are read and

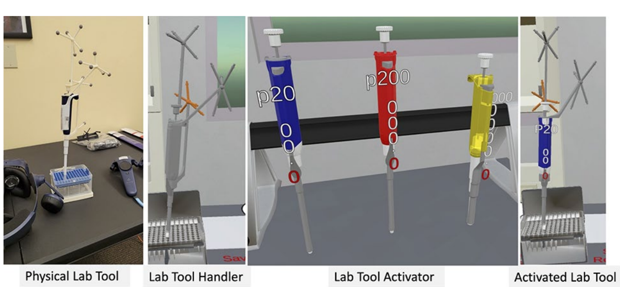

Fig. 5 The handler-activator-activated lab tool system enables the manipulation of lab tools in either MR or VR mode. Lab tool "handlers" are used to pick up unlimited instances of fully functional "activated lab tools" at "lab tool activators" located on a small "infinite" shelf containing all possible lab tools

directly applied to the Motive and SteamVR tracked objects when students log in so that students and staff do not have to worry about this calibration procedure unless new lab tools are added. The global calibration remains stable for about one month when the lab bench, camera, and Lighthouse base stations are not moved.

4.3 Handler-activator-activated lab tool system

In science or chemistry lab experiments, students must manipulate many different lab tools but generally in succession rather than simultaneously. They also often need to manipulate multiple instances of a lab tool. For example, students might have multiple beakers, test tubes, and micropipettes on their bench but are likely to only hold and use one or, at most, two at a time. To allow one tracked handheld physical lab tool to mediate interactions with all virtual instances of that particular lab tool, we designed the handler-activator-activated lab tool system (Fig. 5).

"Handlers" are virtual objects whose position and orientation are spatially registered with the real-life lab tool via the methods described above during gameplay in MR mode. In VR mode, handlers track the positions and orientations of the two Vive controllers, and all the physical lab tools are cleared from the bench. In MR mode, motion-tracked physical lab tools for the current module are positioned on the bench together with the Vive controllers (Fig. 5, leftmost image). The markers used for tracking are visible on handler objects to ensure users are aware of the markers and don't accidentally bump the markers into things during use. They are also greyed out and function only to pick up, move, and drop off "activated" lab tools—functional instances of the corresponding type of lab tool they "handle" (Fig. 5, second picture from the left). "Activators" (Fig. 5, third picture from the left) function to instantiate lab tools and are typically located on the lab shelf. When a "handler" moves onto its corresponding "activator," it picks up a new/unused instance of an "activated" lab tool (Fig. 5, rightmost image), which is now fully functional and can contain/manipulate reagents. The user can use gestures or voice commands to drop off activated (i.e., reagent-containing) instances of lab tools onto the bench. Upon dropping off an activated instance of a lab tool on the lab bench, the handler's grey mesh reappears, and it can be used to pick up another instance of the same lab tool. Users can create an unlimited number of virtual instances of lab tools, each with their reagent, to create virtual reagent libraries.

This system minimizes the number of tracked lab tools required to simulate a given lab experience and minimizes marker occlusion, physical lab bench clutter, and potential marker/lab tool/adapter damage.

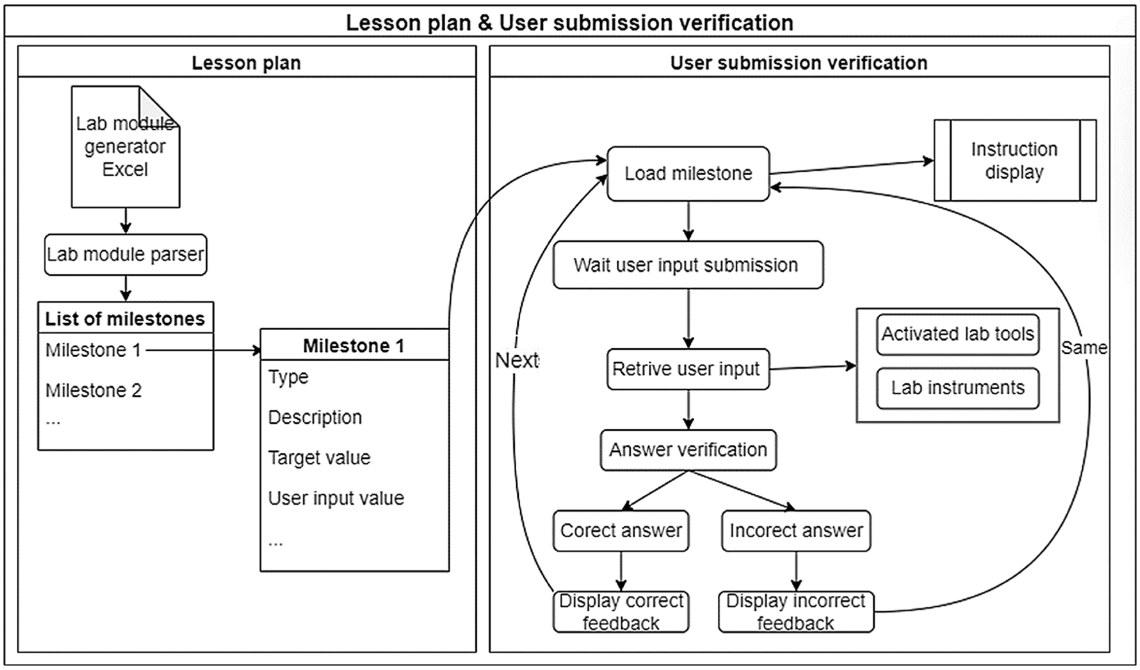

Fig. 6 Lesson plan parsing and student submission verification software design

The content creators can specify which lab tools will be used in MR mode and require handlers and which will be used in VR mode via the Lab Module Generator.

4.4 Lab module lesson plan generation middleware and milestones

Content creators can choose from pre-defined milestone types while constructing their HOVR Lab experience using the Lab Module Generator. Each milestone is defined by logical criteria that the virtual environment must meet for the user to progress to the next milestone.

When ready, the student submits the state of the virtual lab environment for assessment at each milestone. If the milestone criteria are met, positive auditory and written feedback are provided, and the next milestone/task is presented on the task descriptor screen. If the criteria of one (or optionally multiple) milestone is not met (simultaneously), the student is provided appropriate feedback and either encouraged to reattempt the milestone or is returned to an earlier milestone to recollect or reanalyze their data (Fig. 6). The system currently has the following milestone classes: informational, data acquisition, calculator-based data analysis, spreadsheet-based data analysis, physical submission, usage-check, data-dependent assessment, multiple-choice assessment, and conclusion. “Informational” milestones orient the user and provide a text-based overview of the group of milestones that they will be asked to complete; in this case, the user acknowledges that they are ready to proceed. “Physical submission” milestones require that the student make and submit a product or sample that meets specific criteria (e.g., the concentration of a solute is within a specified range, the pH of a buffered solution is within a specified range, etc.). Lab tool “usage check” milestones require that one or more variables of a particular lab tool be in a given state or within a particular range of values (e.g., the pipette tip is on and clean, the pipette top is fully pressed, half-pressed, or not pressed at all, etc.). In “data acquisition” milestones, the student must correctly record raw data from a lab instrument into their lab notebook (see Fig. 7) while accounting for the precision of their measurement.

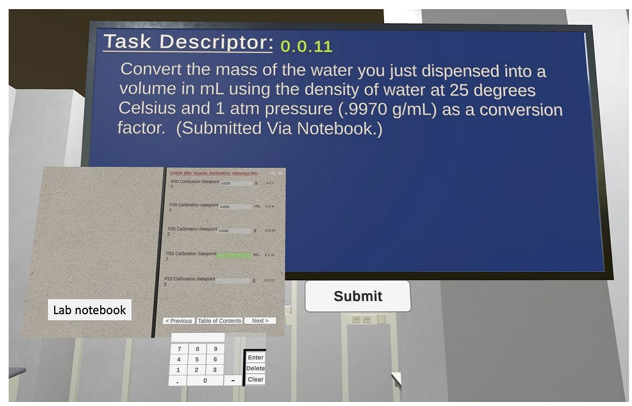

Fig. 7 Data Acquisition Milestone Example. Students need to acquire and record raw data from the scale, round it to the correct number of significant digits, convert this mass into a volume, and submit the result into their lab notebook. Audio,video, and/or written positive or negative feedback are provided to the student upon completion/submission

Some milestones also use the raw data acquired/recorded/stored in earlier milestones to assess user data analysis skills. “Calculator-based Data Analysis” milestones require students to use a virtual calculator to carry out simple calculations using their raw data (e.g., correctly carry out conversions, etc.). “Spreadsheet-based Data analysis” milestones ask students to exit the VR experience and carry out more advanced analysis with their data using a Microsoft Excel spreadsheet (e.g., linear fits, non-linear fits, statistical analyses, etc.). The resulting output of their Excel analyses is sent back to the Unity3D environment for assessment and feedback. A 2D graphical user interface (GUI) on the desktop enables students to see their lab notebook and, thus, their recorded raw data from previous steps/milestones of the module. Figure 8 illustrates the front-end user interface seen by the user on their desktop without their HMD. “Multiple-choice Assessments” are conducted in line with hands-on experimentation to connect concepts and theory taught with practical applications at the lab bench. In some cases, “multiple-choice assessment” milestones are supplied by the content creator; in other cases, assessments can be randomly pulled from an online database of standardized questions that are aligned to particular learning objectives or concept maps defined by disciplinary experts (e.g., American Chemical Society, American Society of Biochemistry and Molecular Biology, etc.). Finally, at the end of a series of “data acquisition,” “data analysis,” and “multiple-choice assessment” milestones, students may be asked to make logical assertions and draw conclusions from their raw and analyzed data in “data-dependent assessments” and “conclusion" milestones respectively. For example, students may be asked whether their data support the assertion that their pipetting was reproducible or their pipette was calibrated in a pipette calibration experience.

Like in a real lab setting, the user may collect poor-quality data. In such cases, the content developer can choose to reveal the mistake immediately and require the student to recollect their data before proceeding to the next milestone, or they may allow the student to proceed with their incorrectly acquired data (as in a real lab) and discover their mistake as they naturally would in later data analysis or conclusion milestones which are both dependent on the outputs of the data acquisition milestones. If the latter option is chosen, the content creator can require the user to reacquire and reanalyze their raw data by returning the user back to the earlier data acquisition milestone.

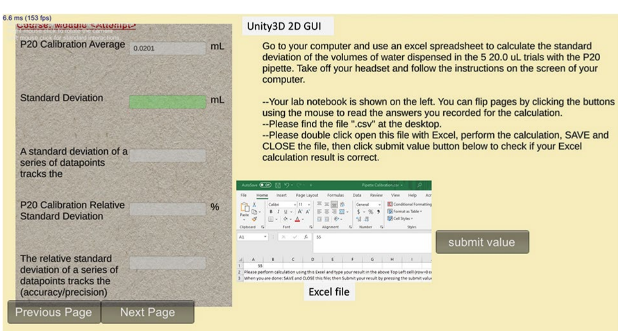

Fig. 8 An example of the Data analysis—Excel milestone. For complicated calculations that cannot be performed with a simple VR calculator, students are asked to take off their HMD and use an Excel template to perform the calculations. Students can view their lab notebook and submit answers via a 2D GUI which shows up on their desktop

4.5 User-lab tool interaction movement verification via a finite state machine

In many cases, it is desirable to monitor and assess lab tool usage in a time-dependent but module independent manner. This would enable assessment of whether the trajectory of states through which a lab tool progresses constitutes correct or incorrect usage and whether the user has achieved long-term retention of the appropriate psychomotor learning outcomes related to lab tool use. The milestone-based, single-state “usage check” described above is insufficient for such “complex usage checks”. The finite state machine is one of the foundational design patterns commonly used in Unity3D programming. Such finite state machines can represent the totality of possible states in which a lab tool can exist and the history or trajectory of states a lab tool has been in during a given experiment. In specifying the state trajectories that define proper and improper usage for a given lab tool, we enable real-time multi-state or “complex usage checks”. For example, in the case of a pipetteman, its tip can be on or off; its top can be released/up, pressed partially, or pressed fully; its tip can (if present) also be filled or empty; and the tip can also be contaminated with reagent, or clean. Correct or incorrect usage of a lab tool can be defined as traversing the state machine of the pipetteman via specific sequences of states. This approach thus enables continuous assessment of lab tool usage across all lab modules.

5 User study

5.1 Participants

Thirty-one students from a sophomore-level Quantitative Analysis Course from the California State University – San Marcos (CSUSM) participated in this study as part of the course assignment. The experiment design was reviewed and approved by the CSUSM IRB. Participants completed the entire virtual lab process within the assigned time (less than 2 h, including the quizzes and the virtual lab experience).

5.2 Method

Users were randomly assigned into three groups: (1) MV, (2) VM, and (3) Control. The users in the MV and VM groups participated in two virtual lab (VL) experiences: Mixed Reality (MR) and Virtual Reality (VR) in a different order (see detail in Table 2). The control group experienced tutorial sessions about interacting with virtual objects but did not complete the milestone-based virtual lab experiment. Users answered both the quiz and survey questions.

There are 34 milestones in the pipette calibration module. The time taken to complete each milestone and how many repetitions users need to take to achieve correct output were recorded in both the MR and VR modes. A quiz consisting of standardized and validated chemistry concept items was given before and after each virtual lab experience (the Pre-VL1, Post-VL1, Pre-VL2, and Post-VL2 quizzes, respectively). The concept quiz consisted of 9 cognitive questions. However, any questions with a facility index above 90% or below 10% (too easy or too hard) were eliminated from the analysis. Analysis was performed based on the average scores of the remaining three questions within each experimental or control group.

In addition, survey questions included items from the following three instruments/categories and were given to the users after each VR experience: (1) Intrinsic Motivation (3 questions) (Intrinsic Motivation Inventory 1994), (2) Self Efficacy (1 question) (Pintrich et al. 1991), and (3) User Experience (7 questions) (Tcha-Tokey et al. 2016).

Table 2 User study groups

Group name	First virtual lab experience (VL1)	Second virtual lab experience (VL2)
MV (11)	MR	VR
VM (13)	VR	MR
Control group (7)	Tutorial only	Tutorial only

Note: MR is mixed reality mode. VR is a virtual reality mode

Table 3 Quiz results

Group name	Percent changes
MV	7.69%
VM	23.1%
Control group	-28.6%

5.3 Results and discussion

5.3.1 Milestone completion time and analysis of the number of retries

Averaging students' time spent on each milestone and how often they repeated it before getting the correct answer yielded exciting insights. Results showed that 24 of the 34 milestones in the pipette calibration module were completed more quickly in the MR mode (average time spent per milestone 75.72 s in MR vs 95.52 s in VR mode). Also, students completed the module with fewer retries in the MR mode (average number of retries = 0.61 in MR vs. 0.82 in VR). This finding suggests that the tactile authenticity of lab tool manipulation provided in MR mode helps students navigate the lab experience more quickly, effectively, and intuitively. Unfortunately, the differences between groups are not statistically significant due to our small sample size.

Of the 24 milestones completed more quickly in MR mode, 8 had average time differences between the MR mode (average time spent = 153.40 s) and VR mode (average time spent = 200.81) greater than 30 s. Also, within these eight milestones, students completed the milestone with fewer retries in the MR mode (average number of retires = 1.19 in MR mode vs. 1.76 in VR mode). Notably, these milestones were the most difficult to perform and involved (1) fine motor skills, such as dispensing liquid from a pipette to measure the mass of the dispensed liquid on a scale, and (2) performing calculations on (e.g., converting measured mass to volume, determining the standard deviation, relative standard deviation, range, systematic error and % systematic error of the collected data). This might suggest that the MR mode facilitates students' understanding of the most challenging concepts required for data analysis while facilitating the acquisition of real fine motor skills and lab techniques.

5.3.2 Analysis of concept quiz results

For the concept quiz analysis, we used a percentage change metric defined as (Post-VL1 concept quiz score- Pre-VL1 concept quiz score/ Pre-VL1 × 100%) to track the learning gains across each sub-population of students as a result of the two interventions. As shown in Table 3, the quiz scores increase for both the MV and VM groups. However, the quiz scores for the control group decreased. This suggests that the virtual lab experience enhances students' understanding of the concepts.

5.3.3 Survey result analyses

Responses to the survey are recorded on a scale of 0–100, with 0 meaning completely disagree and 100 meaning agree entirely.

As shown in Table 4, users rated MR mode experiences more positively than VR mode versions except for the 4th and 5th questions. Users found the MR mode more fun, enjoyable, and practical, and stimulating.

These results from our preliminary analysis are promising. However, we have a limited sample size. Further

Table 4 Summary of the results of the intrinsic motivation (IM), self-efficacy (SE), and user experience (UX) survey

Question	Raw score on a scale of 0–100 after the first VR experience		
	MR	VR	Control
This activity was fun to do (IM)	77.5	55.2	41.8
I am satisfied with my performance at this task. (IM)	72.3	72.3	77.5
I believe this activity could be of some value to me. (IM)	65.0	58.5	40
Considering the difficulty of this activity and my skills, I think I did fairly well on this activity. (SE)	73.3	86.2	89.2
I felt proficient in moving in and interacting with the virtual reality environment by the end of the experience. (UX)	75.5	76.8	56.7
I enjoyed being in this virtual/mixed-reality environment. (UX)	73.0	46.5	45.0
I was engaged by the virtual reality environment experience. (UX)	70.5	61.9	51.7
This experience gave me a great sense of well-being. (UX)	52.0	45.9	42.5
I felt stimulated by the virtual/mixed reality environment. (UX)	67.5	51.7	45.8
I would say the virtual/mixed reality environment is practical rather than impractical. (UX)	59.1	40.4	43.3

studies will be conducted with more users and questions to confirm the findings.

6 Discussion

VR and MR systems are likely to play a valuable role in the future of science laboratory education. While they may never fully replace traditional wet lab experiments, they will almost certainly bridge critical learning gaps by providing detailed and real-time feedback on performance metrics, which often escape instructors in traditional settings. MR systems are far less expensive to purchase, maintain, and implement when compared to traditional wet labs, and they also offer reduced safety concerns/liability, greater freedom to students to learn on their own time, to make the mistakes required to learn, improved engagement, greater focus, and gamification to enhance student interest.

The HOVR Labs system uses motion-tracked or "virtualized" lab tools to provide students with authentic tactile/kinesthetic feedback during experiments. Its handler-activator-activated lab tool system allows each lab tool to function in either MR-mode or VR-mode, thereby enabling tightly controlled studies of the importance of the "hands-on" factor to scientific learning and engagement. It also enables the use of a limited set of motion-tracked physical objects to control/handle an unlimited number of virtual instances of those lab tools. We employ this system to study whether authentic tactile feedback and immersive simulations improve student learning, self-efficacy, and engagement in chemistry and biochemistry labs.

Using the Lab Module Generator as middleware that empowers content developers to tailor the HOVR Lab experience to diverse student populations without coding will significantly reduce the costs of developing, testing, and optimizing HOVR Lab experiences in the physical and life sciences.

The current generation of our system has an acceptable framerate/latency and demonstrates that MR systems can be a viable and cost-effective instructional approach for higher education settings.

Our system design allows convenient classroom teaching integration, as described in Sect. 3.3. The station is compact with low budget equipment and convenient set up process. We tested and improved the workflow with undergraduate classes.

Our preliminary user study results suggest that students spent less time per milestone and needed fewer reattempts per milestone in the MR mode. This suggests that the tactile authenticity afforded for lab tool manipulation in MR mode helps students navigate the virtual lab environment more effectively. Our quiz results indicate that the MR and VR modes of the pipette calibration module enhanced students' understanding of the underlying concepts compared to the control group. Further, students prefer the MR mode more than the VR mode in most of the questions in the Intrinsic Motivation (IM), Self-Efficacy (SE), and User Experience (UE) survey.

Our preliminary data suggest that both virtual lab modalities enhance student learning. Students completed the milestones more quickly in the MR mode and had more favorable attitudes towards the MR mode. Further user studies with larger sample sizes will need to be performed to confirm these findings. Designing, implementing, and testing this system brought insights to our multidisciplinary team of computer scientists, hardware designers, software engineers, digital artists, and chemistry/biochemistry content experts. The active and passive tracker designs and the foundational software underwent several iterations to improve tracking quality, simulation speed, and user interaction design. In the future, we will work on adding more content and functionality to the system. For example, more virtualized lab tools can be made to enlarge the collection of lab tools that educators can use to tailor their experiments. More chemicals and reactions will be added to the reagents' library. We also continue to expand and fine-tune the database integration and large-scale user studies to test the effects of the MR experience on student learning. After building and testing more modules, we are also interested in conducting more long-term effectiveness studies to see whether students' engagement, interest, and knowledge retention improve after experiencing multiple VR or MR lab sessions.

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Authors contributions K.H. is the principal investigator of the project and designed the overall structure of this project. K.H. and A.A. led the hardware student research assistants (J.M. and others) in researching and developing the lab tool motion tracking solutions. Y.J. and K.H. led the software student assistants (A.A. and R.P.) in designing and developing the foundational software simulation system. A.H. and K.H. worked with student assistant J.H. in user information database design and integration. K.N. and K.H. developed the chemistry lab module content, ran the user study, and conducted data analysis. Y.J. wrote the draft for the technical parts of the manuscript. K.N. wrote the draft for the user study part of the manuscript. All co-authors worked on polishing and proofreading the manuscript.

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Availability of data and materials None.

Declarations

Competing interests Kambiz Hamadani, Yuanyuan Jiang, and Ali Ahmadinia are co-inventors on US Patent# 11,694,575 B2 and related foreign patents. Kambiz Hamadani is CEO of Hands-on Virtual reality Labs.

Ethical approval The study is approved by the California State University – San Marcos IRB. All participants were informed prior to the study and gave informed consent.

Informed consent All participants were informed prior to the study and gave informed consent.

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