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Cost-Effective Virtual Reality Simulation for Chemistry Practicum using Hand Gesture

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We developed a virtual reality (VR) simulation of a chemistry practicum that incorporates the act of pouring liquid using hand gestures. This addresses the need for safe, cost-effective alternatives in chemistry education while still exercising practicum motor skills. Our simulation centers on the practicum of making picric acid, which presents significant both cost and safety challenges. Utilizing Leap Motion hand gesture technology as an input method offers a more affordable option than traditional VR controllers. We conducted usability testing with 16 participants, including a lecturer and undergraduate students from multiple backgrounds, to evaluate the application's effectiveness and gather feedback. Results indicate that the simulation works as intended and accurately represents the practicum, achieving marginal usability. The application can reduce costs by at least IDR 658,638.00 per session and eliminates hazards associated with handling picric acid, highlighting its potential as a valuable educational tool.

***Key words*: Leap Motion, making picric acid, simulation, system usability scale, virtual reality.**

I. Introduction

A. Problem Overview

Chemistry practicums rely heavily on glassware, special equipment, and chemical materials. However, the cost associated with these tools and materials can be quite high. Additionally, the maintenance of labs and the hiring of lab assistants further contribute to the substantial expenses involved in organizing practicums, making some practicums inaccessible for educational institutions [1]. Safety is also a major concern as certain tools and materials used can pose a high level of danger if mishandled or if instructions are not followed precisely. Recent incidents have highlighted the risks involved, such as fires caused by a hotplate and explosions during a practicum [2].

To minimize those problems, virtual reality (VR) has been used by institutions as an alternative to traditional teaching and training. The technology has been developed in various fields including architecture, engineering, construction, nurses training, surgical training, and many more [3], [4], [5], [6], [7], [8]. These studies have shown that the implementation of VR is an equally effective method of teaching and training compared to the traditional one, while providing the value of cost-effectiveness and safer learning environment for students, especially when said training is impossible to do due to unaffordability and danger [9].

Numerous studies have incorporated virtual reality into chemistry education in varying degrees for the last few years. Some research incorporates VR by using head-mounted displays as a tool to see a 360-degrees video of a chemistry practicum and chemistry field trip with both studies showing positive feedback by respondents [10], [11]. Several research use virtual reality to visualize atomic structures in a 3D form instead of 2D so students can see the structures from multiple angles, which provide engaging experience for students yet still affordable for institutions [12], [13], [14], [15], [16], [17]. Some of the research made a more interactive visualization of the atom structures by letting users reconstruct the atoms on their own then visualizing it after [18], [19], [20].

A more interactive VR implementation in chemistry education is a simulation of practicums, which several studies have done. Research by Su et al and Tarng et al uses Android as their device where students can do a series of steps in a virtual world to complete the practicum [21], [22]. Research by Suleman et al developed a simulation of a reaction rate practicum where students can wear a head-mounted display to see the 3D visualization of the practicum [23]. Research by Sritrusta et al developed a simulation of a strong acid base titration practicum which is controlled using the hand gestures VR controller Leap Motion and displays the virtual world using a head-mounted display [24].

However, despite the numerous VR implementations in chemistry education, to our knowledge, there is a lack of research developing a practicum simulation containing pouring liquid from one flask to another. This act of pouring is essential to a lot of chemistry practicums, which limits the flexibility and range of chemistry simulations if there are no implementation of it. On top of that, most VR implementations only visualize them in 3D or only are interactable using mouse and keyboard, which makes students unable to exercise their practicum skills. On the other hand, a simulation application needs to be affordable to be accessible by education institutions as a lot of practicums, especially in developing countries, do not offer certain practicums because they are too expensive [1].

B. Proposed Method

Based on the problems, the following objective has been proposed: To develop an interactive virtual reality practicum containing the act of pouring liquid from one flask to another so users can exercise their practicum skills. The second objective is to opt to a more affordable choice of devices so education institutions can afford it.

To provide an interactive and realistic VR experience, this study uses the hand gesture technology of Leap Motion which allows the capturing of a user's hands and fingers, enabling them to interact with digital contents in a natural manner [25]. Several studies have used this technology where they need to make users exercise it realistically such as chemistry practicum [24], Japanese calligraphy writing [26], gamelan [27], and computer assembly [28]. This option is also proposed because of the substantially cheaper price of the Leap Motion Controller compared to other VR controllers. The virtual space on the other hand is displayed through a simple monitor of school PC or laptop so it is more affordable.

The simulation is developed using the game engine Unity as it is free, easy to learn, has a large asset store for an indie application [29], and already has an integration for Leap Motion called Leap Motion Unity Plugin [30]. The practicum material used for this simulation is the college-level practicum of making picric acid. This practicum is proposed as it involves pouring liquid from one flask to another and presents both the cost and safety challenges of chemistry practicum. The making of picric acid involves 3 primary components: phenol, sulfuric acid, and nitric acid [31]. These chemicals are not only expensive [32], but also dangerous to work with, as they can pose severe health risks including potential damage to the liver, kidneys, eyes, teeth, and lungs, and can even be fatal [33].

C. Novelty and Contribution

In general, most VR implementations in chemistry practicums are either too expensive to operate because of the expensive VR displays and controllers or does not contain a crucial aspect of a chemistry practicums, which is practicing holding the flasks and pouring liquid to other flasks.

This research contributes to that by developing a simulation application which contains the act of pouring liquid from one flask to another while also being cost-effective so education institutions can afford it. This research also uses the practicum material of making picric acid which have never been developed before.

II. Previous Works

Prior to our research on the application of 3D virtual reality (VR) simulation for making picric acid using Leap Motion, several studies explored the use of 3D VR simulations in chemistry practicums.

M Suleman et al. developed a 3D visualization for reaction rates, implemented on the Android platform with a feasibility score of 78%, utilizing head-mounted displays for VR experiences [23]. Similarly, Sritrusta et al. created a 3D virtual chemistry lab using Unity as engine, Oculus Rift for visual output, and Leap Motion hand gesture as input, focusing on strong acid-base titration [24]. Furthermore, Cathi et al. designed an organic virtual reality chemistry laboratory for infrared spectroscopy using WondaVR, where students and teaching assistants accessed the virtual lab through a GearVR headset. Their findings indicated minimal performance differences between students using virtual labs and those conducting traditional in-person practicums [10].

These studies show that chemistry practicum can be simulated in 3D virtual reality. Some studies have used Leap Motion as a tool for user interaction within the virtual world instead of mouse and keyboard.

Makoto et al. developed a Japanese calligraphy writing simulation utilizing Leap Motion to accurately capture brush movements in real time without requiring sensors on the brush [26]. Similarly, Frihandhika et al. created a gamelan augmented reality simulation by processing hand movement data from Leap Motion and sending it to smartphone installed on a head-mounted display then visualizing the gamelan virtually, which achieved high success rate and feasibility score [27]. Binbin et al. developed a flight simulation system that allowed users to control an unmanned vehicle through hand movements captured by Leap Motion with high accuracy [34]. Additionally, Marlon et al. built a mixed reality simulation for personal computer assembly, allowing users to interactively assemble a desktop computer using hand movements detected by Leap Motion, which respondents found more engaging than traditional methods [28].

These studies show the versatility of Leap Motion in enhancing interactive simulations which could be used in its application in alternative chemistry practicum. Furthermore, unlike prior works such as Sritrusta et al. [24], which focused solely on gesture-based titration, our approach integrates real-time liquid physics, significantly improving the realism and interactivity of the virtual practicum. This innovation allows students to engage in more complex chemical handling tasks that were previously infeasible in virtual simulations.

III. Research Method

A. Tools and Materials

The VR practicum simulation was developed using Unity, a free game engine used to build and design the virtual environment of the simulation. The application can be run on a desktop or laptop computer connected to a Leap Motion Controller. Leap Motion Controller is a device that captures users' hand gestures, sending the positions of their hands and fingers to the simulation, enabling interaction with objects within the virtual world.

Some virtual objects inside the simulation, such as flasks, were provided by Liquid Volume Pro 2, a Unity asset that includes flask models and code to visualize liquid volumes. Other objects. such as the hotplate and the ice bath, were created using Blender, a software that allows the creations of custom 3D models by manipulating geometric shapes, which can then be exported into game engines like Unity. While the liquid visualization was included in the downloaded asset, additional functions such as pouring said liquid to other flasks, hotplate functions, and the game progression were developed using Visual Studio Code with C#, the programming language used in Unity game engine.

The practicum material used in the simulation is modeled after a video of a practicum for making picric acid which was recommended by a chemistry education lecturer from the University of Mataram.

B. Testing Setting

The testing is conducted in multiple sessions with participants from different backgrounds. The sessions start by introducing the application and showing some examples on how to use it. Then each participant walks up to try the application themselves. At the end of the sessions, the participants are given a link to a Google Form containing a questionnaire where they can submit their response based on their own experiences.

C. Participants

The participants in this research are undergraduate students or university lecturer. To have a more diverse view on the application, the participants come from different backgrounds. The first batch are from chemistry education background to get a more detailed view from the chemistry aspect of the simulation. This is also the only batch where the respondents are asked about the accuracy of the practicum, as they know them the most. The second batch are from informatics engineering background to get a more detailed view from the technical and design aspect of the simulation. The third batch are from neither chemistry nor informatics engineering to get a neutral view of the simulation. From the 16 participants, 8 are female, and 8 are male. 15 participants are college-level students and 1 participant is a chemistry lecturer.

D. Data Collection

The data collected from the testing phase have three quantitative data and one qualitative data. The first quantitative data is Test Case Testing which is filled while the participants use the application to determine if the features within the application are functioning as intended. The last two quantitative data is included in the questionnaire which is System Usability Scale to determine if the developed application is suitable for use by end users [35] and a Likert scale accuracy validation to determine if the simulation accurately replicates the real-life practicum. The accuracy validation is only filled by participants from a chemistry background. The qualitative data is added at the end of the questionnaire as an open-ended question to receive feedback and suggestions from participants.

IV. System Design

A. Practicum Material

The selection of the practicum material was based on an interview with a chemistry education lecturer at the Faculty of Teacher Training and Education in the University of Mataram. After considering various options, he suggested choosing the practicum for making picric acid as it involves the process of pouring substances and because the practicum is both expensive and dangerous. To facilitate understanding and simulation of this practicum, he provided the practicum instruction used in their curriculum and a link to a video demonstration, which is accessible via the following link: https://youtu.be/MOGg9_1TIak.

B. System Architecture

The architectural design of the picric acid practicum simulation can be seen in Fig. 1.

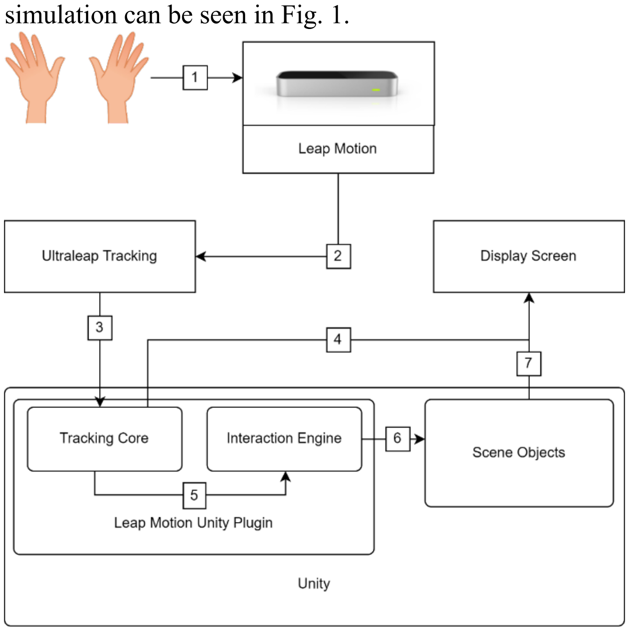


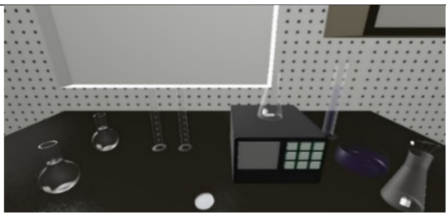
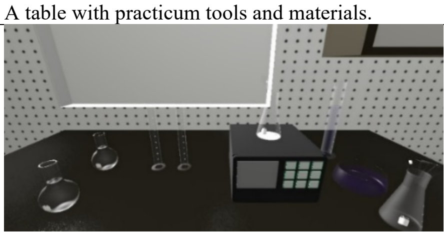
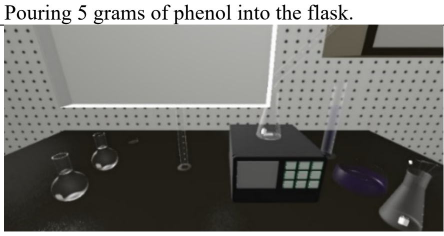
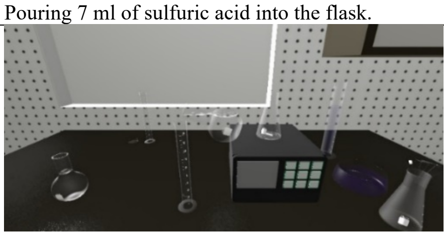
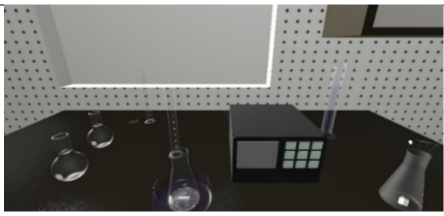
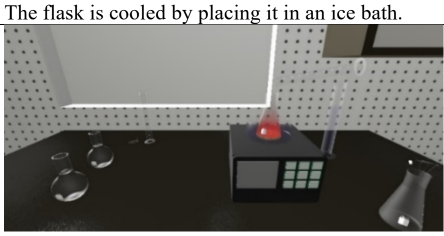
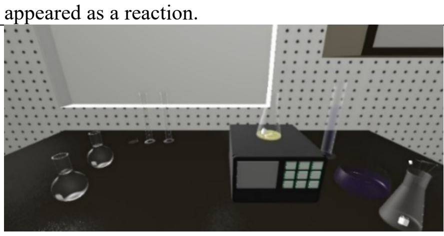
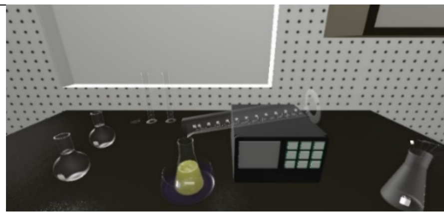
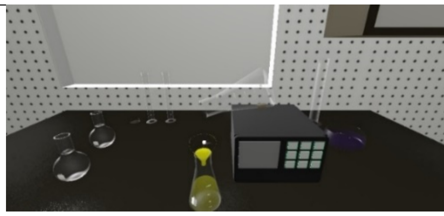
Fig. 1. System architecture

Leap Motion projects infrared light and records the movement, generating video data. This data is then sent via USB to a computer, where Ultraleap Tracking software processes it to determine finger positions. The processed data is sent to Unity, where the hand structure is built using the Tracking Core asset. The hand structure is displayed on the screen, and the finger positions are processed by the Interaction Engine, enabling interaction with objects in the chemistry lab virtual world and displaying them on the screen. These steps run in real time throughout the practicum simulation.

C. Storyboard

The design process is started by creating a storyboard of the simulation from the video provided by the chemistry lecturer. This process is done to describe the content, look, and feel of each step of the practicum and to show what objects and features need to be made in the application. The storyboard is shown in Table 1.

TABLE I. STORYBOARD

No	Illustration
1	 A table with practicum tools and materials.
2	 Pouring 5 grams of phenol into the flask.
3	 Pouring 7 ml of sulfuric acid into the flask.
4	 The hotplate is turned on to raise the temperature and to mix the mixture for 30 minutes.
5	 The flask is cooled by placing it in an ice bath.
6	 The mixture is stirred on the hotplate, and concentrated nitric acid is poured in and a reddish-brown smoke appeared as a reaction.
7	 Once the reaction has halted, the hotplate is turned on for 1.5 hours to heat and stir the mixture.
8	 An ice bath is used to cool the flask before pouring in 200 ml of cold water.
9	 The picric acid is filtered using a suction funnel.

D. User Story

Next, a table of user stories is created based on what the user should be able to do in the application. The user stories shown in Table 2 is derived from the practicum instruction and video provided by the chemistry lecturer.

TABLE II. STORYBOARD

No	Title	Description
1	Navigation menu	Create a UI for the main menu to start the simulation, access the instructions, and exit the application
2	Lifting objects with hand gestures	Incorporate the Leap Motion technology into the simulation
3	Pouring liquid	Develop a spill behavior for the flasks in the simulation
4	Pouring liquid into another flask	Implement a mixing behavior for one flask to allow it to be filled by another flask
5	Turning on the hotplate	Design a hotplate with multiple inputs, a display, and program each input behaviors
6	Turning on the stirrer	Develop a spinning behavior for the magnet upon its activation
7	Chemical reaction	Develop a smoke effect that becomes visible in the glass when a chemical reaction takes place
8	Using a funnel to filter the mixture	Develop a funnel behavior which separate the picric acid
9	Scenes	Create different scenes, code the goal and fail conditions for each scene
10	Instruction page	Create a UI for the instruction page
11	Practicum HUD	Develop an HUD displaying instructions and goals
12	Select specific scene	Design a UI to allow users to start the simulation from a specific scene

V. RESULTS AND DISCUSSION

A. Application Development

The picric acid practicum simulation was developed by creating the features mentioned in the user story Table 2. Each user story was developed and assessed by a chemistry lecturer during multiple iterations of the application. The application consists of various components, some important ones being the Leap Motion implementation, user interface, spill behavior, hotplate, animations, as well as simulation's goals and failure conditions.

A.1. Leap Motion Implementation

Leap Motion is a device that uses optical cameras to capture the movement of a person's hands and fingers, allowing them to interact with digital content naturally [25]. Integrating Leap Motion into a Unity project is done by downloading Ultraleap Unity Plugin from the official page and adding the prefabs to the scene, as shown in Fig. 2. Furthermore, the "Interaction Behaviour" script component is applied to all objects in the scene that users should be able to interact with, as shown in Fig. 3.

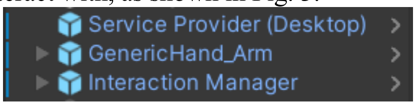


Fig. 2. Leap Motion plugin prefabs

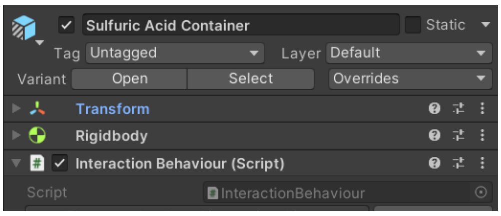


Fig. 3. Interaction behaviour component

A.2. User Interface

The application's user interface (UI) consists of different pages, such as the main menu, scene selection, and instructions. These interfaces were created using Unity's built-in UI system. The UIs designed are presented in Fig. 4, Fig. 5, and Fig. 6.

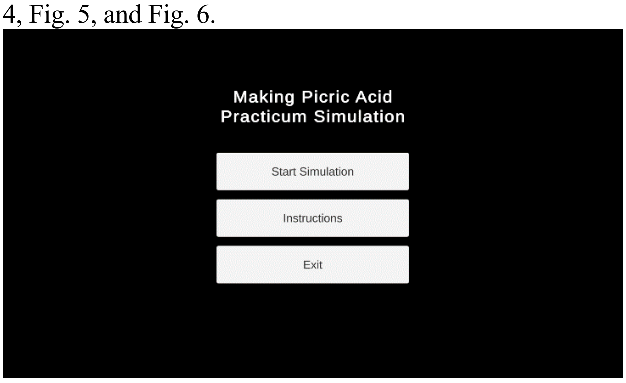


Fig. 4. Navigation menu

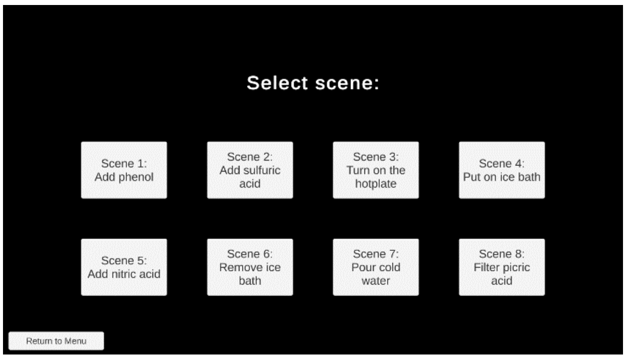


Fig. 5. Select specific scene

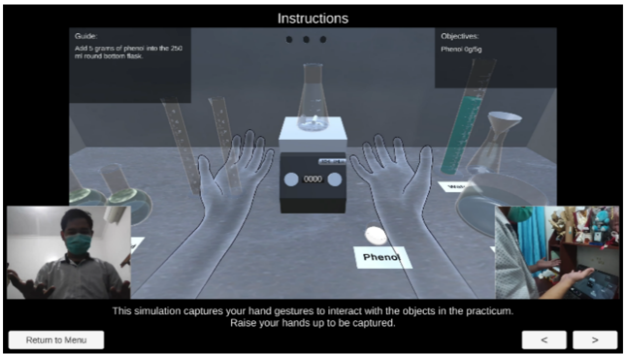


Fig. 6. Instruction page

A.3. Pouring Liquid

The liquid pouring behavior is implemented using C# by spawning liquid particles when the flask is tilted a certain degree or by using the spill point method from the asset. Then another code is executed in the receiving flask, adding liquid to the flask when the liquid particle collides with the collider as shown in Fig. 7.

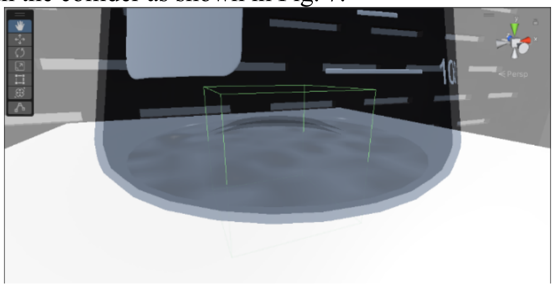


Fig. 7. Liquid surface collider

A.4. Hotplate

The hotplate model used in the simulation was created using the 3D modeling application Blender. A combination of blocks and cylinders was assembled to replicate the appearance of a hotplate. The process of creating the hotplate model is shown in Fig. 8.

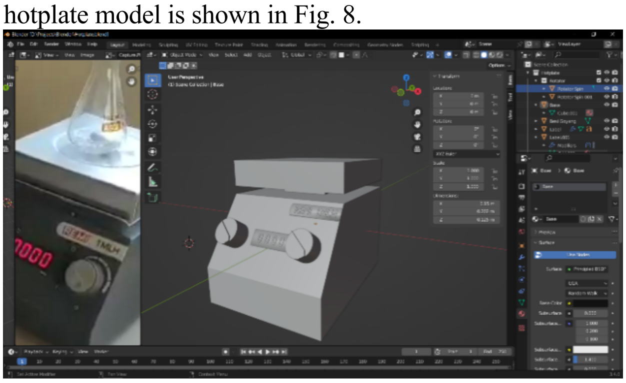


Fig. 8. Hotplate 3D model

After designing the hotplate, we imported it into the Unity project. In Unity, we programmed the hotplate to serve as a platform for holding flasks and to adjust the stirring speed and heat by rotating the spinners. The hotplate also displays the magnet stirrer's RPM and detects when something is placed on it. These functionalities were implemented in Unity with C# programming language.

A.5. Animations

The animations in the simulation were implemented using C# for each object. For example, the magnet stirrer and smoke particles are programmed to spin and emit smoke under specific conditions. The magnet stirrer spins according to the angle at which the knob is rotated, with the script "Hotplate Spinner" applied to the knob itself, as shown in Fig. 9. The smoke particle system is activated when nitric acid is added to the mixture, as shown in Fig. 10. This is detected by the "GameManager" script, which monitors the contents of the mixture. Other animations follow a similar method, each using their respective animation scripts.

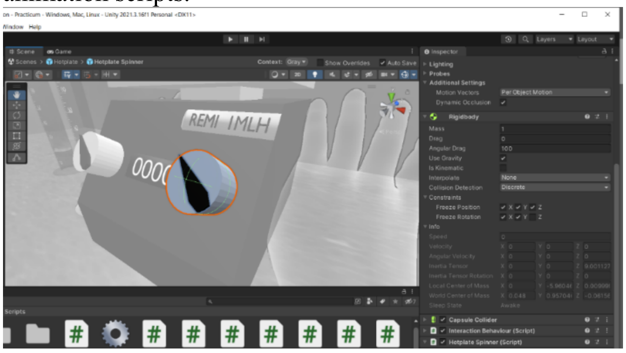


Fig. 9. Hotplate spinner component

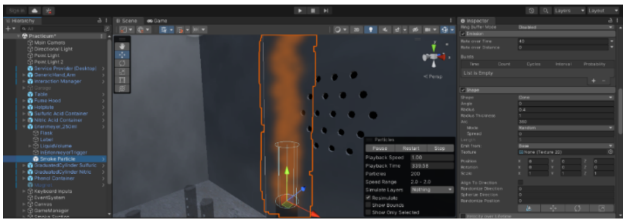


Fig. 10. Smoke particle system

A.6. Goal and Failure Conditions

A "GameManager" script is implemented to facilitate the progression of the simulation. The script performs various tasks including setting goals, monitoring changes in mixtures, tracking completed objectives, shifting between different scenes, and detecting failure condition. Each step of the practicum is accompanied by a list of objectives displayed in a heads-up display situated in the top-right corner as shown in Fig. 11.

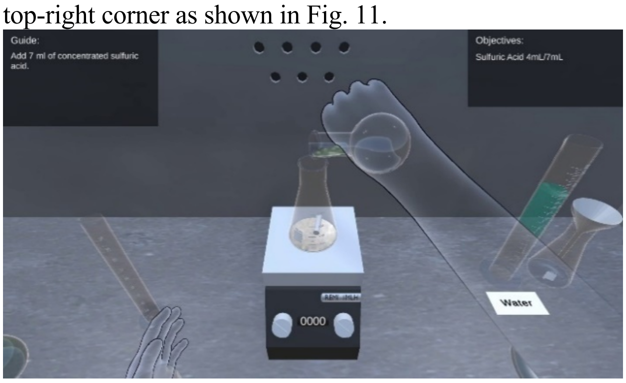


Fig. 11. Simulation scene

Subsequently, the practicum is considered unsuccessful if any liquid is spilled onto the table, prompting a notification to appear, indicating the simulation failed as shown in Fig. 12.

Fig. 12. Failing the practicum

B. Testing Results

A group of 16 participants took part of the testing phase which was conducted on multiple sessions in multiple places such as chemistry lab, information system lab, etc. The questionnaires were delivered via Google Form. With 18 participants present, 16 of the participants completed the demonstration and filled out the questionnaires.

B.1. Test Cases

The test cases are used to determine whether the application work as intended. The actual test cases results are documented and compared with the respective expectations to determine whether the test cases pass.

TABLE III. TEST CASES RESULTS

No	Title	Description	Pass/Fail
1	Starting the simulation	Simulation starts	Pass
2	Opening the instructions page	Instructions page opened	Pass
3	Exiting the application	Application is closed	Pass
4	Lifting an object	Object is lifted	Pass
5	Pouring liquid	Liquid is spilled and its quantity is reduced	Pass
6	Pouring liquid into another flask	The second flask is being filled up with liquid	Pass
7	Turning on the hotplate	The hotplate is turned on	Pass
8	Turning on the stirrer	The magnet spins	Pass
9	Pouring nitric acid into the mixture	A change in color occurs as smoke starts to appears	Pass
10	Using a funnel to filter the mixture	Picric acid is filtered in the funnel	Pass

As shown in Table 3, all test cases have successfully run as expected. This shows that the main functions of the application work as intended.

B.2. System Usability Scale

The System Usability Scale (SUS) is a simple ten scale that provides a global view of the subjective assessment of the usability of a system, created by John Brooke [35]. It is used in this study to provide a broad overview of perceived usability, including ease of use, and provides standardized results, as it is widely used in research worldwide, while remaining robust and flexible [36]. In this study, we use the Indonesian adaptation of the SUS questionnaire, as adapted by Sharfina and Santoso, the most used Indonesian adaptation. This adaptation was specifically designed to offer a more optimal and reliable measurement of usability in Indonesian-speaking country [37]. Given that the participants in this study are Indonesian, using this localized version ensures that the usability evaluation is more suitable and relevant to their language and culture, enhancing the accuracy of the results. The results of each statement from the SUS questionnaire are presented in Table 4.

TABLE IV. INDIVIDUAL SUS STATEMENT RESULTS

No	Statements	SUS Score	
		0-4	0-100
1	I think that I would like to use this system frequently	3,625	90,625
2	I found the system unnecessarily complex	2,375	59,375
3	I thought the system was easy to use	2,6875	67,1875
4	I think that I would need the support of a technical person to be able to use this system	1,4375	35,9375
5	I found the various functions in this system were well integrated	3,3125	82,8125
6	I thought there was too much inconsistency in this system	2,75	68,75
7	I would imagine that most people would learn to use this system very quickly	3,0625	76,5625
8	I found the system very cumbersome to use	2,9375	73,4375
9	I felt very confident using the system	2,3125	57,8125
10	I needed to learn a lot of things before I could get going with this system	0,75	18,75

The survey revealed that the highest score achieved was for statement one, receiving a score of 90,625. This result indicates that the developed application is interesting, thereby leading participants to express their interest in using it again. Several respondents expressed their fascination with the integration of hand gesture recognition technology in the simulation.

The fourth statement has a score of 35,9375, indicating that the system lacks clarity. Users often required assistance on how to summon their hands easier in the simulation. The main issue with the app was the inconsistent recoding of hands by the Leap Motion device. This issue can be reduced by ensuring a sufficiently illuminated environment since the device relies on infrared cameras to detect hands. Additionally, users often ask about how to use the functionalities available within the simulation. Although most respondents skipped the instruction page, providing a translated version in Indonesian can greatly improve comprehension for all users, especially since this research was conducted in Indonesia.

The tenth statement received the lowest score of 18,75, indicating that respondents need more exposure to the application in order to become proficient in its use. This outcome was anticipated as traditional applications and simulation exercises typically use mouse and keyboard to operate, whereas using hand gestures for control is a novel concept.

To assess the system's overall usability, the scores from all respondents' SUS questionnaires were collected and averaged. The scores of each respondent and their corresponding results from the System Usability Scale questionnaire are presented in Table 5.

TABLE V. SYSTEM USABILITY SCALE RESPONDENTS' RESULTS

No	Usability Calculation	SUS Score
1	26 x 2,5	65
2	26 x 2,5	65
3	29 x 2,5	72,5
4	21 x 2,5	52,5
5	23 x 2,5	57,5
6	20 x 2,5	50
7	27 x 2,5	67,5
8	22 x 2,5	55
9	20 x 2,5	50
10	15 x 2,5	37,5
11	33 x 2,5	82,5
12	34 x 2,5	85
13	23 x 2,5	57,5
14	25 x 2,5	62,5
15	24 x 2,5	60
16	36 x 2,5	90
	Final Score (Mean)	63,125

According to the calculations using the SUS method, the average score obtained is 63,125. This indicates that the system falls under the "Marginally Acceptable" category according to the System Usability assessment parameters [38].

B.3. Practicum Accuracy Validation

The survey includes a practicum validation component to confirm that the practicum simulation is accurately represents its real-life counterpart. The survey used a 5-point Likert scale for the practicum accuracy validation component, with scores ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). This component is specifically designed for the five participants with a chemistry background. The validation statements' results and overall score are presented in Table 6.

TABLE VI. PRACTICUM ACCURACY VALIDATION RESULTS

No	Statement	Score
1	The image depicted in this simulation accurately reflects the actual practicum material	95
2	The experiment's relevance is connected to the course's learning objectives	90
3	This simulation enhances students' comprehension of abstract chemical ideas	90
4	The presentation of chemical concepts does not cause misconceptions to arise	65
5	The sequence of steps is outlined in a systematic manner, ensuring clarity and logical progression	85
	Final Score (Mean)	85

The overall results of the accuracy validation for the practicum statements are excellent. The fourth statement received the lowest validation score of 65, indicating a minor misconception in the simulation. According to feedback from the survey, some respondents mentioned that the flasks do not break when dropped from a sufficient height, which is unrealistic. On the other hand, the highest received was for statement number 1, scoring 95, indicating that the depiction of objects in the practicum closely resembles their real-life counterparts.

C. Price Comparison

C.1. Traditional Practicum Comparison

To be applicable, this system needs to be affordable to education institutions. Table 7 and Table 8 compares the initial and running cost between this simulation and the traditional practicum. For the calculation we specify a class with 18 groups over 3 sessions of practicums derived from the University of Mataram. The price of the components is listed from local shops and a price book from Merck [32].

TABLE VII. INITIAL AND RUNNING COST OF THIS SYSTEM

No	Component	One-time	Annual
1	AiO computer x6	Rp5,190,000 x6	
2	Leap motion x6	Rp1,580,000 x6	
	Total	Rp40,620,000	

TABLE VIII. INITIAL AND RUNNING COST OF THE TRADITIONAL PRACTICUM

No	Component	One-time	Annual
1	Hotplate x3	Rp700,000 x3	
2	Fume hood x3	Rp23,152,500 x3	
3	Glassware set x3	Rp180,000 x3	
4	Phenol		Rp245,970
5	Sulfuric acid		Rp40,068
6	Nitric acid		Rp372,600
	Total	Rp72,097,500	Rp658,638

As shown from the tables, this system can save up to IDR 31,477,500 for the one-time purchase and up to IDR 658,638 in yearly material purchases. Additionally, due to place constraint, the traditional practicum could only hold 3 sets of lab equipment, requiring two waves of the practicum per session. It is important to note that the cost of hiring lab assistants is not included in this price comparison and would add additional fees annually.

This price difference will continue to grow as more practicums are added to the system. That is because in traditional practicums, additional practicums require more tools and materials. In contrast, this simulation application uses the same tool for operating additional practicums.

C.2. Other VR Systems Comparison

There are several controllers available for interacting with the virtual environment. Table 9 shows the prices of these controllers listed from local shops. This table shows that Leap Motion is the most affordable option among them.

TABLE IX. CONTROLLER PRICES

No	Controller	Price per unit
1	Leap motion	Rp1,580,000
2	HTC Vive	Rp19,998,600
3	Oculus Quest 3	Rp5,599,000
4	Valve Index	Rp11,368,493

There are also several systems available for displaying the virtual world to the user, with the most cost-effective option used in this research being the computer's built-in display. Other VR display systems and their respective prices are listed in Table 10.

TABLE X. VR DISPLAY PRICES

No	Controller	Price per unit
1	Desktop	-
2	Android VR Box	Rp100,000
3	HTC Vive	Rp19,998,600
4	Oculus Quest 3	Rp5,599,000
5	Valve Index	Rp17,569,517

The Android VR Box requires an Android phone to be inserted in order to display the virtual world, whereas the other devices are standalone units. As a result, the use of the Android VR Box depends on the availability of Android phones among the students using the simulation. Alternatively, providing Android devices for each setup would be necessary to ensure proper functionality, which would incur additional costs.

D. Respondents' Input

An open input section is provided at the end of the survey, allowing respondents to share their thoughts and suggestions about the application. This feedback can help explain the SUS score and help improve the usability of the application in future developments.

Some users suggested improving the grip of objects in the simulation when using the Leap Motion Controller. This could be addressed by ensuring a well-lit environment and testing different Leap Motion positioning setups. Others mentioned the need for more practice with the Leap Motion, as it is a new form of input that requires more time to master. A practice session before the practicum simulation could be the answer for that.

Additionally, some users suggested allowing the ability to view objects from multiple angles, which could improve the success rate of pouring liquid from one flask to another. During testing, some users positioned the flasks directly on top of the other flask, which should have worked but failed because the flasks were either too close or too far from the user's point of view, due to limited perspective of displaying a 3D world on a 2D display. One possible solution is to simplify the action by automatically adjusting the objects to the correct depth, or to use VR displays like the Android VR Box, which supports viewing from multiple angles.

The Android VR Box setup is possible by displaying the virtual world on the smartphone screen, which is mounted on the user's head via the VR box. Head movement is tracked using the smartphone's built-in sensors, such as the accelerometer, gyroscope, and magnetometer. These sensors work together to detect the user's head position, rotation, and tilt, allowing the point of view in the simulation to adjust accordingly.

VI. Conclusion

Based on the findings and discussion presented in this study, it can be inferred that the simulation was developed as intended, given that all test cases yielded desired results. However, the application's usability is only marginally acceptable, as indicated by its SUS score of 63,125. The simulation's accuracy in replicating the practicum for making picric acid has been validated. This alternative has the potential to significantly reduce costs for educational institutions. Nevertheless, further improvements are required to enhance the usability of the application.

To enhance the realism of the practicum, future development of the simulation could include features like flask breaking animations or integrating it with Android devices as a VR headset. Additionally, more research is required to identify the best setup for the Leap Motion device in order to enhance the accuracy of hand gesture tracking during the simulation. Alternatively, the Leap Motion device could be substituted with a conventional VR controller, potentially improving the hand capture's accuracy but at the expense of realistic hand gestures and increased cost.

Beyond the specific context of making picric acid, further research could explore the application of Leap Motion and 3D virtual reality simulations in other areas of chemistry education, as well as in fields such as physics, biology, and so on.

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